2 Typical Industrial Cluster

This chapter presents the steam and cooling demand of a typical refining and petrochemical cluster, so as to inform readers about the particularities of the industry. The data presented below is used in all the cases studies of this thesis.

2.1 Introduction

The aim of this thesis is to investigate energy efficiency and integration measures in the refining and petrochemical industries, with a particular focus on the steam networks. It is therefore necessary determine the contributors to steam supply and demand as well as their properties. A case study is proposed in order to establish these properties for a typical industrial site. In an effort to increase readability, all the developed methods of this thesis are applied the this case study.

The case study concerns an industrial cluster made up of a refinery and a petrochemical site, referred to as the Typical Industrial Cluster (TIC). Refineries are often coupled to petrochemical sites as many of the refining products and derivatives are further transformed in the adjoined petrochemical sites. Other synergies, for example in the utility networks are also made possible through the geographical proximity of the sites.

Given the confidential nature of the industry, the topology of the sites and the data used for the case study is presented below in an anonymised form. Process Unit (PU) names and descriptions are omitted or only briefly described and all data has been scaled by a constant factor in order to be unrecognisable while maintaining its realistic nature.

2.1.1 Choice in data

Data collection and treatment is the most time consuming part of any energy efficiency study. The aim of data collection should be to obtain enough information to close the mass and energy balances and identify representative operational modes of the equipments. Process knowledge and experience in the field are the factors which allow for efficient data collection.

Data can be acquired in the following forms, with specific considerations.

- Online measured data: This time series data corresponds to measured or calculated values that communicate the variation of a property through time. Servers typically store data as discrete data points. The data can be acquired for pre-defined time steps, either as:

    - Time averaged: An average value is taken between time t and $t + 1$.

    - Time sampled: A spot value is taken from time t.

  The resolution of time-series data should be adapted to each type of study.

- Spot measured data: Data obtained through manual sampling. One must always consider the operating conditions at time of sampling to determine accuracy and representativeness of the data.

- Design data: Data corresponding to the original design plans of a plant or process. Care must be taken as PUs often operate outside of their design conditions. Process retrofits, which may not always be clearly detailed can lead to additional variations in these values.

- Estimates: Data obtained through calculation and process knowledge. While estimates should be avoided when possible, they are often necessary given the scale of industrial sites. Engineers must make efforts to identify the sources of the estimates and justify their chosen values.

Data should be verifiable and provide the means to calculate efficiency solutions which match the operating conditions of the individual sites. For example, yearly mean values do not provide any information on the minimum, nominal and maximum values and therefore should not be used without special considerations. Using very high resolution data can often lead to complex engineering calculations. A compromise should therefore be made between the resolution of data and its relevance, the aim being to work with representative data.

The online data used for the case study presented in this thesis was taken from the 1st of January 2014 to the 31st of December 2014. The year in question was considered to be representative of typical operations given the relatively high output of the PUs during that time as well as a system failure leading to several PU D in Site R and then several other PUs going offline. These sorts of incidents may be infrequent but they are important aspects of a cluster's operations. Averaged daily data was sampled from data servers.

2.1.2 Typical Industrial Cluster narrative

The proposed TIC is made up of a Refinery (Site R), a Petrochemical site (Site P) and a Central Boilerhouse (CB) which supplies steam to both sites. A map of the TIC is shown in Figure 2.1 with Site R on the left and Site P on the right. Site R is larger than Site P given the important number of storage tanks for crude oil and its refining products. The TIC is located on a large river and has access to shipping, road and rail infrastructures.

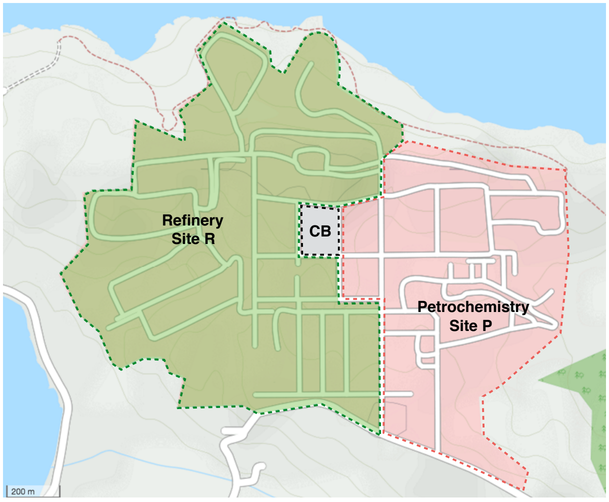


Figure 2.1 – Map of the typical cluster.

The individual sites operate independently from one another and both have boilerhouses to supply their steam demand. The Central Boilerhouse is owned by a third party, which sells steam to the Site R and P for profit.

Sites R and P were constructed at the same time by a single company. Site R refines crude oil and exports naphtha (a key feedstock of Site P), fuels for auto-mobiles, aircrafts and ships as well as bituminous products. The sites and their networks were mostly built independently of each other so as to limit the effects of cascading events. Today Site R and P have separate ownership.

The steam networks are very similar in configuration and operations, with similar architectures of boilers and utility systems. The boilers of Sites R and P were recently upgraded to burn natural gas, however the CB boilers never underwent this retrofit and therefore still burn oil.

The CB provides steam to Sites R and P when demand is high, or when some of their own boilers are offline. The boilers of the CB are old and will require important investments in the near future to remain operational. The third party owning the CB boilers has indicated that the boilers will be decommissioned without re-investment.

Given the economic conjecture, for the past few years both industrial sites have reduced their maintenance budgets have leading to the apparition of many leaks in the steam network and an increase in the number of defective steam traps [42].

When the sites were constructed, energy costs were low. Steam and electricity were often considered to be a cheap utility to which little attention was paid. Over time this mentality has changed and energy costs have now become an important aspect of operational cost reductions second only to process efficiency.

With the introduction of strict environmental controls on air quality, Sites R and P have replaced the oil burners of their boilers by gas burners to reduce the NO_x emissions and eliminate SO_x emissions altogether. Replacing oil with natural gas has led to a reduction of CO_2 emissions which the TIC must pay taxes on.

Both sites are interested in further reducing costs, leading to a number of optimisation studies to identify least cost investment and operations solutions. The management of both sites has expressed a desire to work together, for example on synergy projects to reduce operational costs [1]. Operators across both sites welcome change, at the condition that operations are not affected. Therefore, identified solutions can only be implemented if they can be shown not to impact the operability of either site.

2.1.3 Typical Industrial cluster description

The steam network architecture of the TIC is presented in Section 2.2 and the steam demand in Section 2.3. The two industrial sites making up the TIC are both made up of 6 PU complexes (named A to F) and extensive utility systems. These PUs are briefly detailed in Tables 2.5 and 2.7.

Process cooling takes place through the generation of steam, aero cooling and water cooling, described in Section 2.4. The operational constraints (load shedding plans) are also described in Section 2.5, indicating the order in which to shutdown the PUs in case of emergency.

The electric network of the TIC is not described as it can be considered to operate autonomously from the steam network and has not been the subject of detailed optimisation studies in this thesis.

Energy efficiency within PUs of the refining and petrochemical industry are not addressed either in this work, as the focus has been on utility systems and their optimisation.

2.2 Steam network architecture

Figure 2.2 shows the layout of the TIC's steam network and its interconnections. High pressure superheated steam is created in the boilers of Site R (RB1, RB2), Site P (PB1, PB2, PB3) and the Central Boilerhouse (CB1, CB2) and sent into the high pressure headers of the sites. No connections exist between the networks of Site R and P, though both are supplied by the Central Boilerhouse in high pressure steam.

1. Engaging management is often cited as an key factor in successfully carrying out energy efficiency projects [21]

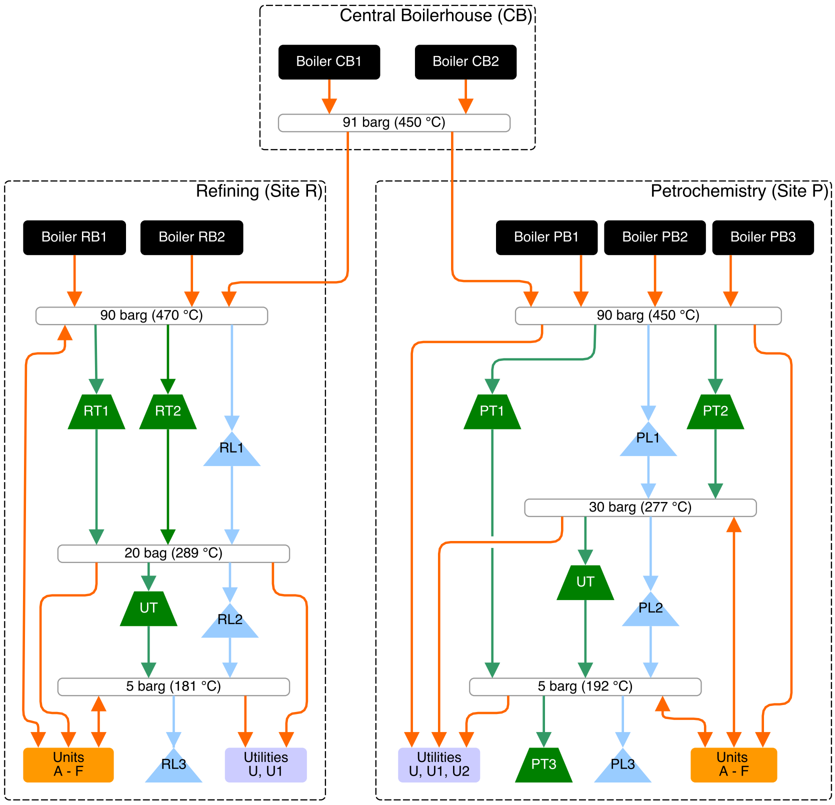


Figure 2.2 – Simplified schematic of the Typical Industrial Cluster steam network.

Both steam networks operates at three pressure levels.

- Site R: 90, 20 and 5 barg.
- Site P: 90, 30 and 5 barg.

2.2.1 Turbines

Cogeneration turbines (RT1, RT2, PT1, PT2, PT3) transport steam across pressure levels while producing electicity. In reality, the electricity produced in these turbines provides the electric safety net for the industrial sites though this is not taken into consideration in this work. Turbine PT3 is a condensing turbine, releasing excess 5 barg steam to the atmosphere. The properties of the cogeneration turbines are described in Table 2.1.

The Utility Turbines (UT) are made up of a number of turbines, which provide power for pumps to move fluids across the site, namely the site products and demineralised water. They are considered as a process requirement of the industrial sites. Throughout this work, these are also referred to as cogeneration turbines.

Table 2.1 – Turbine properties of the Typical Industrial Cluster.

	Inlet [barg]	Outlet [barg]	Min [t/h]	Max [t/h]	Isentropic efficiency η [%]	Mean power
RT1	90	20	52	90	76	
RT2	90	20	52	90	75	
UT	20	5	0	60	30	
PT1	90	5	12.6	62	62	
PT2	90	30	52	112	71	
PT3	5	0	12.5	38.5	60	
UT	30	5	0	60	30	

2.2.2 Letdowns

Isenthalpic letdowns (RL1, RL2, RL3, PL1, PL2, PL3) transport steam across the different steam headers. As the steam is superheated, these letdowns are coupled to desuperheaters. Desuperheaters inject demineralised water into the steam to simultaneously cool it down and increase steam production. Letdowns RL3 and PL3 release excess steam to the atmosphere. The properties of the letdowns are described in Table 2.2.

Table 2.2 – Letdown properties of the Typical Industrial Cluster.

	Inlet [barg]	Outlet [barg]	Min [t/h]	Max [t/h]	Desuperheating temperature [° C]
RL1	90	20	0	220	250
RL2	20	5	0	220	160
RL3	5	0	0	100	
PL1	90	30	0	400	260
PL2	30	5	0	400	165
PL3	5	0	0	100	

2.2.3 Water network and boilers

The water network can be represented schematically using Figure 2.3. The water network imports, demineralises and degases raw water (blue). The boilers and steam networks produce and transport the steam (red) across pressure levels to consumers through letdowns and turbines. PUs may also produce steam from demineralised water. Steam traps ensure that high steam quality is maintained. Condensates are either recovered (green) or discarded (grey) to a WasteWater Treatment Plant (WWTP) depending on their quality and the type of steam use.

The boilers and water networks are described below. Steam purges and losses are addressed in Section 2.6. The WWTP is not addressed in this work though they may offer potential for energy optimisation [28].

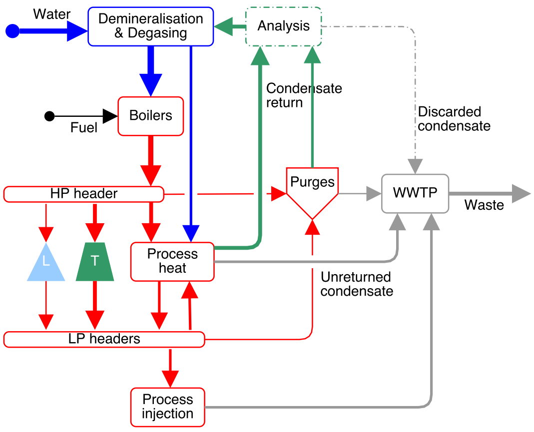


Figure 2.3 – Schematic of the water and steam network.

A schematic of the boiler configurations is presented in Figure 2.4 with average temperatures indicated. The properties of the boilers are described in Table 2.3. The price of steam production is expressed uniquely in $\$/t_{steam}$, which includes maintenance and fuel costs.

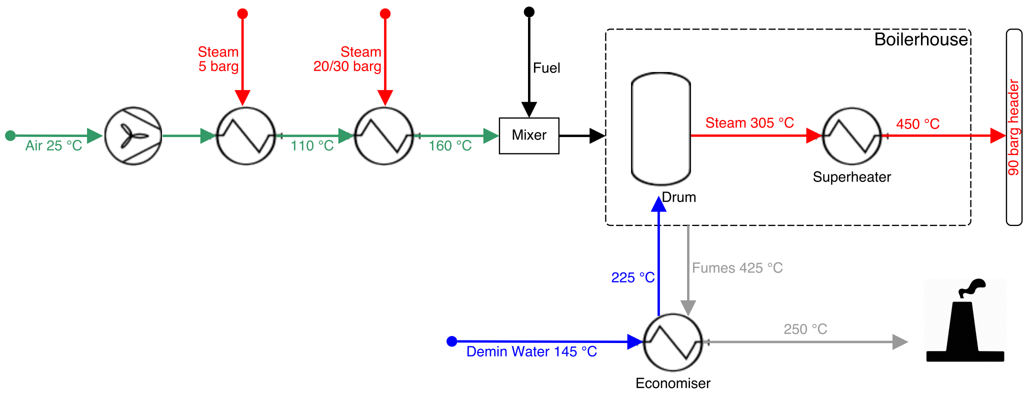


Figure 2.4 – Simplified boiler schematic.

Air (in green) is firstly preheated using 5 barg steam, bringing it to 110 °C and then with 20 barg steam in Site R and 30 barg steam in Site P, up to 160 °C . The fuel (in black) is burned and evaporates the pre-heated demineralised water in a drum and superheater producing 90 barg steam. Radiation dominates at high temperatures (1100 °C) while convection does in lower temperatures (between 1100 and 425 °C). The fumes (in grey) exiting the boiler are cooled in an economiser before being released to the atmosphere at approximately 250 °C .

Table 2.3 – Boiler properties of the Typical Industrial Cluster.

	Outlet [barg]	Temperature [° C]	Min [t/h]	Max [t/h]	Failure rate λ [-]	Steam price [\$/t]	Fuel type
RB1	90	470	30	90	1/365	18	Gas
RB2	90	450	30	90	1/365	18	Gas
PB1	90	450	50	130	1.5/365	18	Gas
PB2	90	450	50	130	1.5/365	18	Gas
PB3	90	450	50	130	1.5/365	18	Gas
CB1	91	450	30	130	2/365	25	Oil
CB2	91	450	30	130	2/365	25	Oil
Demin. water		145	0	∞		5	

Pressurised demineralised water (in blue) arrives from the demineralisation plant at 145 °C and enters the economiser, bringing its temperature to 225 °C. The water evaporates at 305 °C and the superheater brings the steam (in red) to 450 °C in Site P and 470 °C in Site R. The steam is then released into the 90 barg headers.

The failure rate λ in Table 2.3 refers to the frequency of boiler failures per year, otherwise known as the constant failure rate.

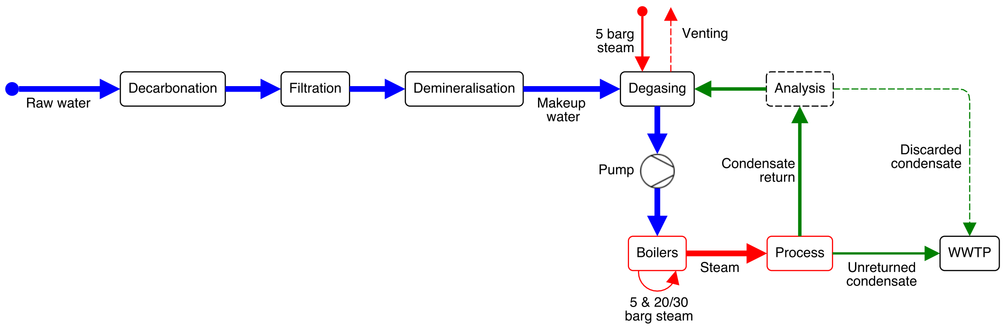


Figure 2.5 – Water network schematic.

The water treatment network is made up of the following processes, schematised in Figure 2.5.

- Decarbonation: Addition of chemicals to water to precipitate calcium.
- Filtration: Sand filtration removes organic and mineral particles from decarbonated water.
- Demineralisation: Anion and cation ion exchange to reduce the quantity of dissolved solids in the water.
- Degasing: 5 barg steam is injected into the demineralised water to strip it of its O_2 and CO_2 content, respectively reducing corrosion in the boilers and increasing the pH of the water to make it less aggressive.

Condensate returns undergo real-time analysis and are disposed of in the WWTP if pollutants are present. Clean condensates are flashed and mixed with the demineralised water before degasing. As Sites R and P cover large geographical areas, piping for condensate return is not installed on each steam trap or heat exchanger. Unreturned condensates are sent to a WWTP.

Table 2.4 – Mean measured water, steam and air flows for utilities in [t/h].

	Output	Condensate return		Makeup water	Air preheat		Degas steam
		5 barg	20/30 barg		5 barg	20/30 barg	
Site R	139.4	7.6	23.8	116.6	6.4	7.6	11.1
Site P	291.5	39.4	54.0	205.0	9.5	9.6	17.3
CB	8.7						

Further details concerning the makeup water, condensate return and air preheating can be found in Table 2.4. It should be noted that the sum of the makeup water and condensate returns do not match the boiler output as data is not reconciled. As the Central Boilerhouse is operated by a third party and owns its own demineralisation plant, only its steam output to each site is obtained.

2.3 Steam demand

The most important property to consider in a steam network is the demand at each pressure level, that is to say the difference between the consumption and auto-production of steam (as a result of process cooling). The demand corresponds to the amount of steam that must be produced by the utility network to supply PUs and utility demand with steam.

The utility and production supports networks consume steam to operate properly. The are both referred to as utility steam demand and may include: boiler preheating, demineralised water degassing, tank tracing and steam turbine activation amongst others. Their share of overall steam demand can be significant on large sites.

The demands for the individual sites are presented in sections 2.3.1 and 2.3.2. Key properties of the steam demand include the mean and maximum steam demand. These properties are important for optimisation studies to calculate expected costs and avoid under or over-sizing the demand. The overall demand of the TIC is presented in Section 2.3.3. Considering the overall demand will permit global optimisation and synergy solutions to be proposed for the TIC.

Due to the important price of metering devices, not all steam consumptions and productions are measured. For this reason, the values presented in Sections 2.3.2 to 2.3.3 correspond to a combination of measured, calculated, estimated and design data.

The steam networks' thermal losses and physical losses (leaks and condensation) contribute towards the steam demand of an industrial site, though they are not quantified here. Losses are addressed in more detail in Section 2.6. This data corresponds to raw data, containing unknown flows and measurement errors. As such mass balances cannot be expected to close.

The cogeneration turbines (RT1, RT2, PT1, PT2) are not included in this analysis as they are not a process requirement. On the other hand, the utility turbines (UT) are included as they are necessary for the proper functioning of the site.

The analysis below presents the steam demand for the PUs of Sites R and P. The internal consumption of steam for the PUs is detailed in Appendix A.

2.3.1 Site R

Site R is made up of six PU complexes, consuming and producing steam at various pressure levels. The principal function of each PU is briefly described in table 2.5 along with the types of steam usage. High pressure 90 barg steam is produced in the furnaces of PU D, while 90 barg is only consumed in PU C, used to power a turbo-compressor. Several such cogenerating devices (turbo-pumps) exist throughout Site R, consuming 20 barg steam and release it at 5 barg.

Table 2.5 – Key function of units and steam consumption type for Site R.

	Function	Production	Consumption	Cogeneration	Injection	Tracing	Losses
Unit A	Separation	x	x	x	x	x	x
Unit B	Isomerisation	x	x		x	x	x
Unit C	Hydrogenation	x	x	x	x	x	x
Unit D	Cracker	x	x	x	x	x	x
Unit E	Separation		x				x
Unit F	Purification	x	x				x
Utilities (U)	Boiler, Degaz		x			x	
Utilities (U1)	Tracing					x	
Utilities (UT)	Turbo pumps			x			

Table 2.6 shows the mean and maximum steam consumption for Site R over a representative year. Negative values indicate a net export of steam from the PU. In general this takes place as a result of the use of turbo-pumps.

PU D has the particularity of exploiting a 2 barg steam network which is not mentioned in Table 2.6 as the demand manifests itself in the form of 5 barg steam.

Figure 2.6 shows the 90 barg steam overview, with the production in graph (a) and the consumption in (b). The legend indicates the mean and maximum (mean/max) steam flowrates. 90 barg steam consumption is slightly higher than the production, with a mean consumption of 0.9 t/h and

Table 2.6 – Measured steam demand for Site R.
Mean demand: 155.1 t/h.

	90 barg [t/h]		20 barg [t/h]		5 barg [t/h]	
	Mean	Max	Mean	Max	Mean	Max
Unit A			10.9	19.8	-4.1	-10.4
Unit B			10.3	16.5		
Unit C	13.5	23.3	9.0	19.3	-12.8	-27.3
Unit D	-12.6	-20.0	7.5	18.5	8.2	18.6
Unit E			20.0	28.5	13.5	19.0
Unit F			16.0	28.0		
Utilities (U)			31.8	67.2	26.2	33.1
Utilities (U1)			6.2	22.6	11.6	26.6
Utilities (UT)			26.9	48.1	-26.9	-48.1
Atmosphere					0.1	19.9
Total	0.9	21.1	138.4	180.2	15.8	43.6
Boiler 1	70.4	90.8				
Boiler 2	79.3	90.8				
CB	5.8	53.4				

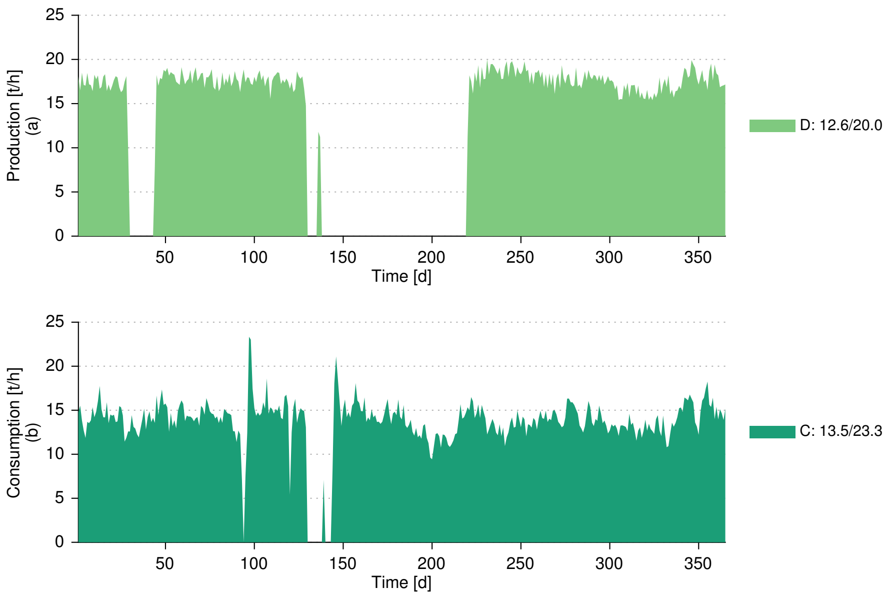


Figure 2.6 – Measured 90 barg steam consumption (a) and production (b) in Site R.

maximum of 21.1 t/h. The high value of the peak demand compared to the mean demand is caused by unsynchronised shutdown periods in PUs C and D. Following an accident on day 129, PU C goes offline for almost 100 days. On the day of the accident, several other PUs of Site R go offline as a result of cascading effects.

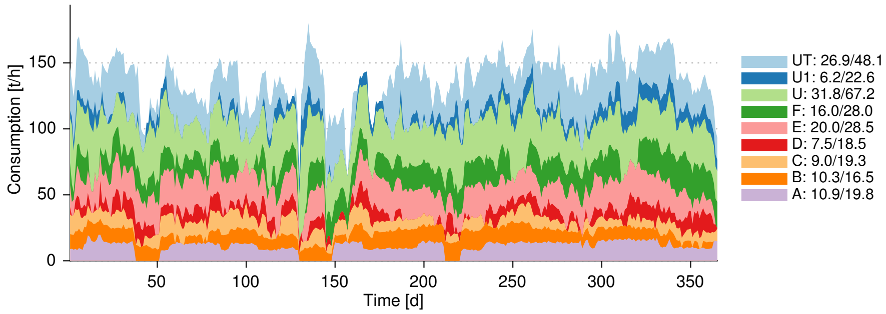


Figure 2.7 – Measured 20 barg steam consumption in Site R.

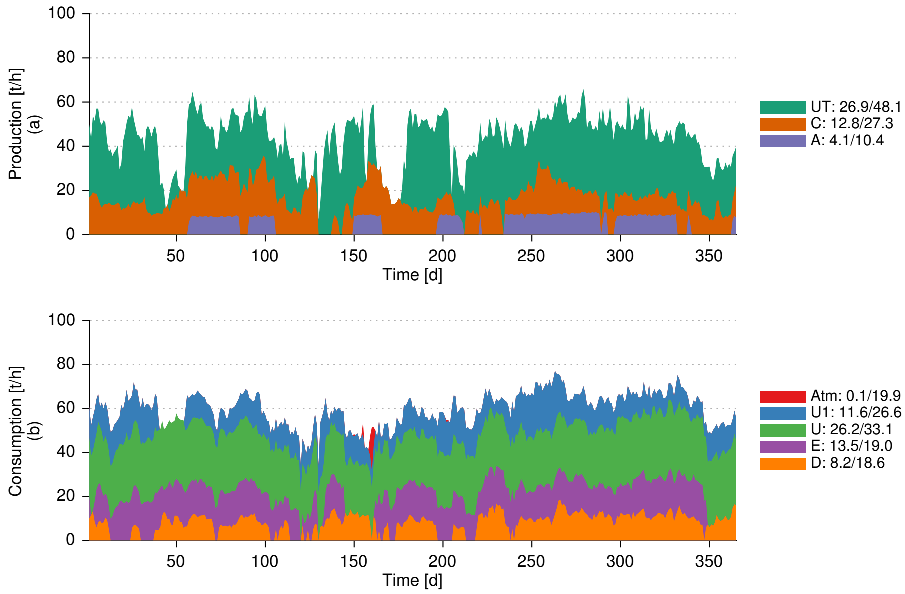


Figure 2.8 – Measured 5 barg steam consumption (a) and production (b) in Site R.

Figure 2.7 shows the consumption of 20 barg steam. No 20 barg steam is exported to the network by the PUs. The mean and maximum 20 barg demand are respectively 138.4 and 180.2 t/h. The principal consumer of 20 barg steam are the Utilities (U), reaching a peak value of 67.2 t/h.

The 5 barg steam production and consumption is shown in Figure 2.8, the mean demand is 15.8 t/h with a peak of 43.6 t/h. The production principally stems from PU C and the utility turbo-pumps (UT), letdown from 20 barg. PU A shows steps consistent with turbo-pump activation. Atmospheric venting only takes place for a short period of time, with a peak venting of 19.9 t/h.

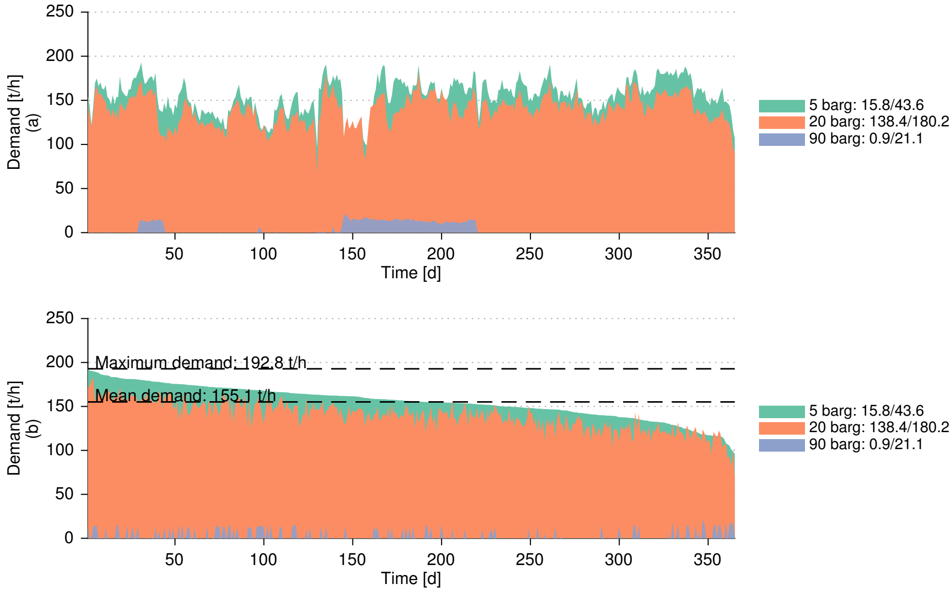


Figure 2.9 – Measured steam demand overview for Site R.

The overall steam demand for Site R is displayed in Figure 2.9 (a), with a mean demand of 155.1 t/h and maximum of 192.8 t/h. Graph (b) shows the load duration curve for Site R, in which the importance of the 20 barg consumption can be clearly seen. The curves also show that overall steam demand is not strongly related to on 90 barg steam demand.

The installed capacity of Site R is 180 t/h (2 × 90 t/h), meaning that if both boilers are online, there is always sufficient steam to supply demand. However, if one of them is offline, Site R is dependant on the Central Boilerhouse to supply almost half of its steam.

2.3.2 Site P

Six PUs are considered in Site P, briefly described in Table 2.7. Table 2.8 shows the mean steam consumption for Site P over a representative year. Negative values indicate a net export of steam from the PU. In general this takes place a a result of the use of turbo-compressors. PU B operates a 2 barg steam network, letdown from 5 barg.

The only demand for 90 barg steam takes place in PU A , shown in Figure 2.10. PU A is a cracker and also produces an equally important of 90 barg steam as a results of reactor cooling. The mean and peak demand for 90 barg steam are respectively 116.5 and 274.8 t/h which takes place when its furnaces are turned off.

Table 2.7 – Key function of units and steam consumption type for Site P.

	Function	Production	Consumption	Cogeneration	Injection	Tracing	Losses
Unit A	Cracker	x	x	x			
Unit B	Butadien		x				
Unit C	Aromatics		x				
Unit D	Polymerisation		x				
Unit E	Oxidation	x	x	x	x		
Unit F	Polymerisation		x		x		
Utilities (U)	Boiler, Degaz		x			x	
Utilities (U1)	Tracing					x	
Utilities (U2)	Tracing					x	
Utilities (UT)	Turbo pumps			x			

Table 2.8 – Measured steam demand for Site P.
Mean demand: 325.1 t/h

	90 barg [t/h]		30 barg [t/h]		5 barg [t/h]	
	Mean	Max	Mean	Max	Mean	Max
Unit A	116.5	274.8	-55.7	-134.9	-38.7	-148.9
Unit B			32.5	69.9	9.4	18.0
Unit C			62.0	93.7	12.9	21.7
Unit D			7.9	13.2		
Unit E			46.2	69.6	-29.3	-52.4
Unit F			18.1	24.8	27.5	35.3
Utilities (U)			22.3	65.3	58.6	95.7
Utilities (U1)			0.9	8.9	14.4	21.7
Utilities (U2)			3.6	14.2	13.7	22.0
Utilities (UT)			4.7	5.5	-4.7	-5.5
Atmosphere					1.5	71.8
Cond. turbine					0.8	29.0
Total	116.5	274.8	142.6	244.6	66.0	148.1
Boiler 1	122.5	129.2				
Boiler 2	124.9	130.8				
Boiler 3	52.9	124.2				
CB	12.2	98.9				

Figure 2.11 shows the 30 barg steam production (a) and consumption (b) over the chosen year. Though PU A consumes 30 barg steam internally, given the large amount of 90 barg steam used to power turbo-compressors, it has a net export of 30 barg steam. PU C is the principal consumer of 30 barg steam with a peak demand of 93.7 t/h. The mean overall demand for 30 barg steam is 142.6 t/h with a peak at 244.6 t/h.

Figure 2.12 shows the 5 barg steam production (a) and consumption (b) over the representative year. Most of the 5 barg steam production comes from PU A, also due to its intense use of turbines. PU E produces an important amount of 5 barg steam as well due to the exothermic

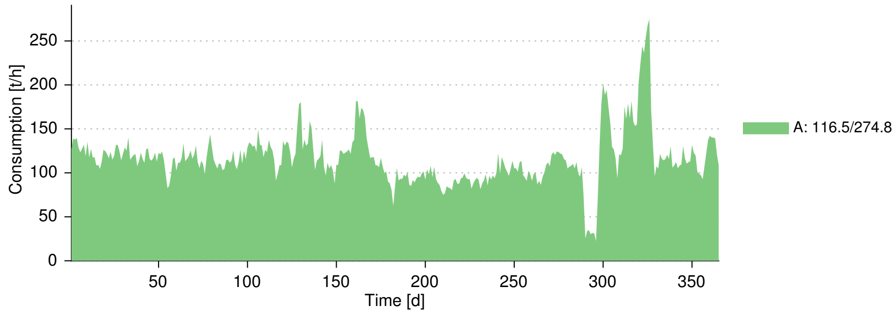


Figure 2.10 – Measured 90 barg steam consumption in Site P.

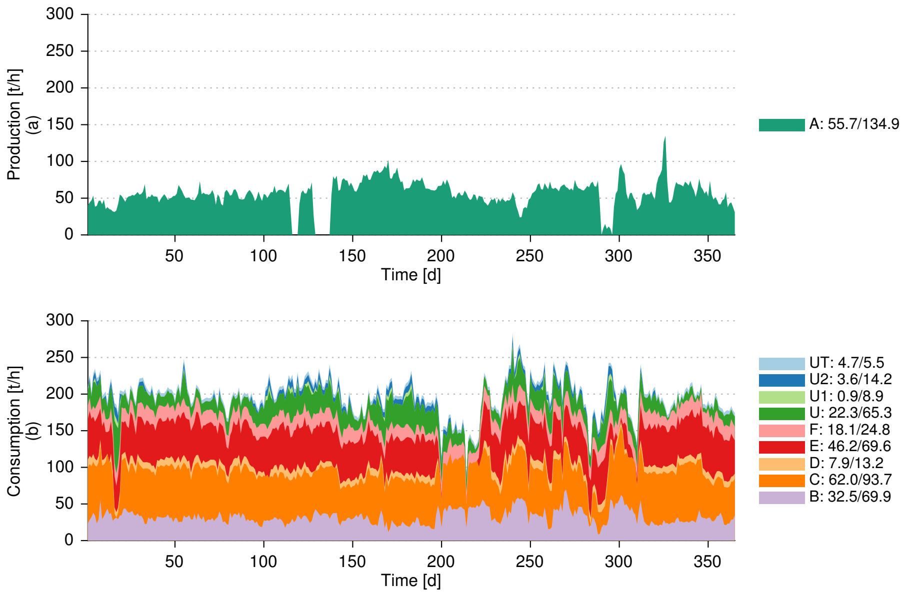


Figure 2.11 – Measured 30 barg steam consumption (a) and production (b) in Site P.

nature of the oxidation reactions. The principal consumer of 5 barg steam are the Utilities (U), reaching up to 95.7 t/h of demand. The average demand in 5 barg for Site P is 66.0 t/h with a peak value of 148.1 t/h.

The activation of the condensation turbine and atmospheric discharge can also be seen in Figure 2.12 around day 130. A high quantity of 5 barg steam is released from PU A during this period, leading to an oversupply which is dealt with by venting and condensing. A maximum of 71.8 t/h of steam is thereby released to the atmosphere.

Figure 2.13 shows an overview of the steam consumption for Site P, with the yearly trends in graph (a) and the load duration curves in graph (b). These figures highlight that the steam demand takes place at each level of the Site, with a relatively constant 90 barg and 30 barg

Figure 2.12 – Measured 5 barg steam consumption (a) and production (b) in Site P.

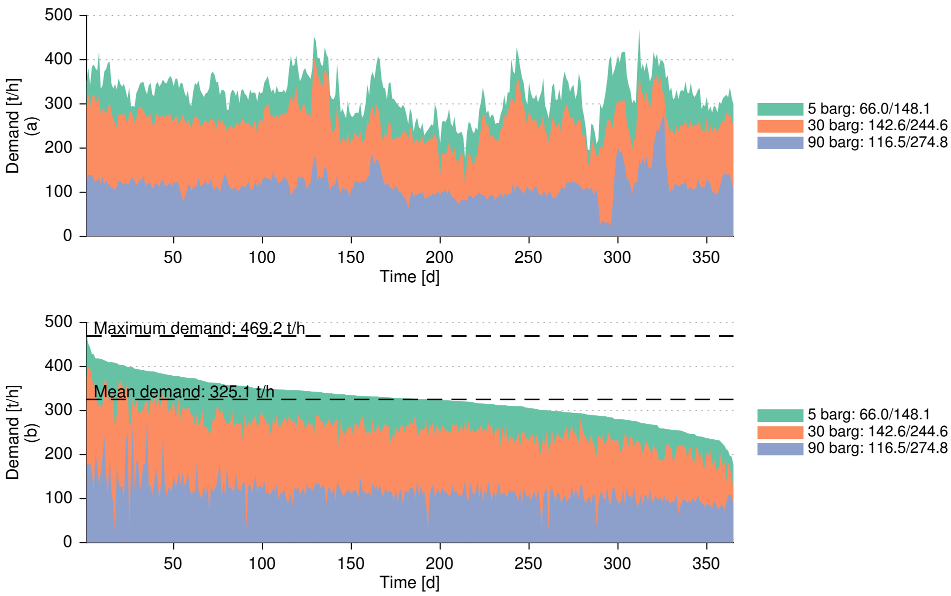


Figure 2.13 – Measured steam demand overview for Site P.

steam demand. High 90 barg steam demand generally leads to high overall demand. This trend is typical of a petrochemical site, as PU A, the cracker is the only consumer of 90 barg steam.

High cracker production (requiring higher 90 barg steam consumption) leads to higher production rates in the downstream PUs and therefore higher overall steam consumption. The mean and maximum demands for Site P are respectively 325.1 t/h and 469.2 t/h.

The design installed capacity of Site P is 390 t/h (3 × 130 t/h), meaning that at peak demand it must import 84.8 t/h of steam from the Central Boilerhouse. Similarly to Site R, an offline boiler in Site P would imply the necessity to import steam from the Central Boilerhouse.

2.3.3 Overall demand

Figure 2.14 shows the overall steam demand for the TIC in graph (a) and the load duration curves in graph (b). The mean overall demand is 480.2 t/h with a peak value of 624.9 t/h on day 312. The figures clearly show that the steam demand in Site P is much larger than that of Site R. Site R's steam demand is dominated by 20 barg steam consumption, while Site P consumes important amounts of steam at each of its pressure levels. Table 2.9 shows the key properties of the TIC's steam demand.

Table 2.9 – Measured total steam demand overview

	Installed	All levels [t/h]		90 barg [t/h]		20/30 barg [t/h]		5 barg [t/h]	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max
Site R	180	155.1	192.8	0.9	21.1	138.4	180.2	15.8	43.6
Site P	390	325.1	469.2	116.5	274.8	142.6	244.6	66.0	148.1
CB	260								
Total	830	480.2	624.9	117.4	273.1	281.0	412.4	81.9	163.4

As the industrial sites operate independently, their peak demands take place at different times. The total installed steam production capacity of the TIC is 830 t/h meaning that there are always operating reserves. The analysis of the steam demand per site has shown that the operating reserves offered by the Central Boilerhouses' steam production capacity is crucial to the proper operation of the site.

2.4 Aero and water cooling

Process cooling is required in both sites, usually for cooling after separation or to remove heat from exothermic reactions. The principal utilities used for cooling are aero and water cooling. Identification of the cooling requirements of an industrial site is an important step towards carrying out energy efficiency and integration studies such as Total Site Analysis as heat may be available for recovery.

Some causes of cooling requirements are detailed below:

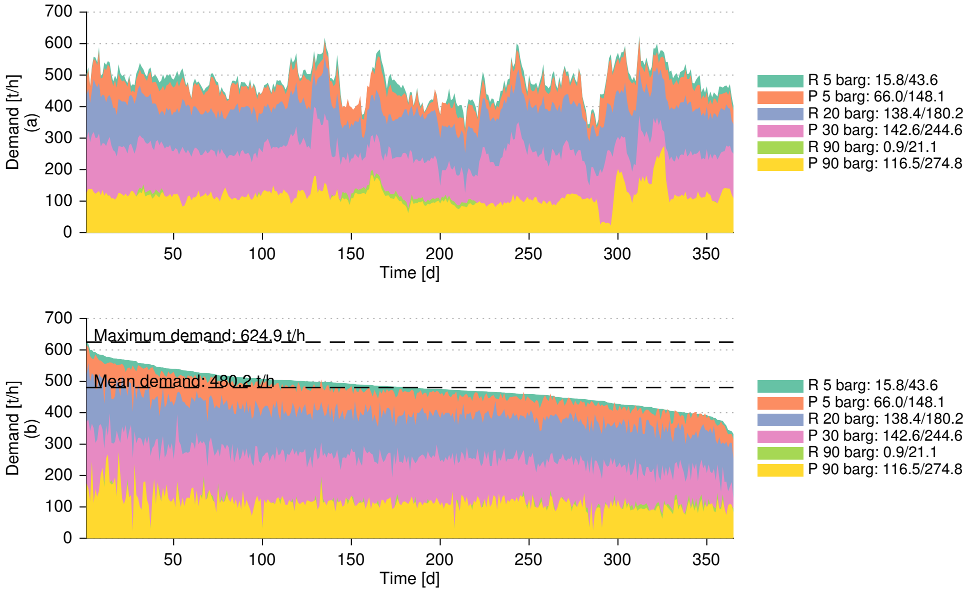


Figure 2.14 – Measured steam demand overview for the Cluster.

- Cooling after separation. Distillation columns are heated using reboilers at their base, allowing for the evaporation and therefore distillation of different fractions of products. Much of the heat contained in these fractions can be integrated (used to heat other streams) and therefore reduce the overall heating requirements, though this is not always done. Cooling after separation refers to the cooling of process streams once they leave distillation columns. These streams may require cooling before entering their next PU, or so as to be stored and transported.

- Exothermic reactions, lead to an important production of heat, especially in petrochemical sites where polymerisation and oxidation reactions take place. In the case of oxidation, steam can be generated using the excess heat, though this is rarely possible in polymersiation due to the relatively low temperature of reaction.

- Crackers often produce significant amounts of high temperature heat as a result of exothermic reactions or furnace operations. Steam may be produced from this heat, contributing towards reduced heating and cooling demand.

Table 2.10 shows the mean and maximum cooling demand for each of the TIC's PUs. The time-series of cooling demand for both sites is shown in Figure 2.15.

The cooling demand of Site R is dominated by the main separation unit (PU A) and the crackers (PUs C and D). Cooling demand falls as a consequence of PU D going offline.

Table 2.10 – Cooling demand for Sites R and P.

	Water cooling [MW]		Aero cooling [MW]	
	Mean	Max	Mean	Max
Site R				
Unit A	5.3	8.1	19.1	28.7
Unit B	5.4	7.8	7.3	10.8
Unit C	8.8	18.4	15.0	22.5
Unit D	9.0	26.2	6.2	15.8
Unit E	7.2	14.9	3.8	5.2
Unit F	12.4	18.4		
Total	48.1	77.1	51.4	75.3
Site P				
Unit A	70.7	102.4	65.2	71.3
Unit B	22.3	26.9	4.0	4.6
Unit C	3.9	5.4	19.2	24.2
Unit C	7.1	7.7		
Unit E	11.6	14.9	2.9	4.2
Unit C	21.7	24.0	27.0	29.8
Total	137.2	173.2	118.3	129.4

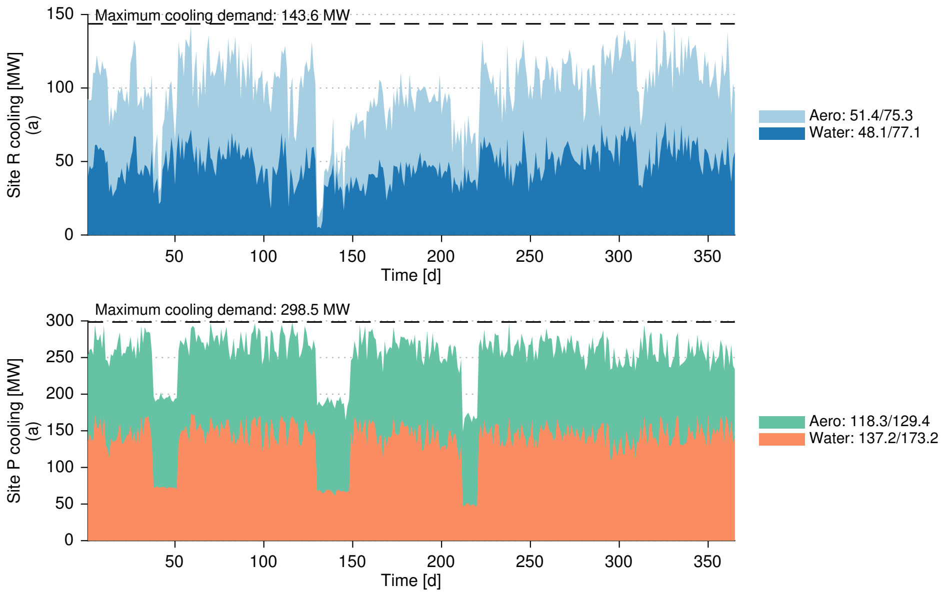


Figure 2.15 – Cooling demands of Site R (a) and Site P (b).

The cooling demand of Site P is dominated by the cracker (PU A), the oxidation plant (PU E) and the polymerisation unit (PU F). The major variations in the demand are caused by PU E shutdowns. As PUs A and F operate quite constantly throughout the year, a cooling water baseload can be seen at around 140 MW. The aero cooling demand is mostly driven by PUs A and E. The shutdown of PU E on three occasions can clearly be observed.

The difference in cooling requirements between the two sites clearly reflects the highly exothermic nature of petrochemical reactions, especially oxidation and polymerisation.

2.5 Operational constraints

As the products of a PU are often the feedstock of others, PUs become interdependent. Furthermore, certain PUs can be considered as critical for the industrial site, their shutdowns should therefore be avoided at all costs. Events leading to PU or utility shutdowns typically include shortages in feedstock, steam or electricity.

For example, the main crude separation unit provides the feedstocks for all the other refining units. As little storage is available for intermediate products, a shutdown of PU A in Site R means that most other PUs must follow suite.

For the above mentioned reasons, operators have elaborated load shedding procedures in the facing of specific events. These describe the order in which PUs can be shutdown leading to reducing utility demand. For example a shortage of electricity will not be dealt with in the same manner as a shortage of steam. Non-critical units will be shutdown first, turbines may be deactivated in favour of letdowns coupled to desuperheaters and critical units will only be shutdown when all other options are exhausted.

Unit shutdowns can be associated to a financial penalty, corresponding to the lost profits resulting from unit shutdown. This value may be complicated to calculate as costs are dependent on the market. Estimates can be made for this value, though in reality an in-depth market and financial analysis may be necessary.

Table 2.11 shows the steam load shedding order for each of the PUs and utility demands in the TIC as well as the penalty costs associated to disturbances from PU shutdown. For the turbines P corresponds to the generation of electricity by the turbine. Disturbances to the steam network may include unexpectedly high steam demand or boiler maintenances and failures. Electrical disturbances are not covered in this work.

Several units may have the same shedding order, which means that operators can choose between them or deactivate all of them. Some units are not given shedding orders or penalty costs as they are considered too critical to shutdown. Seven shedding priority levels are defined for Sites R and P though any number could be chosen.

2.6 Losses

Material and energetic losses can take place for any number of reasons on industrial sites. The cases of thermal, steam and other light losses are described below. Heavy material losses as they are exceptional in nature.

Table 2.11 – Operational constraints for Sites R and P.

	Steam shedding order	Penalty cost [$/h]
Site R		
Unit A	6	20000
Unit B	4	11200
Unit C	5	27600
Unit D	7	29000
Unit E	7	28000
Unit F	3	14400
Utilities (U)	7	28000
Utilities (U1)	2	12000
Utility Turbines (UT)	7	12000
Turbine RT1	1	112 $\times P_{RT1}$
Turbine RT2	1	112 $\times P_{RT2}$
Site P		
Unit A	7	30000
Unit B	5	20000
Unit C	5	3000
Unit D	3	5600
Unit E	6	40000
Unit F	6	30000
Utilities (U)	7	30000
Utilities (U1)	2	2400
Utilities (U2)	4	2400
Utility Turbines (UT)	7	30000
Turbine PT1	1	112 $\times P_{PT1}$
Turbine PT2	1	112 $\times P_{PT2}$

2.6.1 Thermal losses

Figure 2.16 shows several examples of thermal losses identified during an thermo-imaging survey of an industrial site. The pictures in (a–c) show thermal losses in utility pipes while (d–f) show thermal losses from PUs. Each picture is briefly described below.

(a) Thermal losses from temperatures reaching 135 °C in steam pipes indicating bad insulation. Hotspots often occur in valves where thermal losses can be very high

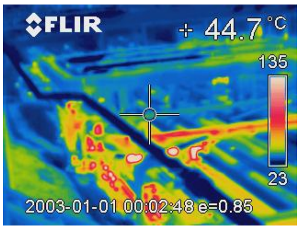
(b) Thermal losses from temperatures reaching 118 °C in steam pipes indicating bad insulation.

(c) Thermal losses from temperatures reaching on a process pipe, reaching 73 °C. Process fluids often leave PUs at relatively high temperatures, either to be cooled for storage or reheated when entering the next PU. Improved insulation reduces the heating requirements.

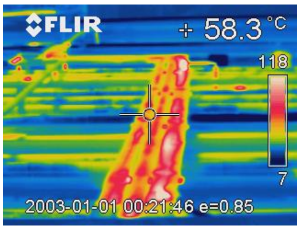
(d) Image of the body of a distillation column, reaching 118 °C, likely at a process stream drawoff. Thermal losses in a column must be compensated through reboiling in the bottom.

(e) Image of a distillation column and process stream drawoff at its head, with a peak temperature of 120 °C. Process heat could be conserved and integrated to reduce overall energy costs.

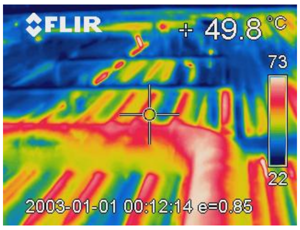
(f) Image of a furnace and its chimney. Given the low resolution of the picture it is likely that hot spots higher than 73 °C would exist. The image highlights that thermal losses take place all over a PU.



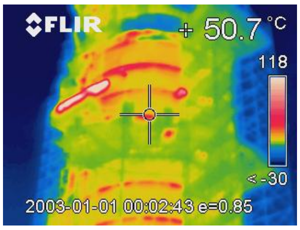
(a) Pipe rack 1



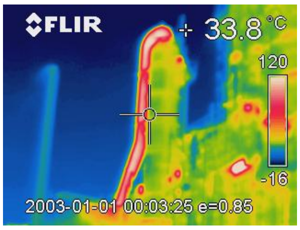
(b) Pipe rack 2



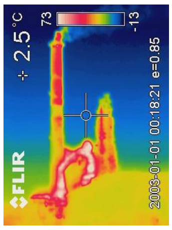
(c) Pipe rack 3



(d) Distillation column body



(e) Distillation column head



(f) Chimney & furnace

Figure 2.16 – Thermal imagery of an industrial site.

Thermal losses in steam pipes imply that the steam will inevitably start to condense, steam traps are therefore installed to recover condensed steam and limit corrosion, reduce steam hammer effects and improve the steam quality [19]. Steam traps are necessary even in the most well insulated steam network as thermal losses cannot be avoided.

2.6.2 Steam losses

Figure 2.17 shows six examples of material losses in a steam network. Image (a) shows a steam leak due to a ruptured pipe, while (b) shows steam billowing through a leaky seal. It is difficult to establish the source of the leak in Image (c) though it seems to occur near a valve. The impressive leak in Image (d) offers equally ambiguous information.

Image (e) of Figure 2.17 shows a steam trap venting to the atmosphere. The steel pipes behave like heat exchangers with the atmosphere and the steam within is cooled, a fraction of which will condensate. It is difficult to know if the steam trap is properly functioning and releasing flashed condensate to the atmosphere or if it is broken and releasing good steam to the atmosphere.

Given that steam traps can be numbered in the thousands and that pipes cannot be perfectly insulated, efforts can be made to reduce losses through proper choices in material and maintenance operations.

Tp reduce demineralised water losses, steam traps should be connected to the condensate return network. Steam released to the environment poses no human threat once it has dissipated, though the economic cost of demineralised water can be important. Table 2.13 shows the mean estimated properties condensed steam and steam leaks.

Table 2.12 – Identified leaks for Site R (a) and Site P (b).

	Condensend steam [t/h]		Steam leaks [-]		Leak flowrate [kg/h]	
	20/30 barg	5 barg	20/30 barg	5 barg	20/30 barg	5 barg
Site R	2.0	1.5	45	77	150	50
Site P	1.0	1.5	62	53	180	50

Table 2.13 – Properties of steam leaks and condensation losses.

Monthly values of the number of identified steam leaks are shown in Figure 2.18. Condensate values are considered constant throughout the year despite the varying external temperature. No 90 barg steam losses are considered in the TIC as they are usually dealt with very rapidly given their extraordinarily rare nature and very high impact.

(a) Ruptured pipe.

(b) Leaky seal.

(c) Leaky valve.

(d) Unidentified leak.

(e) Billowing steam trap.

(f) Dramatic picture.

Figure 2.17 – Steam leaks in industrial sites.

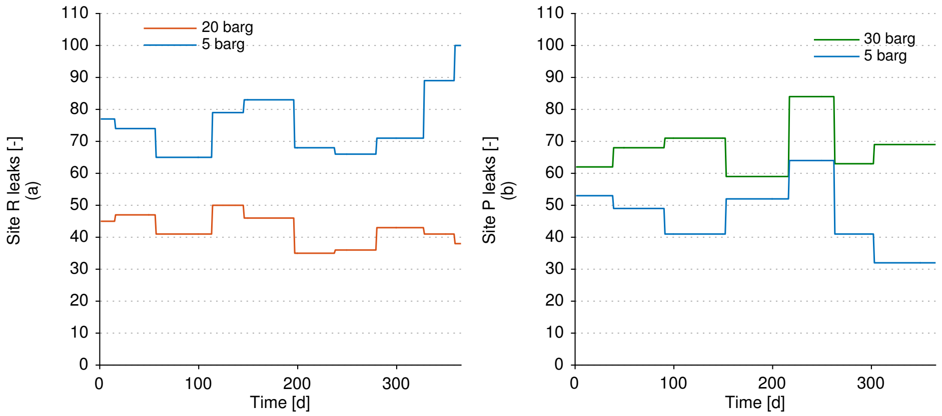


Figure 2.18 – Number of steam leaks in the Typical Industrial Cluster for year 2014.

2.6.3 Other losses

Losses on other utilities are likely to occur, typically on the compressed air and pressurised water networks. As water can cause important damage due to flooding, leaks should be plugged as fast as possible.

Other high value utilities such as natural gas, off-gas, hydrogen, nitrogen and sulphuric acid can be extremely dangerous (explosive and toxic) and are monitored through gas sensors. Leaks generally lead to partial or total site confinement while the source of the flows are stopped and time is given for the gases to disperse. These events are rare in comparison to steam leaks, with very short resolution times.

2.7 Conclusion

This chapter has described several aspects of a refining and petrochemical cluster, the TIC. Particular attention was paid to the steam network of the TIC, with details about the aero and water cooling demand as well. The data collected corresponds to the minimum required to carry out a Total Site Analysis or to optimise a steam network.

The architecture of the steam networks of the refining (Site R) and petrochemical (Site P) sites making up the TIC were detailed, as well as their PUs. More details about the internal steam networks of the PUs can be found in Appendix A.

A brief analysis of the steam production and consumption by the sites of the TIC reveals that mass balances do not close on any of the steam headers. This is due to unaccounted consumers and losses as well as inaccurate steam flow measurements, stemming from unavoidable measurement error. The steam losses of the TIC are considerable though as of yet unquantified. This point will be addressed in Chapter 3.

A first step towards optimising the energy use of an industrial site must be to close the mass and energy balances of the system, so as to ensure a proper understanding of it and measure the impact of energy efficiency solutions. This is the focus of Chapter 3.

The aim of the TIC is to improve understanding about such clusters and to have a reference for all the case studies of this work. Data was chosen so as to be representative of the possible variations in the years to come and therefore to permit the analysis of energy efficiency solutions.

The TIC must undergo important investments within the coming years to replace the ageing CB boiler. The case studies in the chapters to come will focus on preparing its data and the tools necessary to optimise its energy efficiency and establish resilient investment options.