

# **Modeling of the Combined Heat and Power System of Greater Copenhagen**

Esben Friis-Jensen (s042244)

Kongens Lyngby 2010

Technical University of Denmark  
DTU Management  
Building 424, DK-2800 Kongens Lyngby, Denmark  
info@man.dtu.dk  
www.man.dtu.dk

Technical University of Denmark  
Informatics and Mathematical Modelling  
Building 321, DK-2800 Kongens Lyngby, Denmark  
Phone +45 45253351, Fax +45 45882673  
reception@imm.dtu.dk  
www.imm.dtu.dk

# Preface

---

This M.sc thesis was carried out at the Technical University of Denmark and the company Ea Energy Analysis A/S, under supervision of Thomas K. Stidsen and Lars Bregnbæk.



# Summary

---

The Combined Heat and Power System of Greater Copenhagen, which is a district heating system supplied by CHP plants, is one of the largest of its kind. It is a complex system with different kind of production units, transmission lines and heat storages. Huge costs are related to running the total system, thus efficient planning is needed.

Today the daily planning for the system is done by a divided process, where production companies create production plans, which are then re-optimized by the heat companies taking into account transmission limitations and storages. The re-optimizations are done using a mathematical mixed integer linear program model known as The Katja Model.

In the Katja model the production units are included with a fixed production level combined with marginal costs of changing this production level. In this thesis, a much more detailed modeling of the production units of the CHP system is introduced, called The Esben Model. By modifying/extending The Katja Model with The Esben Model, The E&K Model, is derived. This combined model is capable of finding a least cost plan for the entire system in a single process and at the same time represents the production units in a more realistic way than in the original Katja Model.

Tests of The E&K Model using real-life datasets are done. In the initial tests it is seen that the complex modeling of a special energy tax makes the solver run out of memory. Thus the modeling of this should be studied further. When running the model without this energy tax a 24 hour plan is found within a minute and as consequence the energy tax are removed from the model in the

remaining tests.

These remaining tests shows how The E&K Model is capable of representing technical and economical details such as unit commitment, complex production profiles, flexibility with respect to electricity prices and costs, multi-fuel boilers, production level dependent fuel efficiencies, emissions and the taxes on these and much more. All this shows the many capabilities of the powerful and flexible tool which could be used to represent many other CHP systems.

In addition to The E&K Model a framework capable of simulating an optimal periodic rescheduling process is presented. A periodical rescheduling process should diminish the uncertainty of the information which the planning is based upon. A test carried out with the framework illustrates that it is important that the quality of the information is increased as time progresses if the periodical rescheduling should have any effect.

# Resumé

---

Storkøbenhavns samlede kraftvarmesystem, der er et fjernvarme system, som primært modtager varmen fra kraftvarmeværker er et af de største af sin slags. Systemet er komplekst med forskellige produktionsenheder, transmissionsforbindelser og varmelagre. Da der er store omkostninger forbundet til at operere systemet er der behov for effektiv planlægning.

I dag planlægges der for systemet i en todelt proces hvor produktionsselskaberne udformer produktionsplaner, som derefter re-optimeres af varmeselskaberne med hensyn til transmissionsbegrænsninger og varmelagerne. Re-optimeringerne bliver udført vha. en matematisk MILP model kendt som Katja Modellen.

I Katja Modellen er produktionsenhederne repræsenteret ved et fastsat produktionsniveau kombineret med marginale omkostninger ved at ændre dette produktionsniveau. I denne tesis introduceres Esben Modellen, der er en langt mere detaljeret modellering af produktionsenhederne i kraftvarmesystemet. Ved at ændre/udvide Katja Modellen med Esben Modellen opnås en ny model, E&K Modellen. Denne kombinerede model kan bruges til at finde en plan med minimal omkostning i én proces. Samtidigt er produktionsenhederne i denne model repræsenteret på en mere realistisk måde end i Katja Modellen.

Test af E&K Modellen med realistiske datasæt udføres. I de første testkørsler ses det at den komplekse modellering af en speciel energiafgift får problemløseren til at løbe tør for hukommelse. Derfor skal modelleringen af denne studeres nærmere. Når modellen køres uden denne energiafgift kan en 24 timers plan findes indenfor et minut. Som en konsekvens af dette fjernes energiafgiften fra modellen i resten af testkørslerne.

De efterfølgende testkørsler viser hvordan E&K Modellen kan repræsentere tekniske og økonomiske detaljer som: unit commitment, komplekse produktionsprofiler, fleksibilitet med hensyntagen til prisen på elektricitet og omkostninger, multi-brændsel kedler, produktionsniveauafhængige brændselseffektiviteter, udledning af forurening og beskatningen af dette og meget andet. Alt dette viser de mange muligheder med det stærke og fleksible værktøj, som kan bruges til at repræsentere mange andre kraftvarmesystemer.

Udover E&K Modellen præsenteres et framework, som kan simulere en optimal periodisk replanlægnings proces. En periodisk replanlægningsproces skal minimere usikkerheden ved de informationer planlægningen baseres på baggrund af. Én test udført med dette framework viser det er vigtigt at kvaliteten af informationerne stiger, som tiden skrider frem, hvis en periodisk replanlægning skal have en effekt.

# Acknowledgements

---

I would like to thank my supervisors Thomas K. Stidsen and Lars Bregnbæk, for guidance during the creation of this thesis. Furthermore a thanks goes to all the employees at Ea Energy Analysis, which has made the process of writing the thesis a lot more fun and to Mikkel Korsbæk and Lars Lind from VLE, which has helped me to understand the complex CHP system. Finally a special thanks goes to my father for helping me by proofreading the thesis.



# List of Symbols

---

## Symbols used in The Katja Model

### Sets

- $t \in \mathcal{T}$ : Set of time segments
- $s \in \mathcal{S}$ : Set of change steps.
- $e \in \mathcal{E}$ : Set of energy carriers (The carriers of heat)
- $a \in \mathcal{A}$ : Set of areas
- $u \in \mathcal{U}$ : Set of units
- $v \in \mathcal{V}$ : Set of storages
- $(a_1, e, a_2) \in \mathcal{X}$ : Set of transmission lines for energy carrier  $e$  between areas  $a_1$  and  $a_2$
- $u_a \subset \mathcal{U}$ : Set of units  $u$  in area  $a$
- $v_a \subset \mathcal{V}$ : Set of storages  $v$  in area  $a$
- $u^p \subset \mathcal{U}$ : Set of units capable of maintaining pressure
- $z \in \mathcal{Z}$ : Set used dually to represent storage states and to index storage capacities. (in, out, level)
- $z^{act} \subset \mathcal{Z}$ : Set with the active states of a storage (in, out)

- $a_{e_1, e_2}^{e_1 e_2} \subset \mathcal{A}$ : The areas where energy carrier  $e_1$  can be transformed into energy carrier  $e_2$
- $u_{u_1}^{no\Delta h} \subset \mathcal{U}$ : Set of units which cannot change their production load at the same time as unit  $u_1$
- $u_{e_1, e_2}^{both} \subset \mathcal{U}$ : Set of units which must produce both energy carriers  $e_1$  and  $e_2$  when online
- $u_{e_1, e_2}^{induce} \subset \mathcal{U}$ : Set of units for which production of energy carrier  $e_1$  forces production of energy carrier  $e_2$ .

## Parameters

- $A_{a, e, t}^{h-demand} \in \mathbb{R}$ : The demand for energy carrier  $e$  in area  $a$  in time segment  $t$  (MJ/s)
- $U_{u, e, t}^{h-plan}$ : Initial plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $U_{u, e, t}^{h-cost+}$ : Marginal cost for changing the plan for production of energy carrier  $e$  upwards for unit  $u$  in time segment  $t$  (money/MJ/s)
- $U_{u, e, t}^{h-cost-}$ : Marginal cost for changing the plan for production of energy carrier  $e$  downwards for unit  $u$  in time segment  $t$  (money/MJ/s)
- $s_{length}$ : The length of a change step (MJ/s)
- $q$ : The percentage the marginal costs are changed each time a new step  $s$  is reached
- $\underline{U}_u^{on} \in \mathbb{N}^+$ : The minimum number of time segments the unit  $u$  must stay online if started for production
- $\underline{U}_u^{off} \in \mathbb{N}^+$ : The minimum number of time segments  $u$  must stay offline if shut down for production
- $\bar{U}_{u, e, t}^{h-out} \in \mathbb{R}^+$ : Maximum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\underline{U}_{u, e, t}^{h-out} \in \mathbb{R}^+$ : Minimum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\bar{U}_{u, t}^{h-out} \in \mathbb{R}^+$ : Maximum heat production load in total for unit  $u$  in time segment  $t$  (MJ/s)
- $\underline{U}_{u, t}^{h-out} \in \mathbb{R}^+$ : Minimum heat production load in total for unit  $u$  in time segment  $t$  (MJ/s)

- $\bar{U}_{u,e}^{\Delta h-out} \in \mathbb{R}^+$ : Maximum change in heat production load of energy carrier  $e$  possible for unit  $u$  from one time segment to the next (MJ/s)
- $U_{u^p,e}^{pinit} \in \{0,1\}$ : 1 if unit  $u^p$  is pressure maintainer for the networks of energy carrier  $e$  in the initial time segment
- $\underline{U}_e^{pon} \in \mathbb{N}$ : The number of time segments the unit assigned as pressure maintainer for system of energy carrier  $e$  must stay pressure maintainer.
- $U_{u,e}^{ecapratio}$ : Percent of each unit of total capacity used to produce energy carrier  $e$  on unit  $u$ .
- $V_v^{h-ini} \in \mathbb{R}^+$ : Initial content for storage  $v$
- $V_v^{h-term} \in \mathbb{R}^+$ : Terminal content for storage  $v$
- $\underline{V}_{v,z}^{on} \in \mathbb{N}$ : Minimum number of time segments the storage  $v$  must remain in state  $z$
- $\bar{V}_{v,z,t}^h \in \mathbb{R}^+$ : Maximum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\underline{V}_{v,z,t}^h \in \mathbb{R}^+$ : Minimum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\bar{V}_v^{\Delta h} \in \mathbb{R}^+$ : Maximum change in load for storage  $v$  (MJ/s/t)
- $X_{a_1,e,a_2}^{h-ini}$ : The initial transmission load for transmission line  $(a_1, e, a_2)$
- $\underline{X}_{a_1,e,a_2}^{on} \in \mathbb{N}$ : The minimum number of time segments the transmission line  $(a_1, e, a_2)$  must be online
- $\bar{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Maximum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\underline{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Minimum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\bar{X}_{a_1,e,a_2}^{\Delta h} \in \mathbb{R}^+$ : Maximum change in transmission load for transmission line  $(a_1, e, a_2)$

## Variables

- $\mu_{u,e,t,s}^{h-plan+} \in [0, slength]$ : The upwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  in change step  $s$  (MJ/s)

- $\mu_{u,e,t,s}^{h-plan-}$   $\in [0, slength]$ : The downwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  in change step  $s$  (MJ/s)
- $\mu_{u,e,t}^{h-out}$   $\in \mathbb{R}^+$ : The heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-plan+on}$   $\in \{0, 1\}$ : 1 if the production for production of energy carrier  $e$  for unit  $u$  is changed upwards in time segment  $t$
- $\mu_{u,e,t}^{h-plan-on}$   $\in \{0, 1\}$ : 1 if the production for production of energy carrier  $e$  for unit  $u$  is changed downwards in time segment  $t$
- $\alpha_{e_1,e_2,a,t}^{e2e}$   $\in \mathbb{R}^+$ : The amount of energy carrier  $e_1$  converted to energy carrier  $e_2$  in area  $a$  in time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{start}$   $\in \{0, 1\}$ : 1 if unit  $u$  is started for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u,e,t}^{shutdn}$   $\in \{0, 1\}$ : 1 if unit  $u$  is shut down for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u,e,t}^{on}$   $\in \{0, 1\}$ : 1 if unit  $u$  is online for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u,t}^{on}$   $\in \{0, 1\}$ : 1 if unit  $u$  is online for production of one or more energy carriers in time segment  $t$
- $\mu_{u,e,t}^{\Delta h-out}$   $\in \mathbb{R}^+$ : Change in production load of energy carrier  $e$  for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u,t}^{\Delta h-on}$   $\in \{0, 1\}$ : 1 if the production is changed for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u^p,e,t}^p$   $\in \{0, 1\}$ : 1 if unit  $u^p$  is pressure maintainer for system of energy carrier  $e$  in time segment  $t$
- $\mu_{e,t}^{pchange}$   $\in \mathbb{R}^+$ : Related to binary variable 1 if there is a change in pressure maintainer for system of energy carrier  $e$
- $\mu_{u,e,t}^p$   $\in \{0, 1\}$ : 1 if unit  $u$  is pressure maintainer for system of energy carrier  $e$  in time segment  $t$
- $\nu_{v,z,t}^h$   $\in \mathbb{R}^+$ : The heat load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\nu_{v,z,t}^{on}$   $\in \{0, 1\}$ : 1 if storage  $v$  is in state  $z$  in time segment  $t$
- $\nu_{v,z,t}^{start}$   $\in \{0, 1\}$ : 1 if storage  $v$  starts to perform state  $z$  in time segment  $t$

- $\nu_{v,z,t}^{\Delta h} \in \mathbb{R}$ : Change in load from the previous time segment to time segment  $t$  (MJ/s)
- $\chi_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$  (MJ/s)
- $\chi_{a_1,e,a_2,t}^{start} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is started in time segment  $t$
- $\chi_{u,e,t}^{on} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is online in time segment  $t$
- $\chi_{a_1,e,a_2,t}^{\Delta h} \in \mathbb{R}^+$ : Change in transmission load for transmission line  $(a_1, e, a_2)$  from the previous time segment to time segment  $t$  (MJ/s)

## Symbols used in The Esben Model

### Sets

- $t \in \mathcal{T}$ : Set of time segments
- $e \in \mathcal{E}$ : Set of energy carriers
- $u \in \mathcal{U}$ : Set of units
- $g \in \mathcal{G}$ : Set of technologies
- $f \in \mathcal{F}$ : Set of fuels
- $u_{u_1}^{no\Delta h} \subset \mathcal{U}$ : Set of units which cannot change their production load at the same time as unit  $u_1$
- $g_{gath} \subset \mathcal{G}$ : Technologies of the type: Gathering
- $g_{hob} \subset \mathcal{G}$ : Technologies of the type: Heat only boilers
- $g_{bpr} \subset \mathcal{G}$ : Technologies of the type: Back-pressure
- $g_{cnd} \subset \mathcal{G}$ : Technologies of the type: Condensing
- $g_{heatonly} \subset \mathcal{G}$ : Technologies which only has a heat output. This set is created if other heat only technologies should be added to the model besides from  $g_{hob}$
- $g_{elonly} \subset \mathcal{G}$ : Technologies which only has an electricity output. This set is created if other electricity only technologies should be added to the model besides from  $g_{cnd}$

- $g_{el} \subset \mathcal{G}$ : Technologies with a electricity output
- $g_{heat} \subset \mathcal{G}$ : Technologies with a heat output
- $g_u \subset \mathcal{G}$ : Technologies within unit  $u$
- $g_f \subset \mathcal{G}$ : Technologies taking fuel  $f$  as input. If no fuel is assigned to a technology it only takes energy from other technologies as input.
- $g_{g_1}^{on} \subset \mathcal{G}$ : Technologies which can only be online if the technology  $g_1$  is online
- $(g_1, e, g_2) \in \mathcal{GX}$ : The feasible transmission lines for energy carrier  $e$  between technologies  $g_1$  and  $g_2$
- $r \in \mathcal{R}$ : Set of possible of fuel ratios used for the modeling of energy tax

## Parameters

- $B_t^{el.price} \in \mathbb{R}$ : The price of electricity in time segment  $t$  (money/MJ/s)
- $B_t^{NO_x-Tax} \in \mathbb{R}$ : The tax on  $NO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{SO_x-Tax} \in \mathbb{R}$ : The tax on  $SO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{CO_2-qprice} \in \mathbb{R}$ : The  $CO_2$  quote price in time segment  $t$  (money/kg)
- $F_{f,t}^{price} \in \mathbb{R}$ : The price of fuel  $f$  in time segment  $t$  (money/MJ/s)
- $F_f^{CO_2} \in \mathbb{R}$ : The emission of  $CO_2$  for fuel  $f$  (kg/MJ/s)
- $F_f^{SO_x} \in \mathbb{R}$ : The emission of  $SO_x$  for fuel  $f$  (kg/MJ/s)
- $G_g^{Marg.fe} \in \mathbb{R}$ : The marginal fuel/input efficiency for technology  $g$
- $G_g^{interceptfu} \in \mathbb{R}$ : The interception of the fuel/input line on the fuel axis in an input/output diagram
- $\underline{G}_g^{on} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay online if started
- $\underline{G}_g^{off} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay offline if shut down
- $G_g^{Marg.C_b} \in \mathbb{R}$ : The marginal  $C_b$  value used for technologies  $g_{bpr}$
- $G_g^{Interceptbpr} \in \mathbb{R}$ : The interception of the back-pressure line on electricity axis in an heat/electricity output diagram for technologies  $g_{bpr}$  (MJ/s).

- $G_g^{NO_x} \in \mathbb{R}$ : The emission of  $NO_x$  by technology  $g$  (kg/MJ/s)
- $G_g^{DeSO_x} \in [0; 1]$ : The  $DeSO_x$  factor for technology  $g$
- $G_g^{fixstartcost} \in \mathbb{R}$ : The fixed startup cost for technology  $g$  (money)
- $G_{g,f}^{startfuel} \in \mathbb{R}$ : The amount of fuel used to start technology  $g$
- $G_g^{omvcost} \in \mathbb{R}$ : The variable operating and maintenance cost for technology  $g$ . Measured in money/MJ/s input.
- $\bar{G}_g^{\Delta out} \in \mathbb{R}$ : Maximum change in output load from one time segment to the next for technology  $g$
- $\bar{G}_{g,t}^{out} \in \mathbb{R}$ : Maximum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $\underline{G}_{g,t}^{out} \in \mathbb{R}$ : Minimum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $G_{g_1,g_2}^{depmaxshare} \in [0; 1]$ : The output load by technology  $g_1$  must at maximum be equal to this share of the output load of  $g_2$  if online
- $G_{g_1,g_2}^{depminshare} \in [0; 1]$ : The output load by technology  $g_1$  must at minimum be equal to this share of the output load of  $g_2$  if online
- $G_{g_1,e,g_2,t} \in \mathbb{R}$ : The maximum load on the transmission line ( $g_1, e, g_2$ ) in time segment  $t$  (MJ/s)
- $U_u^{tax-eff}$ : The energy taxed heat efficiency for unit  $u$
- $F_{f,t}^{etax}$ : The energy tax pr. MJ/s used of fuel  $f$  to produce heat in time segment  $t$
- $ratio_r \in [0; 1]$ : The value of a certain ratio  $r$  used in the modeling of the energy tax

## Variables

- $\gamma_{g,t}^{start} \in \{0, 1\}$ : 1 if technology  $g$  is started in time segment  $t$
- $\gamma_{g,t}^{shutdn} \in \{0, 1\}$ : 1 if technology  $g$  is shut down in time segment  $t$
- $\gamma_{g,t}^{on} \in \{0, 1\}$ : 1 if technology  $g$  is online in time segment  $t$
- $\gamma_{g,t}^{fuel} \in \mathbb{R}$ : The amount of fuel loaded into the technology  $g$  in time segment  $t$  (MJ/s)
- $\gamma_{g,t}^{el-out} \in \mathbb{R}^+$ : The electricity output load from technology  $g$  (MJ/s)

- $\gamma_{g,t}^{h-out} \in \mathbb{R}^+$ : The heat output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{out} \in \mathbb{R}^+$ : The total output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{\Delta out} \in \mathbb{R}^+$ : Change in output load for technology  $g$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-out} \in \mathbb{R}^+$ : The heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,t}^{\Delta h-on} \in \{0, 1\}$ : 1 if the production is changed for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\gamma\chi_{g_1,e,g_2,t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(g_1, e, g_2)$  in time segment  $t$  (MJ/s)
- $\mu_{u,f,t}^{etax} \in \mathbb{R}^+$ : The energy tax to be payed by unit  $u$  for the use of fuel  $f$  in time segment  $t$
- $\varphi_{r,u,f,t}^{ratio} \in \{0, 1\}$ : 0 if the unit  $u$  consumes a ratio  $r$  of fuel  $f$  out of all the fuels used on the unit in time segment  $t$





# Contents

---

<b>Preface</b>	<b>i</b>
<b>Summary</b>	<b>iii</b>
<b>Resumé</b>	<b>v</b>
<b>Acknowledgements</b>	<b>vii</b>
<b>List of Symbols</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation for the Thesis . . . . .	1
1.2 Purpose of the Project . . . . .	4
1.3 Reading This Thesis . . . . .	5
1.4 Thesis Structure . . . . .	5
<b>2 CHP Systems</b>	<b>7</b>

---

2.1	Production Units . . . . .	8
2.2	Heat Accumulators - Storages . . . . .	17
2.3	Transmission Networks . . . . .	17
2.4	The Costs of Running a CHP System . . . . .	18
2.5	Summary . . . . .	18
<b>3</b>	<b>The CHP System of Greater Copenhagen</b>	<b>19</b>
3.1	Physical Structure of the CHP System . . . . .	20
3.2	The Economy of Running The System . . . . .	26
3.3	Summary . . . . .	30
<b>4</b>	<b>The Katja Model</b>	<b>31</b>
4.1	Modeling Technique . . . . .	31
4.2	The Input . . . . .	33
4.3	The Problem . . . . .	37
4.4	The Output . . . . .	50
4.5	Summary . . . . .	50
<b>5</b>	<b>The Esben Model</b>	<b>53</b>
5.1	The Extension - Generation Technologies . . . . .	53
5.2	The Objective . . . . .	68
5.3	Complexity of The Model . . . . .	72
5.4	Summary . . . . .	72

---

<b>6</b>	<b>Planning with Uncertain Information</b>	<b>75</b>
6.1	Solution Approach . . . . .	75
6.2	The Framework . . . . .	79
6.3	Summary . . . . .	82
<b>7</b>	<b>Results and Discussion</b>	<b>83</b>
7.1	Implementation in GAMS . . . . .	83
7.2	Datasets . . . . .	85
7.3	Testing The E&K Model . . . . .	85
7.4	General Results . . . . .	86
7.5	Production Unit Specific Results . . . . .	90
7.6	Test of the Rescheduling Framework . . . . .	95
7.7	Summary . . . . .	97
<b>8</b>	<b>Conclusion</b>	<b>99</b>
8.1	The Project . . . . .	99
8.2	The Model . . . . .	100
8.3	The Rescheduling Framework . . . . .	101
8.4	The Test Results . . . . .	101
8.5	The Future . . . . .	103
<b>A</b>	<b>Appendix</b>	<b>105</b>
A.1	The Katja Model . . . . .	106
A.2	The Esben Model . . . . .	117

---

<b>B Implementation Report</b>	<b>125</b>
B.1 Short Introduction to The Esben Model . . . . .	125
B.2 The Temporal Dimension . . . . .	126
B.3 Fuels . . . . .	126
B.4 Market Data . . . . .	126
B.5 Technology Networks . . . . .	127
B.6 Objective . . . . .	129
B.7 Implemented Units . . . . .	130
<b>C Results</b>	<b>159</b>
C.1 24 Hour Plan made with DA Dataset 1 . . . . .	160
C.2 24 Hour Plan made with DA Dataset 2 . . . . .	163
C.3 24 Hour Plan made with DA Dataset 3 . . . . .	166
C.4 24 Hour Plan Made With ID Moving Horizon Dataset . . . . .	169
C.5 24 Hour Plan Made With ID Initial Prognoses . . . . .	173
C.6 24 Hour Plan Made With ID Realized Values . . . . .	176

# Introduction

---

## 1.1 Motivation for the Thesis

Every day the world population is growing. Today the population of the world is close to 7 billion [6]. Together with this growth there has also been a huge advance in technology and industry, which has led to many luxuries, especially in the western world. Some of these luxuries are cars, hot water and heated households.

In 1973/74 the energy crisis hit the western world. At this time the energy consumption was extremely high due to the many technologies using a large amount of fossil fuel. The crisis created a focus upon the scarce resources of the world and changes were needed.

In Denmark one of the initiatives was to strengthen the focus on public heat supply. One of the ideas was to increase the number of combined heat and power plants (CHP plants) co-generating heat and electricity. These plants had shown to reduce the amount of fuel used to 30 % compared with separate generation. Another focus was to increase the use and development of district heating (DH). In district heating you have a number of plants generating the heat, which is then sent out to the households as water or steam through transmission lines.

The initiatives were followed strongly and the motivation was increased due to a strengthened focus upon environmental impact of electricity and heat production. As a result 6 out of 10 people receive heat from a public heat supply i.e DH in Denmark today. One of the most extensive DH systems using CHP (CHP systems) in Denmark and the world is the one of Greater Copenhagen. The Greater Copenhagen CHP system consists of 4 CHP plants, 4 waste incineration plants and a transmission network which supply heat to an area of more than 50 million square meters. There are huge costs related to running the total system of production and distribution: Fuel, taxes etc. thus there is a need for efficient planning. [20] [4].

## VLE

In January 2003 the Danish electricity market was liberalized. Before this happened there was only one production company owning all the CHP plants in Denmark, namely Energi E2. Thus in Greater Copenhagen, Energi E2 planned the daily heat load in cooperation with the public owned companies Vestegns Kraftvarmeselskab I/S (VEKS), Centralkommunernes transmissionselskab I/S (CTR) and Københavns Energi (KE), which owns the transmission networks distributing the heat. When the electricity market was liberalized Energi E2 became part of a new company DONG Energy A/S and another company, Swedish Vattenfall A/S entered the market of CHP. Thus today these two large companies and number of smaller waste incineration companies produce electricity and heat in Greater Copenhagen.

To keep a fair competition the production companies can no longer have total insight in the CHP system, thus a single production company can no longer plan the entire heat production. Due to this VEKS, CTR and KE have formed Varmelastenheden (VLE), which has the job of making sure that the production and distribution of the heat load in Greater Copenhagen are done in a least cost way [16]. This is done to pursue the objectives for Danish heat supply, which are [4]:

- Supply security
- Cost efficiency
- Environmental impact
- Consumers first

In figure 1.1 the workflow of creating a heat load plan for Greater Copenhagen is illustrated and the following is a more specific description of the steps [3]:

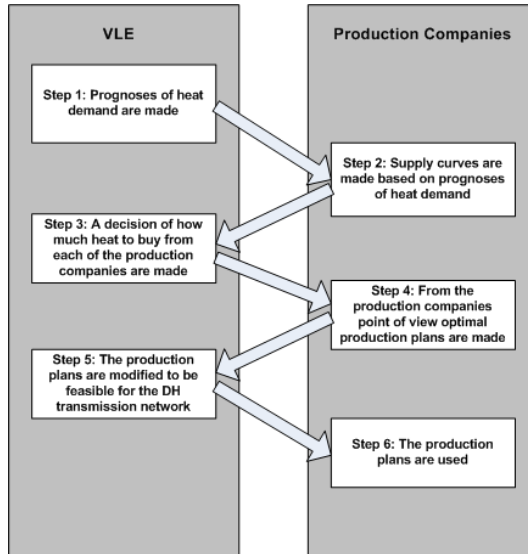


Figure 1.1: The workflow involving VLE and the production companies: DONG and Vattenfall

1. VLE makes prognoses of the demand of heat for each of the 24 hours of the following day and sends these to the production companies
2. Each of the production companies looks at the prognoses and calculates supply curves on the heat. These curves shows the price of the heat as a function of the amount. These curves are sent to VLE
3. VLE chooses how much heat to buy from each of the production companies in order to get a minimal cost. Then orders of heat are sent to the production companies
4. Based on these orders each of the production companies makes a from their point of view optimal production plan for the next day taking no account of the limitations of the transmission network. The plans gives an amount to be produced at a given plant at a given hour and the marginal cost of changing the production plan in this hour. These plans and the marginal costs of changing the plan are sent to VLE
5. VLE use the production plans, the related marginal costs and the demand of heat to find an optimal plan for the entire system i.e. with regards to both production, storage and transmission. This plan is created with an objective of keeping the changes to the original production plan at a minimum.

6. When this heat load plan has been created VLE sends the production part of the plan to the production companies, which uses this final plan

New demand prognoses and marginal costs of changing a plan are produced 3 times during the day of operation. Based on these changes VLE tries to re-optimize the plans.

## The Performance Follow-up

As seen in the workflow the heat load plans for a given day are made based on production plans created by the production companies. Because of this the solution used might not be optimal for the entire system. Today a performance follow-up is made, where VLE attempts to make an ideal plan. This perfect plan is then used to evaluate the used heat load plans. This gives VLE some bargaining power on the production companies. The mentioned follow-up is done using an excel-sheet, which gives some limitations. e.g. the models are simple and the limitations of the transmission network are not taken into account. VLE needs a performance follow-up tool which optimizes the entire system of production, storage and transmission in a single process. This tool could be used to create a better performance follow-up which could lead to better plans.

## 1.2 Purpose of the Project

The main objective of the project described in this thesis is to develop a mixed integer linear program model (MILP Model) of the production units of Greater Copenhagen. The model should represent the technical and economical situation for the production units and especially the CHP units in a high level of detail. Among technical details are capacities, fuel efficiencies, online/offline time, and special production profiles for units. While the economy of running the system should be represented by a cost function which includes prices on electricity and fuels, emission taxes and operating and maintenance costs. By combining this model with a model used by VLE to create heat load plans the model should be capable of finding an optimal plan for the entire CHP system in a single process. This combined model could then be used as a new performance follow-up tool.

The daily planning of the CHP system of Greater Copenhagen is based on prognoses e.g. for demand and electricity prices. These prognoses are uncertain. One method to deal with this uncertainty is to reschedule periodically, based on the newest information. VLE tries to do this by re-optimizing the plans

3 times a day. Therefore a secondary objective of this project is to create a basic framework capable of simulating an optimal period rescheduling process for analytical purposes. This framework could be used to create an even stronger performance follow-up tool.

The model and the framework should be implemented in GAMS (General Algebraic Modeling System) [15], which is a good and flexible program for implementation of MILP models. Both the model and framework should be flexible in order to make them applicable for other purposes e.g. long term scenarios. Analysis and simulations based on real life datasets should be done in order to test and show the applications of these new tools.

The project has been carried out in cooperation with VLE and the consultancy firm Ea Energy Analysis A/S. The cooperation with VLE has been done in order to achieve an acceptable scale of realism and their acceptance of a model which they could use for performance follow-up.

## 1.3 Reading This Thesis

The reader of this thesis should have a basic knowledge about mixed integer linear programming and physics. The thesis will give a basic introduction to CHP, the economy of producing and distributing heat and the implementation language GAMS, which should be sufficient for a reader without knowledge about these.

## 1.4 Thesis Structure

This thesis is divided into 8 chapters. This first chapter gives an introduction to the purpose of the project described in this thesis. The following two chapters give a general introduction to CHP systems and a specific introduction to the system of Greater Copenhagen. Then in chapter 4 The Katja Model used by VLE to create daily heat load plans is introduced before presenting The Esben model in chapter 5 which is a detailed production model extension to The Katja model creating The E&K Model. In chapter 6 the periodical rescheduling framework is introduced. In chapter 7 different simulations and tests are carried out to evaluate and discuss the capabilities and performance of the model and the framework. Finally chapter 8 sums up the thesis with a conclusion.



# CHP Systems

---

This chapter gives an introduction to CHP supplied DH systems, which in this thesis is referred to as CHP systems. A basic illustration of a CHP system is shown in figure 2.1.

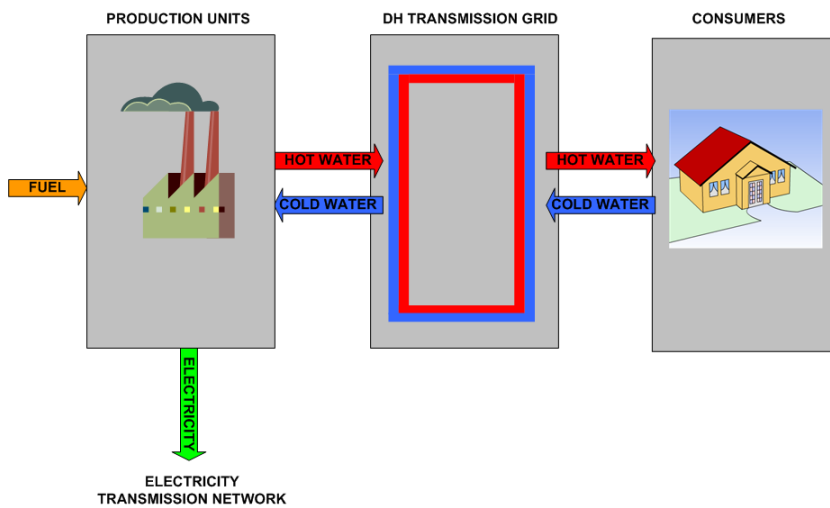


Figure 2.1: CHP system

As seen in the illustration a number of different production units, e.g. CHP units, which are typically placed at production plants utilize fuel to produce heat carried by water. This hot water is then used to heat the hot water of the DH transmission grid of pipelines, which then satisfies the demand of heat from the consumers, e.g. the households by heating the water in the distribution systems. When the heat has been utilized the cold water returns through the transmission grid to the production units to be reheated and the process restarts [29]. As shown in the illustration some of the production units, i.e. CHP production units, also has a production of electricity which is sent to a electricity transmission grid. In this thesis and in the model to be introduced, the electricity transmission network and demand related to this will only be represented by the price of electricity. This is because VLE only plans the heat load and therefore the possible income from electricity production is the only thing which must be taken into account.

In the basic example the heat was carried by water. But for some systems the heat is carried by steam. The reason to use steam for DH is that it has a higher temperature which could be needed in e.g. factories. However today in many modern cities, without much industry these kind of temperatures are not needed and because steam pipelines have a high losses and maintenance cost, water pipelines are preferred[7].

In the following the CHP system is described in greater detail.

## 2.1 Production Units

In CHP systems the heat is primarily produced at the CHP units. To give an understanding of why this is the case the internal mechanisms of the different kind of production units will be introduced. Initially the mechanisms of production units only capable of producing heat or electricity are described.

### Boiler Units

A boiler unit is a simple production unit only capable of producing heat. The simple process is illustrated in figure 2.2. A boiler is fired using fuel. Cold water is then send into the boiler and is heated until it turns into high pressure and high temperature steam which is the output of the boiler. This steam is then used to heat DH water or sent directly to a steam based DH system.

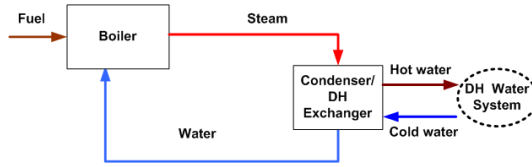


Figure 2.2: The process of a boiler unit

## Condensing Units

A condensing unit only produces electricity. The components making it possible to produce electricity are a turbine and a generator. A turbine uses pressurized input to spin blades running the generators of electricity. In general you divide turbines into two categories. The turbines utilizing steam and the turbines utilizing gas. When the pressurized input goes through the turbine it loses some of the pressure and temperature. Some turbines are built in such a way that they are capable of using input of a certain pressure. High pressure, intermediate pressure and low pressure turbines exist defining the amount of pressure needed in the input to run the turbine. The pressurized output from a turbine using a higher pressure steam still contains enough pressure to be used in a turbine using a lower pressure steam. Thus sequences of turbines can be built in order to generate as much electricity as possible. In many cases these sequences are built into a single turbine creating a multistage turbine. In figure 2.3 the process of a condensing steam turbine unit is illustrated. Water is heated to high-pressure steam by a boiler which is then sent through a multistage turbine to generate electricity. When the steam has gone through the turbine it is partially condensed with a temperature and pressure too low to use it for heating purposes. Instead the output steam is sent to a condenser cooling it to water using water from the sea. When cooled the water is sent to the boiler to restart the process [27].

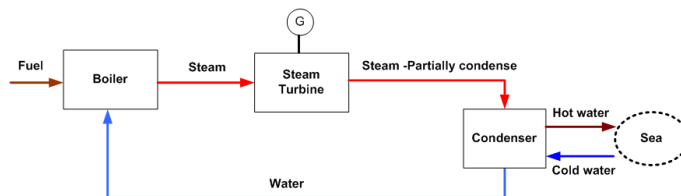


Figure 2.3: The process of a condensing unit

## CHP Units

When electricity is produced at a condensing unit the heat generated throughout the production is lost. CHP units are built in such a way that they are capable of sending the heat on to a DH system instead of a seawater condenser. This makes them more efficient than condensing units and furthermore they are normally better to use for heat production than boiler units, because electricity has to be created anyway. In the following the internal mechanisms of the different kinds of CHP units and the resulting output profiles are introduced.

### Back-Pressure Units

One of the typical CHP units is the back-pressure unit. The process of such an unit with a steam turbine is illustrated in figure 2.4. The process is almost the same as for a condensing unit. The difference is that the turbine does not utilize all the energy from the steam resulting in a output steam with a temperature high enough to be used to heat DH water. This heat exchange process is done in a condenser where the steam is cooled using the DH water instead of sea water as it was the case for the condensing unit.

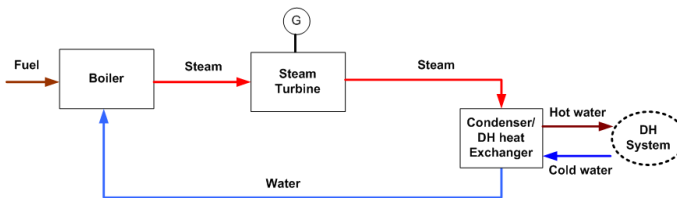


Figure 2.4: The process of a back-pressure unit

This process results in a fixed relationship between production of heat and electricity. For a generic back-pressure unit this fixed relationship is given by a constant known as  $C_b$ . In figure 2.5 the output profile for such an unit is illustrated using a electricity-heat diagram. The slope of the back-pressure line is given by  $C_b$ .

### Extraction Units

An extraction unit is a very flexible CHP unit. The process of this unit with a steam turbine can be seen in figure 2.6. In an extraction unit the steam can

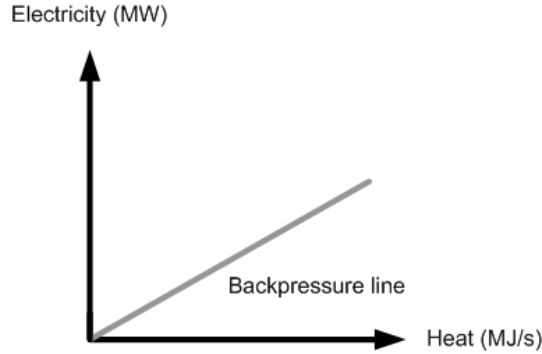


Figure 2.5: The output profile for a generic back-pressure unit

be extracted from the turbine before going all the way through. This extracted steam can then be sent to a condenser exchanging heat to the DH system. The steam not extracted goes all the way through the turbine, which results in an output steam which cannot be used for the DH system therefore it is sent to a sea water condenser. Thus if no steam is extracted along the way the unit only generates electricity like a condensing unit. [27].

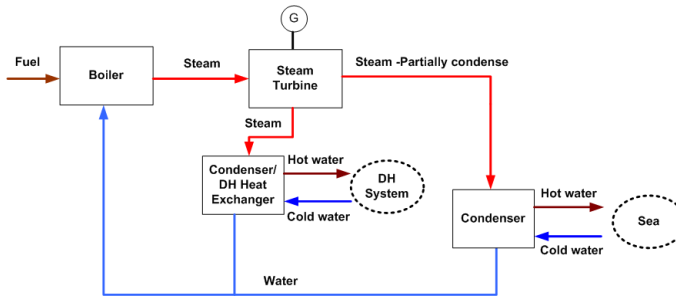


Figure 2.6: The process of an extraction unit

Due to the extraction possibility an extraction unit does not have a fixed relationship between production of heat and electricity, which makes it very flexible. The output profile for a generic extraction unit is given in figure 2.7. A production point can be chosen anywhere within an area limited by the bottom back-pressure line with slope  $C_b$  and the top  $C_v$ -line with a slope known in absolute value as  $C_v$ . The black lines parallel to the top  $C_v$ -line indicates that the fuel used for production is the same for all points a long one of these lines [27]. Thus one way of looking at this is that initially the unit utilize fuel to create heat and electricity in a fixed relationship following the back-pressure line, then

if more electricity is needed some or all of the heat generated can be exchanged to electricity with an exchange rate given by the  $C_v$  value.

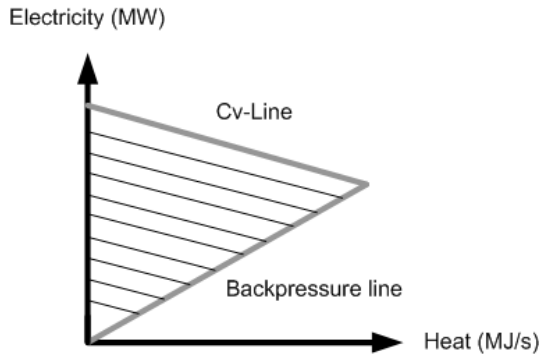


Figure 2.7: The output profile for a generic extraction unit

## Gas Turbine Units

Until now the processes shown has been for units with steam turbines. In figure 2.8 the process of a gas turbine unit is seen. A gas turbine utilize gas and air to produce electricity. In the process exhaust gas is created, which can be used to heat DH water. Alternatively the exhaust gas can be sent to a steam generator in order to use it in a DH steam system. A gas turbine typically has a fixed

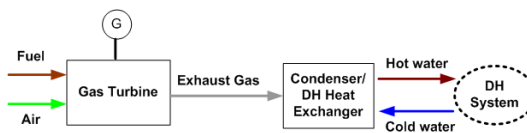


Figure 2.8: The process of a gas turbine unit

relationship between production of heat and electricity giving the same output profile as for a steam back-pressure unit [27].

## Combined Cycle Units

A combined cycle unit can be seen as a combination of a steam turbine unit and a gas turbine unit. The process is shown in figure 2.9. A boiler using

fuel delivers steam to a steam turbine generating electricity. In addition a gas turbine is used to generate electricity and the exhaust gas is converted to steam and sent to the boiler making it more efficient. The steam turbine system used can be of all the types. In the illustrated case it is a back-pressure system where heat is sent to a condenser, which cools the steam using DH water [27].

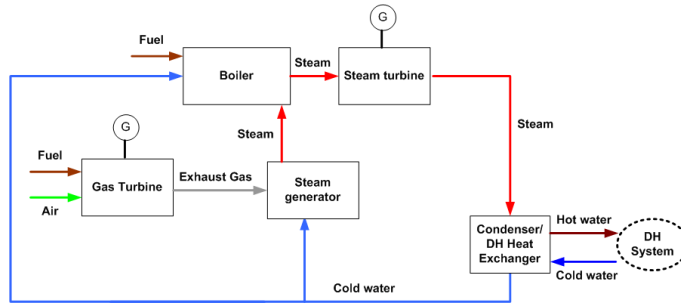


Figure 2.9: The process of a combined cycle unit

## Other Production Units

The CHP units and boiler units are normally the primary production units used in a CHP system. But other kinds of production units exists. One of them is a geothermal heat pump. The idea behind a geothermal heat pump, is to pump up water from the underground. This water has been heated by the interior heat of The Earth. In Denmark you have to fetch water 2-3 km. below the surface to get water which is hot enough. In figure 2.10 you can see an illustration of a geothermal heat pump [4].

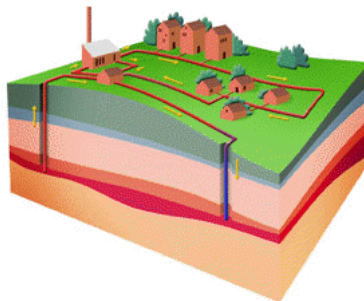


Figure 2.10: Geothermal heat pump

Fuel	Amount
Natural gas	30%
Coal	24%
Waste	23%
Biomass (Wood pellets, Straw etc.)	15%
Oil	7%

Table 2.1: Amount of different fuels used in DK in 2002

## Fuels

The production units presented use different fuels. In 2002 the fuels listed in table 2.1 were used to produce DH in Denmark.

These different fuels can be divided into two groups: fossil and non-fossil fuels. Natural gas, Coal and oil are fossil fuels, while biomass is a non-fossil fuel [4]. Fossil fuels are typically cheaper than non-fossil fuels and coal are typically cheaper than oil.

A gas turbine uses natural gas oil and the boilers used in the boiler units and steam turbine units can use the fuels they are built for. Some boilers can only use one fuel, some can use more than one and some can mix the fuels. The production units using waste as a fuel are typically placed at plants known as waste incineration plants. The units at these plants are often boiler units or back-pressure units. Using waste to generate heat and/or electricity solves the problem of getting rid of the waste in a environment-friendly way.

## Fuel Efficiencies

From when the fuel is loaded into a boiler or a gas turbine and to the point where the electricity and heat is sent out to their respective transmission systems a loss of energy happens. The amount of energy not lost during the production process is given by the efficiency for an unit.

$$\eta = \frac{\text{output}}{\text{input}} \quad (2.1)$$

This efficiency is dependent on the efficiency of the different components and the type of fuel used. The efficiency of a unit can be illustrated in an input/output diagram. A typical example of this is shown in figure 2.11. In this simple example the efficiency is the same for all input loads with a slope of the line given by  $\frac{1}{\eta}$ . But for many production units the efficiency drops when not running

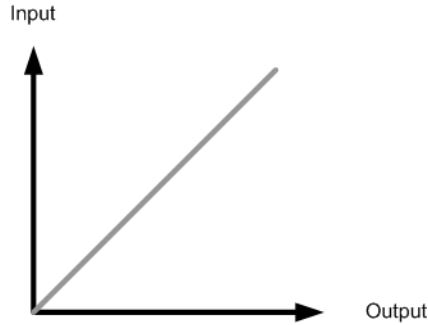


Figure 2.11: An input/output diagram illustrating the efficiency of a unit

at maximum load. By examining this loss of efficiency [3] it shows that the relationship between input and output is approximately linear, but with a in-terception on the input line above 0. This lost amount of input can be looked as the amount of fuel lost by idle running. In figure 2.12 an input/output diagram illustrates this.

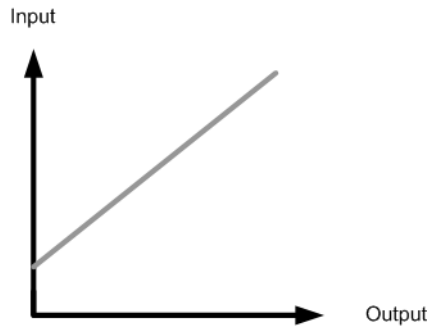


Figure 2.12: An input/output diagram illustrating the efficiency of a unit with load dependent efficiency

The efficiency is sometimes divided into a heat efficiency,  $\eta_{heat}$  and an electricity efficiency  $\eta_{el}$  given by

$$\eta_{heat} = \frac{\text{output}_{heat}}{\text{input}_{total}} \quad (2.2)$$

$$\eta_{el} = \frac{\text{output}_{el}}{\text{input}_{total}} \quad (2.3)$$

For condensing units and extraction units running in a condensing state the electricity efficiency is equal to the total efficiency and is typically approx. 40%

[27] depending on the fuel. For the back-pressure units and extraction units not running in a condensing state the electricity efficiency is lower, but the total efficiency is higher due to the fact that the surplus heat is utilized. Gas turbines typically has a lower total efficiency than the steam turbine units. Finally combined cycle units have a higher efficiency than gas turbine and steam turbine units due to the combination of systems [27].

## Emissions

When the heat and electricity is generated  $CO_2$ ,  $SO_x$  and  $NO_x$  are emitted. These are all considered as a hazard to the environment and many countries have taxes on emission of these. The amount of  $CO_2$  and  $SO_x$  generated are only dependent on the type of fuel used, while the amount of  $NO_x$  also depends on internal processes within the boiler. Due to the increase in focus upon environmental issues and reduction of emissions many new production units have  $deSO_x$  and  $deNO_x$  installations reducing the emission of  $SO_x$  and  $NO_x$  respectively. Furthermore many of the boilers in production units are modified to utilize natural gas, which has a lower  $CO_2$  emission and biomass which is considered to be  $CO_2$  neutral [9], [4].

## Technical Limitations for Production Units

Each of the components in a production unit have a number of technical restrictions. In the following the restrictions which are important to take into account when making a plan for a CHP system are listed:

- Start-up/Shut down: Starting up an CHP unit takes time. Typically a period up to 8 hours [5]. Thus in this period the fuel used does not contribute to the heat and electricity production. When the unit is online it must typically also stay online in a period of up to 8 hours before it can be shut down and detached from the DH system.
- Limitations on the load: The boilers of the production units have a related maximum and minimum load. Likewise the turbines have a capacity on the load which can be sent into the turbine.
- Limitations on change in load: Changing the load of fuel ramped to the boilers of the unit takes time. Therefore a unit has a limitation on the change of load within a time period.

## 2.2 Heat Accumulators - Storages

Besides from the production units a CHP system can also have a number of heat accumulators i.e. storages of heat. The heat accumulators considered in this thesis are large thermo bottles storing the heat as water. In many CHP systems including the one of Greater Copenhagen, the storages play an important role. For instance. If a sudden increase in demand occurs in the DH system the storages can be used as equalizers. This is much cheaper than using so-called peak load production units, which are boiler units using an oil or gas.

A storage typically can be in three states: out, in, level. In the 'in' state the heat is loaded to the storage increasing the content of heat. In the 'out' state the the heat is unloaded from the storage decreasing the content heat. Finally when a storage is in state 'level' heat is neither stored nor released and the content is at level. Some technical limitations for storages are listed below:

- **Commitment:** When a storage goes into an active state it must stay in the state for a period of time
- **Limitations on in/out load:** The in/out load is restricted by a maximum and minimum load
- **Limitation on content:** The content of a storage is limited. It must be above a certain level and below another level.
- **Limitations on change in in/out load:** Due to the pumping capabilities changes to the in/out load is limited by a certain amount within a period of time.

## 2.3 Transmission Networks

The transmission lines of the transmission networks connected to the production units are pipes where either hot water or steam carrying the heat is sent around to heat exchangers of smaller heat distribution systems. Some of the technical limitations to the transmission lines are listed below:

- **Limitations on transmission load:** Each of the transmission lines has a capacity on the amount of water or steam which can be sent through. This limitation can be translated into a limitation on the possible heat transmission load

- Limitation on change in transmission load: Due to the capabilities of the pumps in transmission networks there is a limitation on the change in transmission load possible within a period of time

## 2.4 The Costs of Running a CHP System

There are many costs related to running a CHP system. Below the most important costs are listed [4].

- Cost of fuels
- Start-up costs for production units, which is primarily based on the fuel used before the unit can produce heat or electricity and the manpower used during a start-up process.
- Operating and maintenance costs of the production units
- Operating and maintenance costs of the grid and pipelines
- Costs connected to setting up an installation
- Taxes on  $CO_2$ ,  $NO_x$  and  $SO_x$  emission

Efficient planning of a CHP system should minimize these costs. But it is not only costs which affect the running of a CHP system. Due to the fact that heat and electricity is co-generated the possible income from electricity production also has a huge impact on the choice of where and how to produce the heat. This factor will be described more closely in the next chapter.

## 2.5 Summary

In this chapter a general introduction to CHP systems has been given. As seen a number of different production units exists with different technical limitations. Furthermore a CHP system also consists of transmission systems and storages. Finally a number of costs of running a CHP system has been presented. All these things gives a picture of the complexity of a CHP system. In the next chapter an introduction to the CHP system of Greater Copenhagen will be presented. This CHP system has some differences from the general system described in this chapter which also should be taken into account when making a detailed model for the system.

## CHAPTER 3

# The CHP System of Greater Copenhagen

---

DH in Greater Copenhagen has a long history, which goes back to 1900's. Copenhagen was the first location in Denmark to use DH. In the beginning it was primarily based on waste incineration plants. These plants solved both waste and heat problems. Later on other heat technologies was developed and used, especially due to the firm strategy of the danish government (see chapter 1), CHP plants being one of them. The firm strategy also led to 5 municipalities joining forces developing their transmission networks and the connection between the networks of the municipalities. This large one-pool system displayed in figure 3.1 is known today as the CHP system of Greater Copenhagen. 98% of the households and companies of Greater Copenhagen receive the heat through DH which is primarily supplied by the production units at the large CHP plants.

In the first part of this chapter the physical structure of the CHP system (the characteristics of the plants and the DH transmission networks) is described. The second and last part introduces the economy behind running the system. This part has a focus on the Danish power market, which due to co-generation has a large impact on where and how to produce the heat. [7] [20].

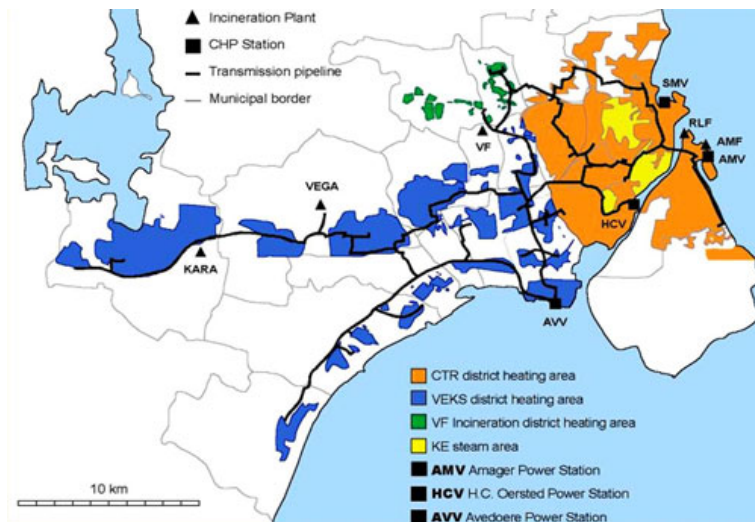


Figure 3.1: A map of the CHP system of greater Copenhagen

### 3.1 Physical Structure of the CHP System

In this section the physical structure i.e. the transmission networks, the plants etc. of the CHP system of Greater Copenhagen is described. The description focus upon specific details for the system, which are different from the general description of CHP systems given in the previous chapter.

#### Heat Distribution Networks

There are two types of networks in Greater Copenhagen: water networks and steam networks.

#### DH Water Networks

There are 3 interconnected DH water networks in the system of Greater Copenhagen. One is controlled by CTR (marked with orange in figure 3.1), one is controlled by VEKS (marked with blue in figure 3.1) and finally a smaller network (marked with green in figure 3.1) is controlled and supplied by the waste incineration plant Vestforbrændingen (VF). The fat black lines are the main

transmission lines from where the heat is exchanged to the local distribution networks.

If a sudden increase in demand or a crash of a production unit occurs in the DH water system the storages of heat, which in the system of Greater Copenhagen are placed at the production plants, can be used as equalizers.

### Steam Based DH Network

KE owns the steam based heat DH networks in Greater Copenhagen, which is marked by yellow in figure 3.1. As mentioned in the chapter 2, a steam system has a high maintenance cost and the high temperatures it can provide is often not needed. But due to historic reasons Greater Copenhagen still have a steam based DH network covering a large area.

There are no storages for steam. Thus to make sure the demand is always satisfied a production unit of one of the CHP plants is assigned to be pressure maintainer. A pressure maintainer must stay a certain margin from its production bounds, thus it can increase or decrease production if needed [3].

### CHP Plants

There are four CHP plants in Greater Copenhagen. These are

- Amagerværket (AMV)
- Avedøreværket (AVV)
- H.C Ørsted værket (HCV)
- Svanemølleværket (SMV)

In the following a short description of each of these plants and which type of production units they contain will be given [13]. It must be noticed that due to the fact that detailed information about especially the CHP production units can be hard to retrieve from the production companies, the appearance and output profiles for some of the units are based on realistic assumptions taken on the basis of available data and an acceptance by VLE. The process diagrams presented for some of the units are simplified to make them easier to understand.

Amagerværket is owned by the production company Vattenfall A/S, the rest are owned by DONG ENERGY A/S. The plant consists of two CHP production units and a heat accumulator. The production units are called AMV1 and AMV3.

### Amagerværket (AMV)

AMV1 is a back-pressure unit with a high pressure turbine generating steam and electricity. The boiler of AMV1 can be fired with biomass, coal or oil. AMV1 is capable of producing a maximum of approx. 80 MW of electricity and a maximum of 250 MJ/s of heat. [13]

The output profile illustrated in figure 3.2 for AMV1 is different from the generic back-pressure unit. As seen the interception of the back-pressure line with the electricity axis is not in origo. Thus the fixed relationship between heat and electricity is not given by the constant  $C_b$ , but by a linear relation with a slope of the back-pressure line given by a marginal  $C_b$  value.

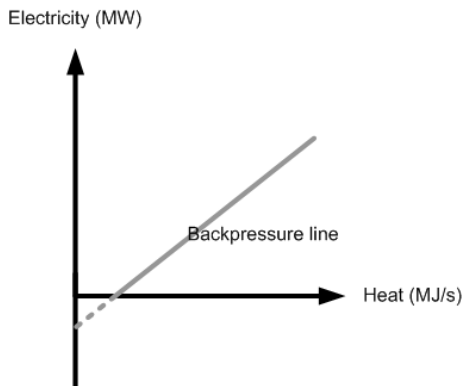


Figure 3.2: output diagram for AMV1

The other production unit AMV3 also has special characteristics. AMV3 is an extraction unit with a multistage turbine and a boiler fired with coal and oil. It has a maximum capacity of approx. 250 MW on electricity and 330 MJ/s on heat. The special characteristics of the unit can be seen in figure 3.3 [3].

As seen there is a kink marked with the number 1 in the  $C_v$ -line dividing it into two separate lines  $C_{v1}$  and  $C_{v2}$ . At this kink there is a drop in the exchange rate for exchanging the steam to electricity instead of extracting it. This kink is

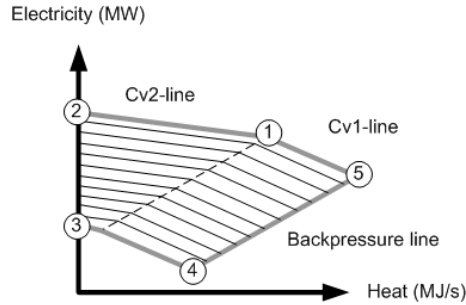


Figure 3.3: Output diagram for the extraction steam turbine unit AMV3 with special characteristics

known to be the point of minimal fuel loss i.e. maximum efficiency. In addition to these special characteristics it is important to notice that the back-pressure line has the same characteristics as the one for AMV1 [3].

### Avedøreværket (AVV)

Avedøreværket has two CHP production units: AVV1 and AVV2. The unit AVV1 is a twin to AMV3. The process diagram for the other unit AVV2 is shown in figure 3.4. AVV2 is a very modern combined cycle unit delivering heat carried by water. It is constructed with an extraction steam turbine, a gas turbine and two boilers: A biomass boiler fired with straw and an advanced multi-fuel boiler which can be fired with natural gas, oil and wooden pellets. The gas turbine and the biomass boiler can only be used if the multi-fuel boiler at least is running at minimum load. AVV2 is known to be one of the most efficient CHP production units in the world and it has a maximum capacity on approx. 575 MW for electricity and 575 MJ/s for heat [9].

Besides from the CHP units there are two heat accumulators placed at the AVV plant. These storages of heat can contain the same quantity of water as the part of the DH network owned by VEKS [29]. A special characteristic for the AVV plant is that sometimes the two production units cannot be regulated at the same time due to operational restrictions [3].

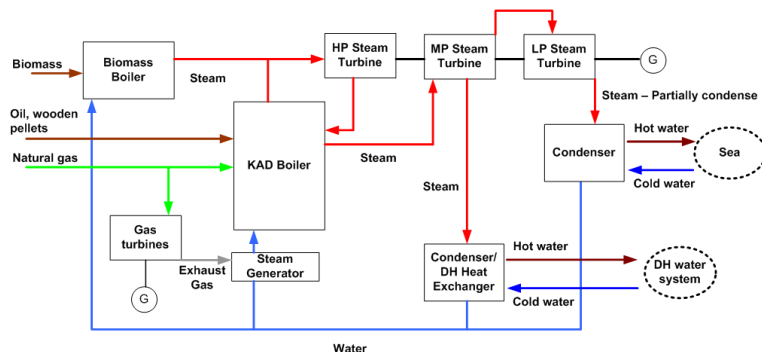


Figure 3.4: Process diagram for AVV2

### H.C Ørsted værket (HCV)

H.C Ørsted værket founded in 1920 consist of two CHP production units HCV7 and HCV8 and two heat boilers HCVK21 and HCVK22. HCV7 is a special steam turbine unit. The process diagram for HCV7 is illustrated in figure 3.5. The production capacities for the units at HCV are confidential, but they are lower than the ones for the units at AMV and AVV.

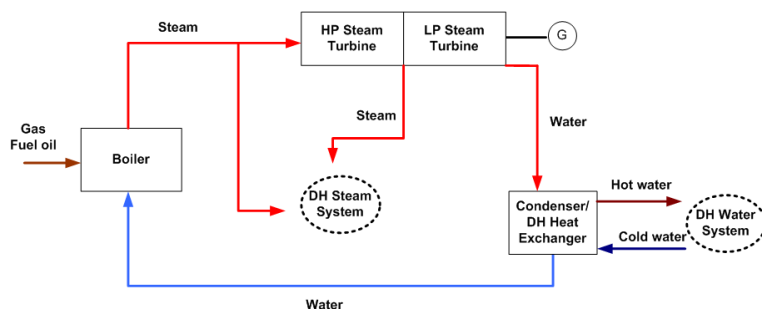


Figure 3.5: Process diagram for HCV7

The boiler generates steam which can be sent directly to the DH steam system or to a sequence of a high pressure turbine and a low pressure turbine. When the steam has gone through the high pressure turbine some or all of it can be extracted and sent to the steam system. The remaining steam is sent through the low pressure turbine to generate more electricity. When the steam has gone through the low pressure turbine it has too low a pressure and temperature to be used in the DH steam system, instead it is sent to a condenser exchanging the heat to the DH water system. Thus HCV7 is capable of producing hot water

and steam simultaneously. Some of the steam must be sent all the way through resulting in a minimum amount of hot water which is always produced.

A process diagram for the other CHP unit HCV8 is shown in figure 3.6. HCV8 is a gas turbine unit with the possibility of attaching a boiler to generate more heat by using the exhaust gas from the turbine and a fuel. The unit primarily produce heat as steam, but to cool the turbine a fixed amount of water is always produced. [13].

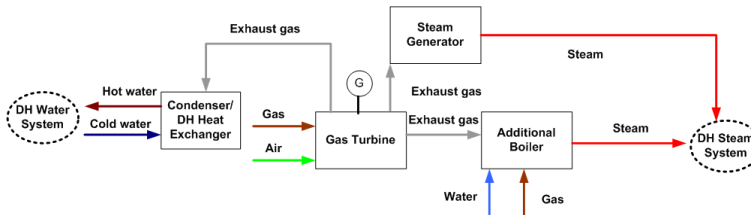


Figure 3.6: Process diagram for HCV8

### Svanemølleværket (SMV)

The final CHP plant in Greater Copenhagen Svanemølleværket has one CHP production unit SMV7 and two heat boilers SMVK21 and SMVK22. Like HCV8, SMV7 is a gas turbine unit. But a boiler fired with oil and an extra steam turbine can be attached to the system creating a combined cycle unit. Like HCV8, SMV7 primarily produce heat as steam and a fixed amount of water due to cooling of the turbine [13]. SMV7 also has confidential production capacities, but like for the units at HCV they are lower than the capacities for the units at AMV and AVV.

### Waste Incineration Plants

The waste incineration plants was originally the primary heat suppliers to the DH system. Today the large CHP plants are dominant, but the waste incineration plants still play a vital role both for heat supply and getting rid of waste [20]. There are four waste incineration plants in Greater Copenhagen, some have more than one production unit. The plants are primarily owned by municipalities in the vicinity. The plants are listed below with a brief description.

- **Vestforbrændingen** consists of the heat boiler units VF1 and VF2 and the back-pressure units VF5 and VF6.
- **Lynettefællesskabet (RLF)** A plant with a single heat producing unit
- **Kara/Noveren (KARA)** has two heat boiler units KARA3 and KARA4. Furthermore there is one back-pressure unit, KARA5.
- **Amagerforbrændingen (AMF)** has a single back-pressure unit AMF, with four identical ovens delivering steam to two steam turbines. Only three ovens are needed to run the turbines at full load, thus the last oven is sometimes looked upon as a heat boiler unit due to the possibility of letting the steam bypass the turbines.

### Other Production Units

Besides from the large CHP plants and waste incineration plants the CHP system of Greater Copenhagen contains a geothermal heat pump and a number of peak boiler units. The peak boiler units are boiler units owned by the transmission companies. These boiler units use the very expensive light oil and are only used in peak load situations to insure demand satisfaction. In the CTR network there are 14 peak boiler units, In the VEKS network there are 39 and KE has 1.

## 3.2 The Economy of Running The System

Due to how the Danish heat market is regulated that you may not charge a customer anymore for heat than the cost of producing and distributing it. In chapter 2 the most significant costs of running a CHP system was given. These are also valid for the system of Greater Copenhagen. In this thesis the primary focus will be on the cost of production, because minimization of this cost is the primary objective for VLE when planning the heat load. In the following a special cost for the CHP system of Greater Copenhagen is described, namely the energy tax. Furthermore a short introduction is given to the Danish power market and its sub-markets. To make a cost-efficient plan these markets should be considered.

## Energy Tax

Denmark has taxes on emission of  $SO_x$  and  $NO_x$  and quote price cost on  $CO_2$ , to keep the environmental damage at a minimum and to insure income to the Danish state. Besides from these taxes there is also a special energy tax. The production companies only have to pay this energy tax of the heat produced by fossil fuels. The energy tax on electricity is put on the consumption and is thereby not relevant for running the system. The formula used to calculate the energy tax on heat is given below

$$\frac{H}{A_{eff}} \cdot \frac{F_f}{\sum_f F_f} \cdot a_f \quad (3.1)$$

$H$  is the heat production of a unit,  $A_{eff}$  is the taxed heat efficiency, which is 1.25 for all production units, following recent change in regulations,  $F_f$  is the amount of fuel  $f$  used by the unit out of the total amount of fuel used by the unit  $\sum_f F_f$  and finally  $a_f$  is the energy tax on fuel  $f$ . The energy tax is only put on fossil fuels [10].

## Importance of the Danish Power Market

When a CHP unit generates heat a high production cost can be accepted if the income from the simultaneously produced electricity is high. An important factor when making a production plan is the price on electricity. This factor is especially important for CHP systems in Denmark due to the large amount of windmills. On days with a lot of wind the mills exceeds satisfaction of the demand for electricity and export capacity resulting in an electricity price equal to 0. Thereby the economical advantage of co-generation is diminished [4] [8]. Due to this a good insight in the market for electricity could lead to better plans. In the following a short description of the Danish power market which is part of the nordic power market Nordpool.com is given.

### The Actors on the Power Market

There are many actors on the Danish power market. In the following two important groups are described [8].

- System responsible: The system responsible is as the name implies responsible for the transmission system in Denmark. The system responsible makes the rules of the market and make sure the rules are followed.

Furthermore they try to make sure that no imbalances occur. In Denmark the system responsible is Energinet.dk

- Balance responsible: The balance responsible actors have the responsibility of keeping balance in the system by increasing or decreasing production or consumption. In this group there are production, consumption and power trading companies. Among the balance responsible in Denmark are DONG Energy A/S and Vattenfall A/S.

### The Different Markets

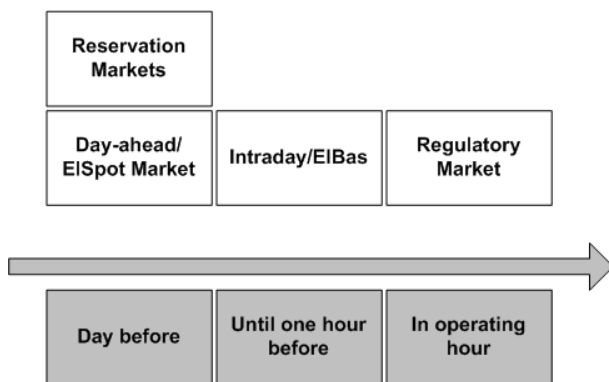


Figure 3.7: Timeline for The Danish Power Market

The Danish Power Market consists of a number of sub-markets which are all used to reach a balance between production and consumption each hour each day. In figure 3.7 a timeline illustrates the different sub-markets and when it is possible to trade on them.

EISpot is the day-ahead market where hourly power contracts are traded the day before the hour the power is delivered. The actors on the market gives bids and offers on prices and amount to sell/buy. Based on these bids and offers a price is determined by Energinet.DK for the given hour. This market closes at 14.00 every day.

EIBas is the intraday market. Here hourly power contracts are traded up to one hour prior to delivery. This market makes it possible to trade electricity after the price fix on EISpot. This gives the actors on the power market a possibility of trading into balance when new and better knowledge about e.g. prognoses for demand, outtages etc. are available.

The final markets which makes sure that balance is kept are the reservation and regulatory markets. The day before operation, some of the producers can sell reserves, which means that they are paid an amount of money by Energinet.DK to reserve an amount of electricity, which could be used to regulate the system if imbalances between electricity production and consumption appear. In this market the production company gives a bid on an amount to reserve and the price. Energinet.DK selects the bids with the lowest price.

A production company can also choose to wait until the operating hour before trying to sell the extra capacity, this trade is done on the regulatory market. The production companies selling a reserve the day before is paid a availability amount in addition to the payoff from the electricity sold while the production companies waiting until the hour of operation are only paid for the electricity.

In the eastern part of Denmark where the Greater Copenhagen area is situated the following types of reserves exists [8]:

- Frequency driven normal running reserve (FDNRR): This reserve is automatically activated when small imbalances up to 100 mHz occur. This reserve should be delivered within 150 sec. The system responsible should make sure that there are always a given amount of electricity capacity ready for activation of this reserve. This amount is determined pr. year and in 2009 the amount was 23 MW for Energinet.dk.
- Frequency driven running disruption reserve (FDRDR): This reserve is also automatically activated, but this is when larger frequency drops, i.e. when the frequency drops more than 200 mHz occur. The frequency drops happens due to disruptions with production units or transmission. This reserve should be delivered within 30 sec. and is then active until equilibrium is achieved or another reserve, namely the manual reserve takes over. Also here Energinet.dk must have a certain capacity ready and in 2009 this amount was 175 MW.
- Manual reserve (MR): The manual reserve takes over when the FDRDR is overloaded. However the manual reserve is not only used for up-regulations but also down-regulations. The manual reserve is used when disruptions on production units happens. The manual reserve should be delivered within 15 min.

Only the manual reserves can be traded both the day before and on the day of operation while the others are only traded on the day before.

Thus many markets must be taken into account when making a cost efficient production plan and good planning should also deal with the large flexibility

of e.g. buying reserves. Furthermore planning is done on the basis of price prognoses with a certain uncertainty. One way to deal with these challenges is to reschedule whenever newer and better information is given and new decision possibilities are available. The rescheduling framework introduced in this thesis could be an inspiration for how to do this.

### 3.3 Summary

In this chapter an introduction was given to the extensive CHP system of Greater Copenhagen. The introduction revealed a number of technical details different from the general introduction to CHP systems given in the previous chapter i.e. the special extraction profile with a kink, production units with forced production and with a simultaneous water and steam production. In the final part of the chapter it was described how the price on electricity plays an important role when making a production plan for the system. Furthermore a specific cost, energy tax, was introduced. As you will see later in this thesis the formula for energy tax is challenging to model.

In the following chapters the model used to plan the daily heat load and an extension model describing the technical and economical details of the production units are presented. The combination of these models gives the possibility of representing the technical and economic details presented in this and the previous chapter in a single model.

# The Katja Model

---

A description of the work flow between VLE and the production companies performed to create a heat load plan for the CHP system of Greater Copenhagen was given in chapter 1. One part of this work flow was to find the heat load plan for the entire system with respect to production, storage and transmission minimizing the cost of changes to an original hour-by-hour production plan created by the production companies with related marginal costs of changes to this plan. VLE finds these heat load plans by using a MIP model known as The Katja Model developed by Katja Buhrkal from EA Energy Analysis A/S in cooperation with VLE. This chapter describes the Katja Model in detail including the mathematics of the model.

## 4.1 Modeling Technique

The Katja Model formulates the problem of finding an optimal heat load plan as a multi-commodity flow (MCF) problem. Multi-commodity flow problems are used as a generalization of many planning problems within many different industries. Examples are the transport sector, the telecom sector and the energy sector [22]. An example of a multi-commodity formulation of an energy planning problem is the Balmorel model introduced in 2001. Balmorel is an open source

model with the initial purpose of analyzing the electricity and CHP markets in the Baltic sea region. Today the Balmorel model is used by energy companies, authorities, transmission system operators, researchers and others for analysis and planning on a long-term level [1],[23], [25], [11], [24]. Subject to assumptions of well functioning markets the Balmorel model can also be interpreted as a partial equilibrium model.

Another example of a MCF formulated energy planning problem is the model of the district heating system of Ferrara, Italy [2], which has many similarities with The Katja Model due to the similarities of the DH systems. Especially the Balmorel model has been an inspiration to the extension to The Katja Model presented later in this thesis.

## Basic Multi-Commodity Flow Problem

MCF problems takes a network with vertices connected by directed edges as input. One or more of the vertices have an excess of some commodity and are called sources. Other vertices called sinks have a demand for this commodity. A basic example of a network with two sources and a single sink is illustrated in figure 4.1.

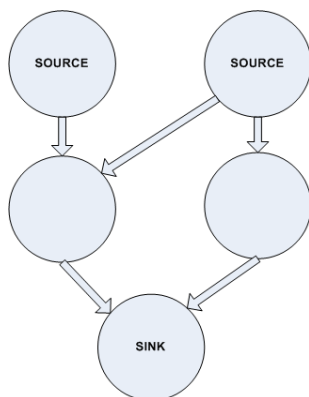


Figure 4.1: A basic example of a network used for a multi-commodity flow problem

The MCF problem is then to send a number of commodities from the source(s) along the edges to the sink(s) while satisfying an objective which typically is defined as a minimization of the costs related to this flow.

Many different types of costs and constraints can be defined for the network.

Examples are costs of using a certain edge and capacity of flow for a certain commodity on a certain edge. One could also look at the sources as production units with a certain cost and/or capacity of production of a certain commodity. These are only examples of a endless list of possibilities which makes the multi-commodity flow formulation great for many purposes. A mathematical description of the basic multi-commodity flow problem is given in the following.

### Sets

- $v \in V$ : Set of vertices
- $(v_1, v_2) \in E$ : Set of edges
- $i \in I$ : Set of commodities

### Parameter

- $d_{i,v} \in \mathbb{R}$ : Demand for commodity  $i$  in vertex  $v$

### Variable

- $f_{v_1, i, v_2} \in \mathbb{R}^+$ : The flow of commodity  $i$  on the edge  $(v_1, v_2)$

### Mathematical Model

$$\min \text{cost} \tag{4.1}$$

s.t

$$\sum_{v_1} f_{v_1, i, v} - \sum_{v_1} f_{v, i, v_1} = d_{i,v} \quad \forall v \tag{4.2}$$

The objective (4.1) is to minimize the cost subject to the balance equation (4.2) which states that the amount of commodity  $i$  flowing out of a vertex  $v$  subtracted from the amount flowing in must be equal to the demand for the given vertex. If  $v$  is a source for  $i$  then  $d_{i,v} < 0$  due to the excess. If  $v$  is a sink for  $i$  then  $d_{i,v} > 0$  and finally if  $v$  is a transportation node i.e. a node with neither excess or demand  $d_{i,v} = 0$  [12].

## 4.2 The Input

The input to The Katja Model is illustrated in figure 4.2.

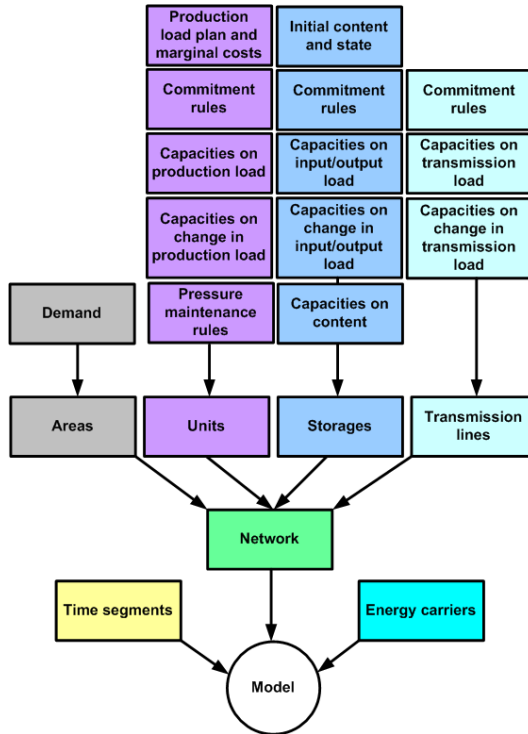


Figure 4.2: The input to the Katja model

The model has three main inputs: The time segments  $t \in \mathcal{T}$  defines the time horizon for the model. In the Greater Copenhagen CHP system hourly heat load plans are found. Thus for the given case a time segment is equal to an hour, but a time segment could be defined as any other fixed amount of time. The energy carriers  $e \in \mathcal{E}$  are the commodities of the model. An energy carrier is a carrier of heat. Therefore the commodities/energy carriers are measured in heat loads (MJ/s). For the Greater Copenhagen system there are two kinds of energy carriers namely steam and water. The final input is the network used to describe the Greater Copenhagen CHP system. In the following this network is described.

## The Network

The basic components of the network used in The Katja Model is illustrated in figure 4.3.

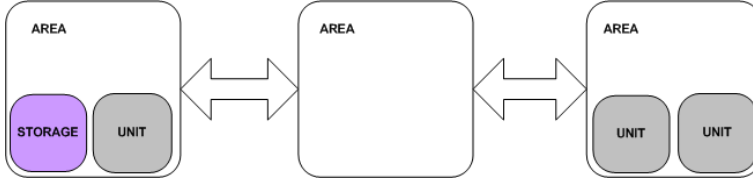


Figure 4.3: The basic parts of the network of The Katja model

The vertices of the network are called areas  $a \in \mathcal{A}$  and they represent local heat distribution networks, places for CHP production, nerve centers or other kind of geographical areas. Within the areas units  $u \in \mathcal{U}$  and storages  $v \in \mathcal{V}$  can be placed. A unit represents a heat producing unit. The storages as the name imply represent the storages of heat also known as the heat accumulators. Between the areas are directed edges  $(a_1, e, a_2) \in \mathcal{X}$  representing transmission lines for heat e.g between a place for CHP production and a distribution network. The location of the production units and the storages are given in the sets  $u_a \in \mathcal{U}_a$  of units  $u$  in area  $a$  and the set  $v_a \in \mathcal{V}_a$  of storages  $v$  in area  $a$ .

### The Network used by VLE

The network illustrated in figure 4.4 is the one used in the Katja Model today. This network is under constant development in order to make it as realistic as possible and to adjust it to new parts in the CHP system.

As seen in the figure the distribution network owned primarily by CTR is represented in the model as four networks CTR, Østerbro, Valby/Vigerslev and Amager. The distribution network owned primarily by VEKS is represented as a single network VEKS and the distribution networks owned by KE is represented as three networks Steam North, Steam South and the converted area. Thus large distribution networks are represented as single areas. This is done under the assumption that heat is distributed freely within these networks.

Each of the CHP units are represented by a unit each. The peak boiler stations in the three larger distribution networks owned by KE, CTR and VEKS respectively are represented by three units, one in each area. These are named Lygten, SpidsCTR and SpidsVEKS. The waste incineration plants are also simplified into three units: AffaldVF-CTR representing the production from VF to the CTR net, AffaldCTR representing the production from AMF and Lynetten and AffaldVEKS representing the production from KARA and the production from VF to the VEKS net. The boilers at the CHP plants are coupled i.e. HCVK21+K22 and SMVK21+K22. The storages at the AVV plant is repre-

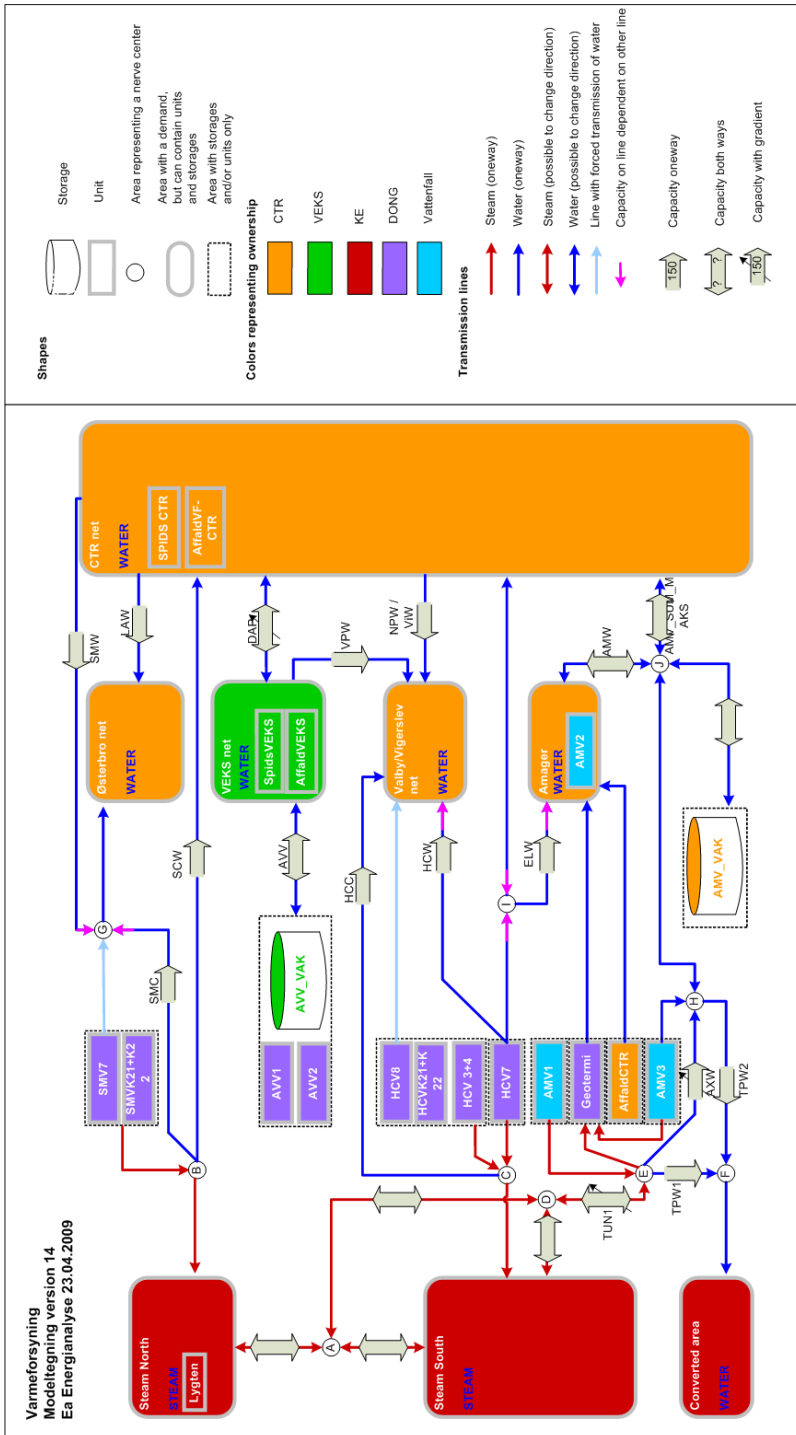


Figure 4.4: The entire network used by VLE in the Katja Model

sented as a single storage and the same is the storage at the AMV plant. Finally the geothermal unit is represented as a production unit Geotermi.

### 4.3 The Problem

For each of the areas representing a heat distribution network a demand is given by hour-by-hour demand prognoses for the next 24 hours received by VLE. The prognoses contains a demand for a load of heat (MJ/s) in a given hour. An imaginary example of a demand prognoses is given in figure 4.5

Demand (MJ/s)	
Area 1	
00-01	30
01-02	30
02-03	13
03-04	25
04-05	25
05-06	25
06-07	25
07-08	25
08-09	..
09-10	..
10-11	..
11-12	..
12-13	..
13-14	..
14-15	..
15-16	..
16-17	23
17-18	..
18-19	..
20-21	..
21-22	..
22-23	..
23-24	..

Figure 4.5: An imaginary example of a 24 hour demand prognoses

This prognoses is given as input to The Katja Model through the following parameter

- $A_{a,e,t}^{h-demand} \in \mathbb{R}$ : The demand for energy carrier  $e$  in area  $a$  in time segment  $t$  (MJ/s)

The problem to be solved by the The Katja Model is then to find a cost-efficient way of satisfying this demand. The demand can be satisfied with an excess of the energy carriers (heat) generated by the units or storages in the area or in other areas connected to the area by transmission lines. Thus the problem becomes to decide where to generate a certain amount of excess and how the excess should be sent around i.e. transmitted through the network.

## Production

As described in the previous chapters VLE buys heat from the production companies, which then calculate from their point of view optimal 24 hour hour-by-hour production plans with information about the load of heat (MJ/s) produced by a certain production unit and related marginal costs (money/MJ/s) of changing this load plan in a given hour. An imaginary example of a production plan with related marginal cost is illustrated in figure 4.6.

	Heat production plan MJ/s		Marginal costs of changes (money/MJ/s)	
	Unit 1	Unit 2	Unit 1	Unit 2
00-01	20	20	100	50
01-02	5	5	100	50
02-03	4	4	100	60
03-04	5	5	100	60
04-05	30	30	100	60
05-06	3	3	100	60
06-07	6	6	100	60
07-08	**	**	**	**
08-09	**	**	**	**
09-10	**	**	**	**
10-11	**	**	**	**
11-12	**	**	**	**
12-13	**	**	**	**
13-14	**	**	**	**
14-15	**	**	**	**
15-16	**	**	**	**
16-17	**	**	**	**
17-18	**	**	**	**
18-19	**	**	**	**
20-21	**	**	**	**
21-22	**	**	**	**
22-23	**	**	**	**
23-24	**	**	**	**

Figure 4.6: An imaginary example of a 24 hour production plan with related marginal costs of changing the plan

In The Katja Model the excess of heat generated by the units is given by this production plan +/- the changes the Katja Model decides to make. The plan is given as input in the parameter  $U_{u,e,t}^{h-plan}$  and the excess which should be generated by a certain unit can be found using the following decision variables

- $\mu_{u,e,t}^{h-out} \in \mathbb{R}^+$ : The heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-plan+} \in \mathbb{R}^+$ : The upwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-plan-} \in \mathbb{R}^+$ : The downwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)

and stating the equation

$$\mu_{u,e,t}^{h-out} = U_{u,e,t}^{h-plan} + \mu_{u,e,t}^{h-plan+} - \mu_{u,e,t}^{h-plan-}, \quad \forall u, e, t \quad (4.3)$$

### Storage

The storages of the model can be in three states  $z \in \mathcal{Z} = \{in, out, level\}$ . In the 'in' state the storage consume heat for later use and thereby increase the demand in the area it is placed. In the 'out' state the storage loads out heat generating an excess in the area and finally in the level state the storage is idle and neither a excess or a demand is created. Thus the main decision variable for the storages is

- $\nu_{v,z,t}^h \in \mathbb{R}^+$ : The heat load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)

### Transmission

The final main decision made by The Katja Model is the decision of how much heat should be transmitted from one area to another connected area. In the model this is represented by the following decision variable

- $\chi_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$  (MJ/s)

### The Balance Equation

Having presented the main decision variables the balance equation corresponding to equation (4.2) in the basic MCF problem can be stated for The Katja Model. But before this is done a new type of area is presented namely the areas where it is possible to convert one energy carrier to another. These areas are given in the set

- $a_{e_1,e_2}^{e_2e} \subset \mathcal{A}$ : The areas where energy carrier  $e_1$  can be transformed into energy carrier  $e_2$

A decision variable is used to decide how much should be converted in these areas.

- $\alpha_{e_1,e_2,a,t}^{e_2e} \in \mathbb{R}^+$ : The amount of energy carrier  $e_1$  converted to energy carrier  $e_2$  in area  $a$  in time segment  $t$  (MJ/s)

Then the balance equation can be stated

$$\sum_{u,a,e} \mu_{u,a,e,t}^{h-out} + \sum_{v_a} \nu_{v_a,'out',t}^h + \sum_{a_1} \chi_{a_1,e,a,t}^h + \sum_{e_1} \alpha_{e_1,e,a,t}^{e2e} \quad (4.4)$$

$$= \sum_{v_a} \nu_{v_a,'in',t}^h + \sum_{a_1} \chi_{a,e,a_1,t}^h + A_{a,e,t}^{h-demand} + \sum_{e_1} \alpha_{e,e_1,a,t}^{e2e} \quad (4.5)$$

$$\forall a, e, t$$

The equation states that the excess of heat generated by units, storages in the 'out' state and incoming flow from other areas stated on the left hand side (5.4) must be equal to the demand generated by the the actual demand of the area, the consumption of storages in the 'in' state and the outgoing flow stated on the right hand side (4.5) for each area  $a$  and each energy carrier  $e$  in each time segment  $t$ . Since the balance is satisfied for each energy carrier the left hand side of the equation also states that an excess of this energy carrier can be generated by conversion from another. Likewise on the right hand side of the equation it is stated that an amount of the energy carrier can be converted to other energy carriers. It is important to notice that these energy conversion terms are only valid for the areas in  $a_{e_1,e_2}^{e2e}$ .

This balance equation makes sure that the plan found by The Katja Model satisfies the demand of each area. But the problem was not only to find a plan doing this. The plan should also be cost-efficient.

## The Objective

For VLE a cost-efficient plan is a plan minimizing the total cost of changes to the original production plan  $U_{u,e,t}^{h-plan}$ . Therefore this is the primary objective of The Katja Model. As mentioned previously the marginal costs of change are sent to VLE together with the production plan. The Katja Model takes these as input through the parameters:

- $U_{u,e,t}^{h-cost+}$ : Marginal cost for changing the plan for production of energy carrier  $e$  upwards for unit  $u$  in time segment  $t$  (money/MJ/s)
- $U_{u,e,t}^{h-cost-}$ : Marginal cost for changing the plan for production of energy carrier  $e$  downwards for unit  $u$  in time segment  $t$  (money/MJ/s)

The objective can now be stated:

$$\min \sum_{u,e,t} U_{u,e,t}^{h-cost+} \mu_{u,e,t,s}^{h-plan+} + U_{u,e,t}^{h-cost-} \cdot \mu_{u,e,t}^{h-plan-} \quad (4.6)$$

This objective (4.6) minimizes the cost of changes to the original production plan. This primary objective is simplified compared to the one actually used by VLE. The primary objective used by VLE namely takes into account that the marginal costs are only valid for marginal changes. This real primary objective is not given and described here as the focus of the thesis is the extended model and in that model this primary objective will not be used. Besides from the primary objective a number of secondary objectives exists e.g. keeping the plans smooth. Some of these are used in the objective of the extended model, but will likewise not be presented here in order to keep the focus on the most important parts of the model.

## Additional Constraints

Keeping balance in the system is not the only constraint in The Katja Model. A number of other constraints are needed to describe the technical limitations of the units, the storages and the transmission lines. In the following these constraints with related input parameters and variables will be introduced.

## Constraints on The Units

The additional constraints for the units can be divided into five categories

- Commitment rules
- Capacities on production load
- Capacities on change in production load
- Pressure maintenance rules
- Unit specific constraints

### Commitment Rules

The commitment rules are needed due to the limitation mentioned in chapter 2 that a unit have to stay online for a period when turned on and offline for a

period when turned off. The periods needed can be given as input to the model through the parameters

- $\underline{U}_u^{on} \in \mathbb{N}^+$ : The minimum number of time segments the unit  $u$  must stay online if started for production
- $\underline{U}_u^{off} \in \mathbb{N}^+$ : The minimum number of time segments  $u$  must stay offline if shut down for production

Furthermore the modeling of unit commitment rules requires the use of binary variables

- $\mu_{u,e,t}^{start} \in \{0, 1\}$ : 1 if unit  $u$  is started for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u,e,t}^{shutdn} \in \{0, 1\}$ : 1 if unit  $u$  is shut down for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u,e,t}^{on} \in \{0, 1\}$ : 1 if unit  $u$  is online for production of energy carrier  $e$  in time segment  $t$

Then the commitment constraints can be stated

$$\mu_{u,e,t}^{start} \geq \mu_{u,e,t}^{on} - \mu_{u,e,t-1}^{on} \quad \forall u, e, t \quad (4.7)$$

$$\mu_{u,e,t}^{shutdn} \geq \mu_{u,e,t-1}^{on} - \mu_{u,e,t}^{on} \quad \forall u, e, t \quad (4.8)$$

$$\mu_{u,e,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{U}_u^{on}\}} \mu_{u,e,t_1}^{start} \quad \forall u, e, t \quad (4.9)$$

$$1 - \mu_{u,e,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{U}_u^{off}\}} \mu_{u,e,t_1}^{shutdn} \quad \forall u, e, t \quad (4.10)$$

The constraints (4.7) and (4.8) registers the start-up and the shutdown of a unit respectively. While the constraints (4.9) and (4.10) makes sure the commitment rules are kept by stating that if the unit is started/shut down in a previous time segment  $t_1$  within the minimum commitment time from  $t$  it must be online/offline in  $t$

## Capacities on Production Load

The capacities on production load i.e. the heat sent out of from a unit are given as input to the model through the parameters

- $\bar{U}_{u,e,t}^{h-out} \in \mathbb{R}^+$ : Maximum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\underline{U}_{u,e,t}^{h-out} \in \mathbb{R}^+$ : Minimum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)

which are used in the following constraints of the model

$$\bar{U}_{u,e,t}^{h-out} \cdot \mu_{u,e,t}^{on} \geq \mu_{u,e,t}^{h-out}, \quad \forall u, e, t \quad (4.11)$$

$$\mu_{u,e,t}^{h-out} \geq \underline{U}_{u,e,t}^{h-out} \cdot \mu_{u,e,t}^{on}, \quad \forall u, e, t \quad (4.12)$$

where (4.11) makes sure that an online unit cannot produce more of a certain energy carrier than the maximum capacity for this energy carrier. If the unit is offline there can be no production. Likewise (4.12) makes sure that the minimum capacity for production of a energy carrier is kept for online units.

### Capacity on Change in Production Load

Besides from the minimum and maximum capacities there is also a technical limit to the change in production load which is possible within a period of time. In reality this change would happen on a continuous basis due to the increase in loading of the boilers,ovens or turbines but in the model it is simplified as a total change in production load possible from one time segment to the next. This upper limit for changing production on a unit is given in the parameter

- $\bar{U}_{u,e}^{\Delta h-out} \in \mathbb{R}^+$ : Maximum change in heat production load of energy carrier  $e$  possible for unit  $u$  from one time segment to the next (MJ/s)

Besides from this parameter a variable is introduced to describe the actual change

- $\mu_{u,e,t}^{\Delta h-out} \in \mathbb{R}^+$ : Change in production load of energy carrier  $e$  for unit  $u$  from the previous time segment  $(t - 1)$  to time segment  $t$  (MJ/s)

The related constraints can be stated

$$\mu_{u,e,t}^{\Delta h-out} \geq \mu_{u,e,t}^{h-out} - \mu_{u,e,t-1}^{h-out}, \quad \forall u, e, t \quad (4.13)$$

$$\mu_{u,e,t}^{\Delta h-out} \geq \mu_{u,e,t-1}^{h-out} - \mu_{u,e,t}^{h-out}, \quad \forall u, e, t \quad (4.14)$$

$$\bar{U}_{u,e}^{\Delta h-out} \geq \mu_{u,e,t}^{\Delta h-out}, \quad \forall u, e, t \quad (4.15)$$

the first constraint (4.13) registers the amount of upward change in production load and (4.14) registers the amount of downward change. Finally (4.15) makes sure that the limit on change in production load is kept.

### Pressure Maintenance Rules

The final production unit related constraints deals with the fact that one of the units producing heat as steam is assigned as pressure maintainer and must stay a certain margin from its bounds. This is generalized in the model for all types of energy carriers and not only steam. A set of  $u_e^p \in \mathcal{U}$  of possible pressure maintainers for the system of energy carrier  $e$  are given together with the following parameters.

- $U_{u,e}^{pinit} \in \{0,1\}$ : 1 if unit  $u$  is pressure maintainer for the networks of energy carrier  $e$  in the initial time segment
- $\rho_e$ : The margin a pressure maintainer for system of energy carrier  $e$  must stay from its bounds
- $\underline{U}_e^{pon} \in \mathbb{N}$ : The number of time segments the unit assigned as pressure maintainer for system of energy carrier  $e$  must stay pressure maintainer.

Furthermore the binary variable  $\mu_{u,e,t}^p \in \{0,1\}$ , which is 1 if unit  $u$  is pressure maintainer for system of energy carrier  $e$  in time segment  $t$  is given. Then the constraints can be stated.

$$\mu_{u_e^p,e,0}^p = U_{u_e^p,e}^{pinit}, \quad \forall u_e^p, e \quad (4.16)$$

$$\mu_{e,t}^{pchange} \geq \mu_{u_e^p,e,t}^p - \mu_{u_e^p,e,t-1}^p, \quad \forall u_e^p, e, t \quad (4.17)$$

$$1 \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{U}_e^{pon}\}} \mu_{u_e^p,t_1}^{pchange}, \quad \forall u_e^p, e, t \quad (4.18)$$

$$\bar{U}_{u_e^p,e,t}^{h-out} \cdot \mu_{u_e^p,e,t}^{on} - \rho_e \cdot \mu_{u_e^p,e,t}^p \geq \mu_{u_e^p,e,t}^{h-out}, \quad \forall u_e^p, e, t \quad (4.19)$$

$$\mu_{u_e^p,e,t}^{h-out} \geq \underline{U}_{u_e^p,e,t}^{h-out} \cdot \mu_{u_e^p,e,t}^{on} + \rho_e \cdot \mu_{u_e^p,e,t}^p, \quad \forall u_e^p, e, t \quad (4.20)$$

The constraint (4.16) assigns the initial pressure maintainer. Constraint (4.17) registers when a new pressure maintainer is assigned while (4.18) makes sure that this only happens a limited number of time during the time horizon. The final pressure maintenance constraints (4.19) and (4.20) makes sure that the assigned pressure maintainer stays the necessary margin from its production bounds.

### Unit Specific Constraints

Until now the most important constraints for the units have been presented. A number of other constraints exists, these are constraints taking into account the specific technical details of the Greater Copenhagen CHP system i.e. the forced production of water at HCV8 and SMV7, the water production induced by steam production at HCV7 and the fact that AVV1 and AVV2 sometimes cannot change their production at the same time. These constraints will not be presented here since the extended model contains a detailed modeling of each of the production units, which means that these current constraints are not used in the extended model and are therefore not relevant for this thesis.

### Constraints on The Storages

As for the production units the additional constraints for the storages can be divided into categories

- Balance
- Commitment rules
- Capacities on input/output load
- Capacities on change in input/output load
- Capacities on content

#### Balance

When heat is loaded in to or out of a storage the content increases or decreases respectively. This balance is represented in the model through the constraint

$$\nu_{v,level,t}^h - \nu_{v,out,t}^h + \nu_{v,in,t}^h = \nu_{v,level,t+1}^h \quad \forall v, t \quad (4.21)$$

The initial content of a storage is given in the parameter

- $V_v^{h-ini} \in \mathbb{R}^+$ : Initial content for storage  $v$  (MWh)

and assigned in the constraint

$$\nu_{v,level,0}^h = V_v^{h-ini}, \quad \forall v \quad (4.22)$$

## Commitment Rules

The commitment rules for the storages are that a storage must remain in the same state  $z$  for a minimum number of time segments  $\underline{V}_{v,z}^{on} \in \mathbb{N}$  and a storage can only be in one state within a time segment. The constraints making sure these rules are kept use the following variables

- $\nu_{v,z,t}^{on} \in \{0, 1\}$ : 1 if storage  $v$  is in state  $z$  in time segment  $t$
- $\nu_{v,z,t}^{start} \in \{0, 1\}$ : 1 if storage  $v$  starts to perform state  $z$  in time segment  $t$

Then the constraints can be stated

$$\nu_{v,z,t}^{start} \geq \nu_{v,z,t}^{on} - \nu_{v,z,t-1}^{on}, \quad \forall v, z, t \quad (4.23)$$

$$\nu_{v,z,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{V}_{v,z}^{on}\}} \nu_{v,z,t_1}^{start}, \quad \forall v, z, t \quad (4.24)$$

$$\sum_z \nu_{v,z,t}^{on} = 1 \quad \forall v, t \quad (4.25)$$

(4.23) registers when a storage goes into a state. (4.24) then states that if the storage has went into a state in a previous time segment within the minimum commitment time the storage must still be in this state. The final commitment constraint for the storages (4.25) makes sure that a storage is only in one state at a time.

## Capacities

The capacities on in/out load, content and change in in/out load are modeled similar to the units. The parameters

- $\bar{V}_{v,z,t}^h \in \mathbb{R}^+$ : Maximum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\underline{V}_{v,z,t}^h \in \mathbb{R}^+$ : Minimum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\bar{V}_v^{\Delta h} \in \mathbb{R}^+$ : Maximum change in load for storage  $v$  (MJ/s/t)

and the variable

- $\nu_{v,z,t}^{\Delta h} \in \mathbb{R}$ : Change in load from the previous time segment to time segment  $t$  (MJ/s)

are used in the capacity constraints, which are stated below

$$\bar{V}_{v,z^{act},t}^h \cdot \nu_{v,z^{act},t}^{on} \geq \nu_{v,z^{act},t}^h, \quad \forall v, z^{act}, t \quad (4.26)$$

$$\nu_{v,z^{act},t}^h \geq \underline{V}_{v,z^{act},t}^h \cdot \nu_{v,z^{act},t}^{on}, \quad \forall v, z^{act}, t \quad (4.27)$$

$$\bar{V}_{v,'level',t}^h \geq \nu_{v,'level',t}^h, \quad \forall v, t \quad (4.28)$$

$$\nu_{v,'level',t}^h \geq \underline{V}_{v,'level',t}^h, \quad \forall v, t \quad (4.29)$$

$$\nu_{v,t}^{\Delta h} \geq (\nu_{v,in,t+1}^h - \nu_{v,in,t}^h) - (\nu_{v,out,t+1}^h - \nu_{v,out,t}^h), \quad \forall v, t \quad (4.30)$$

$$\nu_{v,t}^{\Delta h} \geq (\nu_{v,out,t+1}^h - \nu_{v,out,t}^h) - (\nu_{v,in,t+1}^h - \nu_{v,in,t}^h), \quad \forall v, t \quad (4.31)$$

$$\bar{V}_v^{\Delta h} \geq \nu_{v,t}^{\Delta h}, \quad \forall v, t \quad (4.32)$$

(4.26) and (4.27) limit the in/out load, (4.28) and (4.29) limit the content and finally (4.30) and (4.31) register the change in input/output load which is then limited in (4.32). The reason why (4.30) and (4.31) looks a bit different than the corresponding constraints for the units is due to the fact that the load can be changed from a load in one active state to a load in another active state.

## Constraints on The Transmission Lines

The additional constraints for the transmission lines are also divided into categories

- Commitment rules
- Capacities on transmission load
- Capacities on change in transmission load
- Special constraints

### Commitment Rules and Capacities

The commitment rules state that a transmission line must stay online for minimum period of time. This rule and the capacities are modeled in the same way as for the units and the storages. The parameters used are

- $X_{a_1,e,a_2}^{h-ini}$ : The initial transmission load for transmission line  $(a_1, e, a_2)$
- $\underline{X}_{a_1,e,a_2}^{on} \in \mathbb{N}$ : The minimum number of time segments the transmission line  $(a_1, e, a_2)$  must be online
- $\bar{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Maximum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\underline{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Minimum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\bar{X}_{a_1,e,a_2}^{\Delta h} \in \mathbb{R}^+$ : Maximum change in transmission load for transmission line  $(a_1, e, a_2)$

Furthermore the following variables are used

- $\chi_{a_1,e,a_2,t}^{start} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is started in time segment  $t$
- $\chi_{a_1,e,a_2,t}^{on} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is online in time segment  $t$
- $\chi_{a_1,e,a_2,t}^{\Delta h} \in \mathbb{R}^+$ : Change in transmission load for transmission line  $(a_1, e, a_2)$  from the previous time segment to time segment  $t$  (MJ/s)

Given these the constraints can be stated

$$\chi_{a_1,e,a_2,0}^h = X_{a_1,e,a_2}^{h-ini}, \quad \forall(a_1, e, a_2) \quad (4.33)$$

$$\chi_{a_1,e,a_2,t}^{start} \geq \chi_{a_1,e,a_2,t}^{on} - \chi_{a_1,e,a_2,t-1}^{on}, \quad \forall(a_1, e, a_2), t \quad (4.34)$$

$$\chi_{a_1,e,a_2,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{X}_{a_1,e,a_2}^{on}\}} \chi_{a_1,e,a_2,t_1}^{start}, \quad \forall(a_1, e, a_2), t \quad (4.35)$$

$$1 \geq \chi_{a_1,e,a_2,t}^{on} + \chi_{a_2,e,a_1,t}^{on}, \quad \forall(a_1, e, a_2), t \quad (4.36)$$

$$\bar{X}_{a_1,e,a_2,t}^h \cdot \chi_{a_1,e,a_2,t}^{on} \geq \chi_{a_1,e,a_2,t}^h, \quad \forall(a_1, e, a_2), t \quad (4.37)$$

$$\chi_{a_1,e,a_2,t}^h \geq \underline{X}_{a_1,e,a_2,t}^h \cdot \chi_{a_1,e,a_2,t}^{on}, \quad \forall(a_1, e, a_2), t \quad (4.38)$$

$$\chi_{a_1,e,a_2,t}^{\Delta} \geq (\chi_{a_1,e,a_2,t+1}^h - \chi_{a_1,e,a_2,t}^h) - (\chi_{a_1,e,a_2,t+1}^h - \chi_{a_2,e,a_1,t}^h), \quad \forall(a_1, e, a_2), t \quad (4.39)$$

$$\chi_{a_1,e,a_2,t}^{\Delta h} \geq (\chi_{a_1,e,a_2,t}^h - \chi_{a_1,e,a_2,t+1}^h) - (\chi_{a_2,e,a_1,t}^h - \chi_{a_2,e,a_1,t+1}^h), \quad \forall(a_1, e, a_2), t \quad (4.40)$$

$$\bar{X}_{a_1,e,a_2}^{\Delta h} \geq \chi_{v,t}^{\Delta h}, \quad \forall(a_1, e, a_2), t \quad (4.41)$$

(4.33) defines the initial transmission load, (4.34) and (4.35) make sure the commitment rules are kept. (4.36) states another commitment rule namely that a transmission line can only be online for a flow in one direction at a time, (4.37) and (4.38) limit the transmission load and finally the combination of (4.39), (4.40) and (4.41) limits the change in transmission load. The reason why (4.39), (4.40) looks different from the corresponding constraints for the units here is due to the fact that for some transmission lines it is possible to change the direction of the transmission load.

### Special Constraints

The remaining special constraints for the transmission lines deals with forced transmission and different interdependencies between the lines. These constraints are used to deal with a simplified network, which sometimes are not sufficient to describe the true system. Thus to keep focus on the main goal of

this thesis of presenting the extended model these are omitted from the presentation of The Katja Model.

## 4.4 The Output

When the model is solved, minimizing the objective function (4.6) subject to all of the constraints (4.3) - (4.41) just introduced, an output heat load plan is found together with the costs of changing the original production plan. A typical heat load plan is illustrated in figure 4.7 The plan contains a production

	Heat production plan (MJ/s)		Heat transmission plan (MJ/s)		Heat storage plan		Pressure maintenance
	Unit 1	Unit 2	Unit 1 -> Area 1	Unit 2 -> Area 1	Load/Unload (MJ/s)	Level (MWh)	
					Storage 1	Storage 1	
00-01	30	..	20	..	-10	880	Unit 1
01-02	35	..	25	..	-5	875	Unit 1
02-03	34	..	25	..	12	887	Unit 1
03-04	33	..	25	..	14	901	Unit 1
04-05	30	..	25	..	14	915	Unit 1
05-06	45	..	25	..	14	929	Unit 1
06-07	25	..	25	..	14	943	Unit 1
07-08	..	..	25	..	14	957	Unit 1
08-09	..	..	25	..	14	971	Unit 1
09-10	..	..	25	..	14	985	Unit 1
10-11	..	..	25	..	14	999	Unit 1
11-12	..	..	..	..	14	..	..
12-13	..	..	..	..	-50	..	..
13-14	..	..	..	..	22	..	..
14-15	..	..	..	..	21	1006	..
15-16	..	..	..	..	23	1029	Unit 1
16-17	..	..	..	..	23	1052	Unit 1
17-18	..	..	..	..	..	1052	Unit 1
18-19	..	..	..	..	..	1052	Unit 1
20-21	..	..	..	..	..	1052	Unit 1
21-22	..	..	..	..	..	..	Unit 1
22-23	..	..	..	..	..	..	Unit 1
23-24	..	..	..	..	..	..	Unit 1

Figure 4.7: An imaginary example of a 24 hour heat load plan

plan for the production units, a transmission plan, a storage plan and finally the production unit responsible of maintaining the pressure in the systems with a need for this.

## 4.5 Summary

In this chapter a description of the input, the model and the output of The Katja Model was given. The Katja Model is a detailed MILP model of especially the technical details for the storages and the transmission lines of The CHP System of Greater Copenhagen and it is the model used by VLE to re-optimize the production plans given by the production companies (see chapter 1. An overview of the input and output can be seen in figure 4.8 and furthermore a

full summary of the mathematics of the simplified version of The Katja Model which was presented in this chapter can be found in appendix A.1.

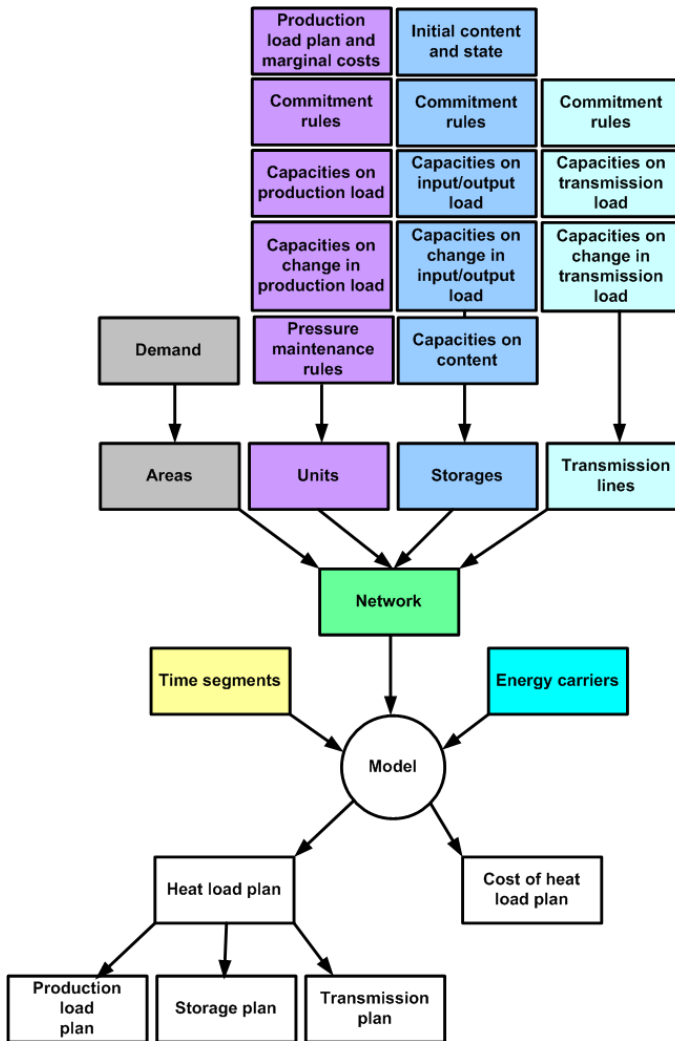


Figure 4.8: The Katja Model

# The Esben Model

---

In the previous chapter The Katja Model used by VLE to create daily heat load plans was introduced. In this model the production by the units was given by a production plan with related marginal costs for changes given by the production companies. In this chapter The Esben Model, which is an extension to The Katja Model, will be introduced. This extension models the economy and the technical details of the production units in a high level of detail. On a model level this is done by introducing a new type of networks with a number of new related constraints and a new objective function. By making this extension the possibility of optimizing the entire CHP system in a single process is achieved. The results from this extended model, which from this point will be referred to as The E&K Model, could then be used to evaluate the daily heat load plans created using the divided planning process where a production plan is found by the production companies and then re-optimized with The Katja Model.

## 5.1 The Extension - Generation Technologies

In order to model the economy and the technical details of the production units a new type of node is introduced to the input network, namely the generation technologies (Technologies)  $g \in \mathcal{G}$ . These technologies are placed within the units represented in the model by the set  $g_u \subset \mathcal{G}$  of technologies within the unit

*u.* The technologies take as input an energy carrier or a new commodity fuel  $f \in \mathcal{F}$  representing the common fuels introduced in chapter 2 e.g. coal or wood pellets and transforms it into either a load of heat, electricity or both as output. In figure 5.1 a technology is shown.

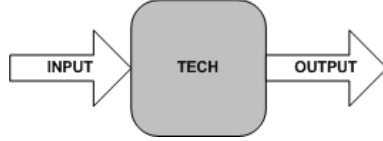


Figure 5.1: A Technology

The technologies are inspired by the generation technologies used in the Balmorel model [1]. In Balmorel a technology also takes a fuel as input and gives heat, electricity or both as output following a certain production profile. A single technology is then typically used to model a production unit. This is sufficient for a model like Balmorel which are primarily used for scenario analysis of larger areas, sometimes many countries. In The Esben Model, which should have a higher level of detail the technologies also take energy carriers (heat) generated by other technologies as input. These energy carriers are sent on through edges  $(g_1, e, g_2) \in \mathcal{GX}$  between the technologies creating a network of technologies within a unit similar to the top level network of the areas.

The idea behind representing the production of the units through such a network originates from looking at the process diagrams normally used to represent production units. As mentioned in chapter 2 a production unit typically consist of boilers and turbines with heat connections. Having a network of technologies could if needed give the possibility of representing these different components and their connections. It is however important to mention that the aim is to model the production profile of the unit, not to create the exact process diagrams as a technology network. But in many situations looking at the technology network as a process diagram can be a great help.

The main decisions to make for the technology network is to decide on the transmission load for energy carriers between the technologies, the amount of fuel loaded into a technology and the amount of electricity and heat a given technology should produce. In The Esben Model these decisions are made using the following variables

- $\gamma_{g_1, e, g_2, t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(g_1, e, g_2)$  in time segment  $t$  (MJ/s)
- $\gamma_{g, t}^{fuel} \in \mathbb{R}$ : The amount of fuel loaded into the technology  $g$  in time segment  $t$  (MJ/s)

- $\gamma_{g,t}^{h-out} \in \mathbb{R}^+$ : The heat output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{el-out} \in \mathbb{R}^+$ : The electricity output load from technology  $g$  (MJ/s)

## Technology Types

The technologies can be distinguished by their output resulting in the following technology types

- Heat boiler technology
- Condensing technology
- Back-pressure technology
- Gathering technology

The heat boiler technologies  $g_{hob} \subset \mathcal{G}$  only have a heat output and likewise the condensing technologies  $g_{cnd} \subset \mathcal{G}$  only have an electricity output. These are quite simple compared to the back-pressure and gathering technologies which requires a more detailed explanation.

### The Back-Pressure Technology

As the name implies the output of the back-pressure technologies can be exemplified by the output of the turbines of a back-pressure unit. In chapter 2 it was described that these turbines, due to the lack of an extraction possibility, typically have a output of heat and electricity which is fixed and given by a value  $C_b$ . However in chapter 3 there was an example of a back-pressure turbine with an output which instead was given by a linear relationship resulting in the type of output profile given in figure 5.2. In The Esben Model a general formulation is used which is valid for both cases.

The fixed linear output profile are capable of representing both cases. The linear relation is represented in the model by introducing the following variables.

- $G_g^{Marg.C_b} \in \mathbb{R}$ : The marginal  $C_b$  value used for technologies  $g_{bpr}$
- $G_g^{Interceptbpr} \in \mathbb{R}$ : The interception of the back-pressure line on electricity axis in an heat/electricity output diagram for technologies  $g_{bpr}$  (MJ/s).

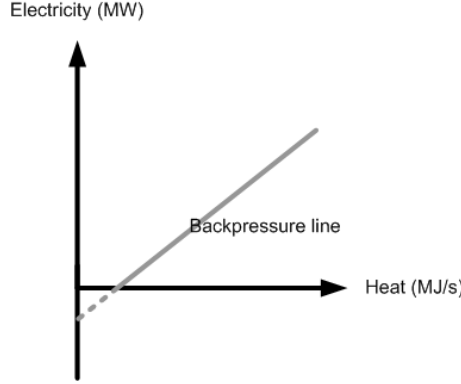


Figure 5.2: Output diagram for a back-pressure technology

and stating the linear relationship

$$\gamma_{g_{bpr},t}^{el-out} \geq \gamma^{h-out} \cdot G_{g_{bpr}}^{Marg.C_b} + G_{g_{bpr}}^{interceptbpr} \cdot \gamma_{g,t}^{on} \cdot \forall g_{bpr},t \quad (5.1)$$

To represent back-pressure turbines where the fixed relationship should be given by a fixed constant like  $C_b$ ,  $G_{g_{bpr}}^{Marg.C_b}$  is set equal to  $C_b$  and  $G_{g_{bpr}}^{Interceptbpr}$  is set equal to zero. The reason why the online variable  $\gamma_{g,t}^{on} \in \{0,1\}$ , which is 1 if technology  $g$  is online in time segment  $t$ , is multiplied to the interception term is to avoid that an output is generated if the technology is offline.

## The Gathering Technology

In a technology network heat is sent from one technology to another technology and in many cases there is more than one technology which contributes to the overall heat production of the unit. Therefore a gathering technology is needed. If a production of heat by a technology carried by steam or water should contribute to the overall heat production of a unit, it is sent to the gathering technology. Thus the sum of the heat sent to the gathering technology carried by a energy certain carrier (steam or water), becomes the overall heat production of the unit for that specific carrier. One way of looking at the gathering technology is as a representation of a DH heat exchanger.

## Differencies on Input

Besides from distinguishing the technologies with respect to output, they are also distinguished on input i.e. the technologies  $g_f \subset \mathcal{G}$  takes fuel  $f$  as input. If

a technology is not represented in this set the only possible input are the energy carriers.

## An Example

Before the rest of the constraints of The Esben Model are introduced an example of how a production unit could be represented using a technology network will be given. A simple process diagram of an imaginary unit is illustrated in figure 5.3.

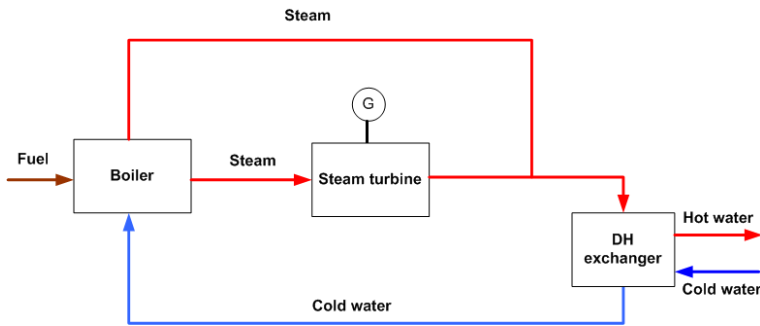


Figure 5.3: A process diagram of an imaginary but yet realistic production unit

This production unit consists of boiler consuming fuel to heat cold water until it becomes steam. The steam can then be sent to a steam turbine which uses the steam to drive a generator of electricity. The turbine is a back-pressure turbine. The remaining steam is sent on to a DH exchanger where the steam heats DH water and then finally returns to the boiler as cold water. The production unit also has the possibility of making a bypass of the steam turbine and thereby the possibility of sending some or all of the steam directly from the boiler to the DH exchanger.

## Representation of the Example

Now the representation of the imaginary production unit can be described. An illustration of the technology network used for this is given in figure 5.4.

As seen in the figure there is a technology network consisting of three technologies within this unit. The technology TECH1 represents the boiler and it is

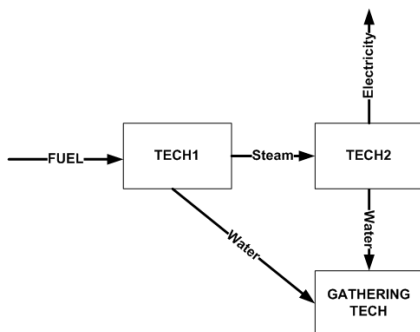


Figure 5.4: Illustration of the model representation of the imaginary production unit

modeled as using a heat boiler technology. TECH1 takes fuel as input and produces heat. The second technology TECH2 represents the steam turbine and is modeled as a back-pressure technology taking heat as input to generate heat and electricity. The final technology is the gathering technology which gathers the heat contributing to the overall heat production. In the figure the possible connections are also shown. TECH1 takes in the fuel and has the possibility of sending the generated heat on to TECH2 which utilize the heat to generate heat and electricity. The electricity production is registered and the generated heat can be sent to the gathering technology. Traveling this way through the network represents the situation where the steam turbine is used before sending the heat to the DH exchanger. TECH1 also has the possibility of sending some or all of the heat directly to the gathering technology. Traveling this way through the network represents the situation where the heat is sent directly from the boiler to the DH exchanger. The returning water seen in the process diagram which is used in the boiler to generate steam is not directly represented in the model. It is just assumed that there is always enough water to generate the steam which carries the energy created by utilizing the fuels.

The example gives an impression of how the heat flows through the network. Like for the general network this flow is balanced using constraints. In the following these balance constraints and how the model deals with production unit fuel efficiencies will be described.

## Balance and Fuel Efficiency

A technology needs an input load to produce an output load. For some technologies these loads are equal, but to give the possibility of modeling the loss of

energy during production the following parameters are introduced.

- $G_g^{Marg.fe} \in \mathbb{R}$ : The marginal fuel/input efficiency for technology  $g$
- $G_g^{interceptfu} \in \mathbb{R}$ : The interception of the fuel/input line on the fuel axis in an input/output diagram for technology  $g$

$\frac{1}{G_g^{Marg.fe}}$  is the slope and  $G_g^{interceptfu}$  the interception of the fuel line on the fuel axis shown in figure 2.12 which was presented in chapter 2. Having both the slope and the interception gives the possibility of modeling a variable input efficiency. Before the balance constraints are stated a new variable is introduced.

- $\gamma_{g,t}^{out} \in \mathbb{R}^+$ : The total output load from technology  $g$  (MJ/s)

Then the constraints can be stated

$$\gamma_{g,t}^{out} = \gamma_{g,t}^{h-out} + \gamma_{g,t}^{el-out}, \quad \forall g, t \quad (5.2)$$

$$\gamma_{g,t}^{fuel} + \sum_{g_1,e} \gamma \chi_{g_1,e,g,t}^h = \frac{\gamma_{g,t}^{out}}{G_g^{Marg.fe}} + G_g^{interceptfu} \cdot \gamma_{g,t}^{on}, \quad \forall g, t \quad (5.3)$$

$$\sum_{g,e} \gamma \chi_{g,e,g_1,t}^h = \gamma_{g_{heat},t}^{h-out}, \quad \forall g, t \quad (5.4)$$

$$\sum_{g_1 \in g} \gamma \chi_{g_1,e,g,t}^h = \mu_{u,e,t}^{h-out}, \quad \forall g \in g_{gath} \wedge g_u, u, e, t \quad (5.5)$$

The first constraint (5.2) states that the total output of a technology equals the electricity output and the heat output.

The second constraint (5.3) states that the load of fuel and heat loaded into a technology should equal the total output divided with the input efficiency. Like it was the case for the linear relationship between heat and electricity for the back-pressure technology the online variable is also multiplied to the constant interception term of the linear efficiency to avoid production when the technology is offline.

The third constraint (5.4) states that the output heat is sent on to other technologies as one of the energy carriers. Thus the electricity is not sent on.

The final balance constraint states, that all the heat represented by the energy carriers, which flows into a gathering technology within a unit from other technologies, are equal to the total production of this energy carrier for the unit. This final constraint is the connection of The Esben Model to The Katja Model and it ensures the balance is kept in the total network of The E&K Model. Thus the heat production of a unit is not given by a plan +/- changes as for The Katja Model (constraint (4.3)) but a technology network representing the technical details for production.

In figure 5.5 the basic network components for The E&K Model is illustrated.

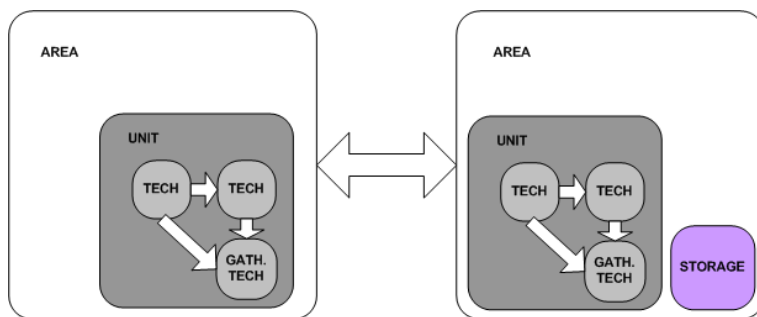


Figure 5.5: Illustration of the components of the input network for The E&K Model

## Additional Constraints

Like for the units, storages and transmission lines of The Katja Model a number of additional constraints exist for the technologies in The Esben Model, which can be used to describe technical details of the units. These additional constraints can be divided into the following categories

- Commitment rules
- Capacities on production load, i.e. the total summed production of electricity and heat
- Capacities on change in production load
- Dependencies on production
- Dependencies on change in production

### Commitment Rules

With regards to commitment rules the technologies have a minimum offline and online time which must be kept. This is modeled in the same way as it was modeled for the units. The following parameters

- $\underline{G}_g^{on} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay online if started
- $\underline{G}_g^{off} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay offline if shut down

and variables

- $\gamma_{g,t}^{start} \in \{0, 1\}$ : 1 if technology  $g$  is started in time segment  $t$
- $\gamma_{g,t}^{shutdn} \in \{0, 1\}$ : 1 if technology  $g$  is shut down in time segment  $t$
- $\gamma_{g,t}^{on} \in \{0, 1\}$ : 1 if technology  $g$  is online in time segment  $t$

are used in the constraints

$$\gamma_{g,t}^{start} \geq \gamma_{g,t}^{on} - \gamma_{g,t-1}^{on} \quad \forall g, t \quad (5.6)$$

$$\gamma_{g,t}^{shutdn} \geq \gamma_{g,t-1}^{on} - \gamma_{g,t}^{on} \quad \forall g, t \quad (5.7)$$

$$\gamma_{g,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{G}_g^{on}\}} \gamma_{g,t_1}^{start} \quad \forall g, t \quad (5.8)$$

$$1 - \gamma_{g,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{G}_g^{off}\}} \gamma_{g,t_1}^{shutdn} \quad \forall g, t \quad (5.9)$$

where (5.6) and (5.7) registers the start-up and shutdown respectively of the technology. While (5.8) and (5.9) makes sure the minimum online and offline time respectively is kept. Besides from the minimum online and offline times another commitment rule exists namely that some technologies  $g_{g_1}^{on} \subset \mathcal{G}$  can only be online if another technology  $g_1$  is also online. This is stated in the following constraint

$$\gamma_{g_1,t}^{on} \geq \gamma_{g_{g_1},t}^{on}, \quad \forall g_{g_1}^{on}, t \quad (5.10)$$

## Capacities

The capacities on the production and change in production are also modeled in the same way as for the units. The following parameters are used

- $\bar{G}_{g,t}^{out} \in \mathbb{R}$ : Maximum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $\underline{G}_{g,t}^{out} \in \mathbb{R}$ : Minimum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $\bar{G}_g^{\Delta out} \in \mathbb{R}$ : Maximum change in output load from one time segment to the next for technology  $g$

in the constraints stated below

$$\bar{G}_{g,t}^{out} \cdot \gamma_{g,t}^{on} \geq \gamma_{g,t}^{out}, \quad \forall g, t \quad (5.11)$$

$$\gamma_{g,t}^{out} \geq \underline{G}_{g,t}^{out} \cdot \gamma_{g,t}^{on}, \quad \forall g, t \quad (5.12)$$

$$\gamma_{g,t}^{\Delta out} \geq \gamma_{g,t}^{out} - \gamma_{g,t-1}^{out}, \quad \forall g, t \quad (5.13)$$

$$\gamma_{g,t}^{\Delta out} \geq \gamma_{g,t-1}^{out} - \gamma_{g,t}^{out}, \quad \forall g, t \quad (5.14)$$

$$\bar{G}_g^{\Delta out} \geq \gamma_{g,t}^{\Delta out}, \quad \forall g, t \quad (5.15)$$

(5.11) and (5.12) limits the production while the combination of (5.13), (5.14) and (5.15) limits the change in production. Having these capacities and the commitment rules for specific technologies gives a possibility of a more detailed modeling of the production units. The corresponding constraints (4.7) - (4.15) for the units could still be kept in The E&K Model in order to represent the commitment rules and capacities for the DH heat exchange.

## Production Dependencies

Multi-fuel boilers often have different capacities and efficiencies for the different fuels. One way of representing these boilers using a technology network is illustrated in figure 5.6.

The network illustrated represents a multi-fuel boiler with the possibility of using FUEL1 and FUEL2. The technology TECH-B-FUEL1 is of type heat boiler technology and takes FUEL1 as input. TECH-B-FUEL2 corresponds to TECH-B-FUEL1 with the difference that it takes FUEL2 as input. Both TECH-B-FUEL1 and TECH-B-FUEL2 have a steam/heat connection to a third heat boiler technology TECH-B. This representation gives the possibility of assigning

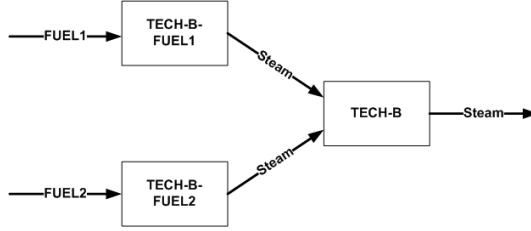


Figure 5.6: One way of representing a multi-fuel boiler with a technology network

capacities and efficiencies on the use of a certain fuel by assigning values for these to TECH-B-FUEL1 and TECH-B-FUEL2 while still limiting the total output through TECH-B.

By using this representation one can also model that some multi-fuel boilers require a certain percentage of a certain fuel compared to the use of another fuel when mixing the fuels. In order to do this some new constraints must be given for the technologies. The following parameters are used

- $G_{g_1, g_2}^{depmaxshare} \in [0; 1]$ : The output load by technology  $g_1$  must at maximum be equal to this share of the output load of  $g_2$  if online
- $G_{g_1, g_2}^{depminshare} \in [0; 1]$ : The output load by technology  $g_1$  must at minimum be equal to this share of the output load of  $g_2$  if online

Then the constraints can be stated

$$\gamma_{g,t}^{on} \cdot G_{g,g_1}^{depmaxshare} \geq \gamma_{g,t}^{out}, \quad \forall g, t \quad (5.16)$$

$$\gamma_{g,t}^{out} \geq \gamma_{g,t}^{on} \cdot G_{g,g_1}^{depminshare}, \quad \forall g, t \quad (5.17)$$

(5.16) states that the output from an online technology  $g$  must at maximum be equal to the maximum share of the output of another technology  $g_1$  and likewise (5.17) states that the output from  $g$  must at minimum be equal to the minimum share of the output from  $g_1$ .

### Dependencies on Change in Production

In chapter 3 it was described that the units AVV1 and AVV2 sometimes cannot be regulated simultaneously. In order to represent this in the model the following set is introduced

- $u_{u_1}^{no\Delta h} \subset \mathcal{U}$ : Set of units which cannot change their production load at the same time as unit  $u_1$

For the units in this set the following constraints are then given

$$\mu_{u,t}^{\Delta hon} \cdot M \geq \sum_g \gamma_{g,t}^{\Delta out}, \quad \forall u, t \quad (5.18)$$

$$1 \geq \mu_{u_1}^{\Delta h-out} + \mu_{u_1,e,t}^{\Delta h-out}, \quad \forall u_{u_1}^{no\Delta h}, e, t \quad (5.19)$$

$M$  represents a large number. The first constraint (5.18) registers a change in production for one of the technologies within a unit and (5.19) then states that the technologies within an unit in  $u_{u_1}^{no\Delta h}$  cannot be regulated at the same time as the technologies within  $u_1$ .

## Model Examples

Now all of the constraints related to balance and technical limitations in The Esben Model have been introduced. Some other constraints related to the new objective function exists and these will be introduced in the description of this. Before the introduction to the objective function is given, some examples of how to use the technology networks to represent some of the challenging technical details for the different units of The Greater Copenhagen CHP System will be given. This is done to give the reader a feel of the use of the model. The focus of the description will be on the parts which are not straightforward. A full implementation report with descriptions and figures of the representation of each of the units in the CHP system is given in appendix B.

### Representation of an Extraction Unit

Modeling heat boiler units, condensing units and back-pressure units should be straightforward using the type of technologies with corresponding output profiles in the technology network. In the Balmorel model a technology exists with an output profile like the one illustrated in figure 2.7. This technology can be used to represent a unit with an extraction turbine. In chapter 3 it was described that the twins AMV3 and AVV1 have an output profile different from this, namely the output profile with a kink illustrated in figure 3.3. The current version of Balmorel cannot deal with a detail like that. Therefore The Esben Model does not have a technology type with an output profile corresponding to the one of an extraction unit instead both kinds of output profiles are made

for an unit by representing the extraction turbine using a combination of back-pressure and condensing technologies. In figure 5.7 an illustration of how to make a technology network representation of an extraction turbine with an output profile without the 'kink' is displayed.

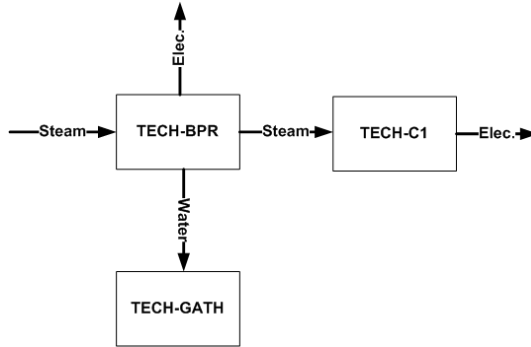


Figure 5.7: Technology network representing an extraction turbine without the 'kink'

The back-pressure technology TECH-BPR takes heat as input and produces heat and electricity. If all of the heat is sent on to the gathering technology TECH-GATH the production of the unit is on any point A on the back-pressure line as displayed in the first step in figure 5.8. Instead the heat produced by TECH-BPR can be sent to the condensing technology TECH-C, which takes the heat as input to produce electricity with an input efficiency given by the  $C_v$  value. This corresponds to an exchange of the heat to electricity with an exchange rate  $C_v$ , which means that if all the heat is sent from TECH-BPR to TECH-C1 the output will be at the point B seen in step 2 in figure 5.8 with an electricity production only. In that way the fact that the same amount of fuel is used along any point on a  $C_v$ -line is represented.

Representing a unit with an extraction turbine output profile with a 'kink' is done by introducing an extra condensing technology as seen in figure 5.9.

The steps for this representation is illustrated in figure 5.10. Like for the previous representation heat is sent to the back-pressure technology TECH-BPR which if all the heat produced is sent to TECH-GATH gives an output on a point A on the back-pressure line. Instead of sending all the generated heat to TECH-GATH the heat can be sent on to TECH-C1 with an input efficiency equal to the absolute value of the slope of the  $C_v$ -line i.e. the  $C_{v1}$  value and a maximum output equal to the difference between the electricity generated in point 5 and 1 which is assumed to be identical to the difference between point

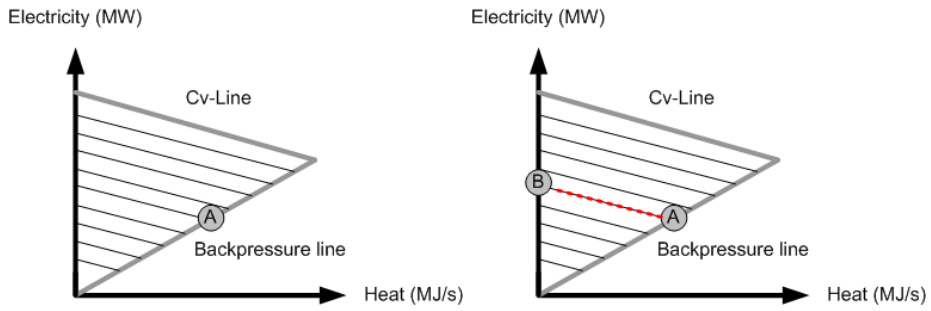


Figure 5.8: The output steps for the representation of an extraction unit without the 'kink'

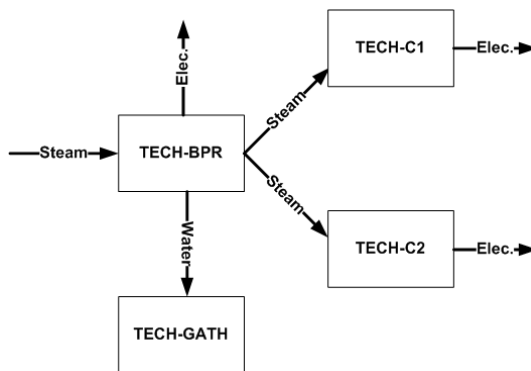


Figure 5.9: Technology network representing an extraction turbine with the 'kink'

4 and 3. Sending the maximum amount of heat possible to TECH-C1 gives an output in the point B. If the model wants to exchange more electricity, heat can also be sent to TECH-C2, with an input efficiency equal to  $C_v2$ . This gives an output on the line between B and C. The model will only sent heat to TECH-C2 when the capacity of TECH-C1 is reached due to dominance on the input efficiency i.e. the exchange rate for heat to electricity.

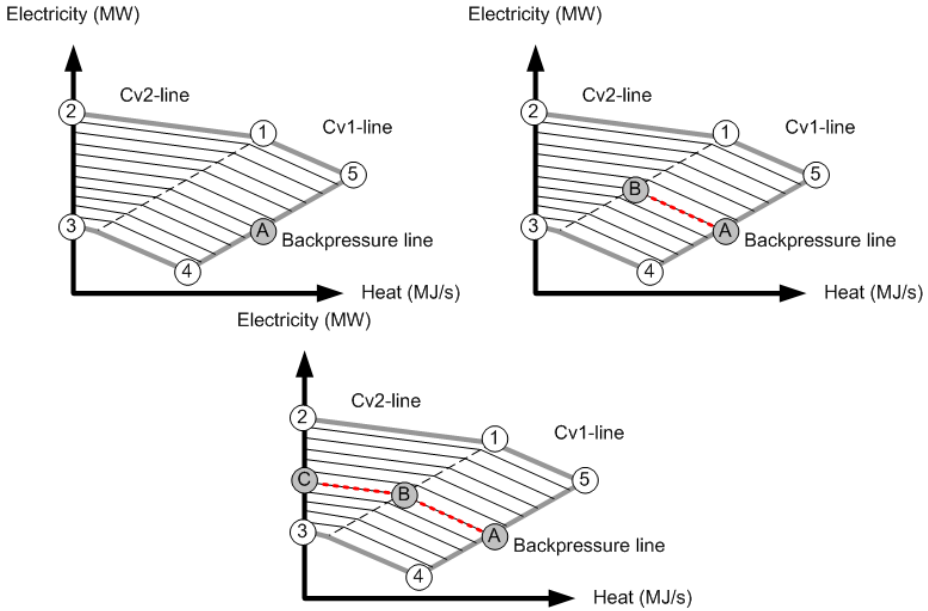


Figure 5.10: The output steps for the representation of an extraction unit with the 'kink'

### Representation of HCV7

In chapter 3 the unit HCV7 was described in detail and the process diagram in figure 3.5 was given. HCV7 is interesting due to the complex technical details with a forced water production and two connected turbines. Figure 5.11 displays how this unit could be represented in a technology network in the model.

The multi-fuel boiler of HCV7 which takes fuel oil and Natural gas as input is represented using the method described previously in this chapter by three heat boiler technologies HCV-B-FUELOIL, HCV7-B-NG and HCV7-B. From this boiler heat can be sent as steam directly to the gathering technology HCV7-

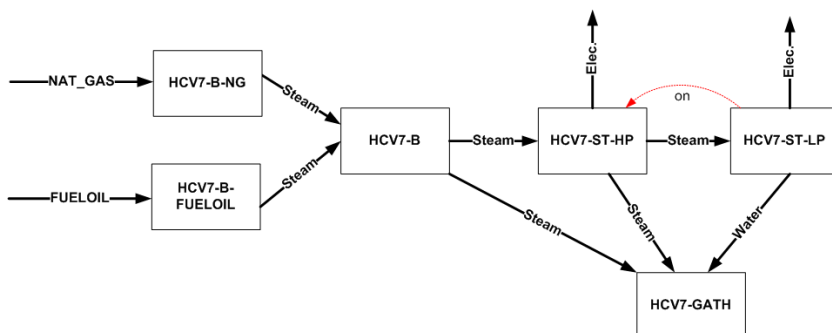


Figure 5.11: Technology network representation of HCV7

GATH representing a bypass of the turbine. The heat from the boiler can also be sent to the back-pressure technology HCV7-ST-HP representing the high-pressure turbine. This technology generates electricity and heat. The heat can be sent to the HCV7-GATH as steam or to the final back-pressure technology HCV7-ST-LP representing the low pressure turbine. This gives an extra electricity production and a heat production which is sent on as water to HCV7-GATH. The red directed line illustrates that HCV7-ST-LP must be online if HCV7-ST-HP should be online. Thus by assigning a minimum production to HCV7-ST-LP an amount of heat is forced to be sent to this technology if HCV7-ST-HP is used. This representation of HCV7 has a high level of detail which shows the capabilities of the model.

## 5.2 The Objective

One vital part of the model has not yet been introduced namely the objective function of The Esben Model, which replaces the objective used in The Katja Model, when the models are combined into The E&K model.

As mentioned previously the main target for VLE, when making a plan, is to keep the cost of production at a minimum. In chapter 2 the most important production costs of a CHP system was given and in chapter 3 it was described how the income from electricity production also has a large influence upon where to produce the heat for the CHP system. Thus this electricity income and the introduced production costs are all part of the objective function, which like the objective for The Katja Model should be minimized. The parameters used in the objective function are listed below.

- $B_t^{el.price} \in \mathbb{R}$ : The price of electricity in time segment  $t$  (money/MJ/s)
- $B_t^{NO_x-Tax} \in \mathbb{R}$ : The tax on  $NO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{SO_x-Tax} \in \mathbb{R}$ : The tax on  $SO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{CO_2-qprice} \in \mathbb{R}$ : The  $CO_2$  quote price in time segment  $t$  (money/kg)
- $F_{f,t}^{price} \in \mathbb{R}$ : The price of fuel  $f$  in time segment  $t$  (money/MJ/s)
- $F_f^{CO_2} \in \mathbb{R}$ : The emission of  $CO_2$  for fuel  $f$  (kg/MJ/s)
- $F_f^{SO_x} \in \mathbb{R}$ : The emission of  $SO_x$  for fuel  $f$  (kg/MJ/s)
- $G_g^{NO_x} \in \mathbb{R}$ : The emission of  $NO_x$  by technology  $g$  (kg/MJ/s)
- $G_g^{DeSO_x} \in [0; 1]$ : The  $DeSO_x$  factor for technology  $g$
- $G_g^{fxstartcost} \in \mathbb{R}$ : The fixed startup cost for technology  $g$  (money)
- $G_{g,f}^{startfuel} \in \mathbb{R}$ : The amount of fuel used to start technology  $g$  (MJ/s)
- $G_g^{omvcost} \in \mathbb{R}$ : The variable operating and maintenance cost for technology  $g$ . (money/MJ/s input)

And the objective is stated below

$$- \sum_{g_e, t} \gamma_{g_e, t}^{el-out} \cdot B_t^{el.price} \quad (5.20)$$

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot F_{f, t}^{price} \quad (5.21)$$

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot F_f^{CO_2} \cdot B_t^{CO_2-qprice} \quad (5.22)$$

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot (1 - G_{g_f}^{DeSO_x}) \cdot F_f^{SO_x} \cdot B_t^{SO_x-Tax} \quad (5.23)$$

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot G_g^{NO_x} \cdot B_t^{NO_x-Tax} \quad (5.24)$$

$$+ \left( \sum_{g, t} \gamma_{g, t}^{fuel} \cdot \sum_{g_1, e} \gamma_{g_1, e, g_2, t}^h \right) \cdot G_g^{omvcost} \quad (5.25)$$

$$+ \sum_{g, t} \gamma_{g, t}^{start} \cdot G_g^{fxstartcost} \quad (5.26)$$

$$+ \sum_{g, f, t} \gamma_{g, t}^{start} \cdot G_{g, f}^{startfuel} \cdot F_{f, t}^{price} \quad (5.27)$$

As seen the terms are given for the technologies and not the units. This gives the possibility of assigning costs to one or more technologies within a technology network and thereby representing the economy in a higher level of detail.

The first term (5.20) in the objective represents the electricity income, which is found using a single electricity price. The term (5.21) represents the fuel costs.

The 3 following terms (5.22),(5.23) and (5.24) represent the cost of taxes and quoteprices on  $CO_2$ ,  $SO_x$  and  $NO_x$  respectively. For each of them a constant term is given describing the emission pr. MJ/s of a certain fuel loaded into a unit.

In (5.23) a  $DeSO_x$ -factor i.e. the amount of the emission which is removed for a technology is given explicitly in the term while in (5.24) the  $DeNO_x$  factor is an implicit part of the emission constant due to the fact that the emission of  $NO_x$  without any  $DeNO_x$  are not just dependent on the type of fuel but also on the type of boiler.

The sixth term (5.25) of the objective represents the variable operating and maintenance costs which are put on the input load in agreement with VLE [3]. This makes sense because if more is loaded into a technology, the technology is used more and thereby needs more maintenance.

The start-up costs are divided into a fixed cost and a fuel price dependent cost. This is due to the fact that when a unit is started an amount of a certain fuel is used before it gives any output. Furthermore manpower is needed which requires a salary payout. The salary to the manpower can be estimated and given in the fixed start-up cost term (5.26) while the fuel needed for a start-up and the cost of this can be given in the fuel dependent start-up cost term (5.27)

This objective function almost takes all the production costs which have been introduced in this thesis into account. Only one thing is missing namely energy tax.

## Energy Tax

Representing the energy tax in the objective is a challenge. To get an understanding of this challenge the formula introduced in chapter 3 used to calculate

the energy tax is formulated using the variables from the model.

$$\sum_e \frac{\mu_{u,e,t}^{h-out}}{U_u^{taxh-eff}} \cdot \sum_{g_f \in g_u} \frac{\gamma_{g_f,t}^{fuel}}{\sum_{f_1} \sum_{g_{f_1} \in g_u} \gamma_{g_{f_1},t}^{fuel}} \cdot F_{f,t}^{etax}, \quad \forall u, f, t \quad (5.28)$$

Where  $U_u^{taxh-eff}$  is the taxed heat efficiency for unit  $u$  and  $F_{f,t}^{etax}$  is the energy tax pr. MJ/s used of fuel  $f$  for heat production in time segment  $t$ . As seen the constraint (5.28) is non-linear and therefore not valid in a mixed integer linear problem.

To deal with this non-linearity a new set  $r \in \mathcal{R}$  of possible ratios in an ascending order are introduced. An example of how the set could look like is  $r = \{0\% - 10\%, 10\% - 20\%, 20\% - 30\%, \dots\}$ . Furthermore a parameter  $ratio_r$  which gives the value of the ratio is introduced. If a ratio  $r$  is  $0\% - 10\%$  then  $ratio_r = 0.0$ . This parameter should be used to represent the term  $\frac{\gamma_{g_f,t}^{fuel}}{\sum_{f_1} \sum_{g_{f_1} \in g_u} \gamma_{g_{f_1},t}^{fuel}}$  from (5.28). In order to do this three constraints are needed which uses the two new variables given below.

- $\mu_{u,f,t}^{etax} \in \mathbb{R}^+$ : The energy tax to be payed by unit  $u$  for the use of fuel  $f$  in time segment  $t$
- $\varphi_{r,u,f,t}^{ratio} \in \{0, 1\}$ : 0 if the unit  $u$  consumes a ratio  $r$  of fuel  $f$  out of all the fuels used on the unit in time segment  $t$

Then the constraints can be stated

$$\mu_{u,f,t}^{etax} \geq \sum_e \frac{\mu_{u,e,t}^{h-out}}{U_u^{taxh-eff}} \cdot ratio_r \cdot F_{f,t}^{etax} - M \cdot \varphi_{r,u,f,t}^{ratio}, \quad \forall u, f, t \quad (5.29)$$

$$\sum_r 1 - \varphi_{r,u,f,t}^{ratio} \geq 1, \quad \forall u, f, t \quad (5.30)$$

$$ratio_{r+1} \cdot \sum_{f_1} \sum_{g_{f_1} \in g_u} \gamma_{g_{f_1},t}^{fuel} + M \cdot \varphi_{r,u,f,t}^{ratio} \geq \sum_{g_f \in g_u} \gamma_{g_f,t}^{fuel} \quad (5.31)$$

Notice that  $M$  represents a large number. Constraint (5.29) gives the energy tax to be payed when a certain ratio is chosen. (5.30) makes sure that only one ratio can be chosen in a time segment and finally (5.31) states that the amount of fuel  $f$  used by unit  $u$  in time segment  $t$  cannot be larger than the next ratio step of the total fuel consumption for the unit in the time segment.

Having these constraints in the model the energy tax can be added in the ob-

jective through the term

$$+ \sum_{u,f,t} \mu_{u,f,t}^{etax} \quad (5.32)$$

This way of modeling the energy tax is not optimal, primarily because it uses binary variables which adds to the complexity of the problem.

### 5.3 Complexity of The Model

This thesis does not focus on the complexity of the models, but it is an important and interesting topic for others to investigate. The use of binary variables makes the problem difficult to solve. Especially the way energy tax is modeled could cause problems.

One way to deal with high computation times is to adress a good initial solution to the problem before running the model. Another method could be to use a heuristic to solve the problem.

### 5.4 Summary

In this chapter The Esben Model was presented. A mathematical summary of the model can be found in appendix A.2. The Esben Model can be used to extend The Katja Model to create an extended model, The E&K model, which is solved by minimizing the objective (5.20) - (5.32) subject to the constraints - (4.41) from The Katja Model and the constraints (5.1) - (5.31) from The Esben Model. An overview of the input and output of The E&K Model is given in figure 5.12.

The E&K Model could be used to find an optimal production and heat load in a single process for the CHP system of Greater Copenhagen taking into account both technical details and economy for the production units and the technical details of the storages and transmission lines. The model could also be used to describe other CHP systems by using a different input network and data.

Finally the model could easily be extended to describe other kind of production units or other technical limitations. All this makes The E&K Model a powerful and flexible tool with many applications e.g. long and short term analysis of a given system. In the following chapter it is described how a model like this

could be used to create an even more powerful tool using the theory behind Model Predictive Control.

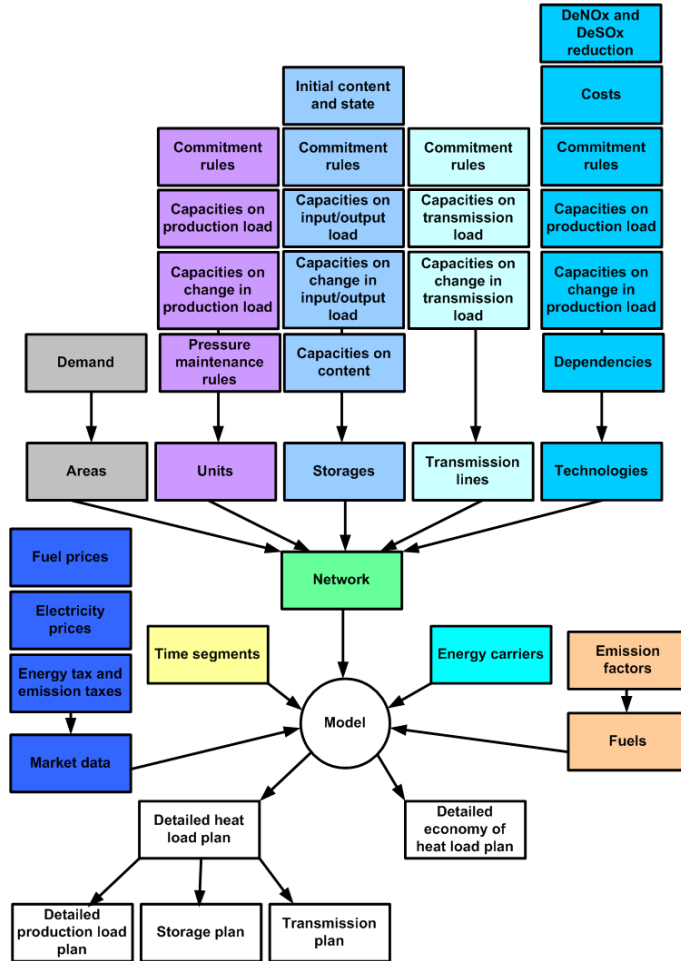


Figure 5.12: The E&K Model



# Planning with Uncertain Information

---

When making a plan for the daily operation of a system like the CHP System of Greater Copenhagen some information are based on prognoses and thereby have some uncertainty connected to it. An example is the customer heat demand which varies with uncertain factors such as the weather and it is thereby difficult to estimate (see figure 6.1). This is just one of the uncertainties; others being the price on electricity and possible crashes in the system. Good plans are made by taking the uncertainty into account and a good planning performance follow-up/analysis tool should therefore also be capable of simulating planning methods where this is done.

## 6.1 Solution Approach

The paper "Dynamic predictive scheduling of operational strategies for continuous processes using mixed-logic dynamic optimization" by Oldenburg et al. [17] describes an interesting approach to making a model framework which could be used to schedule taking the uncertainty into account. Before this approach is described some name definitions taken from the same paper will be given.

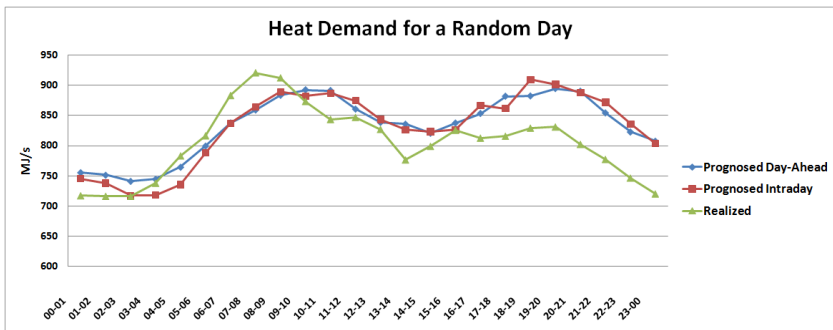


Figure 6.1: Prognosed and realized demands for heat carried by water for a random day using a tool for prognoses

First of all the paper defines a problem where new information arrives as time progresses on an infinite time-horizon as a dynamic scheduling problem. The opposite a static scheduling problem is then a problem with a finite time-horizon where all information is assumed to be known from the beginning. A static scheduling problem could be solved to optimality using a model like The E&K Model without the use of any framework. Whereas solving a dynamic scheduling problem in a satisfying manner taking into account the uncertainties does require something extra.

The paper describes three methods for solving a dynamical scheduling problem: stochastic scheduling, reactive scheduling and periodic rescheduling.

## Stochastic Scheduling

In stochastic scheduling a schedule with some inherent robustness against disturbances such as wrongly prognosed demands is made. The paper does not describe where this inherent robustness comes from. But one way to do it is to use stochastic modeling where a mathematical model which contains a set of possible scenarios with related probabilities of occurrence is used to schedule. Each of the uncertain input parameters to the model then has a scenario dependent value. Thus the problem is solved like a static scheduling problem but the model optimizes taking into account the uncertainty of information at hand. Much more information about stochastic modeling can be found in the book Practical Financial Optimization by Stavros A. Zenios [21].

### Reactive Scheduling

In reactive scheduling a new schedule is made each time a certain event occurs. An event could be that a prognoses shows to be wrong etc. One approach for simulating such a planning method is using a model constructed using the event-by-event principle known from stochastic simulation [19].

### Periodic Rescheduling

The final method presented in the paper is called periodic rescheduling. This method is analyzed in the rest of the paper and shows promising results. An illustration of the concept behind periodical rescheduling can be seen in figure 6.2.

The idea is to only schedule for a limited part of a total period you have information about, however when making this scheduling you take all the current information of the total period into account. When the first scheduled period has passed you schedule for the next short period taking into account newly obtained information for the future. By making this rescheduling the uncertainty of the information is diminished.

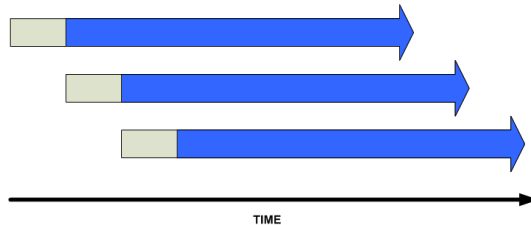


Figure 6.2: An illustration of periodic rescheduling. Each bar represent a rescheduling. An entire bar represents the horizon which is looked upon while making the rescheduling while the white area represent the area which is actually rescheduled

The method originates from the process control theory called Model Predictive Control (MPC) [17] [26]. Process control theory deals with control of dynamic systems such as a chemical plant. A controller typically manipulate the input to a system in order to achieve a desired output. In most control processes a certain set point is given for a process and the assignment of the controller is then to keep the process as close to the set point as possible. Control theory has been widely used and developed through time.

## MPC

MPC is an advanced method for process control. In MPC a mathematical model of the process is used to decide on the process input for a finite time horizon. This horizon is divided into a number of time steps. In each time step the mathematical model is given the current state and predictions of future disturbances as input. The model then calculates the process inputs for the rest of the time horizon, but only the input in the current time step is implemented. By doing this the controller does not only choose the best process input for the current time step, but also takes the future into account. Because the MPC assumes to know the future disturbances in each iteration it is a so-called open loop controller.

In figure 6.3 an open loop control system is illustrated. The current state  $x$  is fed into the controller together with the predicted disturbance  $d1$ . The controller then generates an input to the process. This input deals with the predicted disturbance  $d1$ , but not the unpredicted disturbance  $d2$ . Thus you cannot be sure to get the desired output  $y$  [14].

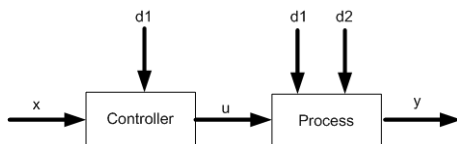


Figure 6.3: An open loop control system

Most MPC's uses a linear model and a set point which is compared to a measurement of the current state [26]. The objective is then typically to minimize the difference between the set point and the output. For the model going to be introduced in this thesis the cost of producing heat is minimized. Thus no set point comparison is done. However such a model could also be used in a MPC system.

There are many papers upon the topic MPC. Two of them "Tutorial Overview of Model Predictive Control" and "Model Predictive Control with Linear Models" [26] [18] by Rawlings et al. gives a good overview of MPC and refers to other good papers on the topic.

## 6.2 The Framework

In this project a periodical rescheduling framework based upon the theory behind MPC is created with the purpose of simulating and analyzing a periodic rescheduling process. This means that the framework will only be used on historical data. A periodical rescheduling framework could also be used in the actual scheduling process. Creating such a framework is beyond the scope of this thesis, but the analytical periodical rescheduling framework could serve as an inspiration on how to do it.

The framework uses The E&K Model to schedule. To keep things simple the varying information which is renewed in each rescheduling is only the customer heat demand prognoses. Thus other information which could be uncertain e.g. the electricity prices are assumed to be fixed for the entire planning time horizon. This simplification is primarily made due to the data available for testing.

In figure 6.4 the idea behind the framework is illustrated. A number of periods  $p$  are given. Each period  $p$  represent a time horizon  $t \in p$  looked upon when rescheduling. The white area of a period represent the part of the period  $t_{imp} \subset t \in p$  which is actually implemented and used while the remaining blue area represents the part of the period which is taken into account besides from the white area when making the rescheduling.

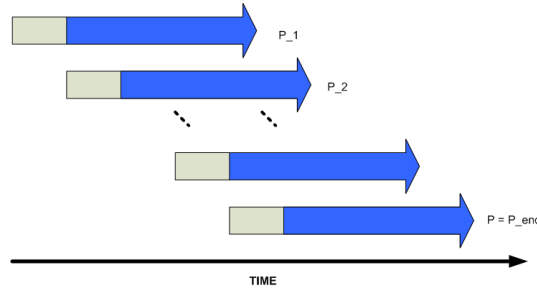


Figure 6.4: An illustration of a Periodic Rescheduling Framework

In the following a pseudocode for the framework will be stated. Before this is done a new input parameter is defined

- $A_{a,e,t}^{ph-demand} \in \mathbb{R}$ : The demand for energy carrier  $e$  in area  $a$  in time segment  $t$  in period  $p$  (MJ/s)

Such a parameter could be stated for any information which is uncertain and

thereby could have different values from period to period. Having this parameter defined the pseudocode can be given.

```

1: for  $p = p_1$  to  $p_{end}$  do
2:   Update state
3:   if  $t \in p$  then
4:      $A_{a,e,t}^{h-demand} \rightarrow A_{a,e,t,p}^{ph-demand}$ 
5:   end if
6:   Solve The E&K Model for  $t \in p$ 
7:   Save results for  $t_{imp} \subset t \in p$ 
8:    $p \leftarrow p + 1$ 
9: end for

```

The state update and results saving are not described in detail due to the many variables involved in these. The primary results which are saved are the heat and electricity production, the level of the storages and the commitment of technologies which is then used to update the state of the system when planning for a new period  $p$ .

When VLE reschedule 3 times during the actual day of operation the reschedulings are also primarily based on new customer heat demand prognoses. Thus this basic framework can be used to simulate a day of rescheduling for VLE.

## Improving the Framework

The framework presented is a powerful simulation tool. In the following some ideas on how to make the tool even more powerful is given. This is done in order to inspire others who wants to work with models and frameworks like the one presented in this thesis.

### Making the Model Stochastic

Stochastic scheduling and periodic rescheduling can be combined by using a stochastic model in a MPC. But typically the many possible scenarios given in such a model results in a long computation time.

### Time Varying Decision Possibilities

As mentioned in a previous chapter the market for electricity is very flexible with a number of different decision possibilities at different times. By making time varying decision possibilities available in the model this flexibility could be handled. One way of doing this is to introduce a subset of time segments  $t_{valid} \subset t$  and defining the possibilities through constraints which are only valid in  $t_{valid}$  in the model. This method of controlling constraints with sets has been widely used in the implemented version of The E&K Model and should be possible to implement.

Due to the time varying decision possibilities one could also assume that an actor would like to pursue different strategies at different times. This can be handled in the model by making the terms in the objective function time set dependent. If one would like the model to choose between a number of strategies at each time step a method used in the framework from the paper by Oldenburg et al. [17] could be applied. The method is basically to multiply a binary variable  $W_{str}$ , which is 1 if a certain strategy  $str$  is chosen and 0 otherwise, to the terms of the objective which is part of that specific strategy. If only one strategy can be chosen the following must then be valid

$$\sum_{str} W_{str} = 1 \quad (6.1)$$

### Different Levels of Detail

The MPC framework can have a high computation time. One way to deal with this is to shorten the length of the period looked upon for each scheduling. Another and maybe better way to deal with the problem has been presented in the paper "Optimization of vendor-managed inventory systems in a rolling horizon framework" by Al-Ameri et al. [28]. The idea is to divide the time horizon of the period into two parts: A detailed part and a less detailed part. This can be done by introducing a subset of time segments  $t_{nodetail} \subset t$  and using the set control explained earlier. Then a number of constraints or terms in the objective function in the model are not valid for the time segments in  $t_{nodetail}$  which simplifies the problem. Great thought should be given on which constraints that should and should not be valid. An illustration of the concept behind the theory is given in figure 6.5.

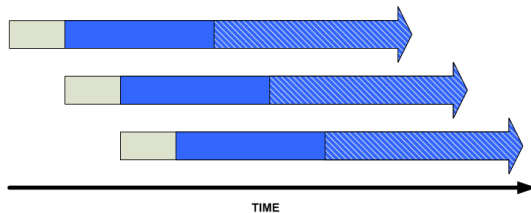


Figure 6.5: An illustration of periodic rescheduling with division of the time horizon used in the model into a full detailed and a lesser detailed horizon. Each bar represent a rescheduling. An entire bar represents the horizon which is looked upon while making the rescheduling. The white areas represent the area which is actually rescheduled and the area with white stripes is looked upon in a less detailed level

### 6.3 Summary

When making plans for a system like The CHP System of Greater Copenhagen the information the plans are based upon often have some degree of uncertainty. In this chapter a description of how one can deal with this uncertainty was given. A paper "Dynamic predictive scheduling of operational strategies for continuous processes using mixed-logic dynamic optimization" by Oldenburg et al. [17] was used as an inspiration. This paper introduces three methods: Stochastic scheduling, reactive scheduling and periodic rescheduling. Especially the periodical rescheduling where you reschedule based on new and better information has shown good results.

Therefore an analytical periodical rescheduling framework using The E&K Model has been created and was presented in this chapter. This framework is based on the process control theory known as Model Predictive Control (MPC) and it could be used in a strong performance follow-up tool capable of simulating a day of planning at VLE with a periodic rescheduling process. As it was also explained in this chapter the framework could be enhanced to become an even stronger tool. These enhancements are beyond the scope of this thesis but should serve as an inspiration to others.

# Results and Discussion

---

In this chapter tests of The E&K Model and the analytical periodical rescheduling framework will be presented. The tests will show some of the capabilities of the derived tools and thereby how they could be used for different analytical purposes. In order to test the model and the framework they have been implemented in a programming system which is known to be efficient for solving MILP problems. These implementations have been tested using real-life datasets. Before describing the test results a short description will be given of the implementation and the datasets.

## 7.1 Implementation in GAMS

The Katja Model, The Esben Model and the framework are all implemented in the programming language "General Algebraic Modeling System" (GAMS)

### GAMS

GAMS is a high level modeling system working together with some excellent mathematical program solvers such as CPLEX. The GAMS syntax is quite easy

when you know how LP and MILP problems are formulated. You basically state the parameters, the variables, the constraints and the objective function and use a solver to solve the problem. Furthermore basic programming features such as if-statements and for-loops are possible. More information and user guides to GAMS can be found on their homepage [www.gams.com](http://www.gams.com).

## The Code

The implementations of the models and the framework can be found on a confidential CD owned by Ea Energy Analysis A/S. Different files are used in the program. The most important ones are given in the following with a short description

- **ESBENFULL.gms:** The file to be executed in order to run The E&K Model. Contains the objective function and the model statement
- **outside.inc:** The file with all the parameters, variables and constraints related to fuels
- **productionmodel.inc:** The file with all the parameters, variables and constraints related to units
- **storagemodel.inc:** The file with all the parameters, variables and constraints related to storage
- **transmissionmodel.inc:** The file with all the parameters, variables and constraints related to transmission
- **tech.inc:** The file with all the parameters, variables and constraints related to generation technology networks
- **esimmoving.inc:** The file with the periodic rescheduling framework

By looking closer at the implemented version of the model compared to the model presented in the thesis a large amount of set control has been used to reduce the problem. E.g. a constraint on maximum capacity for a generation technology is only valid if a maximum capacity is assigned. This is done by using the so-called \$ operator, which is also described in the GAMS user guide.

## 7.2 Datasets

The datasets used in the tests described in the following are all historical real-life datasets, which originally has been used as input to The Katja Model. The additional data which is needed for The Esben Model is also based on real-life data provided by VLE. Using real-life datasets makes the tests much more interesting in both a theoretical and practical aspect. As mentioned in chapter 1 each day VLE makes a 24 hour plan for the following day. Three datasets with the data which was available when making these day-ahead plans (DA datasets) for three random days will be used to test and show the capabilities of The E&K Model.

Besides from making the day-ahead plan VLE also periodically reschedule three times during the actual day of operation. The intraday datasets with the prognoses for customer heat demand which was available at each of the 3 reschedulings during a random 24 hour period will be used to test the framework. The plan found with the framework will be compared to a plan found by solving the model using a heat demand prognoses created at the beginning of the planning time horizon as input. The quality of these plans will be evaluated using a benchmark plan found by solving The E&K Model with realized demands as input (A "perfect" plan).

## 7.3 Testing The E&K Model

The separate models and The E&K Model has been both functionally and structurally tested. These tests has been made in order to avoid errors in the code, the input/output data and/or the modeling. In this thesis a description of the functional and structural tests will not be given. This is due to the fact that it is much more interesting to display some of the capabilities of the model.

The test runs of the model and the following analytical case-runs has been carried out on a computer with a 2.1 GHz processor and 3.0 GB RAM.

### Problem with Energy Tax

In the functional tests three runs were made with the three DA datasets. In these tests it was seen that the problem could not be solved before the solver ran out of memory. As expected this was due to the complexity of the modeling of

the energy tax. Thus if the constraints and term in the objective related to this were removed from the model the problems could be solved within a minute.

To study the problem further different intervals for the ratio  $r$  used in the energy tax formulation was tried. 10% intervals, 25% intervals and 50% intervals was tested. Furthermore tests were carried out reducing the datasets to only consider a 7 hour period. All tests however showed the same result, namely that the problem could not be solved due to lack of memory.

Due to the mentioned problem the modeling of energy tax should be analyzed in more detail and maybe it should be reconsidered. In the following tests/simulation cases the energy tax has been removed from the model. This is of course not optimal but it is found sufficient in order to show how the model could be used.

## 7.4 General Results

The three day-ahead datasets for three different random days has been used as input to The E&K Model to generate three 24-hour day-ahead plans. Some graphs displaying the most important input to the model and some of the resulting important output i.e. the plan can be found in appendix C.1,C.2 and C.3.

In figures 7.1, 7.2, 7.3 and 7.4 Some of the graphs for the plan made with one of the datasets (DA dataset 1) are given. The four graphs show the heat demand and the electricity price given as input to The E&K Model and some of the most important output: the heat production, storage heat unload and the electricity production.

In the rest of this section the figures displayed will also be from the plan created using DA dataset 1. The graphs displayed in these figures and the appendices are primarily related to production, due to the fact that the main focus of this thesis is The Esben Model, which models the technical and economical details of the production units.

Before discussing the results it should be noted that the production of heat from the waste incineration units was fixed before the optimization due to the fact that the production from these must always be used in the DH system. Furthermore the storage at AMV was not possible to use in any of the plans, due to repairs at the time period of the datasets.

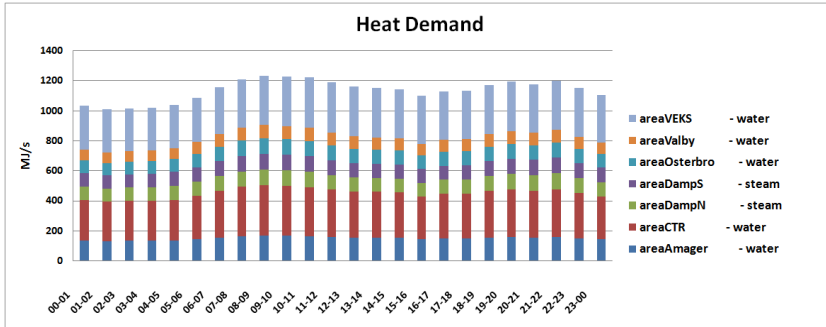


Figure 7.1: 24 hour plan made with Day-Ahead (DA) Dataset 1: The heat demand given as input to The E&K Model

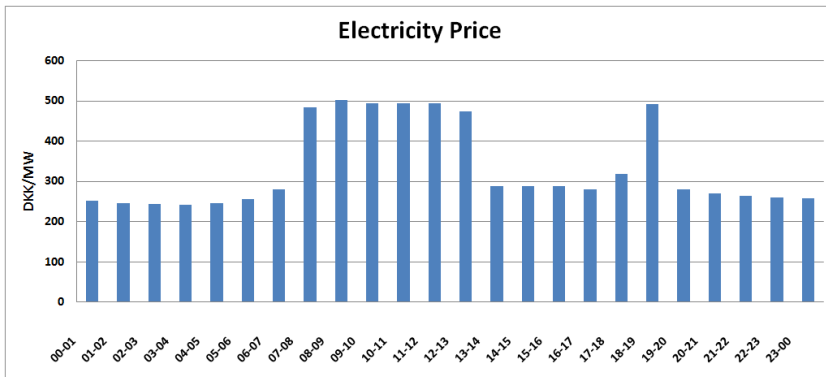


Figure 7.2: 24 hour plan made with Day-Ahead (DA) Dataset 1: The electricity price given as input to The E&K Model

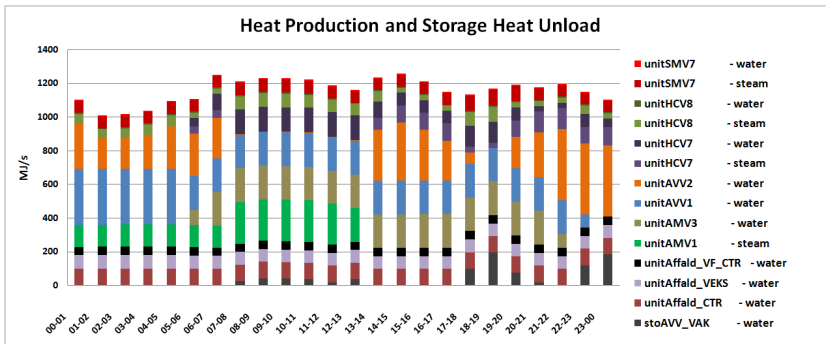


Figure 7.3: 24 hour plan made with Day-Ahead (DA) Dataset 1: The heat production and storage heat unload given as output from The E&K Model

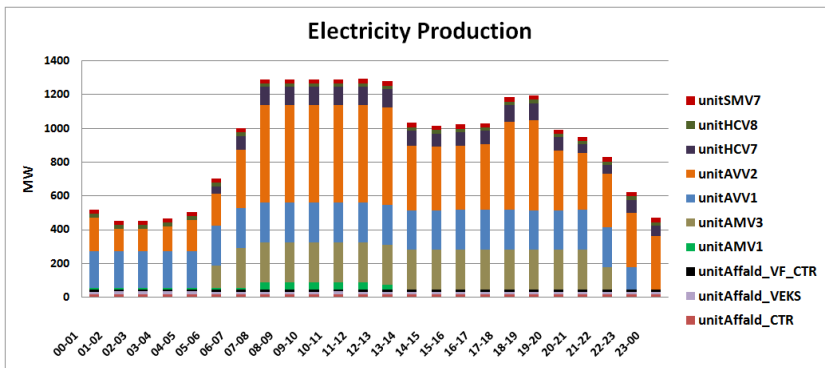


Figure 7.4: 24 hour plan made with Day-Ahead (DA) Dataset 1: The electricity production given as output from The E&K Model

## Production Levels

When looking at the figures with the production levels of the plan created using DA dataset 1 it is seen that the production is dominated by the CHP units. Taking a closer look at the electricity and heat production, it is seen, that most of the units find an optimal production point for the most of the day. When the electricity price rise the units increase the total production to earn more money. The flexible units AVV1 and AMV3 with the special extraction turbine which has the production/output profile presented in chapter 3 in figure 3.3 do almost always run at maximum load and thereby does not change its fuel consumption. Both of them most of the time produce in the optimal production point, the 'kink', the point of minimal fuel loss i.e. maximum efficiency (marked with 1 in the figure).

The advanced production unit AVV2 does not stay in optimal production point but uses its flexibility to generate more electricity and less heat when the price on electricity is high and more heat and less electricity when the price is low. This flexibility is possible due to the storage at AVV which unloads heat to equalize the heat demand when AVV2 strengthens its electricity production and lower its heat production.

## Fuel Consumption

In figure 7.5 the fuel consumption of the plan is given. The units which finds an optimal production point use the same amount of fuel throughout the period

they are online. But when the electricity price is high more units are online and furthermore the flexible AVV2 increases its fuel consumption resulting in an overall increase. When looking at the type of fuels used, it is seen, that the cheaper priced fossil fuels i.e. coal and natural gas are primarily used. These fuels are taxed higher, but due to the lack of the energy tax this aspect which might have given another solution cannot be shown.

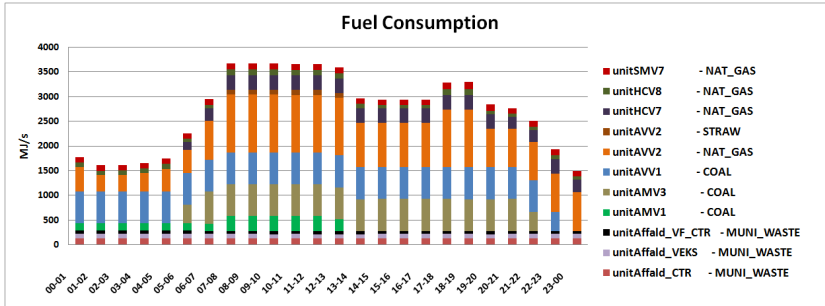


Figure 7.5: 24 hour plan made with Day-Ahead (DA) Dataset 1: The fuel consumption given as output from The E&K Model

## Economy of The Plan

The economy of the plan i.e. the hour-by-hour total cost and electricity income of the plan is given in figure 7.6. It is seen that, when the electricity price is high and a possibility for a higher income exists, some of the units and especially AVV2 increase its production level which results in a higher fuel consumption and thereby a higher cost. This cost can however be justified due to a higher total profit.

The large costs seen at the time segments 00-01 and 05-06 are due to the large start-up costs of HCV7 and AMV3 respectively. A large start-up cost is accepted because producing at these units will result in a lower cost for the total 24 hour plan, which has a total cost of 78174845 DKK and a total electricity income of 8009650 DKK.

These general results show how the electricity price is taken into account and also the possibility of representing the flexibility of some of production units in the model.

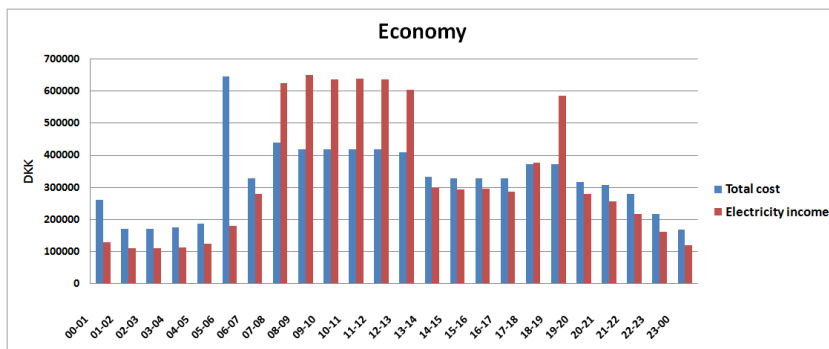


Figure 7.6: 24 hour plan made with Day-Ahead (DA) Dataset 1: The economy given as output from The E&K Model

## 7.5 Production Unit Specific Results

Besides from looking at the general graphs, The E&K Model also makes it possible to take a more specific look at the individual production units. In the following this will be exemplified with HCV7, AMV1 and AVV2. The following results are also taken from the 24 hour day-ahead plan generated with The E&K Model using the DA dataset 1.

### HCV7 Technology Network

In chapter 5 a description of how the unit HCV7 was represented in The Esben Model was given. In order to understand the following results one must have this representation in mind.

The result figures 7.7 and 7.8 namely shows the transmission of heat between the technologies of HCV7 and the technology specific electricity production respectively.

It can be seen how the boiler technology HCV7-B-NG utilizing natural gas sends heat as steam on to the other boiler technology HCV7-B, which has a fuel/input efficiency assigned to it. Therefore a lesser amount of heat is sent on from HCV7-B to the back-pressure technology HCV7-ST-HP representing the high pressure steam turbine. HCV7-ST-HP generates electricity and heat. The output heat can then be sent as steam directly to the gathering technology HCV7-GATH to give a unit heat production carried by steam or to the representation of the low

pressure steam turbine HCV7-ST-LP which generates more electricity and gives a heat output which can be sent on as water to HCV7-GATH to give a unit heat production carried by water. The last case happens when the electricity price is high and a higher electricity production is beneficial.

This example shows the capability of the model to deal with a complex unit and hopefully also gives a better idea about the function of the technology networks

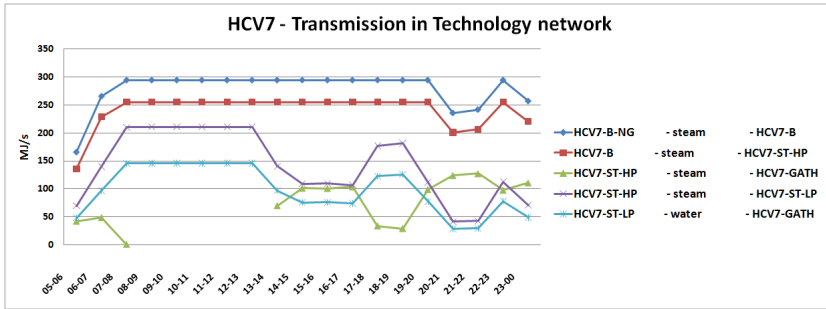


Figure 7.7: 24 hour plan made with Day-Ahead (DA) Dataset 1: The transmission between the technologies for HCV7

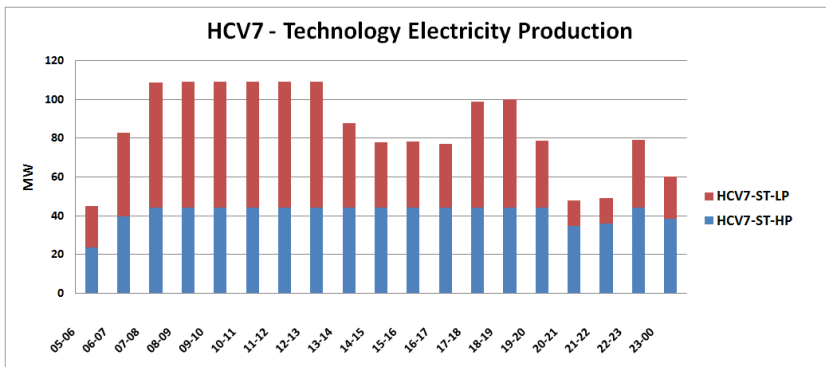


Figure 7.8: 24 hour plan made with Day-Ahead (DA) Dataset 1: The technology specific electricity production at HCV7

### HCV7 Fuel Efficiency

As described previously one of the technologies used to represent the boiler at HCV7 has a certain fuel efficiency assigned. This fuel efficiency is variable. This can be seen by looking at the fuel efficiencies for the unit in the found plan given

in figure 7.9. By comparing this figure to the production loads for HCV7 shown in figure 7.10 it can be seen that the fuel efficiency drops when the production load drops.

This variable fuel efficiency is represented in the model by assigning the linear fuel efficiency relationship to the boiler technology HCV7-B.

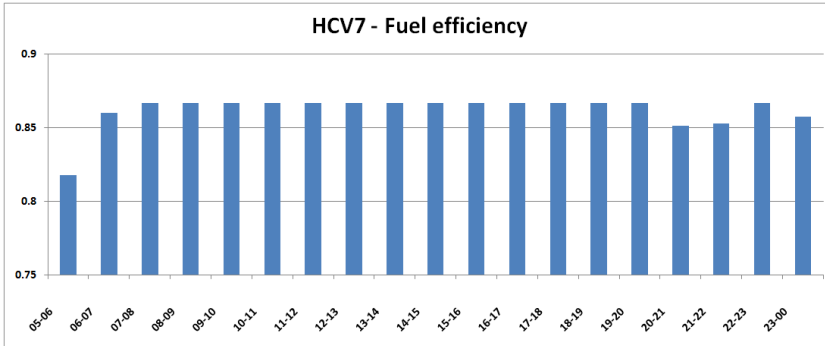


Figure 7.9: 24 hour plan made with Day-Ahead (DA) Dataset 1: The fuel efficiency for HCV7 ( $\frac{\text{Total production}}{\text{Fuel consumption}}$ )

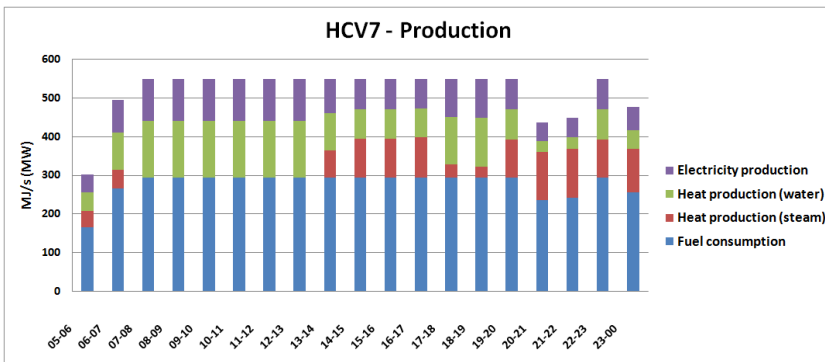


Figure 7.10: 24 hour plan made with Day-Ahead (DA) Dataset 1: The production at HCV7

### AMV1 Production Ratio

As described in chapter 3 AMV1 is a back-pressure turbine unit producing electricity and heat carried by water. The process diagram of AMV1 is very similar to the one for the imaginative unit shown in chapter 5 in figure 5.3.

Likewise it is also represented in The Esben Model in the same way as the imaginative unit by a technology network similar to the one shown in figure 5.4. However in the network given as input to The E&K Model when finding the plan the direct transmission line from the boiler technology to the gathering technology was removed. Thus full bypass is not possible.

The actual production levels at AMV1 according to the plan found are shown in figure 7.11. By looking at this figure and the ratio between heat and electricity production shown in figure 7.12 it can be seen that the ratio variate with the production level. When the production is increased the amount of electricity created compared to heat is also increased.

This variable ratio,  $C_b$ , has been represented in the model by assigning the linear relationship between electricity and heat output described in chapter 5 to the technology representing the back-pressure turbine.

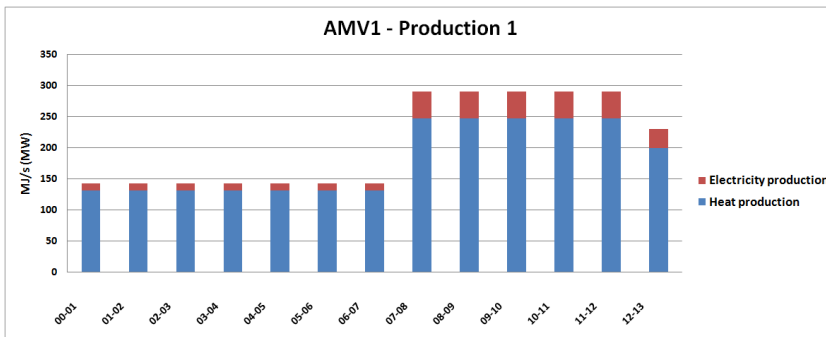


Figure 7.11: 24 hour plan made with Day-Ahead (DA) Dataset 1: The production at AMV1

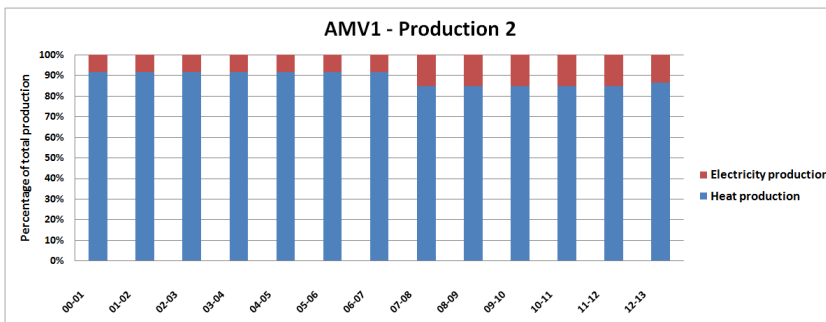


Figure 7.12: 24 hour plan made with Day-Ahead (DA) Dataset 1: The ratio between heat and electricity production at AMV1

## AVV2 Economy

The economy of a unit can also be looked upon in a more specific way. In figure 7.13 the costs of running AVV2 when using the plan is given. The dominating cost is the cost of fuel. Especially the cost of natural gas which is both used in the multi-fuel boiler and in the gas turbine (when running) is high. Straw is only used in the period where the electricity price is high and it is beneficial to have the biomass boiler running and therefore there is only a cost upon this in a limited time period. The actual start-up of this biomass boiler also has a cost which can be seen in the time segment 07-08. A final high cost is the cost of  $CO_2$  which is due to the large amount of fossil fuel used.

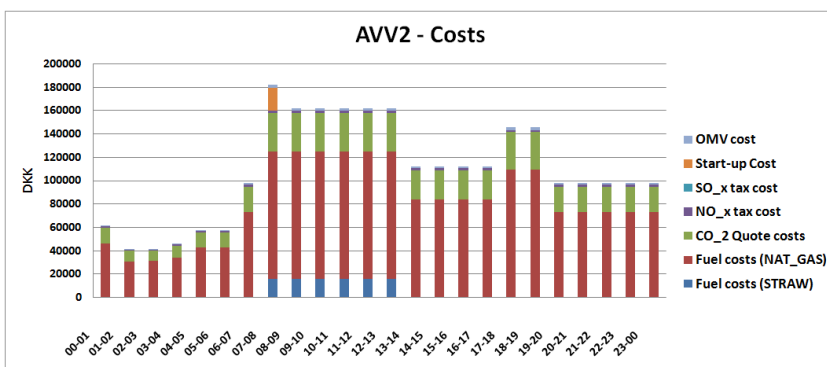


Figure 7.13: 24 hour plan made with Day-Ahead (DA) Dataset 1: The costs for the unit AVV2

All these unit specific results shows how it is possible to represent the technical possibilities and the economy of the production units in a high level of detail when using The E&K Model to create plans. This makes the model a powerful tool.

## Performance Follow-Up

In order to use output plans from The E&K Model for performance follow-up a comparison to another plan should be done. Such a plan could be the original production plans given by the production companies, the plans retrieved by re-optimizing these original plans with The Katja Model or the actual running of the system at the given day.

A small comparison test has been carried out. In this test a plan created with

The E&K Model is compared to an original production plan provided by the production companies. The cost of the original production plan is found solving The E&K Model with a heat production fixed to this plan throughout the optimization. This does most likely not result in the true production profiles used by the production companies, but it gives a good estimate of the cost.

The result shows that the cost of the original production plan is approx. 400.000 DKK higher than the one found with The E&K Model.

However no conclusion about the plans generated by the production companies can be made from such a test. First of all in order to evaluate the plans a full statistical analysis of a longer period should be done. Furthermore the electricity prices used as input might not be the same as the ones used by the production companies. Making a detailed evaluation of the different plans and the planning method is beyond the scope of this thesis, but The E&K Model is a great tool for making such an analysis.

Another thing noted is, that the original production plans (graphs are not shown due to confidentiality) does not have changes in the heat production as often as the plans found with The E&K Model. One reason for this could be that the original production plans are not optimal. Another reason could be that the flexibility of changing production settings given as input to The E&K Model might be unrealistic. A third reason is that the production companies maybe take into account the flexibility of the electricity market. No matter the reason The E&K Model is a good tool for starting a discussion about the issue.

## 7.6 Test of the Rescheduling Framework

As mentioned previously VLE reschedule 3 times during the day of operation and each time new demand prognoses are made. The specifics of the reschedulings are illustrated in figure 7.14.

Each arrow represent a rescheduling and the white areas represents the period of the schedule actually used while the remaining blue area represents the period which is taken into account in addition to the white area when making the rescheduling. Thus for each arrow the customer heat demand prognoses are renewed.

The data used to test the framework is taken from a random 24 hour period with 3 reschedulings/periods and thereby three demand prognoses. The most important input and output data for the resulting plan are illustrated in appendix

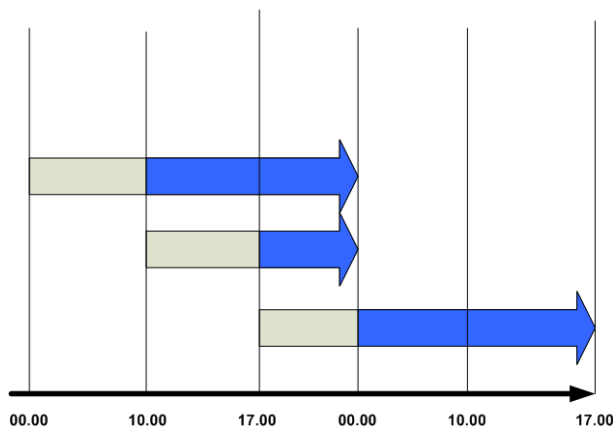


Figure 7.14: An illustration of The Periodic Rescheduling done by VLE

#### C.4.

Besides from the plan found using the periodic rescheduling framework two other plans has been generated.

The first one is a plan found by solving The E&K Model without the framework given the initial heat demand prognoses of the 24 hour period as input (see figure 7.14). The important input and output data are illustrated in appendix C.5. This plan is thereby created using a single demand prognoses and is assumably of a lower quality than the plan found using the framework.

The second plan is a "perfect" plan found by solving The E&K Model without the framework given the realized heat demand as input. This plan can be used as a benchmark in order to compare the plan created with the framework and the plan created found without the framework taking the single initial demand prognoses as input. The important input and output for this "perfect" plan are illustrated in appendix C.6.

From just looking at the plans (especially the total heat production) it is seen that the plan made with the framework and the plan made without the framework are very similar. Both of them however seems to be far from the perfect plan.

One would expect the plan made with periodical rescheduling framework to be closer to the optimal plan. By comparing the demand prognoses used as input to create the plans to the realized demand (see figure 7.15), it can be seen that the uncertainty about the period to be rescheduled is not decreased as

time progresses. In order to reschedule periodically it is not sufficient that the information is new. The uncertainty of the information must also decrease as time progresses. This is not the case for the demand prognoses used in this test and therefore a better plan is not achieved using the framework. VLE could have reason to have high prognoses and therefore no conclusions about their daily planning could be made from this.

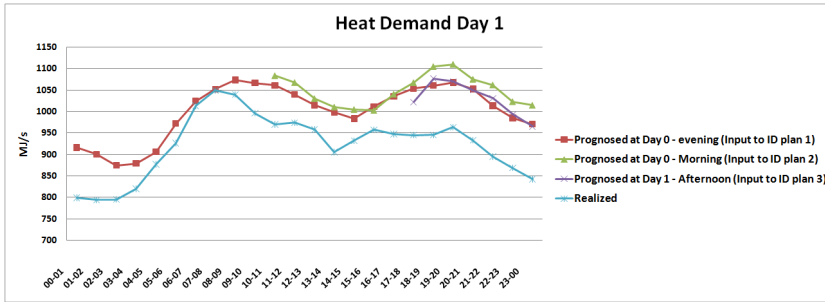


Figure 7.15: The prognosed heat demands used to create schedules compared to the realized values

Simple comparisons of plans with "perfect" plans which the results in this thesis has been based upon might not be sufficient to determine the true quality of a plan. A better way could be to create some kind of evaluation tool. Creating such a tool is beyond the scope of this thesis

## 7.7 Summary

In this chapter a short introduction to GAMS and the implementation of The E&K Model was given before presenting results found using the model implementation. It was described that a structural and functional test of the implementation has been carried out and that the functional test unfortunately showed that the model could not be solved due to the complex modeling of the energy tax. This energy tax modeling should be studied further in the future, but it is beyond the scope of this thesis and it was therefore removed from the model, which made it possible to solve the model within a short computation time.

A description of tests carried out with The E&K Model without energy tax was then given. The tests had been carried out using real-life datasets to produce 24 hour plans illustrating the capability of the model to produce both general and more specific production results on both an economical and a technical level.

Among other things the tests showed how it is possible to represent the following in the model

- Different production possibilities e.g. the flexibility of AVV2 and the two turbines at HCV7
- A variable production level dependent fuel efficiency
- A variable production level dependent back-pressure profile
- A detailed economy description of a production unit

All this makes it possible to find a realistic and detailed plan for the CHP System of Greater Copenhagen which could be used to evaluate the daily heat load planning.

In the final part of the chapter the periodical rescheduling framework using The E&K Model was tested. A plan found using the framework was compared to a plan created on the basis of an initial demand prognoses as input. The comparison was done using a benchmark "perfect plan" created with the realized demand as input.

Surprisingly the plan created with the framework did not seem to better than the plan created without the framework. By looking closer at the demand prognoses used as input to framework it was seen that the uncertainty of the information was not decreased as time progressed which is necessary if a periodical rescheduling should have an effect.

# Conclusion

---

## 8.1 The Project

In this thesis a project of developing a mixed integer linear program model of the technical and economical details of the production units of The Combined Heat and Power System (CHP) of Greater Copenhagen was described. This model which is named The Esben Model described in chapter 5 can extend an already existing model, The Katja Model described in 4, which is a model of the production units, the storages and transmission lines of the system. Today The Katja Model is used to find daily heat load plans by re-optimizing production plans created by the heat production companies.

Extending The Katja Model with The Esben Model resulted in a combined model, The E&K Model where the production units are represented in a higher level of detail. This makes The E&K Model capable of finding an optimal plan for the CHP system of Greater Copenhagen in a single process. Thus the plan found with The E&K Model can be used to perform a performance follow-up of the plans created in the divided planning process.

## 8.2 The Model

Both The Katja Model and The Esben Model is modeled using a multi-commodity flow formulation. This kind of formulation takes a network of vertices and directed edges with related constraints as input describing a given system. The problem is then to send a number of commodities from vertices with a surplus of the commodity to a vertex with a demand of this commodity.

While the input network to The Katja Model represents the connections between areas of production, storage or demand the so-called generation technology networks of The Esben Model represents the different components of each of the production units. In the chapter about The Esben Model it was described that the idea for these generation technology networks came from looking at process diagrams of the units and an inspiration from Balmorel, another energy system model.

### Technical Limitations

Some general technical limitations of the system e.g. capacities, change capacities, commitment rules etc. can be assigned to the components of the input networks of both The Katja and The Esben Model. Additionally The Esben Model gives the possibility of representing complex production units with production level dependent production ratios between heat and electricity production, production level dependent fuel efficiencies, multi-fuel boilers, simultaneous production of heat as water and steam, emission etc.

### System Economy

With respect to economy The Esben Model takes into account the price on electricity, fuel costs, emission taxes and operating and maintenance cost. The electricity price and the electricity production is important due to the co-generation of heat and electricity. The mentioned costs are the most important production costs and the ones to reduce when making a plan for the daily heat load.

The possibility of representing these technical and economical production details makes The Esben Model and thereby The E&K Model a strong analytical tool with many applications.

## 8.3 The Rescheduling Framework

When planning for a system like The CHP System of Greater Copenhagen the plans are often based on uncertain information. In chapter 6 a method, periodical rescheduling, which can be used to deal with this uncertainty was presented. This idea inspired the creation of an analytical periodical rescheduling framework using The E&K Model and the theory behind the process control theory of Model Predictive Control. It was described how this framework can be used to simulate a day of rescheduling of the heat load at VLE. The chapter also gave some ideas on how this framework and The E&K Model could be enhanced to become even stronger tools, many of the suggested enhancements was related to planning for a system with high flexibility and uncertainty.

## 8.4 The Test Results

In chapter 7 The E&K Model and the framework was tested in order to test their performance and to show some of their capabilities. In order to make these tests The E&K Model and framework both had been implemented in a modeling system called GAMS. The tests was carried out using real life input datasets for 24 hour plans provided by VLE.

### Problem with Energy Tax

The initial tests of The E&K Model unfortunately showed that the planning problems could not be solved because the solver ran out of memory. As expected this was due to a complex modeling of a special emission energy tax. When removing this energy tax part from the model the problems could be solved to generate a 24 hour plan within a minute. Thus the modeling of this energy tax should be studied further in the future. As a consequence the rest of the tests was carried out without the energy tax.

### Test of The E&K Model

In the test of The E&K Model it was generally seen that the production plans created with the model was dominated by the CHP units. Most of these units stayed at an optimal production production most of the time and increased their

fuel consumption when the price on electricity was increase. The more flexible units AMV3 and AVV1 stayed at a production level, the point of minimal fuel loss throughout the plans. Another flexible unit (AVV2) used its flexibility to increase its electricity production when the price on electricity was high resulting in a lower production of heat, which was equalized by a storage. Thus this kind of flexibility is possible to represent in the model.

Besides from the general test results a closer look was also taken upon specific results for the CHP units HCV7, AMV1 and AVV2. These results showed flow between unit components, a production level dependent fuel efficiency, a production level dependent back-pressure profile and a detailed production unit economy. All this shows that the production units can be represented in The E&K model in a very high level of detail which makes the model a powerful tool.

One of the plans created in the tests was compared to the original production plan created by the production companies for the same day of operation. This comparison showed that the plan created with The E&K Model had a lower cost, but it also had more and larger changes in production level for especially AVV2. Thus the degree of freedom of production level change in the data provided to the model could be too high.

## Test of The Framework

The test of the framework was a simulation a day of a periodical rescheduling at VLE based on new customer heat demand prognoses at each rescheduling. The resulting plan was compared to a plan found by solving The E&K Model with the initial heat demand prognoses and both plans was then benchmarked to a plan created with realized values. Surprisingly the test showed that the plan created with the framework was very similar to the plan created without the framework. Both of them was however not close to the perfect plan.

In order to use periodical rescheduling to create good plans the quality of the information about the period to be implemented at each rescheduling must increase. This was however not the case for the customer heat demand prognoses used in this test. Thus with the given dataset a better plan was not achieved. However if the quality of the information was decreased the framework would most likely result in a plan closer to the optimum due to the fact that the plan will be based on better information. Studies of this is actually the case should be done in the future.

---

## 8.5 The Future

As described The E&K Model is a strong tool which could be used to perform many analysis of CHP systems. Two important strengths of the model is that it can represent most CHP systems of the world in a high level of detail and if the current model is not sufficient it is easy to add new constraints.

A possible and very interesting addition could be to model the flexible Danish Power market presented in chapter 3 in order to create a model capable of finding an optimal plan with respect to this or to simulate how one should have acted on a given day of operation. The framework could then be used to simulate a periodical rescheduling process taking into account new and better information about this market.

This is just one of the future applications out of many. However already now The E&K Model and the framework could be used to do performance follow-up of the planning of the daily heat load in The CHP System of Greater Copenhagen.



APPENDIX A

# Appendix

---

## A.1 The Katja Model

### Sets

- $t \in \mathcal{T}$ : Set of time segments
- $s \in \mathcal{S}$ : Set of change steps.
- $e \in \mathcal{E}$ : Set of energy carriers (The carriers of heat)
- $a \in \mathcal{A}$ : Set of areas
- $u \in \mathcal{U}$ : Set of units
- $v \in \mathcal{V}$ : Set of storages
- $(a_1, e, a_2) \in \mathcal{X}$ : Set of transmission lines for energy carrier  $e$  between areas  $a_1$  and  $a_2$
- $u_a \subset \mathcal{U}$ : Set of units  $u$  in area  $a$
- $v_a \subset \mathcal{V}$ : Set of storages  $v$  in area  $a$
- $u^p \subset \mathcal{U}$ : Set of units capable of maintaining pressure
- $z \in \mathcal{Z}$ : Set used dually to represent storage states and to index storage capacities. (in, out, level)
- $z^{act} \subset \mathcal{Z}$ : Set with the active states of a storage (in, out)
- $a_{e_1, e_2}^{e_2 e_1} \subset \mathcal{A}$ : The areas where energy carrier  $e_1$  can be transformed into energy carrier  $e_2$
- $u_{u_1}^{no\Delta h} \subset \mathcal{U}$ : Set of units which cannot change their production load at the same time as unit  $u_1$
- $u_{e_1, e_2}^{both} \subset \mathcal{U}$ : Set of units which must produce both energy carriers  $e_1$  and  $e_2$  when online
- $u_{e_1, e_2}^{induce} \subset \mathcal{U}$ : Set of units for which production of energy carrier  $e_1$  forces production of energy carrier  $e_2$ .

## Parameters

- $A_{a,e,t}^{h-demand} \in \mathbb{R}$ : The demand for energy carrier  $e$  in area  $a$  in time segment  $t$  (MJ/s)
- $U_{u,e,t}^{h-plan}$ : Initial plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $U_{u,e,t}^{h-cost+}$ : Marginal cost for changing the plan for production of energy carrier  $e$  upwards for unit  $u$  in time segment  $t$  (money/MJ/s)
- $U_{u,e,t}^{h-cost-}$ : Marginal cost for changing the plan for production of energy carrier  $e$  downwards for unit  $u$  in time segment  $t$  (money/MJ/s)
- $s_{length}$ : The length of a change step (MJ/s)
- $q$ : The percentage the marginal costs are changed each time a new step  $s$  is reached
- $\underline{U}_u^{on} \in \mathbb{N}^+$ : The minimum number of time segments the unit  $u$  must stay online if started for production
- $\underline{U}_u^{off} \in \mathbb{N}^+$ : The minimum number of time segments  $u$  must stay offline if shut down for production
- $\bar{U}_{u,e,t}^{h-out} \in \mathbb{R}^+$ : Maximum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\underline{U}_{u,e,t}^{h-out} \in \mathbb{R}^+$ : Minimum heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\bar{U}_{u,t}^{h-out} \in \mathbb{R}^+$ : Maximum heat production load in total for unit  $u$  in time segment  $t$  (MJ/s)
- $\underline{U}_{u,t}^{h-out} \in \mathbb{R}^+$ : Minimum heat production load in total for unit  $u$  in time segment  $t$  (MJ/s)
- $\bar{U}_{u,e}^{\Delta h-out} \in \mathbb{R}^+$ : Maximum change in heat production load of energy carrier  $e$  possible for unit  $u$  from one time segment to the next (MJ/s)
- $U_{u^p,e}^{pinit} \in \{0,1\}$ : 1 if unit  $u^p$  is pressure maintainer for the networks of energy carrier  $e$  in the initial time segment
- $\underline{U}_e^{pon} \in \mathbb{N}$ : The number of time segments the unit assigned as pressure maintainer for system of energy carrier  $e$  must stay pressure maintainer.
- $U_{u,e}^{ecapratio}$ : Percent of each unit of total capacity used to produce energy carrier  $e$  on unit  $u$ .

- $V_v^{h-ini} \in \mathbb{R}^+$ : Initial content for storage  $v$
- $V_v^{h-term} \in \mathbb{R}^+$ : Terminal content for storage  $v$
- $\underline{V}_{v,z}^{on} \in \mathbb{N}$ : Minimum number of time segments the storage  $v$  must remain in state  $z$
- $\bar{V}_{v,z,t}^h \in \mathbb{R}^+$ : Maximum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\underline{V}_{v,z,t}^h \in \mathbb{R}^+$ : Minimum load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\bar{V}_v^{\Delta h} \in \mathbb{R}^+$ : Maximum change in load for storage  $v$  (MJ/s/t)
- $X_{a_1,e,a_2}^{h-ini}$ : The initial transmission load for transmission line  $(a_1, e, a_2)$
- $\underline{X}_{a_1,e,a_2}^{on} \in \mathbb{N}$ : The minimum number of time segments the transmission line  $(a_1, e, a_2)$  must be online
- $\bar{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Maximum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\underline{X}_{a_1,e,a_2,t}^h \in \mathbb{R}^+$ : Minimum transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$
- $\bar{X}_{a_1,e,a_2}^{\Delta h} \in \mathbb{R}^+$ : Maximum change in transmission load for transmission line  $(a_1, e, a_2)$

## Variables

- $\mu_{u,e,t,s}^{h-plan+} \in [0, slength]$ : The upwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  in change step  $s$  (MJ/s)
- $\mu_{u,e,t,s}^{h-plan-} \in [0, slength]$ : The downwards change in the original production plan for production of energy carrier  $e$  for unit  $u$  in time segment  $t$  in change step  $s$  (MJ/s)
- $\mu_{u,e,t}^{h-out} \in \mathbb{R}^+$ : The heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-plan+on} \in \{0, 1\}$ : 1 if the production for production of energy carrier  $e$  for unit  $u$  is changed upwards in time segment  $t$
- $\mu_{u,e,t}^{h-plan-on} \in \{0, 1\}$ : 1 if the production for production of energy carrier  $e$  for unit  $u$  is changed downwards in time segment  $t$

- $\alpha_{e_1, e_2, a, t}^{e2e} \in \mathbb{R}^+$ : The amount of energy carrier  $e_1$  converted to energy carrier  $e_2$  in area  $a$  in time segment  $t$  (MJ/s)
- $\mu_{u, e, t}^{start} \in \{0, 1\}$ : 1 if unit  $u$  is started for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u, e, t}^{shutdn} \in \{0, 1\}$ : 1 if unit  $u$  is shut down for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u, e, t}^{on} \in \{0, 1\}$ : 1 if unit  $u$  is online for production of energy carrier  $e$  in time segment  $t$
- $\mu_{u, t}^{on} \in \{0, 1\}$ : 1 if unit  $u$  is online for production of one or more energy carriers in time segment  $t$
- $\mu_{u, e, t}^{\Delta h-out} \in \mathbb{R}^+$ : Change in production load of energy carrier  $e$  for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u, t}^{\Delta h-on} \in \{0, 1\}$ : 1 if the production is changed for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u^p, e, t}^p \in \{0, 1\}$ : 1 if unit  $u^p$  is pressure maintainer for system of energy carrier  $e$  in time segment  $t$
- $\mu_{e, t}^{pchange} \in \mathbb{R}^+$ : Related to binary variable 1 if there is a change in pressure maintainer for system of energy carrier  $e$
- $\mu_{u, e, t}^p \in \{0, 1\}$ : 1 if unit  $u$  is pressure maintainer for system of energy carrier  $e$  in time segment  $t$
- $\nu_{v, z, t}^h \in \mathbb{R}^+$ : The heat load/content for storage  $v$  in state  $z$  in time segment  $t$  (MJ/s)
- $\nu_{v, z, t}^{on} \in \{0, 1\}$ : 1 if storage  $v$  is in state  $z$  in time segment  $t$
- $\nu_{v, z, t}^{start} \in \{0, 1\}$ : 1 if storage  $v$  starts to perform state  $z$  in time segment  $t$
- $\nu_{v, z, t}^{\Delta h} \in \mathbb{R}$ : Change in load from the previous time segment to time segment  $t$  (MJ/s)
- $\chi_{a_1, e, a_2, t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(a_1, e, a_2)$  in time segment  $t$  (MJ/s)
- $\chi_{a_1, e, a_2, t}^{start} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is started in time segment  $t$
- $\chi_{u, e, t}^{on} \in \{0, 1\}$ : 1 if transmission line  $(a_1, e, a_2)$  is online in time segment  $t$
- $\chi_{a_1, e, a_2, t}^{\Delta h} \in \mathbb{R}^+$ : Change in transmission load for transmission line  $(a_1, e, a_2)$  from the previous time segment to time segment  $t$  (MJ/s)

## Objective

- The primary objective is to keep the cost of changing the original production plans at a minimum. The change steps  $s$  makes sure that the marginal costs are increased when larger changes occur.

$$\min \sum_{u,e,t,s} U_{u,e,t}^{h-cost+} \cdot (1+q)^{|s|-1} \cdot \mu_{u,e,t,s}^{h-plan+} + U_{u,e,t}^{h-cost-} \cdot (1-q)^{|s|-1} \cdot \mu_{u,e,t,s}^{h-plan-} \quad (\text{A.1})$$

Besides from this primary objective a number of other objectives exists e.g. costs on throwing out energy and costs to insure smooth plans.

## Balance Constraint

- The balance equation states that the production by the units, the output from the storages, the incoming flow of heat and the contribution from another energy carrier converted to the energy carrier  $e$  stated on the left hand side A.2 must be equal to what goes into the storages, the outgoing flow, the thrown out, the amount of the energy carrier  $e$  converted to another energy carrier and the demand stated on the right hand side A.3 for each area  $a$  and energy carrier  $e$  in each time segment  $t$ . Notice that the conversion of energy carriers are only possible if the area is in the set  $a_{e_1, e_2}^{e_2 e}$ .

$$\sum_{u_a, e} \mu_{u_a, e, e, t}^{h-out} + \sum_{v_a} \nu_{v_a, 'out', t}^h + \sum_{a_1} \chi_{a_1, e, a, t}^h + \sum_{e_1} \alpha_{e_1, e, a, t}^{e_2 e} \quad (\text{A.2})$$

$$= \sum_{v_a} \nu_{v_a, 'in', t}^h + \sum_{a_1} \chi_{a, e, a_1, t}^h + A_{a, e, t}^{h-demand} + \sum_{e_1} \alpha_{e, e_1, a, t}^{e_2 e} \quad (\text{A.3})$$

$$\forall a, e, t$$

## The Production Constraints

- The production load of heat carried by a certain energy carrier for a certain unit is given by the production plan given as input to the model +/- the changes to this plan. Mathematically this is stated in the model as

$$\mu_{u, e, t}^{h-out} = U_{u, e, t}^{h-plan} + \sum_s (\mu_{u, e, t, s}^{h-plan+} - \mu_{u, e, t, s}^{h-plan-}), \quad \forall u, e, t \quad (\text{A.4})$$

- Registration of upwards change to the production plan

$$\mu_{u,e,t}^{h-plan+on} \cdot M \geq \sum_s \mu_{u,e,t,s}^{h-plan+}, \quad \forall u, e, t \quad (\text{A.5})$$

- Registration of upwards change to the production plan

$$\mu_{u,e,t}^{h-plan-on} \cdot M \geq \sum_s \mu_{u,e,t,s}^{h-plan-}, \quad \forall u, e, t \quad (\text{A.6})$$

- Upwards and downwards changes to the production plan must not occur

$$1 \geq \mu_{u,e,t}^{h-plan+on} + \mu_{u,e,t}^{h-plan-on}, \quad \forall u, e, t \quad (\text{A.7})$$

- Registration of a start-up of a unit

$$\mu_{u,e,t}^{start} \geq \mu_{u,e,t}^{on} - \mu_{u,e,t-1}^{on} \quad \forall u, e, t \quad (\text{A.8})$$

- Registration of a shut down of a unit

$$\mu_{u,e,t}^{shutdn} \geq \mu_{u,e,t-1}^{on} - \mu_{u,e,t}^{on} \quad \forall u, e, t \quad (\text{A.9})$$

- If a unit was started in a previous time segment within the number of time segments the unit must stay online, the unit must be on.

$$\mu_{u,e,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{U}_u^{on}\}} \mu_{u,e,t_1}^{start} \quad \forall u, e, t \quad (\text{A.10})$$

- If a unit was shut down in a previous time segment within the number of time segments the unit must stay offline, the unit must be off.

$$1 - \mu_{u,e,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{U}_u^{off}\}} \mu_{u,e,t_1}^{shutdn} \quad \forall u, e, t \quad (\text{A.11})$$

- The production load for an online unit must be below the maximum load

$$\bar{U}_{u,e,t}^{h-out} \cdot \mu_{u,e,t}^{on} \geq \mu_{u,e,t}^{h-out}, \quad \forall u, e, t \quad (\text{A.12})$$

- The production load for an online unit must be above the minimum load

$$\mu_{u,e,t}^{h-out} \geq \underline{U}_{u,e,t}^{h-out} \cdot \mu_{u,e,t}^{on}, \quad \forall u, e, t \quad (\text{A.13})$$

- The upward change in production load for an unit from one time segment to the next is registered

$$\mu_{u,e,t}^{\Delta h-out} \geq \mu_{u,e,t}^{h-out} - \mu_{u,e,t-1}^{h-out}, \quad \forall u, e, t \quad (\text{A.14})$$

- The downward change in production load for an unit from one time segment to the next is registered

$$\mu_{u,e,t}^{\Delta h-out} \geq \mu_{u,e,t-1}^{h-out} - \mu_{u,e,t}^{h-out}, \quad \forall u, e, t \quad (\text{A.15})$$

- The change in production load for an unit from one time segment to the next must be below the maximum change in load

$$\bar{U}_{u,e}^{\Delta h-out} \geq \mu_{u,e,t}^{\Delta h-out}, \quad \forall u, e, t \quad (\text{A.16})$$

- The change in production load is registered

$$\mu_{u,t}^{\Delta hon} \cdot M \geq \sum_e \mu_{u,e,t}^{\Delta h}, \quad \forall u, t \quad (\text{A.17})$$

- The production load for an unit cannot be changed at the same time as another unit if not possible

$$1 \geq \mu_{u_1}^{\Delta h-out} + \mu_{u_1,e,t}^{\Delta h-out}, \quad \forall u_1^{no\Delta h}, u, e, t \quad (\text{A.18})$$

- Some units must produce both energy carriers when online

$$\mu_{u_{e_1,e_2}}^{on,both} = \mu_{u_{e_1,e_2}}^{on}, \quad \forall u_{e_1,e_2}^{both}, t \quad (\text{A.19})$$

- For some units the production of one energy carrier induce production of another energy carrier

$$\mu_{u_{e_1,e_2}}^{on,induce,e_2,t} \geq \mu_{u_{e_1,e_2}}^{on,induce,e_1,t}, \quad \forall u_{e_1,e_2}^{induce}, t \quad (\text{A.20})$$

- Registration of the unit is online for production of one of the energy carriers

$$|e| \cdot \mu_{u,t}^{on} \geq \sum_e \mu_{u,e,t}^{on}, \quad \forall u, t \quad (\text{A.21})$$

- The units which has the capability of producing two energy carriers must have a total weighted production below the maximum total load

$$\bar{U}_{u,t}^{h-out} \cdot \mu_{u,t}^{on} \geq \sum_e \mu_{u,e,t}^{h-out} \cdot U_{u,e}^{ecapratio}, \quad \forall u, t \quad (\text{A.22})$$

- The units which has the capability of producing two energy carriers must have a total weighted production above the minimum total load

$$\sum_e \mu_{u,e,t}^{h-out} \cdot U_{u,e}^{ecapratio} \geq \underline{U}_{u,t}^{h-out} \cdot \mu_{u,t}^{on}, \quad \forall u, t \quad (\text{A.23})$$

- One unit is initially pressure maintainer

$$\mu_{u^p,e,0}^p = U_{u^p,e}^{pinit}, \quad \forall u^p, e \quad (\text{A.24})$$

- The change of pressure maintainer for a system of  $e$  is registered

$$\mu_{e,t}^{pchange} \geq \mu_{u^p,e,t}^p - \mu_{u^p,e,t-1}^p, \quad \forall u^p, e, t \quad (\text{A.25})$$

- The pressure maintainer cannot be changed if the pressure maintainer was changed in a previous time segment within the minimum number of time segments the pressure maintainer must be the same.

$$1 \geq \sum_{\{t_1 \leq t \wedge t_1 > t - \underline{U}_e^{pon}\}} \mu_{u^p,t_1}^{pchange} \quad (\text{A.26})$$

- The production load for a pressure maintainer must be below the maximum load minus the pressure margin

$$\bar{U}_{u^p,e,t}^{h-out} \cdot \mu_{u^p,e,t}^{on} - \rho_e \cdot \mu_{u^p,e,t}^p \geq \underline{\mu}_{u^p,e,t}^{h-out}, \quad \forall u^p, e, t \quad (\text{A.27})$$

- The production load for a pressure maintainer must be above the minimum load plus the pressure margin

$$\mu_{u^p,e,t}^{h-out} \geq \underline{U}_{u^p,e,t}^{h-out} \cdot \mu_{u^p,e,t}^{on} + \rho_e \cdot \mu_{u^p,e,t}^p, \quad \forall u^p, e, t \quad (\text{A.28})$$

- The unit which has the capability of producing two energy carriers and are assigned as pressure maintainer must have a total weighted production below the maximum total load minus the pressure margin

$$\bar{U}_{u,t}^{h-out} \cdot \mu_{u,t}^{on} - \rho_e \cdot \sum_e \mu_{u^p,e,t}^p \geq \sum_e \mu_{u,e,t}^{h-out} \cdot U_{u,e}^{ecapratio}, \quad \forall u, t \quad (\text{A.29})$$

- The unit which has the capability of producing two energy carriers and are assigned as pressure maintainer must have a total weighted production above the minimum total load plus the pressure margin

$$\sum_e \mu_{u,e,t}^{h-out} \cdot U_{u,e}^{ecapratio} \geq \underline{U}_{u,t}^{h-out} \cdot \mu_{u,t}^{on} + \rho_e \cdot \sum_e \mu_{u^p,e,t}^p, \quad \forall u, t \quad (\text{A.30})$$

## The Storage Constraints

- The initial level of a storage is given

$$\nu_{v,level,0}^h = V_v^{h-ini}, \quad \forall v \quad (\text{A.31})$$

- The terminal level of a storage is given

$$\nu_{v,level,end}^h = V_v^{h-term}, \quad \forall v \quad (\text{A.32})$$

- The level of a storage in a given time segment is given by the level in the previous time segment plus the input minus the output

$$\nu_{v,level,t}^h - \nu_{v,out,t}^h + \nu_{v,in,t}^h = \nu_{v,level,t+1}^h \quad \forall v, t \quad (\text{A.33})$$

- Registration of when a storage goes into a state

$$\nu_{v,z,t}^{start} \geq \nu_{v,z,t}^{on} - \nu_{v,z,t-1}^{on}, \quad \forall v, z, t \quad (\text{A.34})$$

- If a storage went into a state in a previous time segment within the minimum commitment period the storage must still be in this state.

$$\nu_{v,z,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{V}_{v,z}^{on}\}} \nu_{v,z,t_1}^{start}, \quad \forall v, z, t \quad (\text{A.35})$$

- A storage can only be in one state at a time

$$\sum_z \nu_{v,z,t}^{on} = 1 \quad \forall v, t \quad (\text{A.36})$$

- The load of output, input from/to a storage if in the given state must be below the maximum load

$$\bar{V}_{v,z^{act},t}^h \cdot \nu_{v,z^{act},t}^{on} \geq \nu_{v,z^{act},t}^h, \quad \forall v, z^{act}, t \quad (\text{A.37})$$

- The load of output, input from/to a storage if in the given state must be above the minimum load

$$\nu_{v,z^{act},t}^h \geq \underline{V}_{v,z^{act},t}^h \cdot \nu_{v,z^{act},t}^{on}, \quad \forall v, z^{act}, t \quad (\text{A.38})$$

- The level of a storage must be below the maximum level

$$\bar{V}_{v,'level',t}^h \geq \nu_{v,'level',t}^h, \quad \forall v, t \quad (\text{A.39})$$

- The level of a storage must be above the minimum level

$$\nu_{v,'level',t}^h \geq \underline{V}_{v,'level',t}^h, \quad \forall v, t \quad (\text{A.40})$$

- The upwards change of input load or downward change in output load from one time segment to the next is registered

$$\nu_{v,t}^{\Delta h} \geq (\nu_{v,in,t+1}^h - \nu_{v,in,t}^h) - (\nu_{v,out,t+1}^h - \nu_{v,out,t}^h), \quad \forall v, t \quad (\text{A.41})$$

- The upwards change of output load or downward change in input load from one time segment to the next is registered

$$\nu_{v,t}^{\Delta h} \geq (\nu_{v,out,t+1}^h - \nu_{v,out,t}^h) - (\nu_{v,in,t+1}^h - \nu_{v,in,t}^h), \quad \forall v, t \quad (\text{A.42})$$

- The change in load from one time segment to the next must be below the maximum change

$$\bar{V}_v^{\Delta h} \geq \nu_{v,t}^{\Delta h}, \quad \forall v, t \quad (\text{A.43})$$

## The Transmission Constraints

- The initial transmission load of the transmission lines are given

$$\chi_{a_1,e,a_2,0}^h = X_{a_1,e,a_2}^{h-ini} \quad (\text{A.44})$$

- Start-up of a transmission line is registered

$$\chi_{a_1,e,a_2,t}^{start} \geq \chi_{a_1,e,a_2,t}^{on} - \chi_{a_1,e,a_2,t-1}^{on}, \quad \forall (a_1, e, a_2), t \quad (\text{A.45})$$

- If a transmission line was started in a previous time segment within the minimum online time the transmission line must still be on.

$$\chi_{a_1,e,a_2,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{X}_{a_1,e,a_2}^{on}\}} \chi_{a_1,e,a_2,t_1}^{start}, \quad \forall (a_1, e, a_2), t \quad (\text{A.46})$$

- The transmission lines with possibility of sending flow both ways must only be online for one direction at a time

$$1 \geq \chi_{a_1,e,a_2,t}^{on} + \chi_{a_2,e,a_1,t}^{on}, \quad \forall (a_1, e, a_2), t \quad (\text{A.47})$$

- The transmission load on a transmission line must be below the maximum load

$$\bar{X}_{a_1,e,a_2,t}^h \cdot \chi_{a_1,e,a_2,t}^{on} \geq \chi_{a_1,e,a_2,t}^h, \quad \forall (a_1, e, a_2), t \quad (\text{A.48})$$

- The transmission load on a transmission line must be above the minimum load

$$\chi_{a_1,e,a_2,t}^h \geq \underline{X}_{a_1,e,a_2,t}^h \cdot \chi_{a_1,e,a_2,t}^{on}, \quad \forall (a_1, e, a_2), t \quad (\text{A.49})$$

- The upward change in transmission load from one time segment to the next is registered

$$\chi_{a_1,e,a_2,t}^{\Delta} \geq (\chi_{a_1,e,a_2,t+1}^h - \chi_{a_1,e,a_2,t}^h) - (\chi_{a_1,e,a_2,t+1}^h - \chi_{a_1,e,a_2,t}^h), \quad \forall (a_1, e, a_2), t \quad (\text{A.50})$$

- The downward change in transmission load from one time segment to the next is registered

$$\chi_{a_1,e,a_2,t}^{\Delta h} \geq (\chi_{a_1,e,a_2,t+1}^h - \chi_{a_1,e,a_2,t}^h) - (\chi_{a_1,t+1}^h - \chi_{v,store,t}^h), \quad \forall(a_1, e, a_2), t \quad (\text{A.51})$$

- The change in transmission load from one time segment to the next must be below the maximum change possible.

$$\bar{X}_{a_1,e,a_2}^{\Delta h} \geq \chi_{v,t}^{\Delta h}, \quad \forall(a_1, e, a_2), t \quad (\text{A.52})$$

A number of other transmission constraints exists, which deals with interdependencies of the transmission lines and forced transmission. In this thesis these have not been described to keep the focus on the extension to this model.

## A.2 The Esben Model

### Sets

- $t \in \mathcal{T}$ : Set of time segments
- $e \in \mathcal{E}$ : Set of energy carriers
- $u \in \mathcal{U}$ : Set of units
- $g \in \mathcal{G}$ : Set of technologies
- $f \in \mathcal{F}$ : Set of fuels
- $u_{u_1}^{no\Delta h} \subset \mathcal{U}$ : Set of units which cannot change their production load at the same time as unit  $u_1$
- $g_{gath} \subset \mathcal{G}$ : Technologies of the type: Gathering
- $g_{hob} \subset \mathcal{G}$ : Technologies of the type: Heat only boilers
- $g_{bpr} \subset \mathcal{G}$ : Technologies of the type: Back-pressure
- $g_{cnd} \subset \mathcal{G}$ : Technologies of the type: Condensing
- $g_{heatonly} \subset \mathcal{G}$ : Technologies which only has a heat output. This set is created if other heat only technologies should be added to the model besides from  $g_{hob}$
- $g_{elonly} \subset \mathcal{G}$ : Technologies which only has an electricity output. This set is created if other electricity only technologies should be added to the model besides from  $g_{cnd}$
- $g_{el} \subset \mathcal{G}$ : Technologies with a electricity output
- $g_{heat} \subset \mathcal{G}$ : Technologies with a heat output
- $g_u \subset \mathcal{G}$ : Technologies within unit  $u$
- $g_f \subset \mathcal{G}$ : Technologies taking fuel  $f$  as input. If no fuel is assigned to a technology it only takes energy from other technologies as input.
- $g_{g_1}^{on} \subset \mathcal{G}$ : Technologies which can only be online if the technology  $g_1$  is online
- $(g_1, e, g_2) \in \mathcal{GX}$ : The feasible transmission lines for energy carrier  $e$  between technologies  $g_1$  and  $g_2$
- $r \in \mathcal{R}$ : Set of possible of fuel ratios used for the modeling of energy tax

## Parameters

- $B_t^{el.price} \in \mathbb{R}$ : The price of electricity in time segment  $t$  (money/MJ/s)
- $B_t^{NO_x-Tax} \in \mathbb{R}$ : The tax on  $NO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{SO_x-Tax} \in \mathbb{R}$ : The tax on  $SO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{CO_2-qprice} \in \mathbb{R}$ : The  $CO_2$  quote price in time segment  $t$  (money/kg)
- $F_{f,t}^{price} \in \mathbb{R}$ : The price of fuel  $f$  in time segment  $t$  (money/MJ/s)
- $F_f^{CO_2} \in \mathbb{R}$ : The emission of  $CO_2$  for fuel  $f$  (kg/MJ/s)
- $F_f^{SO_x} \in \mathbb{R}$ : The emission of  $SO_x$  for fuel  $f$  (kg/MJ/s)
- $G_g^{Marg.fe} \in \mathbb{R}$ : The marginal fuel/input efficiency for technology  $g$
- $G_g^{interceptfu} \in \mathbb{R}$ : The interception of the fuel/input line on the fuel axis in an input/output diagram
- $\underline{G}_g^{on} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay online if started
- $\underline{G}_g^{off} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay offline if shut down
- $G_g^{Marg.C_b} \in \mathbb{R}$ : The marginal  $C_b$  value used for technologies  $g_{bpr}$
- $G_g^{Interceptbpr} \in \mathbb{R}$ : The interception of the back-pressure line on electricity axis in an heat/electricity output diagram for technologies  $g_{bpr}$  (MJ/s).
- $G_g^{NO_x} \in \mathbb{R}$ : The emission of  $NO_x$  by technology  $g$  (kg/MJ/s)
- $G_g^{DeSO_x} \in [0; 1]$ : The  $DeSO_x$  factor for technology  $g$
- $G_g^{fxstartcost} \in \mathbb{R}$ : The fixed startup cost for technology  $g$  (money)
- $G_{g,f}^{startfuel} \in \mathbb{R}$ : The amount of fuel used to start technology  $g$
- $G_g^{omvcost} \in \mathbb{R}$ : The variable operating and maintenance cost for technology  $g$ . Measured in money/MJ/s input.
- $\bar{G}_g^{\Delta out} \in \mathbb{R}$ : Maximum change in output load from one time segment to the next for technology  $g$
- $\bar{G}_{g,t}^{out} \in \mathbb{R}$ : Maximum output load for technology  $g$  in time segment  $t$  (MJ/s)

- $\underline{G}_{g,t}^{out} \in \mathbb{R}$ : Minimum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $G_{g_1,g_2}^{depmaxshare} \in [0; 1]$ : The output load by technology  $g_1$  must at maximum be equal to this share of the output load of  $g_2$  if online
- $G_{g_1,g_2}^{depminshare} \in [0; 1]$ : The output load by technology  $g_1$  must at minimum be equal to this share of the output load of  $g_2$  if online
- $GX_{g_1,e,g_2,t} \in \mathbb{R}$ : The maximum load on the transmission line  $(g_1, e, g_2)$  in time segment  $t$  (MJ/s)
- $U_u^{taxh-eff}$ : The energy taxed heat efficiency for unit  $u$
- $F_{f,t}^{etax}$ : The energy tax pr. MJ/s used of fuel  $f$  to produce heat in time segment  $t$
- $ratio_r \in [0; 1]$ : The value of a certain ratio  $r$  used in the modeling of the energy tax

## Variables

- $\gamma_{g,t}^{start} \in \{0, 1\}$ : 1 if technology  $g$  is started in time segment  $t$
- $\gamma_{g,t}^{shutdn} \in \{0, 1\}$ : 1 if technology  $g$  is shut down in time segment  $t$
- $\gamma_{g,t}^{on} \in \{0, 1\}$ : 1 if technology  $g$  is online in time segment  $t$
- $\gamma_{g,t}^{fuel} \in \mathbb{R}$ : The amount of fuel loaded into the technology  $g$  in time segment  $t$  (MJ/s)
- $\gamma_{g,t}^{el-out} \in \mathbb{R}^+$ : The electricity output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{h-out} \in \mathbb{R}^+$ : The heat output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{out} \in \mathbb{R}^+$ : The total output load from technology  $g$  (MJ/s)
- $\gamma_{g,t}^{\Delta out} \in \mathbb{R}^+$ : Change in output load for technology  $g$  from the previous time segment to time segment  $t$  (MJ/s)
- $\mu_{u,e,t}^{h-out} \in \mathbb{R}^+$ : The heat production load of energy carrier  $e$  for unit  $u$  in time segment  $t$  (MJ/s)
- $\mu_{u,t}^{\Delta h-on} \in \{0, 1\}$ : 1 if the production is changed for unit  $u$  from the previous time segment to time segment  $t$  (MJ/s)
- $\gamma\chi_{g_1,e,g_2,t}^h \in \mathbb{R}^+$ : The heat transmission load for transmission line  $(g_1, e, g_2)$  in time segment  $t$  (MJ/s)

- $\mu_{u,f,t}^{etaax} \in \mathbb{R}^+$ : The energy tax to be payed by unit  $u$  for the use of fuel  $f$  in time segment  $t$
- $\varphi_{r,u,f,t}^{ratio} \in \{0, 1\}$ : 0 if the unit  $u$  consumes a ratio  $r$  of fuel  $f$  out of all the fuels used on the unit in time segment  $t$

## Objective

There are 8 terms in the objective function which is minimized

- The income from electricity production

$$- \sum_{g^{el,t}} \gamma_{g,t}^{el-out} \cdot B_t^{el.price} \quad (A.53)$$

- The fuel costs

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot F_{f, t}^{price} \quad (A.54)$$

- The  $CO_2$  quote costs

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot F_f^{CO_2} \cdot B_t^{CO_2-qprice} \quad (A.55)$$

- The  $SO_x$  tax costs

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot (1 - G_{g_f}^{DeSO_x}) \cdot F_f^{SO_x} \cdot B_t^{SO_x-Tax} \quad (A.56)$$

- The  $NO_x$  tax costs

$$+ \sum_{g_f, f, t} \gamma_{g_f, t}^{fuel} \cdot G_g^{NO_x} \cdot B_t^{NO_x-Tax} \quad (A.57)$$

- The variable operating and maintenance costs

$$+ (\sum_{g,t} \gamma_{g,t}^{fuel} \cdot \sum_{g_1, e} \gamma \chi_{g_1, e, g_2, t}^h) \cdot G_g^{omvcost} \quad (A.58)$$

- The fixed start up costs

$$+ \sum_{g,t} \gamma_{g,t}^{start} \cdot G_g^{fxstartcost} \quad (A.59)$$

- The fuel based start up costs

$$+ \sum_{g,f,t} \gamma_{g,t}^{start} \cdot G_{g,f}^{startfuel} \cdot F_{f,t}^{price} \quad (\text{A.60})$$

- Energy tax

$$+ \sum_{u,f,t} \mu_{u,f,t}^{etax} \quad (\text{A.61})$$

## Constraints

- Registration of a start-up of a technology

$$\gamma_{g,t}^{start} \geq \gamma_{g,t}^{on} - \gamma_{g,t-1}^{on} \quad \forall g, t \quad (\text{A.62})$$

- Registration of a shut down of a technology

$$\gamma_{g,t}^{shutdn} \geq \gamma_{g,t-1}^{on} - \gamma_{g,t}^{on} \quad \forall g, t \quad (\text{A.63})$$

- If a technology was started in a previous time segment within the number of time segments the technology must stay online, the technology must be on.

$$\gamma_{g,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{G}_g^{on}\}} \gamma_{g,t_1}^{start} \quad \forall g, t \quad (\text{A.64})$$

- If a technology was shut down in a previous time segment within the number of time segments the technology must stay offline, the technology must be off.

$$1 - \gamma_{g,t}^{on} \geq \sum_{t_1 \in \{t_1 \leq t \wedge t_1 > t - \underline{G}_g^{off}\}} \gamma_{g,t_1}^{shutdn} \quad \forall g, t \quad (\text{A.65})$$

- A certain technology can only be online if another certain technology is online

$$\gamma_{g_1,t}^{on} \geq \gamma_{g_2,t}^{on}, \quad \forall g_1^{on}, t \quad (\text{A.66})$$

- The output of heat and electricity of a technology equals the total output

$$\gamma_{g,t}^{out} = \gamma_{g,t}^{h-out} + \gamma_{g,t}^{el-out} \quad (\text{A.67})$$

- Technology balance. The input to a technology gives an output reduced with respect to the efficiency

$$\gamma_{g,t}^{fuel} + \sum_{g_1,e} \gamma \chi_{g_1,e,g,t}^h = \frac{\gamma_{g,t}^{out}}{G_g^{Marg.fe}} + G_g^{interceptfu} \cdot \gamma_{g,t}^{on}, \quad \forall g,t \quad (A.68)$$

- The heat output is sent on to other technologies

$$\sum_{g,e} \gamma \chi_{g,e,g_1,t}^h = \gamma_{g_{heat},t}^{h-out}, \quad \forall g \in g_{heat}, t \quad (A.69)$$

- The gathering technologies gather the heat which becomes the heat output of the unit

$$\sum_{g_1 \in g_{heat}} \gamma \chi_{g_1,e,g,t}^h = \mu_{g,u,e,t}^{h-out}, \quad \forall g \in g_{gather} \wedge g_u, u, e, t \quad (A.70)$$

- The output load for an online technology must be below the maximum load

$$\bar{G}_{g,t}^{out} \cdot \gamma_{g,t}^{on} \geq \gamma_{g,t}^{out}, \quad \forall g,t \quad (A.71)$$

- The output load for an online technology must be above the minimum load

$$\gamma_{g,t}^{out} \geq \underline{G}_{g,t}^{out} \cdot \gamma_{g,t}^{on}, \quad \forall g,t \quad (A.72)$$

- The upward change in output load for a technology from one time segment to the next is registered

$$\gamma_{g,t}^{\Delta out} \geq \gamma_{g,t}^{out} - \gamma_{g,t-1}^{out}, \quad \forall g,t \quad (A.73)$$

- The downward change in output load for a technology from one time segment to the next is registered

$$\gamma_{g,t}^{\Delta out} \geq \gamma_{g,t-1}^{out} - \gamma_{g,t}^{out}, \quad \forall g,t \quad (A.74)$$

- The change in output load for a technology from one time segment to the next must be below the maximum change in load

$$\bar{G}_g^{\Delta out} \geq \gamma_{g,t}^{\Delta out}, \quad \forall g,t \quad (A.75)$$

- The change in output load for one of the technologies within a unit is registered

$$\mu_{u,t}^{\Delta hon} \cdot M \geq \sum_g \gamma_{g,t}^{\Delta out}, \quad \forall u,t \quad (A.76)$$

- The output load cannot be changed for a technology within a unit at the same time as the technologies within another unit if not possible

$$1 \geq \mu_{u_1^{no\Delta h},e,t}^{\Delta h-out} + \mu_{u_1,e,t}^{\Delta h-out}, \quad \forall u_1^{no\Delta h}, e, t \quad (\text{A.77})$$

- The back-pressure technologies has a certain output profile

$$\gamma_{g_{bpr},t}^{el-out} \geq \gamma_{g,t}^{h-out} \cdot G_{g_{bpr}}^{Marg.C_b} + G_{g_{bpr}}^{interceptbpr} \cdot \gamma_{g,t}^{on}, \forall g_{bpr}, t \quad (\text{A.78})$$

- The output of a technology with an output dependent on another technology must at most produce a certain percentage of the output of the other technology

$$\gamma_{g,t}^{on} \cdot G_{g,g_1}^{depmaxshare} \geq \gamma_{g,t}^{out}, \quad \forall g, t \quad (\text{A.79})$$

- The output of a technology with an output dependent on another technology must at least produce a certain percentage of the output of the other technology

$$\gamma_{g,t}^{out} \geq \gamma_{g,t}^{on} \cdot G_{g,g_1}^{depminshare}, \quad \forall g, t \quad (\text{A.80})$$

- The capacities of the technology transmission lines must be kept

$$GX_{g_1,e,g_2,t} \geq \gamma \chi_{g_1,e,g,t}^h, \quad \forall (g_1, e, g_2), t \quad (\text{A.81})$$

- The energy tax to be payed when a certain ratio is chosen is given

$$\mu_{u,f,t}^{etax} \geq \sum_e \frac{\mu_{u,e,t}^{h-out}}{U_{taxh-eff}^u} \cdot ratio_r \cdot F_{f,t}^{etax} - M \cdot \varphi_{r,u,f,t}^{ratio}, \quad \forall u, f, t \quad (\text{A.82})$$

- only one ratio can be chosen

$$\sum_r 1 - \varphi_{r,u,f,t}^{ratio} \geq 1, \quad \forall u, f, t \quad (\text{A.83})$$

- The amount of fuel  $f$  used by unit  $u$  in time segment  $t$  cannot be larger than the next ratio step of the total fuel consumption for the unit in the time segment.

$$ratio_{r+1} \cdot \sum_{f_1} \sum_{g_{f_1} \in g_u} \gamma_{g_{f_1},t}^{fuel} + M \cdot \varphi_{r,u,f,t}^{ratio} \geq \sum_{g_f \in g_u} \gamma_{g_f,t}^{fuel} \quad (\text{A.84})$$



## APPENDIX B

# Implementation Report

---

This report gives a short introduction to the components and input to the technology networks of the Esben model and a full description of the representation of each of the production units in the CHP system of Greater Copenhagen.

## B.1 Short Introduction to The Esben Model

The Esben Model is an extension/modification to/of The Katja Model used by VLE to create daily heat load plans for The CHP System of Greater Copenhagen. In The Katja Model a plan for production is given as input together with related marginal costs of changing this plan. The Katja Model then reoptimize this plan with respect to transmission and storage minimizing the cost of changes.

The Esben Model is a detailed model of the economy and technical details of the production units which replaces the production plan and related marginal costs.

In order to read this implementation report a knowledge about the CHP system of Greater Copenhagen and how it is represented in The Katja Model is

required. Such a knowledge could be achieved by reading the master thesis by Esben Friis-Jensen: Modeling the Combined Heat and Power System of Greater Copenhagen. This thesis also gives a detailed introduction to The Esben Model.

## B.2 The Temporal Dimension

The Esben Model has a temporal dimension called time segments  $t$ . A time segment could correspond to any fixed amount of time. In the implemented version of The Esben Model a time segment is defined as an hour.

## B.3 Fuels

A unit utilize fuel, therefore a set of fuels  $f$  can be assigned in The Esben Model. To each of the fuels the following input parameters can be assigned.

- $F_f^{CO_2} \in \mathbb{R}$ : The emission of  $CO_2$  for fuel  $f$  (kg/MJ/s)
- $F_f^{SO_x} \in \mathbb{R}$ : The emission of  $SO_x$  for fuel  $f$  (kg/MJ/s)

## B.4 Market Data

Market data is needed to find cost efficient plans. The Esben Model takes the following market input into account when finding a plan.

- $B_t^{el.price} \in \mathbb{R}$ : The price of electricity in time segment  $t$  (money/MJ/s)
- $B_t^{NO_x-Tax} \in \mathbb{R}$ : The tax on  $NO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{SO_x-Tax} \in \mathbb{R}$ : The tax on  $SO_x$  emission in time segment  $t$  (money/kg)
- $B_t^{CO_2-quoteprice} \in \mathbb{R}$ : The  $CO_2$  quote price in time segment  $t$  (money/kg)
- $F_{f,t}^{price} \in \mathbb{R}$ : The price of fuel  $f$  in time segment  $t$  (money/MJ/s)
- $U_u^{taxh-eff}$ : The energy taxed heat efficiency for unit  $u$
- $F_{f,t}^{etax}$ : The energy tax pr. MJ/s used of fuel  $f$  to produce heat in time segment  $t$

## B.5 Technology Networks

In the Esben model a production unit is represented using the components/building bricks called technologies  $g$ . A technology can either take an energy load of fuel or an energy load created by another technology as input resulting in an output of electricity and heat in a ratio dependent on the type of technology. There are three types of technologies

- Condensing technology: A technology which only has an electricity output
- Back-Pressure technology: A technology with an output of both heat and electricity in a fixed linear relationship
- Heat-only technology: A technology which only has a heat output

The technologies are connected by directed edges  $(g_1, e, g_2)$  in a technology network. Where the directed edges represent a feasible heat connection between the technologies and are distinguished by the type of energy carrier (steam or water) possible to sent through the edge. These networks gives the possibility of representing a production unit in a high level of detail.

### Input Parameters

The input parameters needed for the technology network can be divided into general input, type related input and dependency input.

#### General Input

The general input which is possible to assign to a technology is listed below with a short description

- $g_u$ : Technologies within unit  $u$
- $g_f$ : Technologies taking fuel  $f$  as input. If no fuel is assigned to a technology it only takes energy from other technologies as input.
- $g_g^{type} \in [0, 1, 2, 3]$ : Defining the type of technology  $g$ . 0. Gathering technology, 1. Condensing technology, 2. Back-pressure technology, 3. Condensing technology

- $G_g^{Marg.fe} \in \mathbb{R}$ : The marginal fuel/input efficiency for technology  $g$
- $G_g^{interceptfu} \in \mathbb{R}$ : The interception of the fuel/input line on the fuel axis in an input/output diagram
- $\underline{G}_g^{on} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay online if started
- $\underline{G}_g^{off} \in \mathbb{N}^+$ : The minimum number of time segments the technology  $g$  must stay online if started
- $\bar{G}_{g,t}^{out} \in \mathbb{R}$ : Maximum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $\underline{G}_{g,t}^{out} \in \mathbb{R}$ : Minimum output load for technology  $g$  in time segment  $t$  (MJ/s)
- $\bar{G}_g^{\Delta out} \in \mathbb{R}$ : Maximum change in output load from one time segment to the next for technology  $g$
- $G_g^{NO_x} \in \mathbb{R}$ : The emission of  $NO_x$  by technology  $g$  (kg/MJ/s)
- $G_g^{DeSO_x} \in [0; 1]$ : The  $DeSO_x$  factor for technology  $g$
- $G_g^{fixstartcost} \in \mathbb{R}$ : The fixed startup cost for technology  $g$  (money)
- $G_{g,f}^{startfuel} \in \mathbb{R}$ : The amount of fuel used to start technology  $g$
- $G_g^{omvcost} \in \mathbb{R}$ : The variable operating and maintenance cost for technology  $g$ . Measured in money/MJ/s input.
- $G_{g_1,g_2}^{depmaxshare} \in [0; 1]$ : The output load by technology  $g_1$  must at maximum be equal to this share of the output load of  $g_2$  if online
- $G_{g_1,g_2}^{depminshare} \in [0; 1]$ : The output load by technology  $g_1$  must at minimum be equal to this share of the output load of  $g_2$  if online
- $g_{g_1}^{on}$ : Technologies which can only be online if the technology  $g_1$  is online
- $\bar{G}_{g_1,e,g_2}^{xcap}$ : The capacity on transmission line for energy carrier  $e$  between technologies  $g_1$  and  $g_2$

## Output Profiles for Technology Types

The output profiles for the three different technology types are given in electricity-heat diagrams in figure B.1. For the back-pressure technologies additional input is needed to define the output profiles. This input is given below.

- $G_g^{Marg.C_b} \in \mathbb{R}$ : The marginal  $C_b$  value used for technologies  $g_{bpr}$ .
- $G_g^{Interceptbpr} \in \mathbb{R}$ : The interception of the back-pressure line on electricity axis in an heat/electricity output diagram for technologies  $g_{bpr}$  (MJ/s).

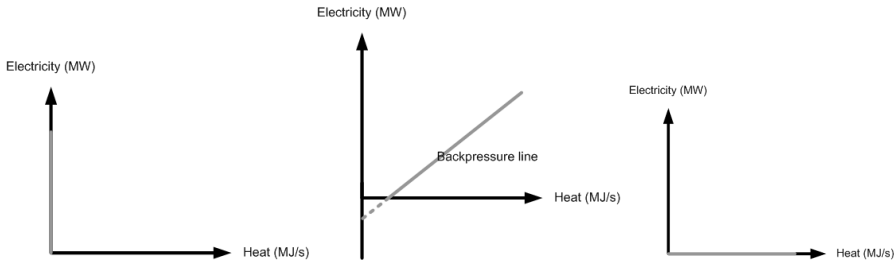


Figure B.1: The output profiles for the different technology types. From the left it is output profile of the condensing technology, the back-pressure technology and finally the heat-only technology

The fourth technology, the gathering technology, does not have a output profile because it only gathers the heat of the technologies and thereby it is a representation of the connection of the units to the DH system.

## B.6 Objective

The objective of The Esben Model which is minimized is given below

- Electricity income + Fuel costs +  $CO_2$  quote costs +  $NO_x$  tax costs +  $SO_x$  tax costs + Variable operating and maintenance costs + Fixed start-up costs + Fuel dependent start-up costs + Energy tax

## B.7 Implemented Units

In the following a description of how each of the implemented units in The Katja Model are represented in The Esben Model will be given.

### AMV1

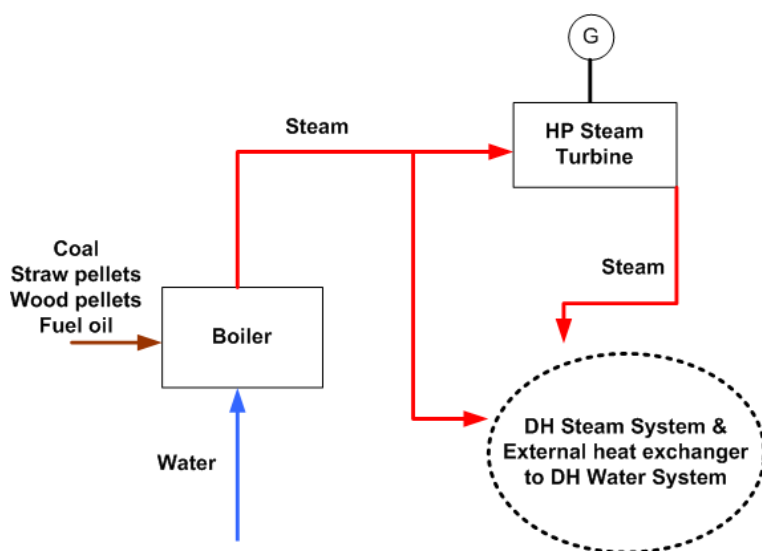


Figure B.2: Process Diagram

AMV1 is placed at Amagerværket. A simplified process diagram is displayed in figure B.2. The unit utilize coal, straw pellets, wood pellets and fueloil to heat water to steam in a boiler. This steam can then be sent directly to the steam DH system or to a high pressure back-pressure steam turbine generating electricity. When the steam has passed through the turbine it still contains enough pressure to be sent to the steam DH system.

AMV1 is represented in a technology network using seven technologies, the network is displayed in figure B.3. AMV1-B-WP, AMV1-B-SP, AMV1-B-COAL, AMV1-B-FUELOIL are all heat only technologies representing the possibility of using each of the different fuels. These all have a steam connection to AMV1-B. Thus these five technologies represent the boiler of AMV1. By representing the boiler in this way it is possible to mix the fuels, limit the usage of a certain fuel by setting limits on the technologies taking in fuel, limit the the total usage of fuels

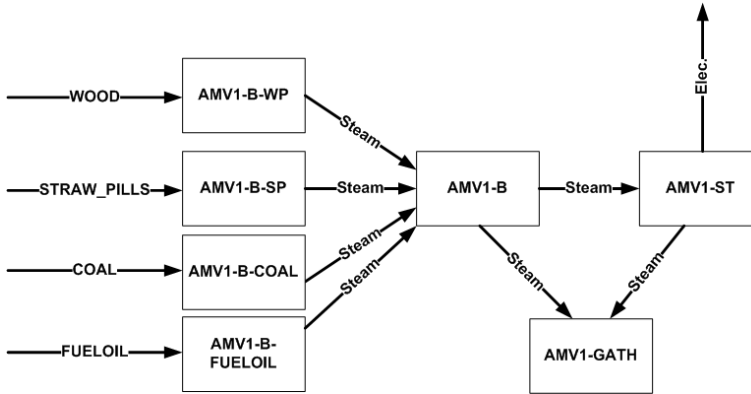


Figure B.3: Model Representation

by setting limits on AMV1-B and to make interdependencies between the fuels. From AMV1-B there is a steam connection to the gathering technology AMV1-GATH representing the bypass of the turbine and a steam connection to AMV1-ST which is a back-pressure technology representing the high pressure turbine. This technology generate electricity and heat in a fixed linear relationship. The heat is sent on as steam through a connection to AMV1-GATH.

The different input data can be put on the different technologies dependent on the available data.

## AMV3

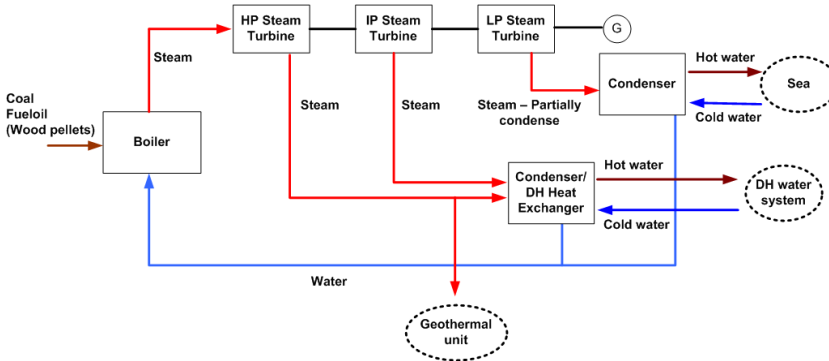


Figure B.4: Process Diagram

AMV3 is placed at Amagerværket and a simplified process diagram of the unit is displayed in figure B.4. The unit use coal and fueloil in a boiler heating water to steam. The steam is sent to a multistage extraction turbine from which some of the steam can be extracted during the process to be sent to a heat exchanger heating DH water or directly to a geothermal facility. If the steam is not extracted it is sent all the way through the turbine to a sea water condenser which results in electricity generation only. The output profile for the unit is displayed in figure B.5. This output profile is special for an extraction unit due to the hack in the  $C_v$  line which divides the line into two lines  $C_v$ 1-Line and  $C_v$ 2-Line.

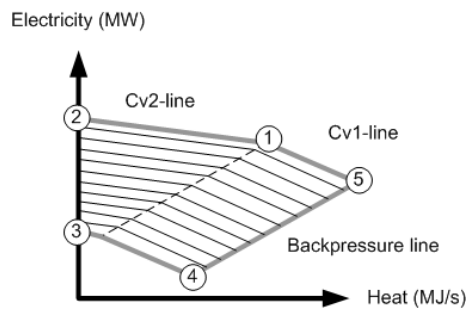


Figure B.5: Model Representation

The technology network representation of the AMV3 unit is displayed in figure B.7. The technology network consist of seven technologies. The technologies AMV3-B-COAL, AMV3-B-FUELOIL AND AMV3-B are heat only technologies representing the boiler in the same way as for AMV1. From AMV3-B there is a

steam connection to the back-pressure technology AMV3-ST which has steam connections to the condensing technologies AMV3-C1, AMV3-C2 and a water and a steam connection to the gathering technology AMV3-GATH. Thus AMV3-GATH represent the connection to the DH water system and the geothermal facility and AMV3-3 AMV3-ST, AMV3-C1 and AMV3-C2 is a representation of the special extraction turbine. A description of how they represent the turbine can be given using the steps in figure B.6. When heat is sent a steam to AMV3-ST it produces electricity and heat in a fixed linear relationship following the back-pressure line shown in the first step. If all the heat is sent to AMV3-GATH the output of the unit would be on any point A along the back-pressure line. Instead of sending the generated heat to AMV3-GATH some or all of the heat can be sent on as steam to AMV3-C1 with an input efficiency equal to the absolute value of the slope of the  $C_v$ 1-line (The  $C_v$ 1-value) and a maximum output equal to the difference between the electricity generated in point 5 and 1 which is assumed to be identical to the difference between point 4 and 3. Sending the maximum amount of heat possible to AMV3-C1 gives an output in the point B seen in step 2. If the model wants to exchange more electricity heat can also be sent to AMV3-C2, with an input efficiency equal to  $C_v$ 2. This gives an output on the line between B and C. The model will only sent heat to AMV3-C2 when the capacity of AMV3-C1 is reached due to dominance on the input efficiency i.e. the exchange rate for heat to electricity

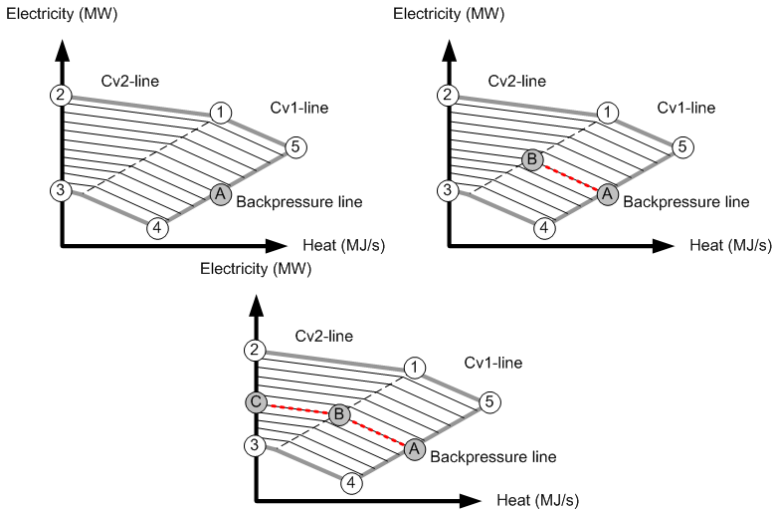


Figure B.6: The three steps

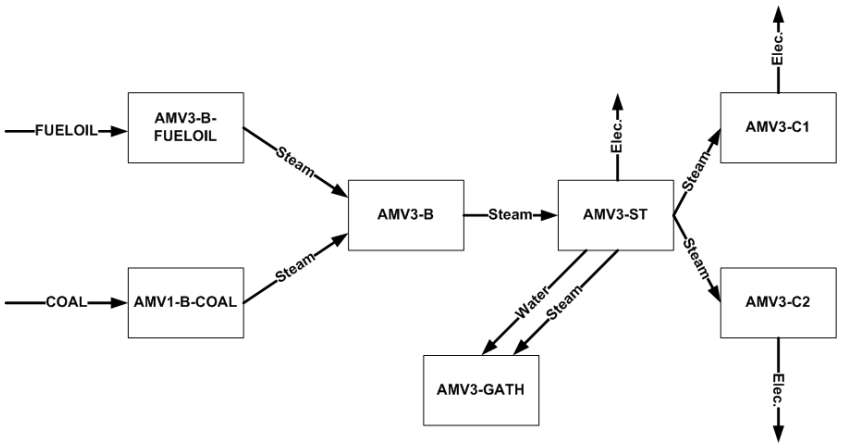


Figure B.7: Model Representation

AVV1

AVV1 is a twin to AMV3. Therefore the process diagram in figure B.8 and the technology network representation in figure B.9 are almost identical to the ones for AMV3. The only difference is that AVV2 does not produce heat as steam.

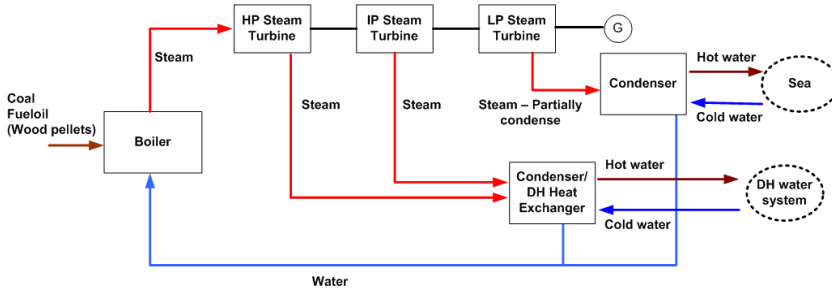


Figure B.8: Process Diagram

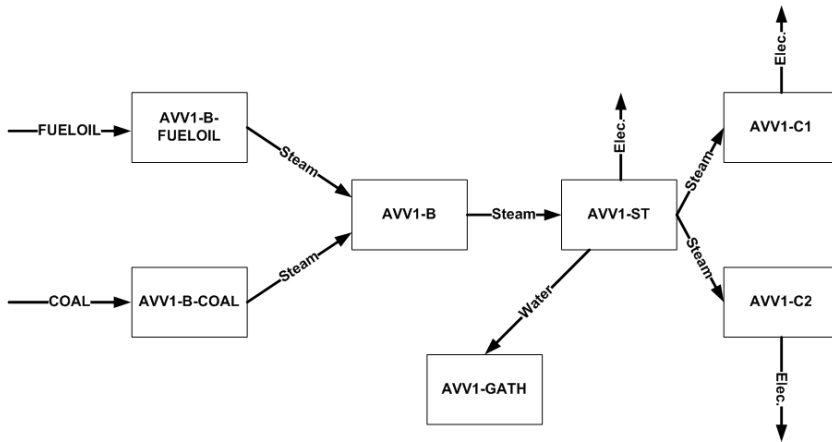


Figure B.9: Model Representation

## AVV2

AVV2 is a very modern combined cycle unit delivering heat carried by water. It is constructed with an extraction steam turbine, a gas turbine and two boilers: A biomass boiler fired with straw and an advanced multi-fuel boiler which can be fired with natural gas, oil and wooden pellets. The gas turbine and the biomass boiler can only be used if the multi-fuel boiler at least is running at minimum load. A process diagram for AVV2 is illustrated in figure B.10

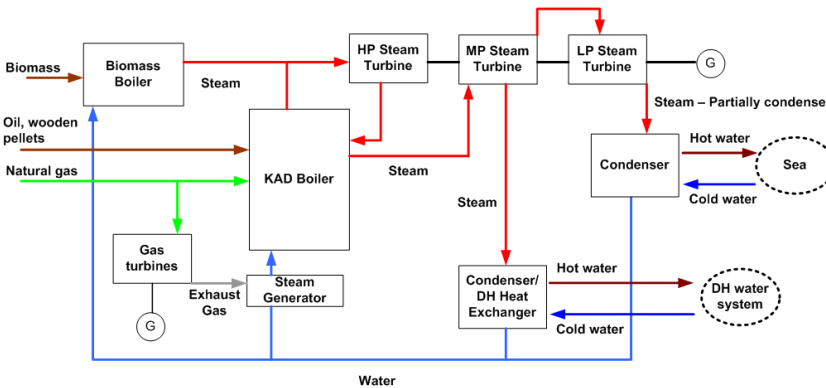


Figure B.10: Process Diagram

AVV2 is represented in The Esben Model by the technology network shown in figure B.11. The biomass boiler is represented by the heat boiler technology AVV2-B-STRAW. The advance multi-fuel boiler (KAD boiler) is represented in the same way as the multi-fuel boilers of the previous presented unit using 4 heat boiler technologies: AVV2-B-KAD-NG, AVV2-B-KAD-FUELOIL, AVV2-B-KAD-WP. The Gas turbine is represented by the back-pressure technology AVV2-GT and finally the extraction steam turbine is represented by the combination of the back-pressure technology AVV2-ST and the condensing technology AVV2-C. This way of representing the extraction turbine corresponds to the representation used for the turbine in AMV3 and AVV1. Compared to them only one condensing technology is used here, due to the fact that the extraction turbine of AVV2 does not have a 'hack' in the  $C_v$  line. From AVV2-B-STRAW, AVV2-B-KAD and AVV2-GT delivers heat as steam to AVV2-ST which generates electricity and heat following a back-pressure profile. The output heat can be sent as steam to condensing technology with an input efficiency given by  $C_v$  or as water to the gathering technology AVV2-GATH.

The red lines with a 'on' on them represents that there is a on dependency that AVV2-B-KAD must be on if AVV2-GT or AVV2-B-STRAW is on. This

dependency is given through the set  $g_{g_1}^{on}$ .

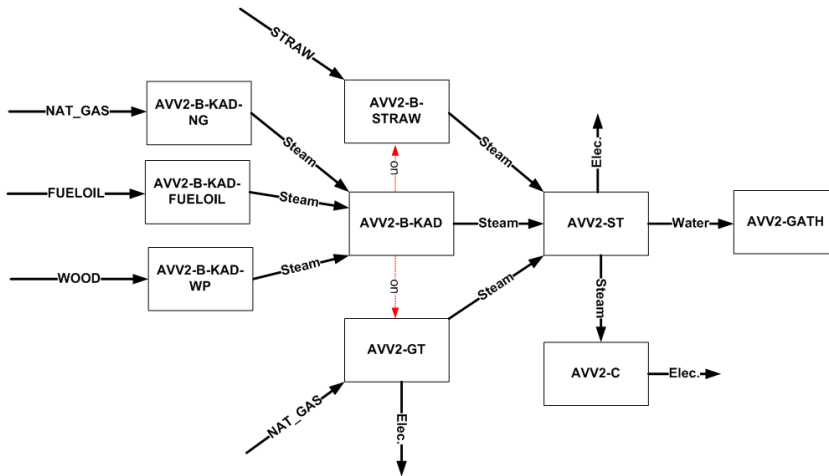


Figure B.11: Model Representation

## HCV7

HCV7 is a special steam turbine unit. The process diagram for HCV7 is illustrated in figure 3.5.

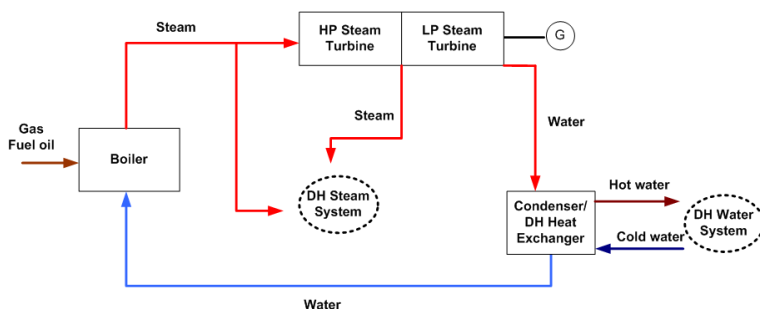


Figure B.12: Process diagram

The boiler generates steam which can be sent directly to the DH steam system or to a sequence of a high pressure turbine and a low pressure turbine. When the steam has gone through the high pressure turbine some or all of it can be extracted and sent to the steam system. The remaining steam is sent through the low pressure turbine to generate more electricity. When the steam has gone through the low pressure turbine it has too low a pressure and temperature to be used in the DH steam system, instead it is sent to a condenser exchanging the heat to the DH water system. Thus HCV7 is capable of producing water and steam simultaneously. Due to the cooling of turbine some of the steam must be sent all the way through resulting in a minimum amount of water which is always produced.

Figure B.13 displays how this unit could be represented in a technology network in the model.

The multi-fuel boiler of HCV7 which takes fuel oil and Natural gas as input is represented using the method described previously in this chapter by three heat boiler technologies HCV-B-FUELOIL, HCV7-B-NG and HCV7-B. From this boiler heat can be sent as steam directly to the gathering technology HCV7-GATH representing a bypass of the turbine. The heat from the boiler can also be sent to the back-pressure technology HCV7-ST-HP representing the high-pressure turbine. This technology generates electricity and heat. The heat can be sent to the HCV7-GATH as steam or to the final back-pressure technology HCV7-ST-LP representing the low pressure turbine. This gives an extra electricity production and a heat production which is sent on as water to HCV7-GATH.

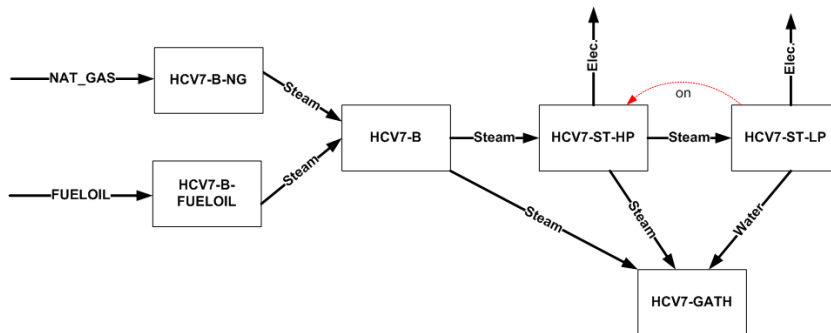


Figure B.13: Model Representation

The red directed line illustrates that HCV7-ST-LP must be online if HCV7-ST-HP should be online. Thus by assigning a minimum production to HCV7-ST-LP an amount of heat is forced to be sent to this technology if HCV7-ST-HP is used.

## HCV8

The process diagram of HCV8 is illustrated in figure B.14. The unit is a gas turbine unit delivering heat as steam to the steam DH system. The gas turbine has a back-pressure profile. A possibility of attaching an additional boiler to generate even more heat exists, but this is only possible if the gas turbine is used. Finally a fixed amount of hot water is produced when the gas turbine is used due to cooling of the turbine. This water can be sent to the DH water system.

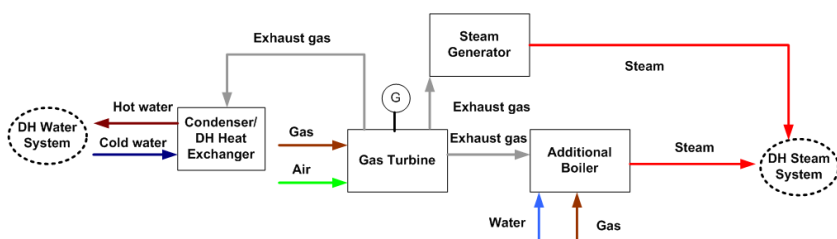


Figure B.14: Process Diagram

HCV8 is represented in The Esben Model using 4 technologies. The back-pressure technology HCV8-GT represents the gas turbine and takes natural gas as input to produce heat and electricity. the heat can either be sent directly as steam to the gathering technology HCV8-GATH or as steam to the heat boiler technology HCV8-TILSATS representing the additional boiler which also takes natural gas as input to generate more heat which then can be sent as steam to HCV8-GATH. The red line between HCV8-GT and HCV8-TILSATS indicates that HCV8-GT should be online in order to use HCV8-TILSATS. The fixed water production is represented by using the heat boiler technology HCV8-FORCEDWATER with a min/max production equal to the fixed amount. This technology should then be online in order to use HCV8-GT which means if HCV8-GT is online some of its produced steam will be forced to be sent to HCV8-FORCEDWATER which sends it on as water to HCV8-GATH.

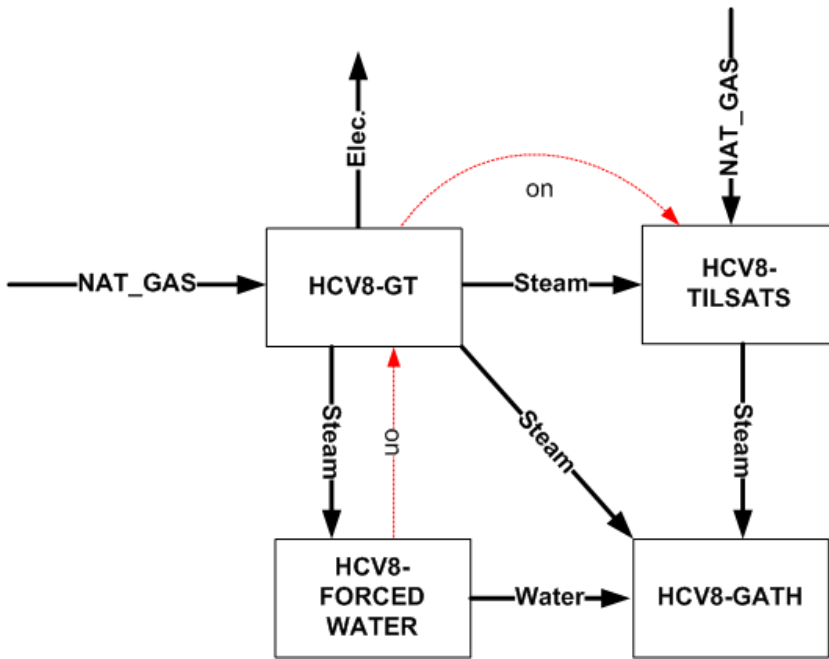


Figure B.15: Model Representation

## HCVK2122

In The Katja Model the boilers HCVK21 and HCVK22 are represented by one unit. Thus this is also the case for The Esben Model. A process diagram of one of the boilers are given in figure B.16. As seen the boiler utilize natural gas or lightoil to produce heat as steam to the DH steam system.

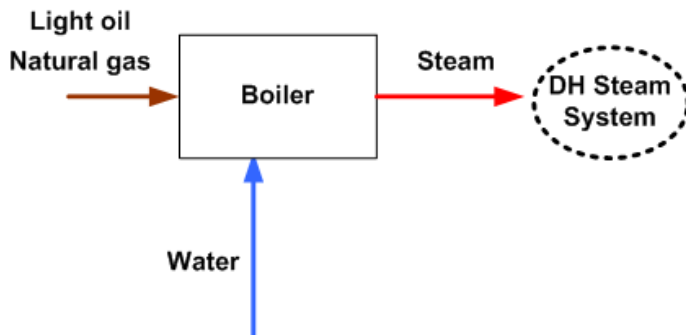


Figure B.16: Process Diagram

HCVK2122 is represented in The Esben Model by constructing the multi-fuel boiler using the same method as for e.g. AVV2 with the heat boiler technologies HCVK21-22-B-LIGHTOIL, HCVK21-22-B-NAT-GAS and HCVK21-22-B. From HCVK21-22-B steam is then sent to the gathering technology HCVK21-22-GATH. This representation is illustrated in figure B.17

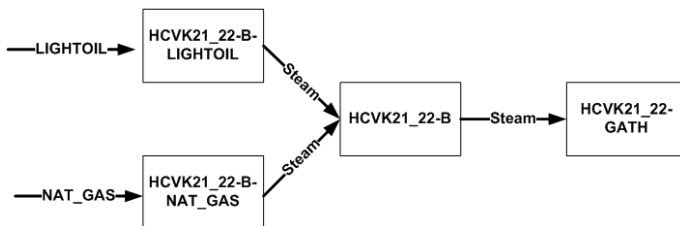


Figure B.17: Model Representation

SMV7

SMV7 is very similar to HCV8. The only difference is that in addition to the additional boiler an addition steam turbine can be attached. The process diagram is given in figure B.18.

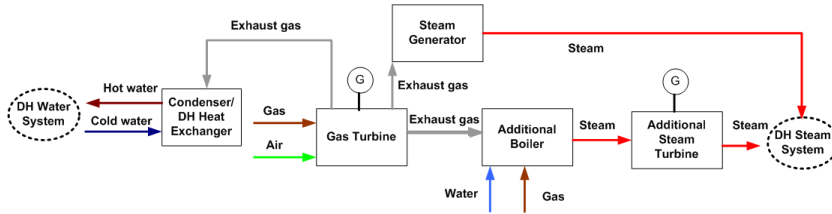


Figure B.18: Process Diagram

The representation of SMV7 in The Esben Model is illustrated in figure B.19. The unit represented in the same way as HCV8 with the only difference that SMV7-TILSATS is not a heat boiler technology but a back-pressure technology, which represents the additional boiler and turbine.

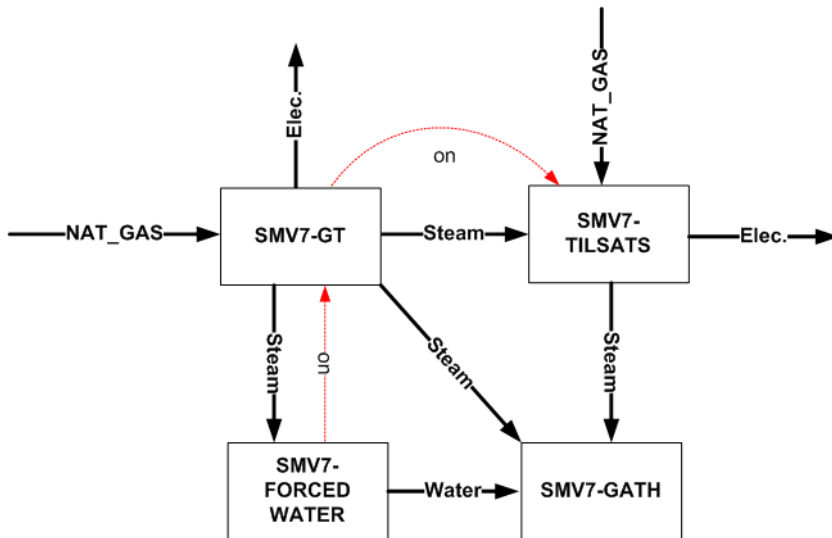


Figure B.19: Model Representation

## SMVK2122

SMVK2122 representing the two boilers SMVK21 and SMVK22 is identical to HCVK2122 as seen in the proces diagram in figure B.20. Thus the representation shown in figure B.21 of the unit in The Esben Model is also identical to the one for HCVK2122.

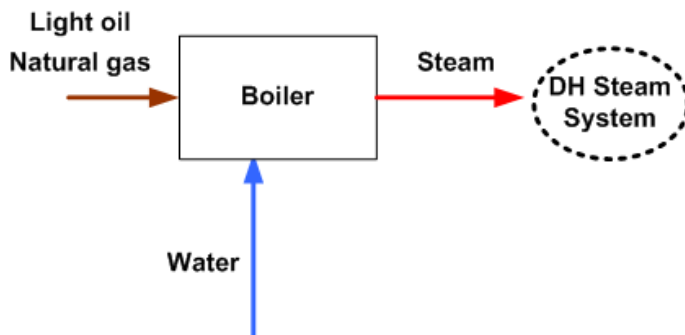


Figure B.20: Process Diagram

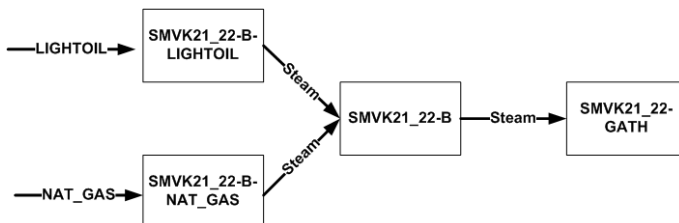


Figure B.21: Model Representation

## Waste Incineration Units

In The Katja Model and thereby The Esben Model all the waste incineration units are represented by three units: unitAffald-VEKS, unitAffald-CTR and unitAffald-VF-CTR. In The Esben Model all of the waste incineration units are represented as single units. Thus in order to represent them by only using three units a gathering technology is made for each of the three. The representations of the single units then deliver heat to a certain one of these gathering technologies. How the single units are divided on the three main units can be seen in figures B.22, B.23 and B.24. As seen the VF units delivers heat to both unitAffald-VF-CTR and unitAffald-VEKS. In the following sections the representation of each of the single units are illustrated. Most of them are simple units with a oven or a oven and a back-pressure turbine. These are easily represented in the model and will only be illustrated and not explained. However the representation of one of the units namely AMF does require some explanation.

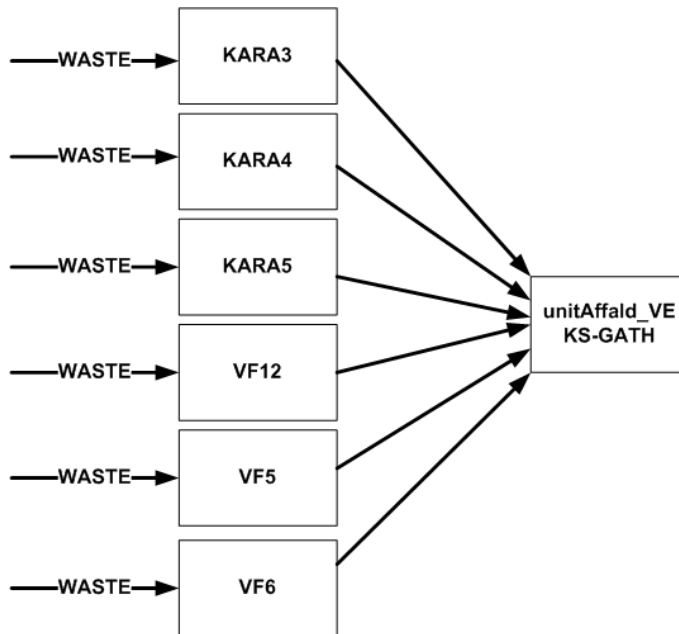


Figure B.22: Model Representation

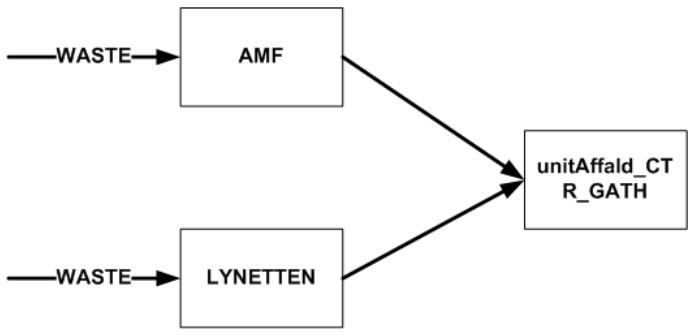


Figure B.23: Model Representation

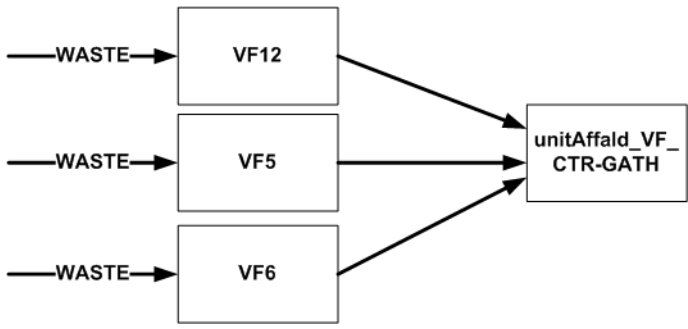


Figure B.24: Model Representation

## AMF

A proces diagram of the AMF unit is given in figure B.25. 4 ovens heats water to steam which can be sent directly to the DH steam system or through a chimney. It can also be sent directly to a DH heat exchanger to heat water in the DH water system or through one of two back-pressure turbines before reaching the DH heat exchanger.

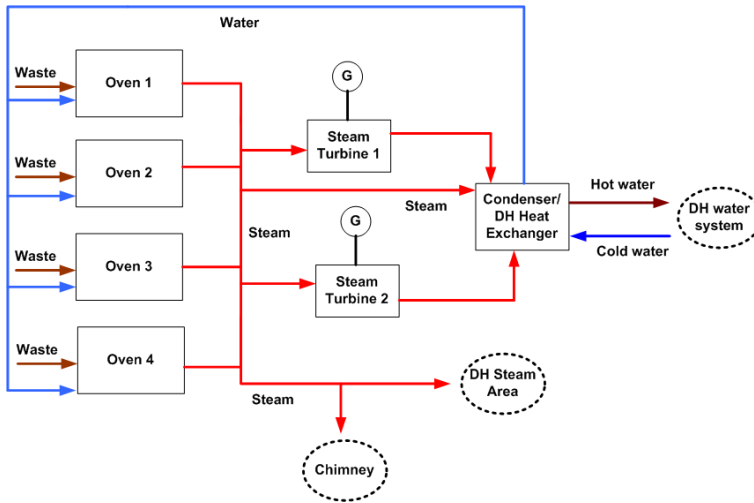


Figure B.25: Process Diagram

The unit is represented as seen in figure B.26. the 4 ovens are represented by 4 heat boiler technologies AMF-B1,AMF-B2,AMF-B3 and AMF-B4 delivering heat as steam to another heat boiler technology AMF-AREA. AMF-AREA is used to represent that the steam produced can be sent to many places therefore it is only an area and it has no input efficiency. From AMF-AREA the heat can be sent as steam or water to the gathering technology AMF-GATH representing the direct production of heat. One can also sent the heat as steam to the back-pressure technologies AMF-ST1 and AMF-ST2 to generate electricity and the remaining heat is then sent to AMF-GATH as water.

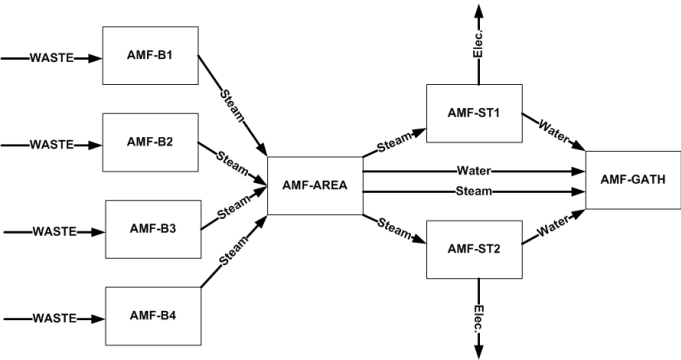


Figure B.26: Model Representation

## KARA3

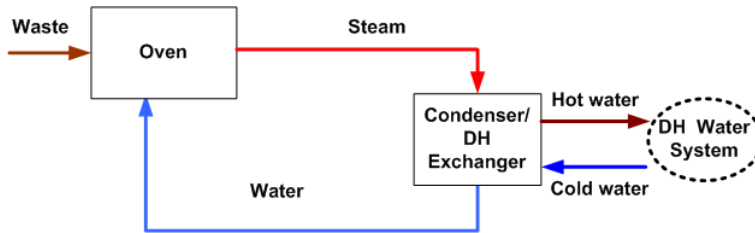


Figure B.27: Process Diagram



Figure B.28: Model Representation

### KARA4

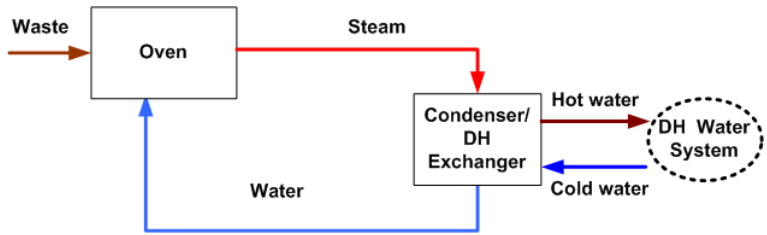


Figure B.29: Process Diagram



Figure B.30: Model Representation

## KARA5

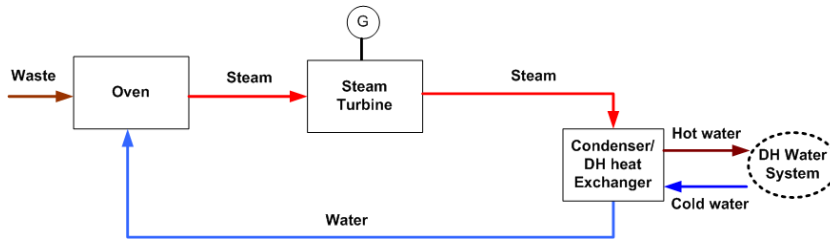


Figure B.31: Process Diagram

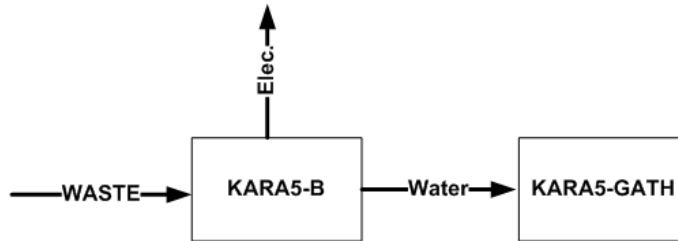


Figure B.32: Model Representation

## VF12

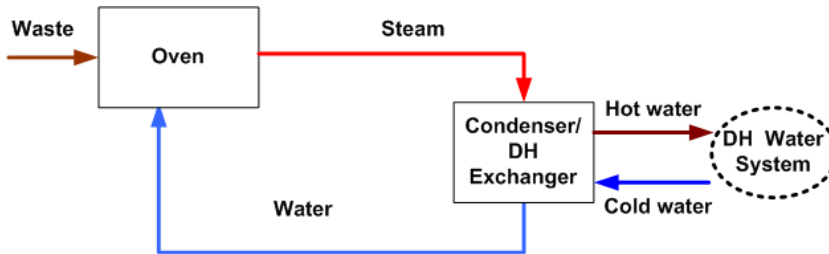


Figure B.33: Process Diagram

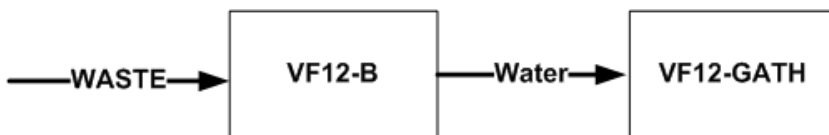


Figure B.34: Model Representation

VF5

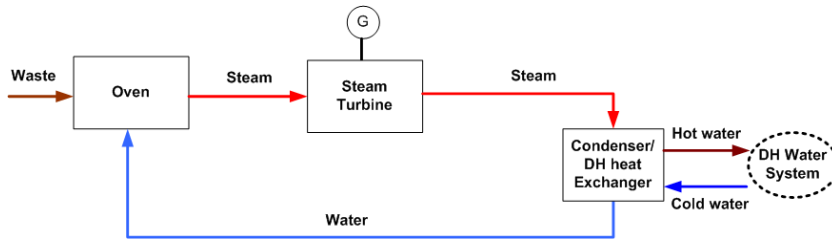


Figure B.35: Process Diagram

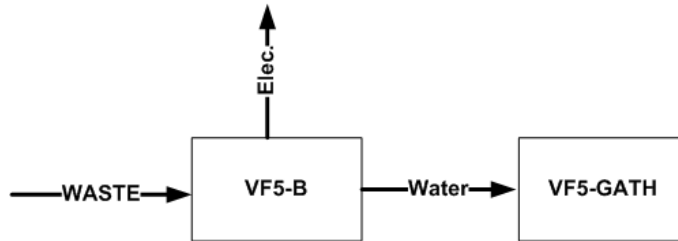


Figure B.36: Model Representation

VF6

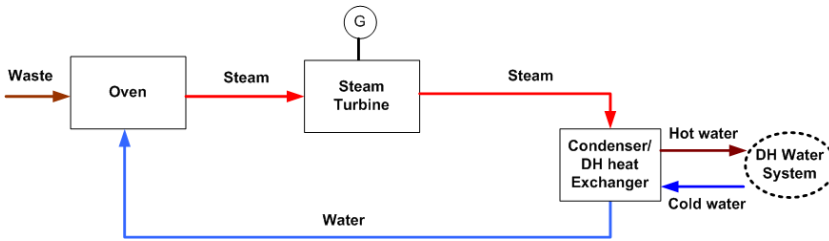


Figure B.37: Process Diagram

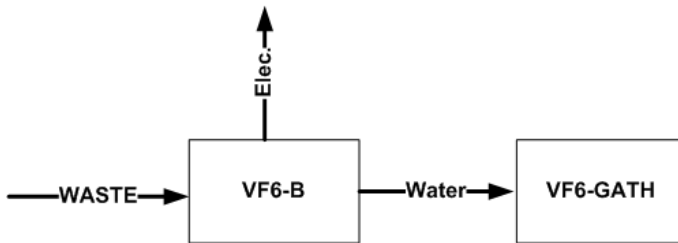


Figure B.38: Model Representation

## Lynetten

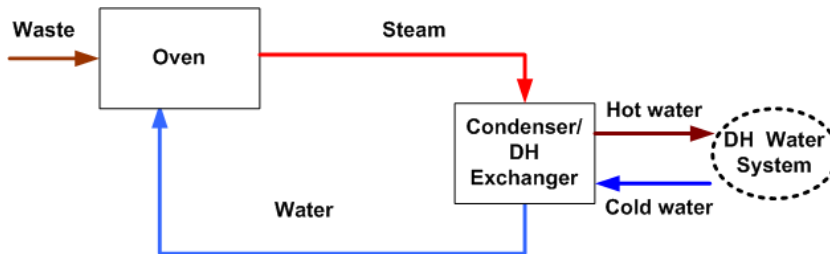


Figure B.39: Process Diagram



Figure B.40: Model Representation

## SpidsVEKS

The peak boiler units are represented as single boilers.



Figure B.41: Model Representation

## SpidsCTR



Figure B.42: Model Representation

## SpidsLygten



Figure B.43: Model Representation

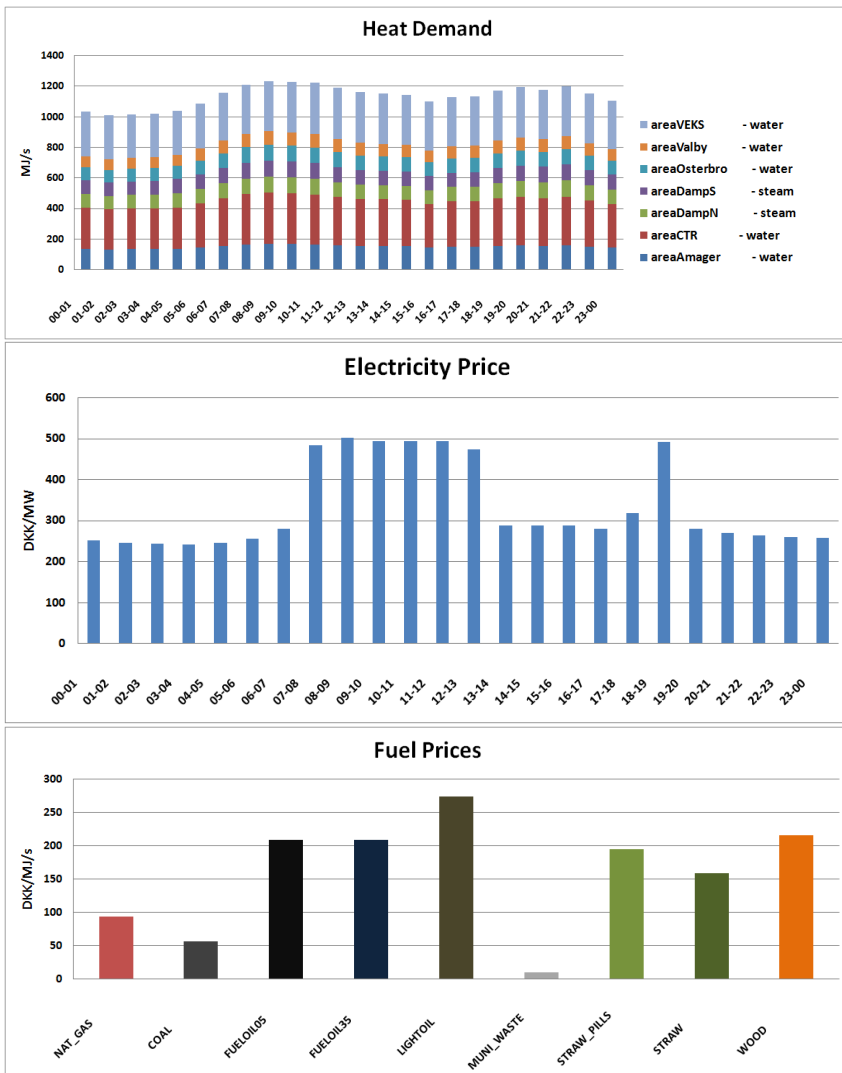
APPENDIX C

## Results

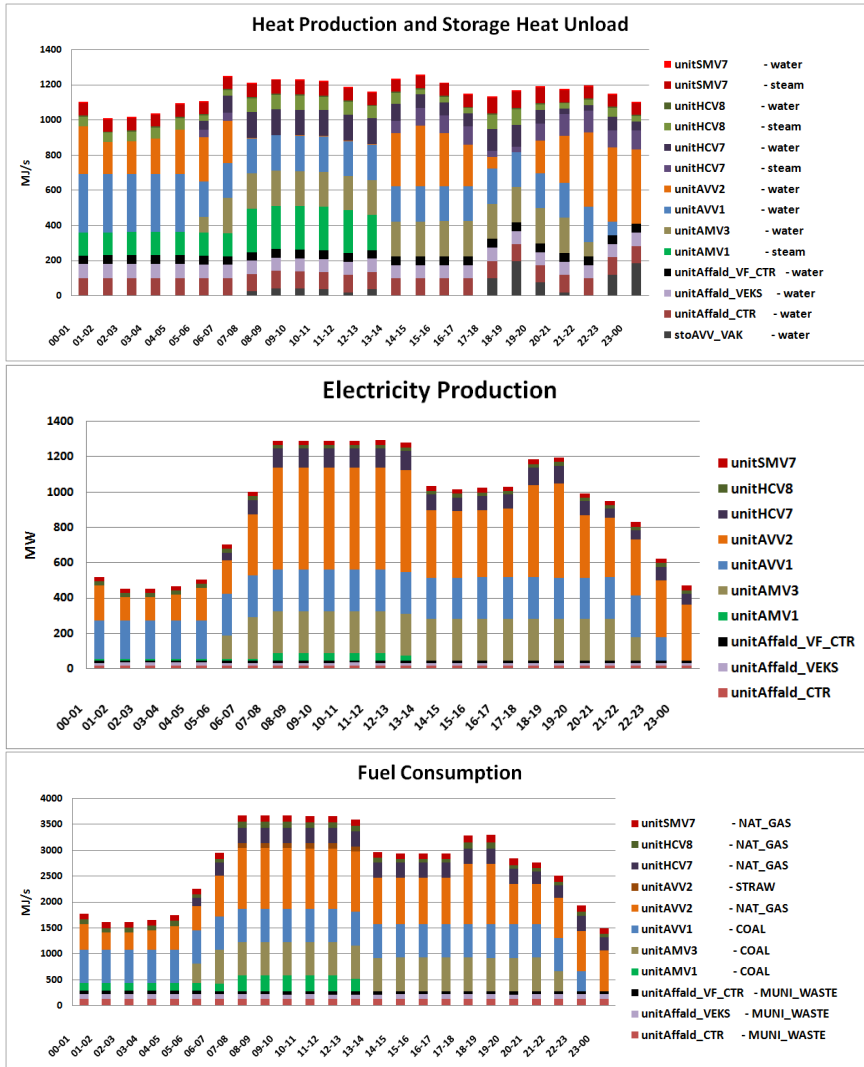
---

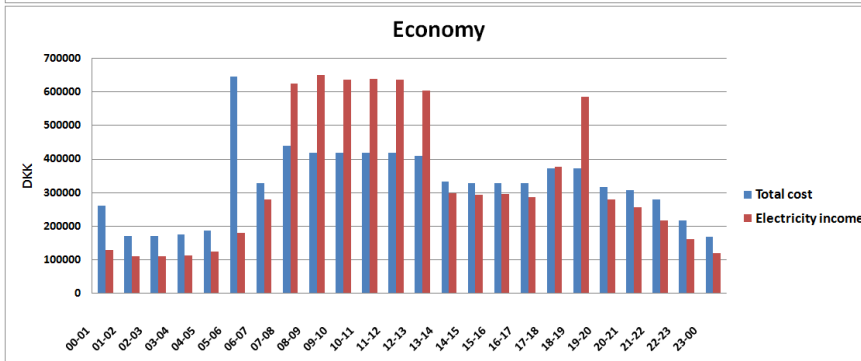
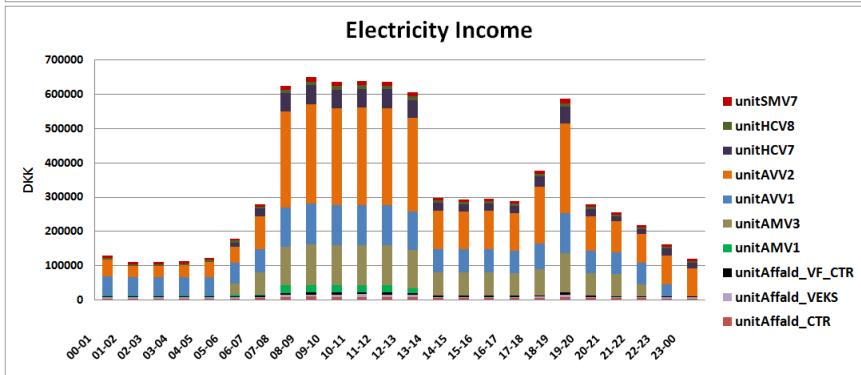
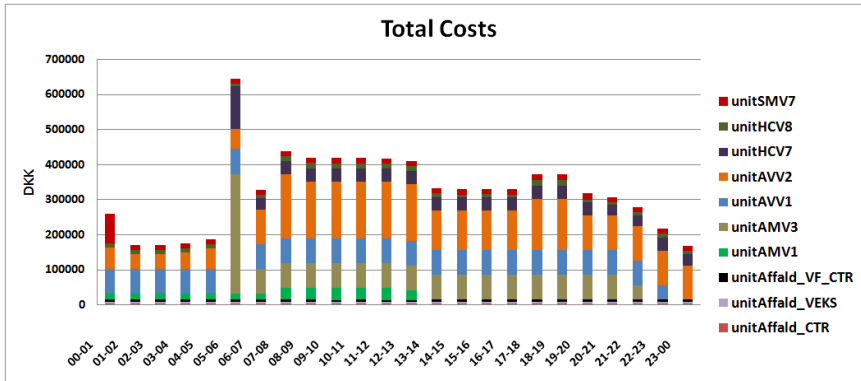
# C.1 24 Hour Plan made with DA Dataset 1

## Input Data



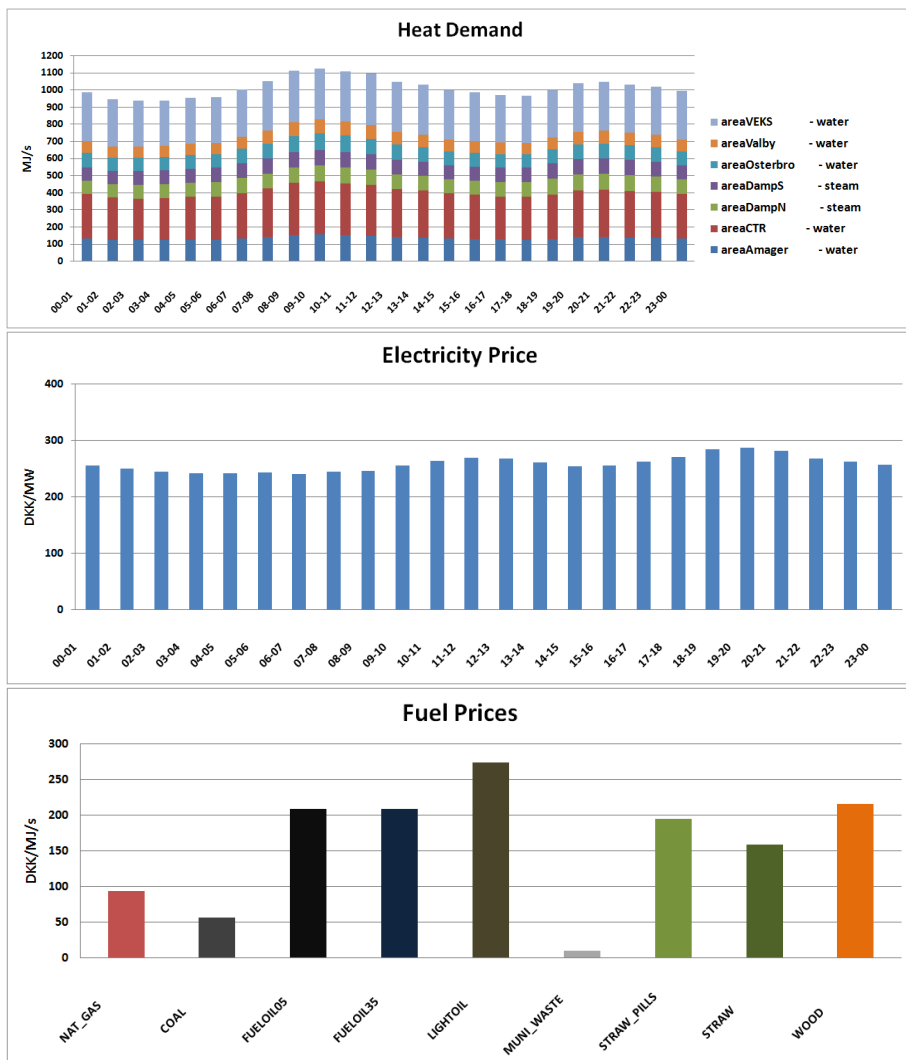
## Output Plan



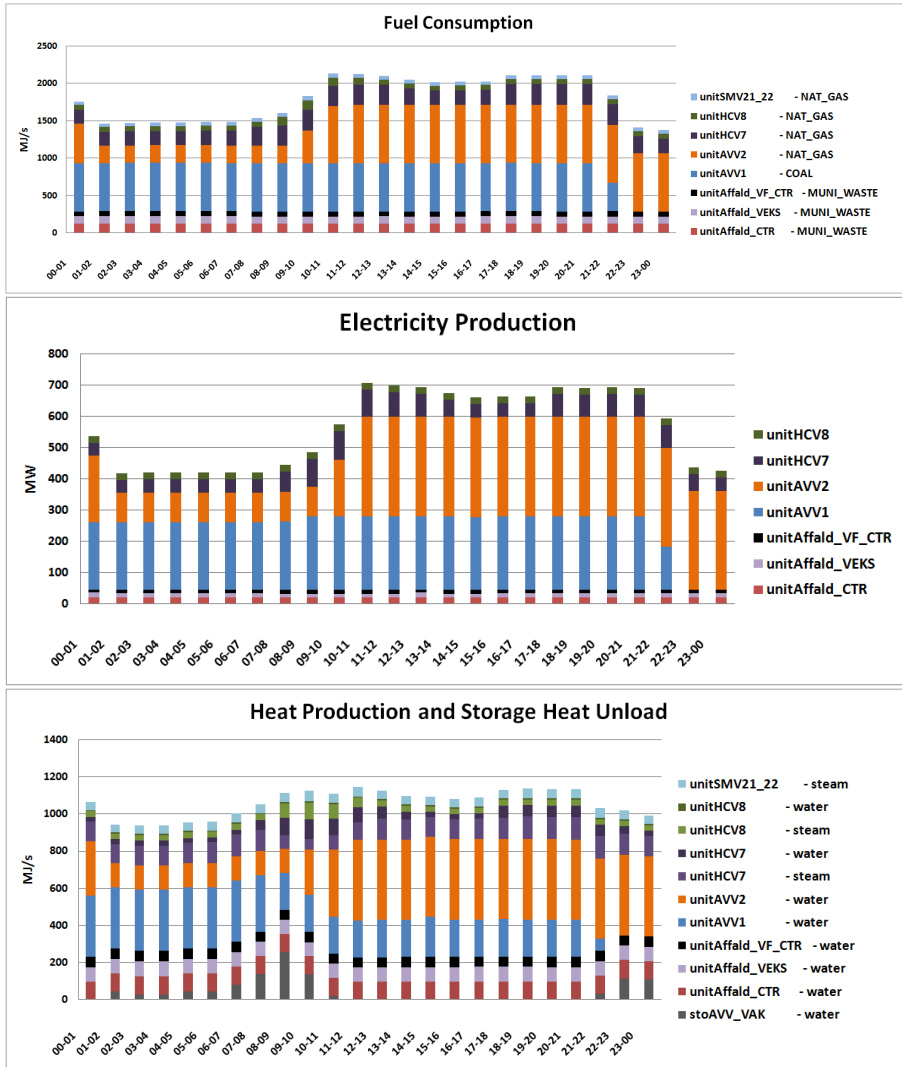


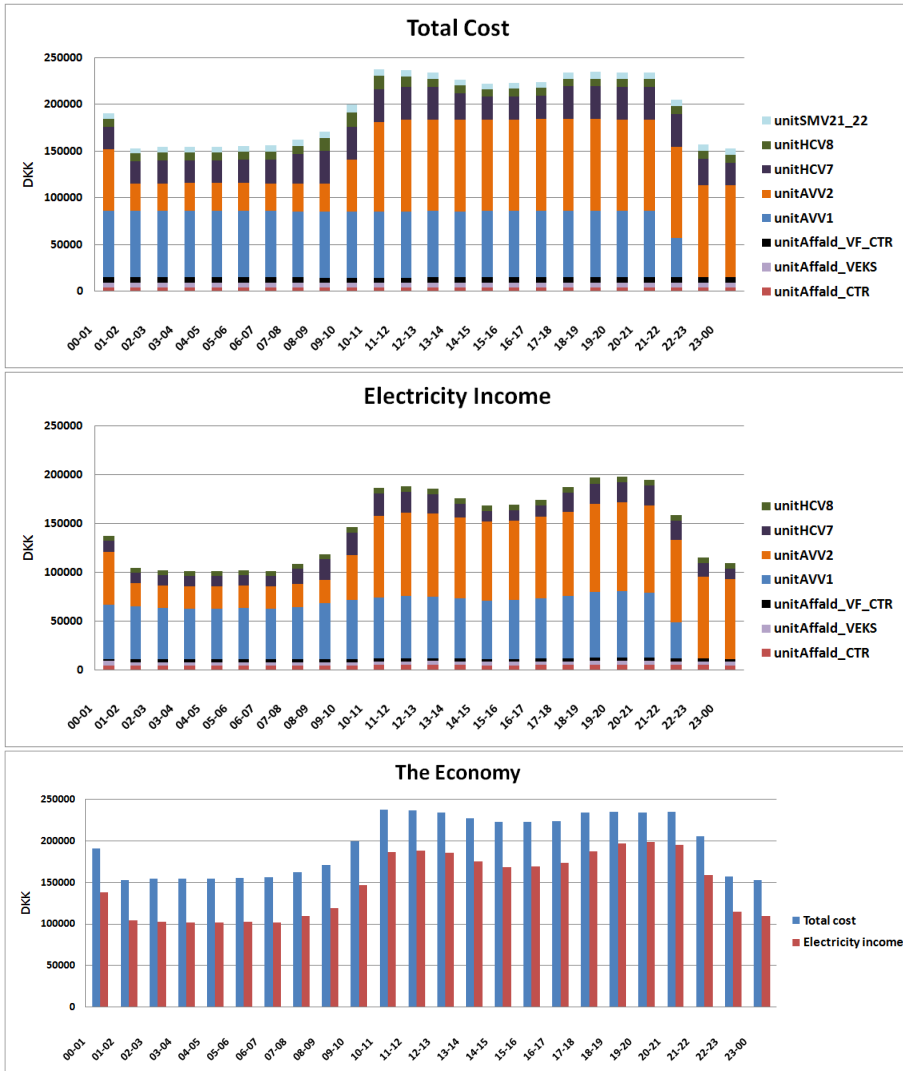
## C.2 24 Hour Plan made with DA Dataset 2

### Input Data



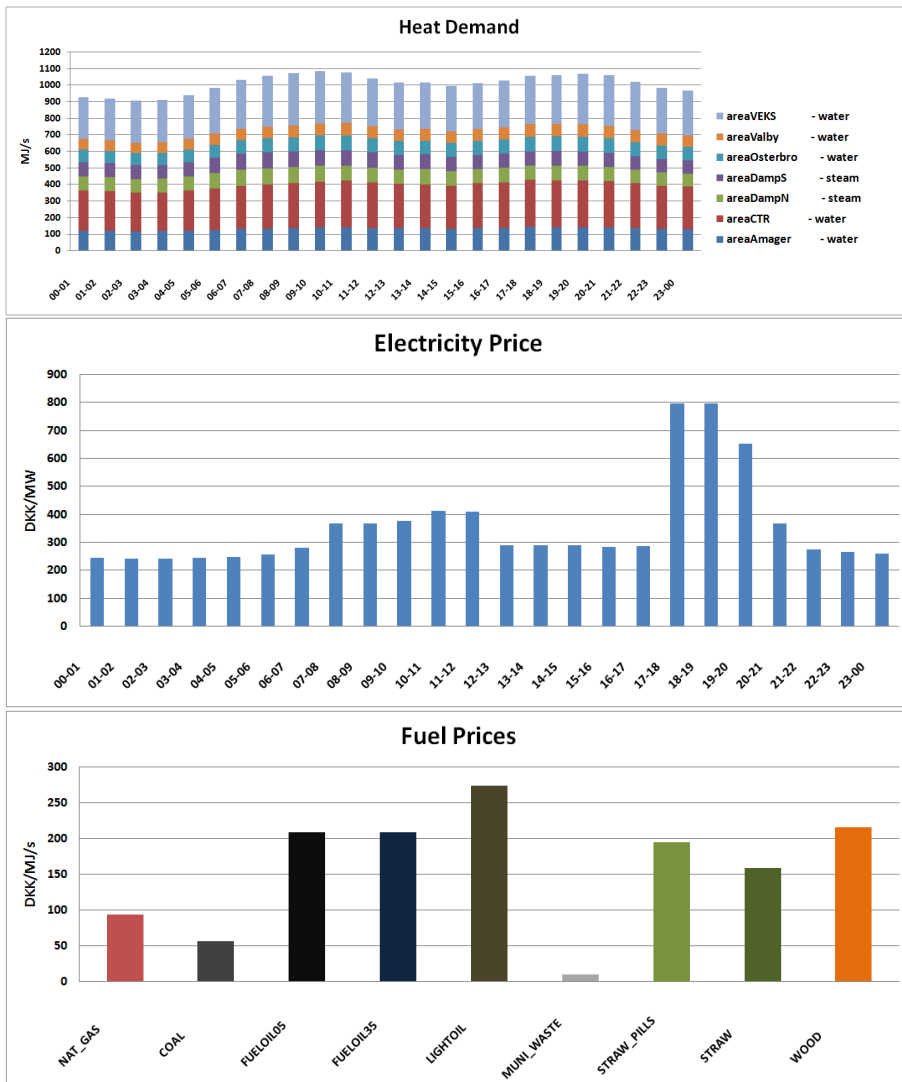
# Output Plan



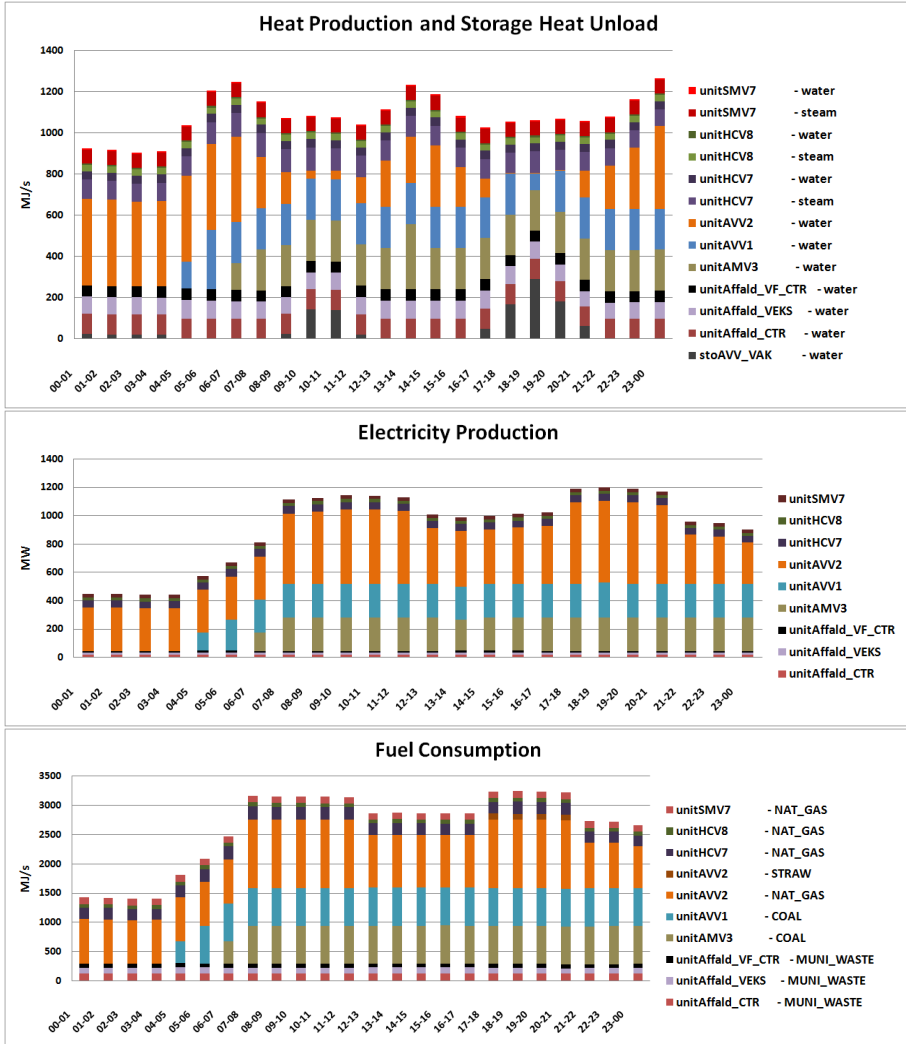


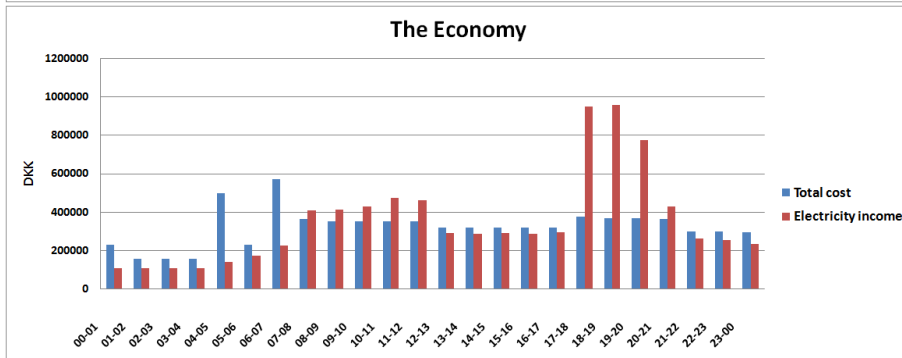
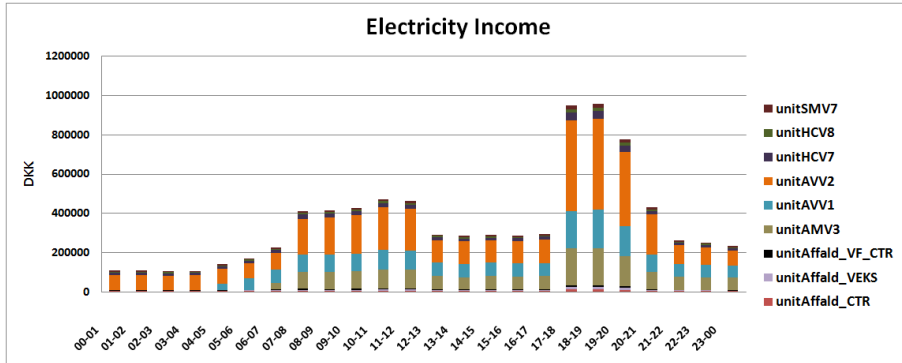
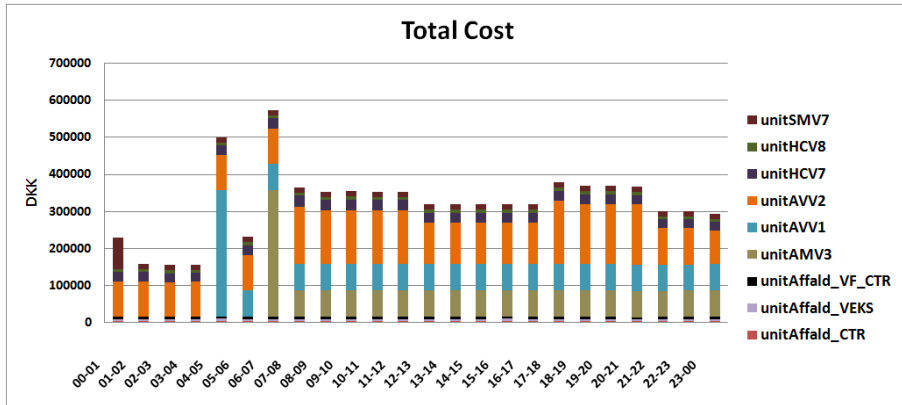
### C.3 24 Hour Plan made with DA Dataset 3

#### Input Data



## Output Plan

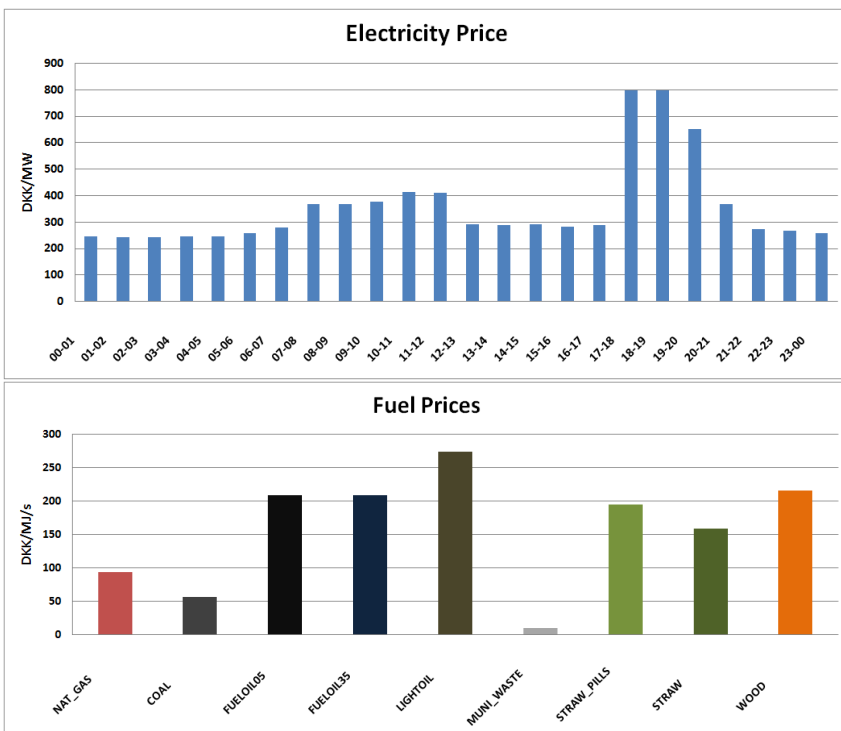




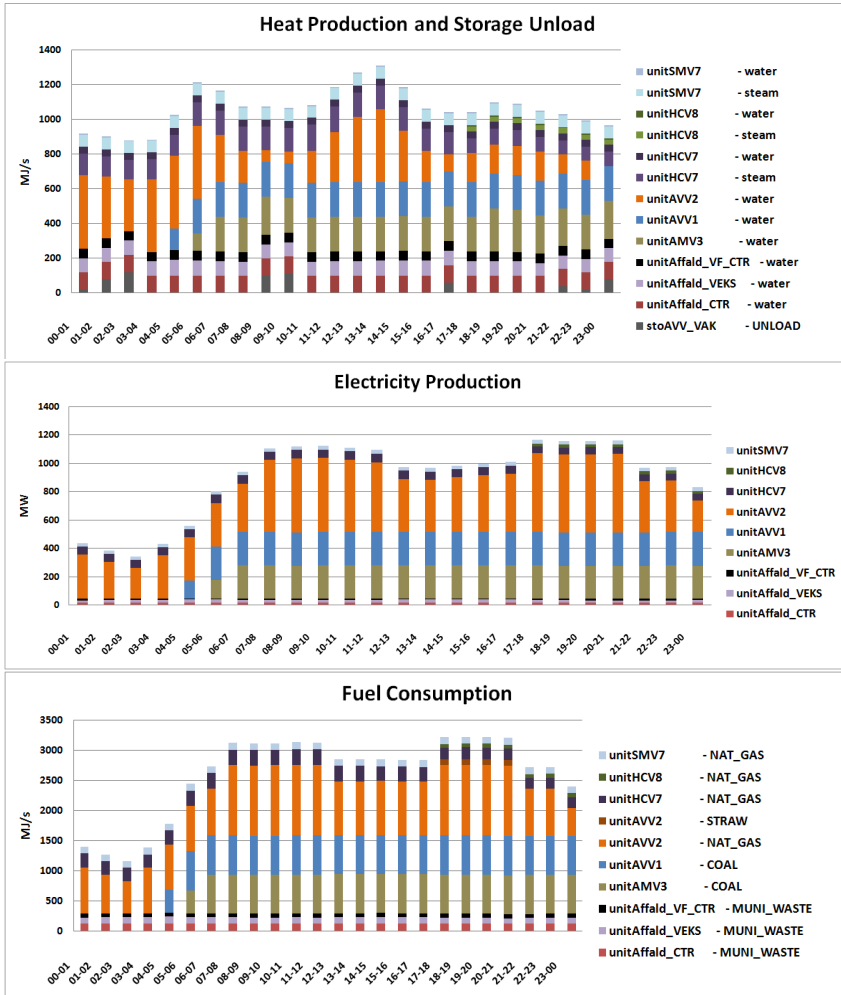
## C.4 24 Hour Plan Made With ID Moving Horizon Dataset

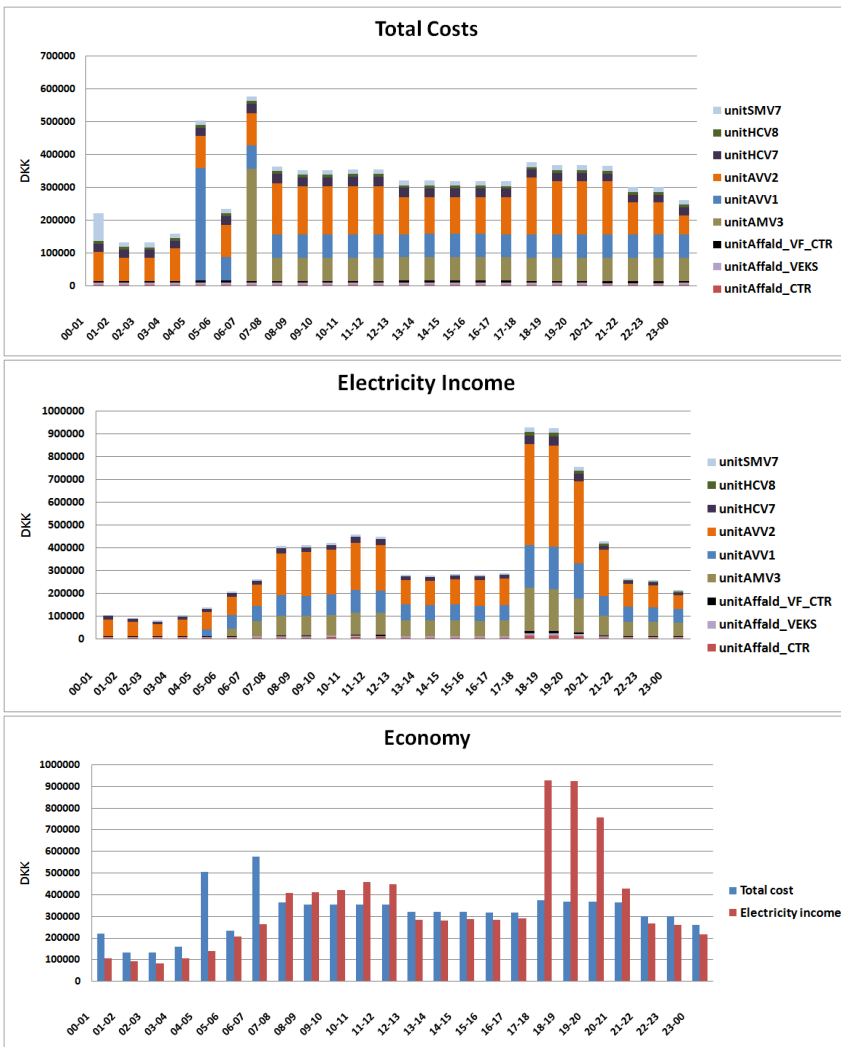
### Input Data





## Output Plan



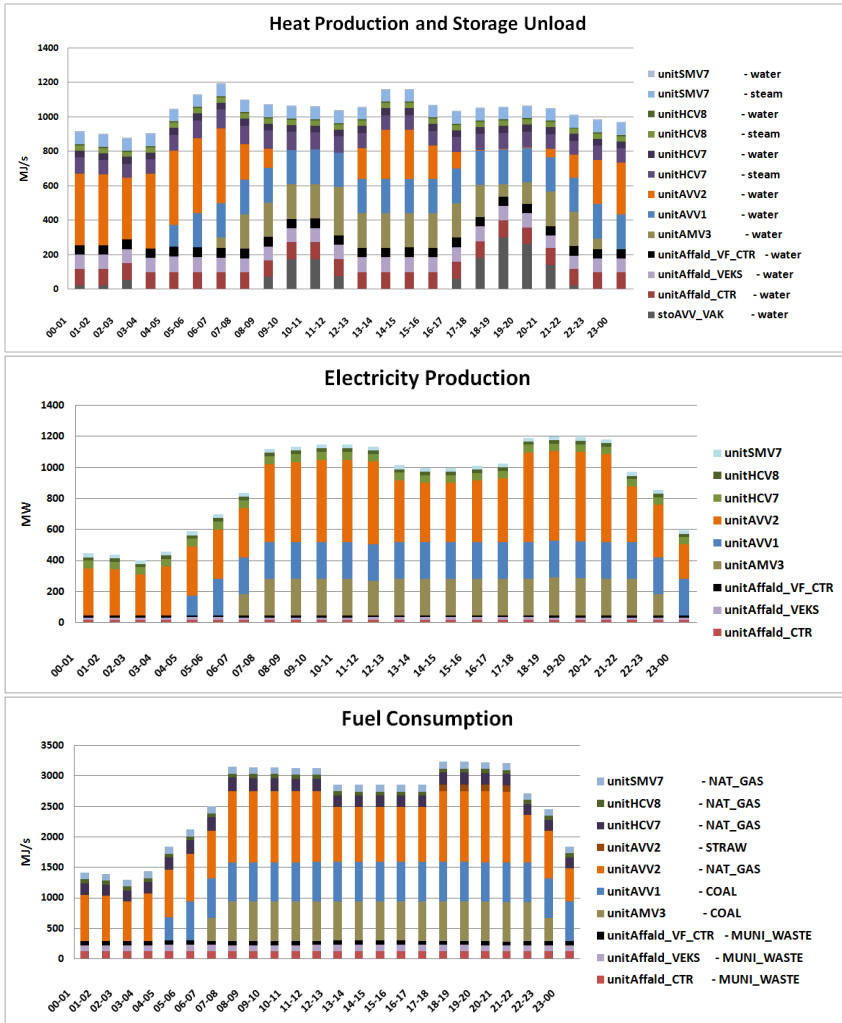


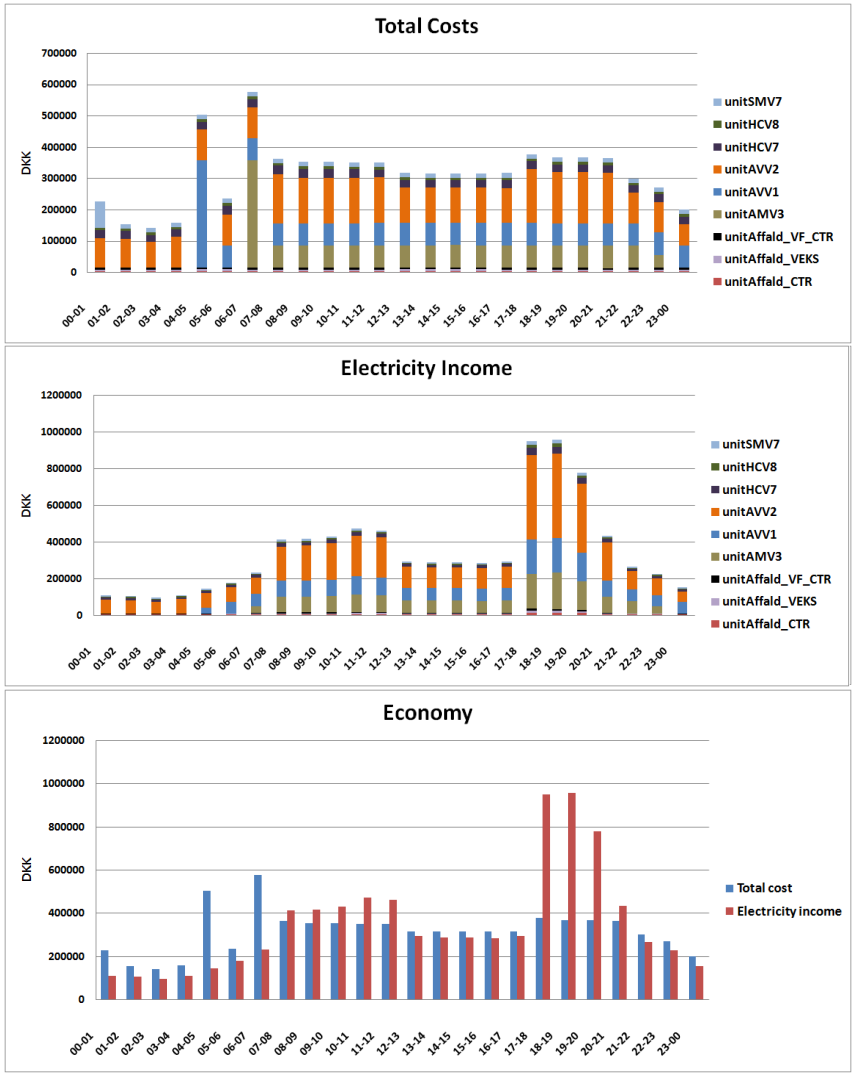
## C.5 24 Hour Plan Made With ID Initial Prognoses

### Input Data



# Output Plan



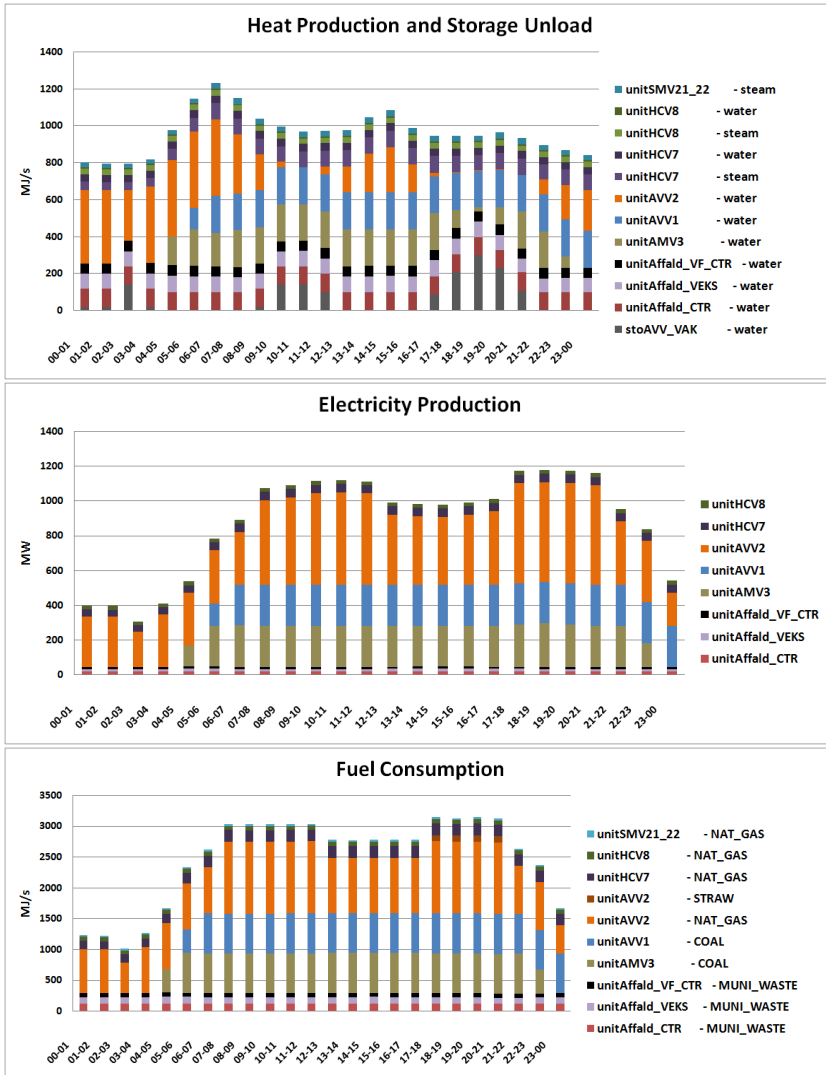


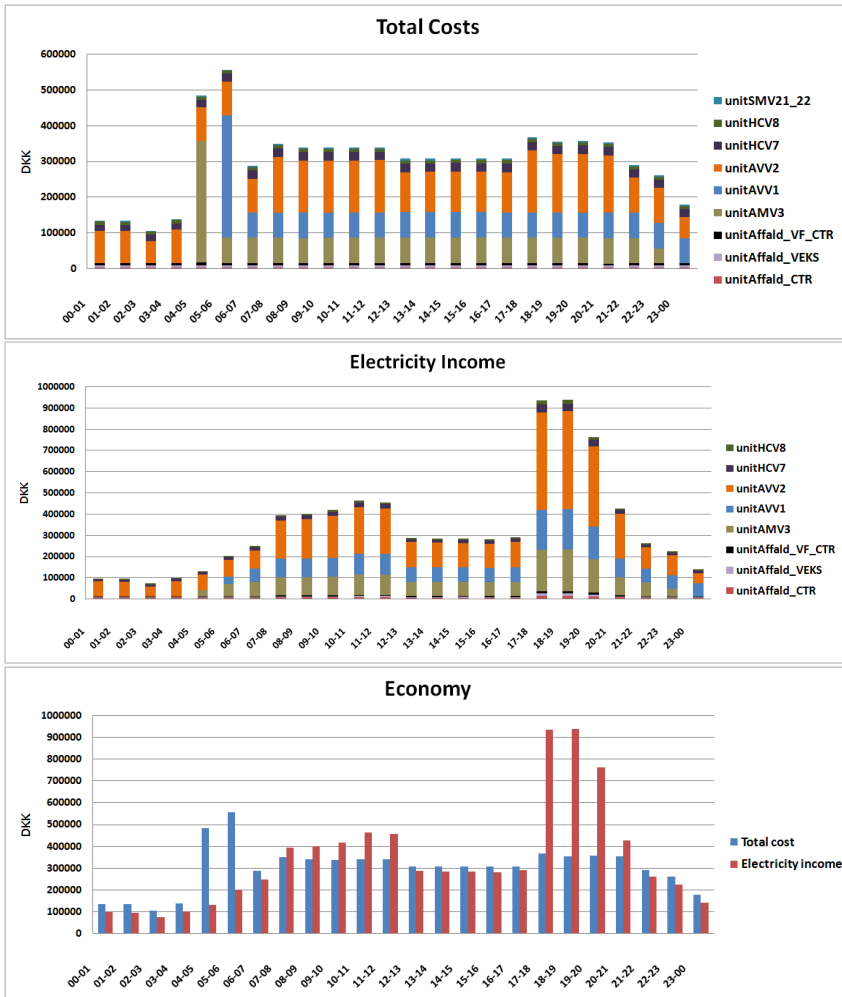
## C.6 24 Hour Plan Made With ID Realized Values

### Input Data



### Output Plan





# Bibliography

---

- [1] Balmorel Project 2001. Balmorel a model for analyses of the electricity and chp markets in the baltic sea region. <http://www.balmorel.dk>, 2001.
- [2] Roberto Aringhieri and Federico Malucelli. Optimal operations management and network planning of a district heating system with a combined heat and power plant. Paper, 2003.
- [3] EA Energianalyse A/S. Confidential data. Paper, 2009.
- [4] Danish Energy Authority. Heat supply in denmark - who what where and - why. Technical report, Danish Energy Authority, 2005.
- [5] E. Pelgrum W.L. Kling B.C. Ummels, M. Gibescu. System integration of large-scale wind power in the netherlands. Paper, 2002.
- [6] U.S Census bureau. <http://www.census.gov/>. Webpage, unknown 2009. Population statistics.
- [7] Kobenhavns Energi. Fjernvarme i kobenhavn. Brieflet, 2003.
- [8] Energinet. [Energinet.dk](http://energinet.dk).
- [9] DONG Energy. Avedore power station. Brieflet, 2008.
- [10] Dansk Fjernvarme. Dansk fjernvarmes hvidbog, 2009.
- [11] Poul Erik Grohnheit and Helge V. Larsen. Balmorel - data and calibration. <http://www.balmorel.dk>, 2001.
- [12] Hillier and Lieberman. Introduction to operations research, 2001.

- 
- [13] Varmeplan Hovedstaden. Data for teknologier til produktion af varme. Paper, 2009.
- [14] <http://www.atp.ruhr-uni-bochum.de/rt1/syscontrol/node4.html>. Ruhr university-bochum from the course on dynamics of multidisciplinary and controlled systems.
- [15] <http://www.gams.com>. Gams - general algebraic modeling system.
- [16] <http://www.veks.dk>. Fremtidens varmeproduktion. Technical report, 2007.
- [17] Marcella Santos Andreas Cruse Wolfgang Marquardt Jan Oldenburg, Jan Busch. Dynamic predictive scheduling of operational strategies for continuous processes using mixed-logic dynamic optimization, 2006.
- [18] Kenneth R. Muske and James B. Rawlings. Model predictive control with linear model, 1993.
- [19] Bo Friis Nielsen. Discrete simulation/event-by-event, 2009.
- [20] Danish Board of District Heating. <http://www.dbdh.dk/>. webpage, 2009. DH History.
- [21] Practical Financial Optimization. Stavros a. zenios, 2002.
- [22] T. Magnanti R.Ahuja and J. Orlin. Network flows. theory, algorithms and applications, 1993.
- [23] Hans F. Ravn. The balmorel model: Theoretical background. <http://www.balmorel.dk>, 2001.
- [24] Hans F. Ravn. Balmorel: Getting started v. 2.12. <http://www.balmorel.dk>, 2005.
- [25] Hans F. Ravn. The balmorel model structure v. 2.12. <http://www.balmorel.dk>, 2005.
- [26] James B. Rawlings. Tutorial overview of model predictive control, 2000.
- [27] Elkraft System. Decentral kraftvarme i danmark - baggrundsrapport - systemplan 2002. Paper, 2002.
- [28] Lazaros G. Papageorgiu Tareq A. Al-Ameri, Nilay Shah. Optimization of vendor-managed inventory systems in a rolling horizon framework, 2008.
- [29] VEKS. Veks's district heating system. Brieflet, 2003.