Exergy-based methods applied to the processes of LNG regasification integrated into air separation units

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Abstract

The share of natural gas on the overall energy supply is among the other fossil fuels (coal and oil) the fastest growing. The market for the liquefied natural gas (LNG) has increased during the last years. In the import terminal, the LNG is regasified using direct or indirect heat transfer. Within these conventional regasification systems the low-temperature exergy of LNG is destroyed. Thus, different concepts with the utilization of the low-temperature exergy are of particular interest. The LNG regasification can be integrated into power plants or chemical-related systems which leads to their improvement from the thermodynamic point of view.

In this work, different concepts for the integration of the LNG regasification into air separation units are developed and analyzed using the exergy-based methods which consist of a conventional and an advanced exergetic analysis, an exergoeconomic analysis, an exergoenvironmental analysis, and an exergy-risk-hazard analysis.

As a base for the integration of the LNG regasification two different air separation units are selected. The main difference between the two systems is the product compression: external compression (Case A) and internal compression (Case B). The concepts for the integration of the LNG regasification differ regarding the complexity: simple (Case AD1) and complex (Case AD2). In addition, two concepts with consideration of safety issues (Cases AD2S and BD2S) are analyzed.

The results demonstrate that the power consumption decreases by up to 50% if the low-temperature exergy of LNG is used within an air separation unit. A maximum exergetic efficiency that can be obtained is 49 % (Case AD2S). The results obtained from economic and exergoeconomic analyses show a decrease of the total capital investment costs of up to 25 % which consequently leads to lower specific product costs up to 60% if the LNG regasification is integrated into an air separation unit. The highest decrease of the product costs is achieved for the system with the complex integration of the LNG stream (Case AD2S). The safety related systems have higher specific product costs but the consideration of the safety aspect results in a lower risk of hazards of the overall systems.

The analyzed concepts show the advantages of the integration of the LNG regasification into air separation units by using the low-temperature exergy of LNG.

Zusammenfassung

Der Anteil von Erdgas an der weltweiten Energieversorgung steigt im Vergleich zu den anderen fossilen Energieträgern (Kohle und Öl) am stärksten, was insbesondere in den letzten Jahren zu einem Anstieg des Marktes für Flüssigerdgas geführt hat. Das Flüssigerdgas (englisch Liquefied Natural Gas (LNG)) wird im Einfuhrterminal mittels direkter oder indirekter Wärmeübertragung regasifiziert. Da bei diesen konventionellen Regasifizierungssystemen die Tieftemperaturexergie des LNG nicht verwendet wird, ist die Entwicklung verschiedener Konzepte mit der Nutzung der Tieftemperaturexergie von LNG von besonderer Bedeutung. Die Regasifizierung von LNG kann in Kraftwerke oder verfahrenstechnische Systeme integriert werden, um diese aus thermodynamischer Sichtweise zu verbessern.

In der vorliegenden Arbeit werden verschiedene Konzepte zur Integration der Regasifizierung von LNG in Luftzerlegungsanlagen entwickelt und mittels der exergiebasierten Methoden analysiert. Diese beinhalten die konventionelle und erweiterte Exergieanalyse, die exergoökonomische Analyse, die exergoökologische und die Exergie-Risiko-Gefahren-Analyse.

Als Grundlage zur Integration der Regasifizierung von LNG dienen zwei unterschiedliche Luftzerlegungsanlagen, die sich hauptsächlich hinsichtlich der Verdichtung des Sauerstoffstroms unterscheiden: externe Verdichtung (Case A) und interne Verdichtung (Case B). Es werden vier Konzepte für die Integration der Regasifizierung von LNG werden analysiert, die bezüglich der Komplexität der Integration von LNG (einfach (Case AD1) und komplex (Case AD2)) und der Berücksichtigung von Sicherheitsaspekten (Cases AD2S und BD2S) variieren.

Die Ergebnisse zeigen, dass der Stromverbrauch der Luftzerlegungsanlagen durch die Integration von LNG um bis zu 50 % reduziert werden kann. Es kann ein maximaler exergtischer Wirkungsgrad von 49 % erreicht werden (Case AD2S). Die Ergebnisse zeigen eine Abnahme der Investitionskosten um bis zu 25 % bei der Integration von LNG in Luftzerlegungsanlagen, was zu einer Verringerung der spezifischen Produktkosten von bis zu 60 % führt. Die niedrigsten spezifischen Produktkosten werden durch die komplexe Integration von LNG erreicht (Case AD2S). Die Systeme unter Berücksichtigung von Sicherheitsaspekten weisen höhere spezifische Produktkosten auf, haben aber ein geringeres Gefahrenpotential.

Die analysierten Konzepte zeigen die Vorteile der Nutzung der Tieftemperatur von LNG in Luftzerlegungsanlagen.

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symbol	explanation	unit
A	heat transfer area	m^2
₿	environmental impact rate	Pt/h
b	specific environmental impact	Pt/J
С	cost	\$
Ċ	cost rate	\$/h
С	specific costs	\$/J, \$/kg
CC	carrying charges	\$/a
CEPCI	chemical engineering plant cost index	-
CRF	capital recovery factor	1/a
d	differential	-
DC	direct costs	\$
Ė	exergy rate	W
e	specific exergy	J/kg
F	fatality	inj
f	factor	-
f	exergoeconomic factor	-
FC	fuel costs	\$/a
FCI	fixed capital investment	\$
FLH	full load hours	h/a
<i>Η</i>	enthalpy rate	W
h	height	m
h	specific enthalpy	J/kg
i	interest rate	%
IC	indirect costs	\$
k	factor	-
KE	kinetic energy	W

symbol	explanation	unit
ke	specific kinetic energy	J/kg
т	factor	-
т	cost exponent	-
'n	mass flow rate	kg/s
n	factor	-
n	time	а
Р	probability	1/a
p	pressure	bar
PE	potential energy	W
pe	specific potential energy	J/kg
PEC	purchased equipment cost	\$
PFI	plant facility investment	\$
r	relative cost difference	-
Ŕ	risk rate associated with the components	inj/a
Ż	heat transfer rate	W
S	specific entropy	J/kgK
Т	temperature	°C
TCI	total capital investment	\$
TRR	total revenue requirement	\$
U	overall heat transfer coefficient	W/m ² K
U	internal energy	W
V	volume	m ³
V	product of intensity and the duration of exposure	-
	(risk-hazard analysis)	
Ŵ	power	W
w	specific power consumption	Wh/kg, Wh/Nm ³
X	risk rate	inj/a
x	specific risk	inj/J, inj/kg
x	molar composition	kmol/kmol, mol-%
Y	Probit (risk-hazard analysis)	-
Ý	environmental rate associated with the construction of a	Pt/h
	component	
y, y^*	exergy destruction ratio	%

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symbol	explanation	unit
Ż	cost rate associated with the investment cost of a component	\$/h
Greek symbo	ls:	
Δ	difference	various
ε	exergetic efficiency	%
η	efficiency	%
τ	time	S

symbol explanation

Subscripts:

0	environmental conditions (exergetic analysis)
0	basic costs (economic analysis)
А	state point at T_0 and p
AC	air compressor
ACPB	air compression and purification block
b	refers to environmental impact
BM	bare module
BS	base size
CB	column block
CO	construction
CV	control volume
D	destruction
d	design
diff	difference
eff	effective
el	electricity
ex	expolsion
F	fuel
ff	flash fire
g	general
GAN	gaseous nitrogen
GOX	gaseous oxygen
i	inlet
i	i-th chemical substance
IC	interstage cooler
int	intermediate
is	isentropic
j	<i>j</i> -th stream
jt	jet fire
k	k-th component
L	levelized (economic analysis)
L	loss (exergetic analysis)

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symbol	explanation
LN	liquid nitrogen
LNG	liquefied natural gas
LOX	liquid oxygen
М	material
m	mean
max	maximum
MHE	main heat exchanger
min	minimum
net	netto
NC	nitrogen compressor
NLB	nitrogen liquefaction block
0	outlet
OC	oxygen compressor
org	original year
Р	product
р	pressure
Q	quantity
SC	sump of the column
sys	system
Т	temperature
TC	top of the column
ref	reference year
tot	total

symbol explanation				
	symbol	explanation		

Superscripts:

1 st	first year of operation
AV	avoidable
СН	chemical
CI	capital investment
CO	construction
DI	disposal
EN	endogenous
EX	exogenous
KE	knietic
Μ	mechanical
OM	operating and maintenance
PE	potential
PH	physical
Т	thermal
UN	unavoidable

symbol explanation

Abbreviations:

AC	air compressor
ACPB	air compression and purification block
AD	adsorption block
ALARP	al low as responsible possible
ASU	air separation unit
AAV	ambient air vaporizers
BAC	booster air compressor
BOG	boil-off gas
BLEVE	boiling liquid expanding vapor explosion
CA	Case A
CAD1	Case A Design 1
CAD2	Case A Design 2
CAD2S	Case A Design 2 Safety
CB	Case B
CB	column block
CBD2S	Case B Design 2 Safety
CD/REB	condenser/reboiler
CEPCI	chemical engineering plant cost index
CNG	compressed natural gas
CRF	capital recovery factor
DC	direct costs
EXP	expander
FCI	fixed capital investment
FSRU	floating storage and regasification unit
GAN	gaseous nitrogen
GTL	gas-to-liquids
GOX	gaseous oxygen
GTS	gas-to-solid
GTW	gas-to-wire
HAZID	hazard identification
HAZOP	hazard and operability
HE	heat exchanger

symbol	explanation
HPC	high-pressure column
IC	interstage cooler
IC	indirect costs
ICO	interstage cooler oxygen
ICN	interstage cooler nitrogen
IFV	intermediate fluid vaporizer
ITM	ion transport membrane
IGCC	integrated gasification combined cycle
LCA	life cycle assessment
LPC	low-pressure column
LN	liquid nitrogen
LNG	liquefied natural gas
LNGP	LNG pump
LOX	liquid oxygen
MHE	main heat exchanger
MIX	mixer
NC	nitrogen compressor
NG	natural gas
NLB	nitrogen liquefaction block
OC	oxygen compressor
OP	oxygen pump
ORV	open-rack vaporizer
PEC	purchased equipment costs
PFI	plant facility investment
PPPB	post product-processing block
PMHPC	pseudo mix HPC
PMLPC	pseudo mix LPC
PSA	pressure swing adsorption
QRA	quantitative risk assessment
SCV	submerged combustion vaporizer
SP	splitter
STV	shell and tube vaporizer
SUB	subcooler

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symbol	explanation	
TCI	total capital investment	
TRR	total revenue requirement	
TSA	temperature swing adsorption	
TV	throttling valve	
V	vapor	
VSA	vacuum swing adsorption	
WP	water pump	

Chapter 1 Introduction

The world energy supply consists of coal, oil, natural gas, nuclear, and renewable energies while the sum of the shares of coal, oil, and natural gas accounts for 81.4 % in 2016 of the total primary energy supply [1]. The comparison of the shares of the three most important energy sources with data for the year 1973 shows an increase of the natural gas share by 35 %, an increase of the coal share by 15 %, and a decrease of the oil share by 31 % [1]. Among fossil fuels, the share of natural gas is the fastest growing with an average increase of 1.8% per year [2]. Especially emerging countries like China and India and the Middle East region are responsible for this fast growth.

The amount of traded natural gas is divided according to the kind of transportation: pipeline or liquefied natural gas (LNG). In 1990, the share of LNG was approximately 4 % of the global gas supply [2]. This value increased significantly to 10 % in 2015 [2, 3]. According to [3], the LNG supply grew rapidly with an average rate of 6.2 % per year from 2000 to 2015.

In 2016, the total trade of LNG reached an amount of approximately 260 MT which corresponds to an increase of 7.5 % compared to the year 2015 [3, 4]. The number of exporting and importing countries amounts to 18 and 35, respectively. Qatar and Australia are the countries with the highest export of LNG which correspond to a percentage of 30 % and 17 % of the world traded LNG, respectively [3]. The highest amount of LNG is imported by Japan (32 %), South Korea (13 %), and China (10 %) [3].

The comparison of transporting natural gas in liquid or gaseous state shows lower transportation costs for the LNG in case the distance between exporting and importing countries is larger than 2,000 km [5]. LNG enables a flexible gas market and a continuous supply of natural gas.

The entire LNG chain consists of the exploration of natural gas, liquefaction, transportation, storage, and regasification, as well as the final distribution to the gas grid. Nowadays, the LNG is regasified in the importing countries using mainly seawater or the combustion gases coming from the combustion of natural gas. A disadvantage of these vaporization technologies is that the low-temperature exergy of the LNG is destroyed. This can be avoided if the LNG regasification is integrated in systems where the low-temperature of the LNG can be used. This leads to an improvement of the original process from the thermodynamic point of view. Different integration

structures are discussed in literature, as for example the integration into electricity generating processes [6] or Rankine cycles [7]. The introduction into desalination plants [8] or air separation units [9] is also feasible.

The aim of this thesis is the development of efficient processes for the LNG regasification. The liquefaction of natural gas is an energy-intensive process, however conventional regasification systems do not use the available low-temperature exergy of LNG. The integration of LNG regasification into air separation units is a promising possibility in order to use the low-temperature exergy of LNG and in parallel to improve the air separation unit from the thermodynamic point of view. The industrial use of air separation plants has started already 100 years ago and is the only available technology to gain large amounts of products with high purities. In this thesis, two different air separation units are selected as a base. Then, the LNG regasification is integrated which leads to different schematics. The systems are simulated using Aspen Plus and are evaluated using the exergy-based methods.

Chapter 2 State of the art

2.1 Regasification of LNG

The entire LNG chain consists of four steps: exploration and purification, liquefaction, transportation and storage, as well as regasification and distribution, which is graphically shown in Figure 2.1.



Figure 2.1: LNG chain

The natural gas is extracted from subsurface using drilled wells and then purified. In the purification unit, components of the natural gas which will freeze while the natural gas is liquefied are removed. These components are for example water and carbon dioxide. Afterwards, the natural gas is liquefied. Detailed reviews of different systems for the liquefaction of natural gas are given for example in [10–13]. The LNG is stored temporarily and transported with an LNG ship to the importing country. Here, the LNG has a temperature of around -160 °C and a pressure slightly above the atmospheric pressure. For the transportation, specialized LNG carriers with spherical or membrane tanks are used. During transportation, loading, and unloading, a part of the LNG evaporates which is called boil-off gas (BOG). The storage of LNG in the liquefaction and regasification plants also leads to boil-off gas. The amount of boil-off gas mainly depends on the heat ingress in the LNG tanks during the transportation [14] and amounts in average to 0.05 mass-%/day [15]. In the regasification terminal, the LNG is stored and subsequently regasified.

In general, all LNG import terminals contain the same component blocks. According to [16], these are unloading arms, cryogenic pipelines, storage tanks with supporting pumps, boil-off gas compressors, recondenser and vaporizer. Before leaving the LNG regasification terminal, the LNG is compressed and an odor is added to the regasified natural gas stream. The adding of the odor is required, because natural gas is odorless and a leakage can only be detected by appropriate instruments. Typically, tetrahydrothiophene or mercaptan are used as odor [17]. Finally, the natural gas is fed to the national gas grid.

For the regasification of LNG different technologies can be used as shown in Figure 2.2. The LNG is either regasified using different kinds of heat sources or by the integration into another process. Figure 2.2a shows the classical regasification by heat transfer between the LNG and other working fluids. For this process air, seawater, or combustion gases coming from the combustion of natural gas are used as heat source. The use of waste heat from power plants or industries as a heat source for the LNG regasification is shown in Figure 2.2b. The first two technologies do not use the low-temperature exergy of LNG and are described in detail in Paragraph 2.1.1. The LNG regasification integrated into a power plant or a chemical-related plant is shown in 2.2c and 2.2d, respectively. In these two options for the LNG regasification, the low-temperature exergy of LNG is used in the integrated process which improves this process from the thermodynamic point of view. The different possibilities of the integration are discussed in detail in Paragraph 2.1.2.

The composition of LNG slightly varies among the exporting countries (Table 2.1). In average, it consists of 95 mol-% of methane and the remaining 5 % of higher hydrocarbons [19].

Table 2.1. Composition of Ereo in different countries (adopted from [5])						
country	composition in %-mol					
	methane	ethane	propane	butane	nitrogen	
Abu Dhabi	86.00	11.80	1.80	0.20	0.20	
Alaska	99.72	0.06	-	-	0.20	
Algeria	86.98	9.35	2.33	0.63	0.71	
Indonesia	90.00	5.40	1.50	1.35	0.05	

Table 2.1: Composition of LNG in different countries (adopted from [5])

The transportation of natural gas in liquid state offers several advantages. First of all, the volume of LNG is 600 times lower compared to gaseous natural gas which increases the specific energy density and enables the transportation by ship, truck, or railway. Secondly, the transportation costs are lower for the transport of LNG by a ship if the distance between exporting and importing countries is larger than 2,000 km [5], as shown in Figure 2.3.

In addition to the two before mentioned transportation opportunities, natural gas can also be transported using the technologies gas-to-liquid (GTL), gas-to-solid (GTS), gas-to-wire (GTW), and compressed natural gas (CNG) as given in Figures 2.3 and 2.4. For the transportation technology



(a) Classical LNG regasification using a heat source



(b) LNG regasification using waste heat



(c) LNG regasification integrated into power plants



(d) LNG regasification integrated into chemical-related plants

Figure 2.2: Technologies for the LNG regasification (adopted from [18])



Figure 2.3: Costs for different transportation technologies for natural gas (adopted from [5] and [20])

GTW, the energy of the natural gas is converted into electricity. Therefore, the natural gas is used as fuel for a power plant and the electricity is transported using a wire. For the transportation of natural gas using the technology GTL, the natural gas is converted into synthetic fuels (for example kerosene or gasoil) or chemical products (methanol or dimethyl ether). For GTL technology, different processes are used like Fischer-Tropsch GTL, stranded GTL, methanol GTL or Di-Methyl-Ether GTL as given in [5]. GTL as well as GTW are commercially available but further investigations are required in order to improve the operation conditions and efficiency [21, 22]. For the transportation technology CNG the natural gas has to be compressed to high pressure which ranges from 124 bar to 250 bar [21]. The marine transportation of CNG is still under development, while CNG as an alternative fuel for buses or cars is already commercially available in several countries. The first CNG tanker was built and tested in the 1960s, but due to high investment costs associated with the construction of the ship the marine transportation of CNG was not further investigated [23]. In general, CNG marine transportation is a promising technology for stranded gas and small quantities of associated gas [21] where LNG and pipelines are not economical. Several publications, demonstrate the advantages of CNG marine transportation for small to medium volumes and distances up to 4,000 km [24, 25]. During the last years new CNG ships were developed with significantly lower investment costs.

Natural gas is transformed into hydrates for the transportation by GTS. Studies conducted on a small-scale pilot plant demonstrate the technical feasibility of this technology. However, it is not yet commercially available [22].

Typical volume rates for different transportation technologies depending on the distance are given in Figure 2.5. As shown in this figure, the transportation of natural gas via pipeline is feasible for small and large ranges of gas production rates, but this technology is limited with regard to the distance to the gas consuming market. The transportation of natural gas in liquid state is used for gas production rates of $5 \cdot 10^9 \text{ m}^3/\text{a}$ to $16 \cdot 10^9 \text{m}^3/\text{a}$. In comparison, CNG is only applicable to small ranges of the volume flow. The transportation technology GTL comprises a huge range of distance as well as production rates. Nowadays, pipeline transportation accounts for 70 % and transportation as liquefied natural gas for 30 % of the overall transportation of natural gas [17].



Figure 2.4: Different technologies for the transportation of natural gas (adopted from [21, 22])

Another advantage of the transportation of natural gas in liquid state instead of gaseous state is the flexibility. The use of pipelines as transportation technology limits possible connections between exporting and importing countries. Thus, LNG enables a flexible gas market which is represented by the increasing spot and short-term LNG market. The LNG market was dominated by long-term contracts until the middle of the 1990s and the spot market amounted only 1.3 % of the global LNG trade in 1992. In 2002, this share increased to 7.6 % and will further increase to 15-30 % [26].

2.1.1 Regasification without utilization of low-temperature exergy

The vaporizers for the LNG regasification are distinguished by the heat source and the kind of heat transfer. As already mentioned, the heat sources are air, seawater, or combustion gases coming from the combustion of natural gas. The kind of heat transfer differentiates between direct and indirect heat transfer whereby an intermediate heat transfer medium is used for the indirect heat transfer. Table 2.2 gives an overview of different types of vaporizers.



Figure 2.5: Different transportation technologies for natural gas and their applicable ranges (adopted from [17])

Today, mostly open rack vaporizers with a market share of 70 % as well as submerged combustion vaporizers with a market share of 20 % are used for LNG regasification [17]. The selection of the kind of vaporizers depends on several factors like the site conditions and location, the availability of the heat source, environmental conditions, regulatory restrictions, and characteristics of operability [17, 28]. LNG can also be regasified in floating storage and regasification units (FSRU). These are special types of ships which use the same regasification technology as onshore terminals and are adjusted to marine operation. These ships are typically not used for the transportation of LNG, instead they are moored long-term. The regasified natural gas is transported to the harbor via an undersea pipeline. The advantages of the FSRU are lower capital costs which amount to 60 % of the costs of an onshore terminal [29], more flexibility, and construction in less time. FSRU are built within two years in comparison to four years for onshore units, this is related to the independence of land access, building constraints, and onshore regulations [30]. Especially for smaller markets, the FSRU are a good alternative to onshore terminals.

vaporization system	type of heat source		heat source		
		ambient air	combustion gases from natural gas	sea water	
ambient air vaporizer (AAV)	direct heat or indirect heat	Х			
open rack vaporizer (ORV)	direct heat			х	
shell and tube vaporizer (STV)	direct heat			х	
submerged combustion vaporizer (SCV)	indirect heat		Х		
intermediate fluid vaporizer (IFV) (propane or refrigerant)	indirect heat	Х		х	
intermediate fluid vaporizer (IFV) (water/glycol)	indirect heat	Х	Х	х	

Table 2.2: Vaporization systems for LNG regasification (adopted from [27])

Ambient air vaporizers

In the ambient air vaporizers, air is used as a heat source in order to regasify LNG. In these vaporizers, the LNG is inside the tubes of the heat exchangers and the air is outside whereby the air flow can be either a natural or forced.

Comparing the AAV with the ORV and SCV, the AAV is more environmental friendly, because no fuel or seawater is used. In addition, the air ambient vaporizers are cost competitive, because of low operating and maintenance costs. In contrary, these vaporizers are only used for small regasification plants and require a high number of heat exchanger units which results in a large site area [17]. Furthermore, the use of the AAV in hot and humid regions can be a problem due to the formation of fog while in cold regions the water vapor in the air will freeze on the heat exchanger tubes which would also lead to problems. Therefore, defrosting cycles are necessary [17]. In addition, external heaters are required in regions where the ambient temperature is too low in winter time. This leads to the conclusion that AAV are very well suitable in hot dry regions, where the temperature is high enough throughout the whole year.

Open rack vaporizers

In the open rack vaporizers, seawater is the thermal heat source. Before the seawater can be used, chlorine has to be added to prevent the growth of algae [27]. The cooled sea water is collected in a basin below the vaporizer and is then fed back to the sea. The LNG flows inside the tubes while the seawater flows outside. The regasified natural gas leaves the open rack vaporizer at a temperature of 5 to 15 $^{\circ}$ C [31].

Open rack vaporizers have low operating costs because only the electricity consumption for the water pump has to be considered [32]. In addition, the open rack vaporizers are simple systems

which have a good operability and high reliability [32]. A further advantage is the adjustment of the vaporizing capacity by increasing or decreasing the number of used blocks [32]. Finally, this technology has no direct CO_2 -emissions because no natural gas is burned. Indirect CO_2 -emissions are associated with the electricity consumption for the operation of the water pump. However, there are also some disadvantages related to the open rack vaporizers. The cooled and treated seawater can affect the marine eco-system, even if there are strong limitations regarding the temperature decrease of the returned water and the chlorine content. However, the difference of the water temperature between inlet and outlet is less than 5 K according to [31]. For these vaporizers large amounts of seawater are used which can also influence the marine eco-system. Due to the fact that only seawater is used as a heat source, these vaporizers are sensitive regarding climate and an effective use is only possible for a seawater temperature higher than 18 °C [27].

Shell and tube vaporizer

Shell and tube vaporizers use seawater as the thermal energy source as well. The STV can be operated as open-loop, closed-loop, or combined mode. In the open-loop, the LNG is vaporized in the tubes while the seawater is in the shell. The closed-loop configuration uses an intermediate heat transfer fluid, for example, propane or a water-glycol mixture. For the closed-loop configuration, a second heat exchanger is used which increases the site area needed for this application [17, 27]. The environmental impact associated with seawater is similar to the open rack vaporizer.

Submerged combustion vaporizers

The submerged combustion vaporizers use the heat coming from the combustion of natural gas to regasify the LNG. During the operation of the SCV, 1.5 % to 2 % of the total regasified LNG are used for the combustion itself [27] which has a strong influence on the operating costs. LNG is regasified while it flows inside the tubes which are submerged in a water bath. The water is heated by the combustion gases which are emitted through an underwater burner. The advantages associated with this heat source lead to a smaller size of the vaporizer compared with other technologies for the same LNG regasification capacity. Furthermore, submerged combustion vaporizers do not need additional units for the water intake and discharge which will affect the construction costs positively [32]. In addition, due to the fact that water has a high heat capacity the LNG can be further regasified, even if the natural gas supply for the burner is stopped. However, a disadvantage is that the water bath becomes acidic due to the combustion products and, thus, increases the operating costs due to the treatment of water [7].
Intermediate fluid vaporizer (IFV)

In intermediate fluid vaporizers, a heat transfer medium is used to regasify LNG. The heat source for the intermediate heat transfer medium is seawater. This regasification technology was developed by Osaka Gas Co., Ltd. [32]. As an intermediate heat transfer medium, for example, ethylene- or propylene-glycol or hydrocarbons (propane or butane) are used. The vaporizer consists of three different heat exchanger sections. First, the intermediate fluid gets vapor using the heat of the seawater. Then, the LNG is regasified by the heat of the intermediate fluid which leads consequently to the condensation of the intermediate fluid. The regasified LNG is heated to ambient temperature using the heat of the seawater [33].

Waste heat from industries

The use of waste heat from power plants or industries is another possibility for the LNG regasification without the utilization of low-temperature exergy [34, 35]. This technology does not improve the industrial process from thermodynamic point of view, because the LNG regasification and the power plant/industry are separate blocks with different system boundaries [18]. An advantage of this regasification technology is that no natural gas is burned which decreases the operation costs. The avoidance of seawater is advantageous from the environmental point of view. However, this technology can be only used if power plants or industries with waste heat are located next to the import terminal.

2.1.2 Regasification with utilization of low-temperature exergy

In order to recover a part of the exergy invested for the liquefaction of natural gas, the LNG regasification with utilization of low-temperature exergy is of particular interest. During the regasification of LNG 240 kWh/t_{LNG} of electrical energy can be "returned" as reported by [36]. Compared to the liquefaction of LNG which requires about 850 kWh/t_{LNG} [36–38], the recovered amount of energy corresponds to approximately one third. There are several options for the utilization of low-temperature exergy of the LNG [39]:

- power generation using LNG as heat sink
- air separation or other low-temperature fractionation
- air conditioning, cold storage, and warehousing
- district cooling

- · refineries and petrochemical plants using LNG as cooling medium
- cryogenic crushing
- boil-off gas re-liquefaction
- dry-ice manufacturing

These options can be roughly divided into two categories: (1) integration of LNG regasification into power generating plants, and (2) integration of LNG regasification into chemical-related plants. Table 2.3 gives an overview of different facilities using the low-temperature exergy of LNG and their start of operation in LNG import terminals in Japan. All three terminals are operated by Osaka Gas Co., Ltd. The LNG terminal Senboku Terminal 1 uses 100 % of the low-temperature exergy of LNG [40, 41] while the LNG terminals Senboku Terminal 2 and Himeji use approximately 50 % of the low-temperature exergy of LNG.

Table 2.4 shows the use of the low-temperature exergy of LNG in other processes by Tokyo Gas Co., Ltd. in the year 2003. A comparison of the LNG utilization rates shows that the use of LNG as a heat sink in power plants, the use of low-temperature exergy of LNG for the boil-off gas treatment, and the integration of LNG in air separation units have the highest utilization rates.

In the Putian Terminal (China), an air separation unit is installed where 10-18 % (based on the overall mass flow of LNG) of the low-temperature exergy of LNG are recovered [38]. Due to

facility using low-temperature exergy of LNG	start of operation	installation site	LNG utilization rate (based on total volume)		
Senboku Terminal 1					
air-condition	1978	in the terminal			
carbon dioxide liquefaction	1980, 2004	in the terminal			
warm water chilling	1987	in the terminal			
brain chilling	1987	in the terminal	approximately 100%		
expansion turbine	1989	in the terminal			
air liquefaction and separation	1993	in the terminal			
ethylene plant	2011	in a neighboring factory			
Senboku Terminal 2					
cryogenic power generation	1979, 1982	in the terminal			
air liquefaction and separation	1983	in the terminal	approximately 50%		
BOG re-liquefaction	1997	in the terminal			
Himeji Terminal					
power generation	1987	in the terminal			
expansion turbine	2000	in the terminal	approximately 50%		
intake air cooler	2004	in the terminal			

Table 2.3: Utilization of low-temperature exergy of LNG in Japanese import terminals (examples) (data
adopted from [40, 41])

facility using low-temperature exergy of LNG	LNG utilization rate 10^3 t
cold storage	48
production of liquefied CO ₂ and dry ice	53
cryogenic power generation	850
liquefied oxygen and nitrogen	541
production ¹³ C-methane	15
BOG treatment	760
total	2,267

 Table 2.4: Utilization of low-temperature exergy of LNG by Tokyo Gas Co., Ltd. [42]

the integration of LNG regasification, the air separation plant consumes approximately 50 % less energy [43].

Osaka Gas Co., Ltd. [41] implements a cascading process which uses the low-temperature exergy of LNG in collaboration with an oil refinery, a petrochemical plant, and the Senboku Terminal (all located close to Sakai-Senboku coastal industrial complex). There, the low-temperature exergy of LNG is used for the liquefaction of CO₂, and the cooling of butane and water. Figure 2.6 shows a simplified schematic of the complex process integration.

Utilization of low-temperature exergy in power generating plants

Since the end of the 1970s, several concepts for the integration of LNG regasification into power generating plants were studied in literature. LNG can be used as a heat sink in gas turbine cycles, Rankine cycles, or Stirling cycles. A review of power generating plants with LNG vaporization as heat sink is given in [44].

The integration of LNG regasification in a closed-cycle gas turbine system is discussed in [45]. In this publication, several different schematics are proposed which are analyzed and optimized in terms of working medium, number of intercoolers, pressure ratio, and turbine inlet temperature. In [46], a closed-cycle gas turbine system with LNG vaporization which uses nitrogen as working medium is discussed. The system generates 100 MW of electrical power and simultaneously vaporizes 100 kg/s of LNG which results in an energetic efficiency of 55 %. The feasibility of the integration of a combined cycle power plant in an existing LNG import terminal, located in the harbor of Barcelona, is discussed in [47]. The LNG is vaporized using a mixture of water-ethylene-glycol. The chilled water-ethylene-glycol is used afterwards to cool the inlet air of the gas turbine which leads to a higher power generation. In [48], a combined heat and power plant using LNG as heat sink is presented. The system consists of a gas turbine system, an organic Rankine cycle,



Figure 2.6: Cascading process of the utilization of low-temperature exergy of LNG regasification (adopted from [41])

and open-rack vaporizers. Sensitivity analyses were applied and the results show that from the thermodynamic point of view helium is the most suitable working fluid in comparison to nitrogen and carbon dioxide.

Three different processes for the integration of LNG regasification are discussed in [49]: a direct expansion process, a Rankine cycle, and a closed-cycle gas turbine system. The simplest process for the power generation is the direct expansion process. The Rankine and closed-cycle gas turbine system are analyzed with several working fluids in order to find the most appropriate one from the thermodynamic point of view. Different schematics of organic Rankine cycles using ethane, ethene or methane, or a mixture of propane and ethene are described in the patents [50, 51]. An organic Rankine cycle and a closed-cycle gas turbine system with LNG regasification are compared in [52]. The Rankine system uses butane as working fluid while the closed-cycle gas turbine system uses nitrogen as working fluid. The results demonstrate that at a fixed top temperature the closed-cycle gas turbine system is less efficient compared to the Rankine system. Also in [53], the electricity generation by using an organic Rankine cycle with LNG vaporization is discussed. As the working

fluid, a ternary mixture of refrigerants is selected. This system uses low-pressure steam from a coal power plant as heat source and LNG as heat sink. Different sensitivity analyses like the composition of the working fluid and turbine inlet and outlet pressure were applied to achieve a maximum power output.

The composition of a mixture as working fluid for an organic Rankine cycle using LNG as heat sink is also discussed in [54]. Two different system configurations are evaluated: (a) organic Rankine cycle and (b) organic Rankine cycle with additional electricity production from direct LNG expansion. A combined cycle which consists of an organic Rankine cycle and the direct expansion of LNG is also discussed in [55]. A mixture of ammonia-water is chosen as working fluid for the Rankine cycle. This systems reaches an energetic efficiency of 33.3 %. A simple gas turbine with interstage cooling and LNG vaporization is described in the patent [56]. A heat transfer medium circulates between the interstage cooler in order to cool the compressed air and a second heat exchanger, where the LNG is vaporized by the heat transfer medium. In [9], different possibilities for the use of the low-temperature exergy of LNG are discussed, for example the precooling of air of a gas turbine system. It is stated that the decrease of the inlet temperature by 1 K results in an increase of the power consumption of 0.5 %. For the air cooling, a heat transfer medium is used, as for example water ethylene-glycol.

A different process in comparison to the previously discussed processes is presented in [57]. Here, a Stirling cycle with nitrogen as working fluid and LNG regasification is analyzed from the thermodynamic point of view. In order to reach isothermal processes within the compressor and expander, the compressor is cooled using the LNG stream and the expander is heated using sea water. The incoming LNG stream is pumped to vaporization pressure, then is heated to saturation temperature using sea water and starts to vaporize by cooling the nitrogen compressor of the Stirling cycle. The total vaporization takes place in a subsequent heat exchanger again by using sea water as heat source. The main influence for the amount of electricity is the pressure of the vaporizing LNG, the mass flow rate of LNG, and the temperature of the heat source.

Real data from an LNG terminal in Marmara Ereglisi (Turkey) are used for an evaluation in [58]. This plant has been working since 1994 and the LNG is vaporized using submerged combustion and open-rack vaporizers. The possible power generation is calculated depending on different power cycles (direct expansion process and direct expansion process combined with Rankine cycle). In addition, the influence of the turbine inlet pressures, and the temperatures at the outlet of the evaporator and condenser on the overall power generation are discussed.

In [59], a system is proposed which consists of a direct expansion process of LNG and a Kalina cycle (working fluid: water-ammonia). The exergy, economic, and exergoeconomic analysis have been applied and a parametric study has been conducted (vapor generator pressure, turbine inlet pressure, evaporator and condenser temperature, heat source temperature, effect of ammonia

concentration). The results show that the heat exchanger, where the LNG is regasified, and a throttling valve have the highest exergy destruction.

The concept for cryogenic power generation containing a direct expansion cycle of LNG, a closed-cycle gas turbine system, and an open-cycle gas turbine system has been studied in detail in [6, 60–65].

Utilization of low-temperature exergy in chemical-related plants

Several different concepts for the use of low-temperature exergy in chemical-related plants as for example air separation units, ethylene plants, agro food industry, light hydrocarbon separation units, and desalination plants are reported in literature. The integration of the LNG regasification into an industrial complex with multiple users is also feasible and advantageous. The integration of the LNG regasification into air separation units is discussed in detail in Section 2.3.

In [66], the integration of LNG regasification in a freeze desalination process is discussed to decrease the overall energy consumption. In [8], the LNG regasification is integrated into a solar-powered transcritical CO₂ power cycle with the application to reverse osmosis desalination, where the low-temperature exergy of the LNG is used as a heat sink for the CO₂ Rankine process. The use of the low-temperature exergy of the LNG in the food industry is discussed in [67–69]. As reported in these papers, the low-temperature exergy of the LNG is used in the industrial area with different consumers like hypermarkets, agro-food, or frozen food industries. However, the biggest challenge is the distance between the import terminal and the consumers. Different heat transfer fluids are analyzed whereby carbon dioxide shows the best characteristics. The use of the low-temperature exergy of LNG in a refinery for the separation of light hydrocarbons in China is discussed in [70]. Due to the use of the low-temperature exergy of LNG, the compression refrigeration system is not required anymore which leads to a decrease in the power consumption. The low-temperature exergy of LNG can also be used in an ethylene production process as described in [71].

2.2 Air separation processes

The industrial use of air separation units for producing pure oxygen, nitrogen, argon, helium, and other noble gases has already started more than a 100 years ago. The general composition of dry air is given in Table 2.5 [72]. Processes to separate the air are classified as cryogenic and non-cryogenic air separation units which will be explained in detail in Sections 2.2.1 and 2.2.2, respectively.

Component	Volume fraction	
nitrogen	78.08 vol%	
oxygen	20.95 vol%	
argon	0.93 vol%	
carbon dioxide	400 vppm^1	
neon	180 vppm	
helium	5 vppm	
methane	1.8 vppm	
krypton	1.1 vppm	
hydrogen	0.5 vppm	
nitrous oxide	0.3 vppm	
carbon monoxide	0.2 vppm	
xenon	0.09 vppm	

Table 2.5: Composition of dry air (adopted from [72])

The products of air separation systems are mainly oxygen, nitrogen, and argon which leave the system in liquid and/or gaseous state. The gaseous and liquid products of air separation systems are used for different applications [73, 74] which are briefly described in the following paragraph.

The scope of pure liquid or gaseous oxygen is wide. Approximately 55 % of the produced oxygen is used for the production of steel [75]. One quarter [75] of the provided oxygen is used as an oxidizer in chemical applications, especially for the production of ethylene glycol. Other applications are water and wastewater treatment, metal processing industry (for example welding and cutting), and the air space industry [76]. Oxygen is used in power plants to increase the flame temperature and decrease the NO_x-emissions (e.g. oxy-fuel combustion). In medicine, oxygen is used in emergency cases and for long-term therapies. In the field of bio-technology it enhances the cell growth. It is also used as packaging gas in the food industry, which means that the meat is packed with an increased content of oxygen to keep its color.

The scope of nitrogen is wide as well. Nitrogen is mainly used as an inert or flushing gas in the chemical and metal industry. It is also used to control the temperature in chemical reactions. In medicine and cryotherapy, nitrogen is used as cooling medium for the storing of cells and tissue samples and for removing malignant skin lesions. For high-temperature superconductors, it is used as a cooling medium. A further application is the food industry, where nitrogen is used for the cooling and freezing of food products during transportation and for the extension of the use-by date. Nitrogen is used for the ground freezing in civil engineering.

¹vppm: volume parts per million

		· 1	,	
gas	capacity	purities	separation method	load range
	m _N ³ /h	mol-%	-	%
	1-1,000	<99.5	membrane	30-100
nitrogen	5-5,000	<99.99	pressure swing	30-100
			adsorption	
	200-400,000	any with residual	cryogenic	60-100
		concentrations	rectification	
		down to ppb ²		
		range		
	100-5,000	<95	vacuum pressure	30-100
oxygen			swing adsorption	
	1,000-150,000	any with residual	cryogenic	60-100
		concentrations	rectification	
		down to ppb range,		
		oxygen content		
		mostly > 95		
argon			cryogenic	
			rectification	

 Table 2.6: Production range of cryogenic and non-cryogenic air separation processes

 (data adopted from [77])

Argon is used for applications where nitrogen cannot be used as inert gas (e.g. for the welding of metals which react with nitrogen like titan, tantalum, and tungsten). It is used as an extinguishing agent, as packaging gas in the food industry, as filling gas for light bulbs, as carrier gas for gas chromatography, and as inert and cutting gas in laser technology.

The products of an air separation system are either transported via pipeline or with a truck whereby the gaseous products enter a pipeline system and the liquid products are either filled into gas cylinders, stored tanks, or tankers [78]. The transportation via pipeline is used for gaseous products of air separation systems which are located inside an industrial area, for example a steel mill or an integrated gasification combined cycle.

²ppb: parts per billion

2.2.1 Cryogenic air separation

The working principle of cryogenic air separation units (ASU) for the liquefaction of air is based on the Linde and Claude cycles. The fundamental principle for the liquefaction of air is that the cooling of the inlet air is provided by the air itself. The inlet air is compressed to high pressure, cooled by the returned vapor air stream and expanded in a throttling valve or expander while the air gets partially liquid. The liquid air is removed from the system and the vapor air stream is used in order to cool the compressed inlet air and is mixed afterwards with fresh inlet air. The resulting temperature drop by expanding the air stream is known as the Joule-Thomson-Effect. The Linde cycle was developed in 1895 [76] by Carl von Linde. Seven years later, in 1902, Georges Claude invented a system for the liquefaction of air using an expander [76]. In the same year, Carl von Linde and Georges Claude each established companies for the liquefaction of air which are called Linde AG (since 2006 The Linde Group) and Air Liquide S. A. Nowadays, both are leading companies for gas processing plants with a market share of 24 % in 2015 (The Linde Group) and 28 % (Air Liquide S. A.), respectively [79]. Especially the market share of The Linde Group was more than doubled from 11 % to 24 % in the years 2005 to 2015 [77]. This big increase is related to the acquisition of the British company BOC Gases by the Linde AG in 2006, in order to form The Linde Group [77].

Different configurations of the classical Linde and Claude cycle are discussed in [80, 81]. The precooled Linde cycle is enhanced by an additional heat exchanger. The cooling capacity of this heat exchanger is provided by a refrigeration machine. The pressurized air is cooled within the new and the already existing heat exchanger which results in a higher amount of liquid products. A further possibility to improve the Linde cycle is the introduction of a two-stage compression process which would decrease the specific power consumption. The Claude cycle can also be enhanced by a precooling process or a two-stage compression process. A modification regarding the numbers of heat exchangers used within this process leads to the Heylandt, Kapitza, and Collin cycles.

The first rectification process for the separation of air, invented by Carl von Linde, started operating in 1902 [82]. It was used as a single-column system where pure oxygen and nitrogen with a content of 7 mol-% O_2 were gained [78]. Eight years later, Carl von Linde also developed the first double-column air separation system. This technique enables the simultaneous production of pure nitrogen and oxygen.

Nowadays, there are many different configurations of air separation units depending on specific requirements. Modern air separation units produce up to 6.000 t/d of oxygen and 10.000 t/d of nitrogen [83]. In multi-train air separation plants, production rates of up to 30,000 t/d oxygen are possible. In comparison to that, the first ASU plant had a production rate of 0.1 t/d [84].



Figure 2.7: General schematic of an air separation unit

In general, all air separation units consist of the following blocks:

- air compression block
- · air purification block
- liquefaction of air in the main heat exchanger
- cryogenic separation of air in the column block
- product compression unit (internal or external)

Figure 2.7 shows a simplified schematic of an air separation unit used for the production of liquid and gaseous oxygen and nitrogen with external compression of the gaseous products.

Before the air enters the air compression block, it passes a mechanical filter to remove dust particles. Afterwards, the air is compressed in a multistage compressor with interstage cooling. For the liquefaction of air, a temperature of approximately -172 °C is necessary. All components which freeze at this temperature have to be removed before the air is liquefied within the main heat exchanger. The most important components are water vapor and carbon dioxide. In the first air separation plants, the impurities were removed with caustic bubbler and a drying unit with alumina [85] or within recuperative heat exchangers [86]. In the 1940's, the carbon dioxide and water removal equipment were introduced for low-pressure air separation plants in the form of

regenerators [85]. Ten years later, the regenerators were replaced by reversing heat exchangers. Especially the development of brazed aluminum plate-fin heat exchangers led to the building of lightweight and compact heat transfer equipment [85]. With the beginning of the early 1980s the reversing heat exchangers were replaced by adsorption bed technology which exists in almost all air separation plants today [86]. The improvement in the adsorbent technology and in the regeneration of the adsorbent beds results in an improvement of existing air separation units. Today, the thermal swing adsorption (TSA) or the pressure swing adsorption (PSA) are used. The advantage of these technologies is that water and carbon dioxide are removed above their freezing points and before the air enters the main heat exchanger. For the adsorption process two vessels which are filled with one or more granular adsorbents are used. While the compressed and cooled air (approximately 8 °C [87]) enters one bed, the second bed is regenerated. The regeneration is achieved by a waste nitrogen stream leaving the column block. Independence of the used technology - TSA or PSA - the waste nitrogen is either heated or pressurized to desorb the adsorbed impurities from the bed.

The air is cooled and gets partially liquid within the main heat exchanger. This heat exchanger is a multi-stream heat exchanger which is the most important component in an air separation unit. Typically, a plate and fin heat exchanger is used, because this type of heat exchanger can process several hot and cold streams. The plate and fin heat exchangers were introduced for commercial applications in the 1950s and are used for cryogenic air separation and liquefaction plants nowadays [86]. Plate and fin heat exchangers are more compact and efficient in comparison with shell and tube heat exchangers and can process a low temperature difference as required in cryogenic applications. These heat exchangers consist of corrugated fins which are stacked between the plates to form a passage for the gas flow. The cold stream flows in one passage while the hot stream flows in an adjacent passage in countercurrent direction. Due to the higher number of streams in different passages and especially the high number of channels and the interaction between them, the heat transfer description of such a system is complex. Detailed analyses of the different sections within the main heat exchanger are discussed in [88–90].

Nowadays, a double-column system is used for air separation units in the column block [78] which consists of a high-pressure column (around 5 to 6 bar) and a low-pressure column (around 1.3 bar). The condenser of the high-pressure and the reboiler of the low-pressure column are thermally coupled. The cooled and partially liquid air enters the bottom of the high-pressure column. Due to the different boiling points of nitrogen and oxygen, the top product is gaseous nitrogen and the bottom product is an oxygen-enriched liquid mixture. At the top of the high-pressure column, the gaseous nitrogen is liquefied in the condenser and enters the top of the low-pressure column as a reflux. The bottom product is also fed to the low-pressure column. Liquid oxygen as well as liquid nitrogen leave the air separation unit at the condenser/reboiler. The top product of the low-pressure

column is gaseous nitrogen and the bottom product of the low-pressure column is gaseous oxygen. Both streams are heated within the main heat exchanger while cooling down the air stream.

Until 1980, sieve trays were used in air separation plants, but then structured packing systems were introduced for the low-pressure column [78]. The advantage of this kind of packing is that the contact between the liquid and the vapor phase takes place on very large surface areas, which leads to increasing purities in the oxygen and nitrogen streams. The second advantage is the low pressure drop which is only one-fifth to one-tenth of a column with sieve trays [86] which consequently leads to a decrease of the energy consumption of around 8 % [83, 91]. In order to produce argon, additional columns are required which will be installed subsequently to the high- and low-pressure column.

The air separation process can be extended by expanders, compressors, and heat exchangers in order to obtain specified product requirements. The use of a nitrogen liquefaction block as given in [92] is also possible.

Beside the amount and quality of products, air separation units are roughly distinguished regarding (a) the feed air pressure and (b) the kind of product compression.

Feed air pressure

Air separation systems are classified into low- and elevated-pressure units [93, 94]. In low-pressure systems, the air pressure varies between 4 and 7 bar. In contrast, in the elevated-pressure air separation units the air pressure varies between 10 and 14 bar and the product and by-product streams are required at pressures above the atmospheric pressure [94]. The elevated-pressure plants are mainly operated in combination with another process, for example an integrated gasification combined cycle (IGCC) [93], and are not further discussed in this thesis. Older air separation plants were even operated at higher pressure of up to 182 bar [95].

Product compression

The pressure of the oxygen stream can be increased using an internal or external compression process, which is also called "Pumped LOX cycle" or "GOX cycle", respectively [96]. According to [97, 98], the majority of air separation units built in the beginning of the 21th century produces oxygen with the internal compression process.

In air separation units with external compression, the gaseous oxygen is heated in the main heat exchanger and afterwards compressed to the consumer's pressure.

In the processes with internal compression, the liquid oxygen leaving the column is pumped to an intermediate or final pressure. Afterwards, it is heated in the main heat exchanger and gets gaseous. In order to heat the high-pressure oxygen, a high-pressure stream of air or nitrogen is needed within the main heat exchanger to recover the cold from liquid oxygen [78, 93, 97, 99].

The internal compression process has advantages from a safety point of view. First of all, there are safety-related problems in connection with oxygen compressors which lead to higher costs, less efficiency, and less reliability in comparison with air or nitrogen compressors [93, 97]. Secondly, hydrocarbons accumulate in the sump of the column and can cause an explosion. For this reason, in air separation plants with external compression process, where only gaseous products are produced, a small amount of liquid oxygen needs to be withdrawn from the sump in order to decrease the potential for hazards [96]. In an ASU with internal compression, the liquid oxygen is continuously withdrawn from the sump and, thus, decreases the potential for hazards. The internal compression process can also be applied for the production of gaseous nitrogen. Then, the pressure of the liquid nitrogen is increased with a pump before the nitrogen stream is heated and vaporized in the main heat exchanger [97].

Different configurations of air separation units have been studied extensively in literature.

In [93], six different configurations of air separation units are analyzed and compared as part of an integrated gasification combined cycle. The main focus of this paper are the pressure levels of the column block and the different systems for the compression of the product streams. The results show that the system with the compression of the liquid oxygen stream is a good alternative in comparison to the compression of the gaseous oxygen, especially from a safety point of view. The five remaining systems with elevated pressure of the column block are not further discussed here, because they are especially designed for the use in an integrated gasification combined cycle. A rigorous, non-linear model of a three-column air separation unit under uncertainties is analyzed in [100]. In [101], a cryogenic air separation with a self-heat recuperation unit is discussed. The use of the latent and sensible heat in the column block decreases the power consumption by 36 % compared to a conventional air separation unit.

Different configurations of air separation units are evaluated in [102]. The differences between these plants are (a) the kind of product compression (internal or external) and (b) the amount of produced gaseous oxygen. The results show that for all three cases the specific power consumption is higher than the theoretical benchmark value of 0.28 kW/Nm^3 which was determined in a forecast [83, 103]. In [102], a variation of the specific power consumption from 0.464 kW/Nm^3 to 0.639 kW/Nm^3 is reported. A specific power consumption of $0.196 \text{ kWh/kg}_{O_2}$ was achieved in [104] by applying equation-oriented optimization tools. The detailed analysis of large-scale air separation units in China is reported in [98] where a specific power consumption of 0.38 kWh/Nm^3 is given.

In addition to an energy analysis, exergetic analyses have been applied for several air separation units which will be discussed in the following paragraph. An exergetic analysis was applied to an air separation unit with a nitrogen liquefaction block which is reported in [92]. The nitrogen liquefaction block is the subsystem with the highest exergy destruction, it has an exergy destruction ratio of 51 %. However, the results for the exergetic efficiency are not comparable, because an unacceptable definition of the exergetic efficiency has been used. The definition of the exergetic efficiency reported in [92] is based on the input and output streams while the exergetic efficiency has to be calculated using the exergy of fuel and exergy of product. Two cryogenic air separation units are analyzed from the exergetic point of view in [105]. In this paper, a two- and a three-column system as part of an integrated gasification combined cycle are evaluated and compared. Both systems produce one gaseous oxygen stream and three gaseous nitrogen streams at three different pressure levels (88 bar, 25 bar, and 1.3 bar). However, the paper [105] uses again an unacceptable definition of the exergetic efficiency, therefore, only the exergy destruction ratio can be compared. In the analyzed systems, the pre-processing feed subsystem (air compressors, interstage cooler, and purification system) has the highest exergy destruction ratio which amounts to 47 % and 54 % for the two- and three-column system, respectively.

An energetic, exergetic, and economic analysis for an air separation unit were conducted in [106]. Furthermore, the pinch analysis is applied to the main heat exchanger which results in a minimum temperature difference of 1.7 K. The studied process contains an internal compression unit and produces gaseous nitrogen and oxygen. The exergetic analysis shows that the compression and distillation blocks have the highest exergy destruction.

Different types of distillation columns are analyzed in [107]. The three types are: a simple adiabatic column, a thermally coupled double-column and a diabatic column. The results demonstrate that the diabatic column has 23 % less exergy destruction in comparison with the thermally coupled adiabatic column. The reason for this difference is the replacement of the condenser/reboiler in the adiabatic column system by the overall heat transfer in the diabatic column.

In [108], an exergetic analysis is applied to an air separation unit as part of a gasification-based bio-hydrogen generation system. In the reported system, only 8.8 % of the input exergy is converted to the product of the system while the remaining exergy is lost (43.6 %) or destroyed (47.6 %). This is due to the fact that the analyzed air separation unit is part of a gasification process which only requires the oxygen stream (purity 95 mol-% O_2) and consequently results in a low amount of the exergy of the product. This leads to a huge amount of exergy loss, because the generated nitrogen stream is not further used. In [109], an air separation unit with a double-column distillation which produces the required gaseous oxygen for an oxy-combustion process is analyzed from the exergetic point of view. The purity of the oxygen and nitrogen streams amounts to 95 mol-% and 99 mol-%, respectively. In this paper, the air compression system causes 38.4 % and the distillation system causes 28.2 % of the total exergy destruction. A single-column air separation unit is analyzed in [110]. Four different configurations of a single-column air separation unit are discussed and

compared with a conventional two-column air separation unit. The systems produce gaseous nitrogen, gaseous oxygen, and liquid oxygen. The single-column air separation unit requires 23 % less electrical energy while generating products with industrial purity. The power saving is reached, because the air separation units work near atmospheric pressure. In addition, an exergetic analysis is applied. The exergetic efficiency varies between 28.9 % and 32.8 % for the single-column air separation units and amounts to 26.7 % for the double-column distillation process. In [111], a double-column as well as a single-column air separation unit are also analyzed from the exergetic point of view. In order to decrease the exergy destruction in the MHE, the pressure of the air stream has to be decreased. However, the higher pressure of the air is responsible for the heat transfer in the condenser/reboiler due to the different boiling points of nitrogen and oxygen. In the single-column air separation system, the pressure of the air is just slightly higher than the ambient pressure to be able to overcome the pressure drop, which will lead to a huge amount of energy saving in comparison to the previous discussed two-column systems. The single-column process is adjusted by a booster air and a nitrogen compressor [111]. The changes in the schematic lead to 30 % less power consumption and 30 % less exergy destruction.

Nitrogen production unit

Air separation units which produce only nitrogen have a slightly different design. In these plants, the low-pressure column is not required and the product nitrogen stream is directly taken from the high-pressure column. In this case, the waste nitrogen contains approximately 40 % oxygen.

2.2.2 Non-cryogenic air separation

As already mentioned, non-cryogenic air separation units include adsorption process, chemical process, polymeric membrane, and ion transport membrane [94]. These four processes are briefly explained in the following paragraphs.

Adsorption process

For the air separation, the pressurized air enters a vessel filled with adsorbent. Depending on the adsorbent, the leaving stream is enriched in oxygen or nitrogen. For the production of an oxygen-enriched stream a vacuum pressure swing adsorption process is used while the production of nitrogen requires a pressure swing adsorption with carbon molecular sieves [112]. As already mentioned, the adsorption process contains multiple beds, while in one bed the air is separated, the second bad is regenerated. Afterwards, the beds are switched and the air is separated in the bed

cleaned before. The regeneration of the bed is done by heating it (temperature swing adsorption (TSA)) or by reducing the pressure in the bed (pressure or vacuum swing adsorption (PSA or VSA)) [94]. As a regeneration option, the pressure reduction is most commonly selected, due to fast cycle time and simplified operation [94]. Detailed information, especially for the dynamic simulation of an adsorption process for the air separation is, for example, given in [113].

Chemical process

In the past, different chemical processes have been used for the separation of oxygen from air. The most common chemical process is the MOLTOX process developed and tested using a small-scale pilot plant by Air Products & Chemicals in 1990 [94]. This process is a temperature swing absorption process where alkali metal nitrates and nitrites are used for the production of oxygen [83]. In this process, the air is compressed to approximately 13 bar, and water and carbon dioxide are removed. In a heat exchanger, the dry air is heated to a temperature between 490 °C and 650 °C by the returning product stream (gaseous oxygen). In the absorber, the oxygen in the air reacts with molten liquid salt and leaves the absorber at the bottom. This stream is further heated and the pressure is decreased before entering the desorber. The gaseous oxygen is gained at the top of the desorber while at the bottom an oxygen-lean salt stream is removed. The oxygen-lean stream returns to the top of the absorber bed which closes the loop [94]. An advantage compared to cryogenic air separation is the decreased power consumption by 40 % [84, 114]. Future research for this process should focus on corrosion resistant materials, especially at a high temperature of 650 °C.

Polymeric membrane

The membrane process enables the production of nitrogen with a purity of 90-99% [83] or the production of oxygen with a purity of 25-50% [94]. The air is compressed and particles which can block membranes are removed within filters before the air passes through membranes. The membrane consists of several tube bundles, similar to a shell and tube heat exchanger, which are formed of semipermeable materials. Finally, gases as oxygen, carbon dioxide and water vapor permeate move quickly through the membrane which leads to the nitrogen-enriched product stream [83].

The advantages of the membrane processes are: the operating conditions which are close to ambient conditions as well as the simple and continuous process [94]. The membrane process is a new process in comparison with cryogenic air separation or adsorption processes which is semi-mature developed. Nowadays, membrane processes with a maximum production rate of up to 20 t/d are economic feasible.

Ion transport membrane (ITM)

In the ion transport membrane, the air is compressed and heated to a temperature of 600 °C or even higher. Then, the air passes the ion transport membrane which consists of solid inorganic oxide ceramic materials [94]. In these membranes, the oxygen molecules are broken down into ions and are transported through the membranes. The transport is possible by an electric voltage or a difference in the partial pressure of oxygen. After the oxygen ions have passed the membrane, the oxygen molecules are build [94]. The integration of the ion transport membrane into an energy conversion process which requires pure oxygen is also possible.

2.3 Integration of LNG regasification into air separation units

In general, the integration of the LNG regasification leads to a lower power consumption of 50 % [9] to 66 % [115]. Nowadays, the low-temperature exergy of LNG is already used in air separation units in Japan, Korea, China, Taiwan, and Australia [9, 116].

In [117], an air separation unit which uses a part of the nitrogen stream in order to evaporate liquefied natural gas is discussed. Another attempt to integrate LNG regasification into an air separation is reported in [118]. The integration of the LNG regasification leads to a reduction of the power consumption. It decreases from 1.3 kWh/ $m_{O_2+N_2}^3$ to 0.8 kWh/ $m_{O_2+N_2}^3$.

In several patents, the combination of LNG regasification and air separation units are invented. In [119], the LNG is used for cooling the feed air after the first air compressor which leads to a lower power consumption. In [120], a method is invented which uses a nitrogen cycle in order to evaporate LNG. In the two patents [121, 122], the production of liquid nitrogen from a cryogenic air separation unit using liquefied natural gas as a heat sink is reported. In [123], the low-temperature exergy of LNG is introduced in an air separation unit. Consequently, the specific product compression decreases from 1.0 kWh/kg to 0.3 kWh/kg.

In 2010, the first LNG integration was established in an air separation unit in China [9, 43]. The plant is located in Putian and produces up to 600 t/d of liquid oxygen, nitrogen, and argon. The integration of the LNG regasification leads to a decrease of the power consumption by 50 % which also reduces the CO₂-emissions. The LNG is used to cool glycol. Thus, water resources are saved because no cooling water is required.

An exergetic analysis was applied to the integration of LNG into an air separation unit in [124]. The authors reached a reduction in the power consumption of 42.5 % in comparison with the air separation unit without integration of LNG. The specific power consumption of the liquid products decreased from 0.358 kWh/kg to 0.313 kWh/kg. The novel process has some advantages like e.g. a high-efficiency heat exchanger network and lower operating pressure which increase the safety

of the system. The results of the exergetic efficiency are not comparable due to an unacceptable definition.

The integration of LNG regasification into an air separation unit where the oxygen and a part of the gaseous natural gas are fed to a power plant in order to produce electricity are patented in [125]. In this system, a part of the LNG is vaporized within the main heat exchanger and a second part within the air interstage coolers of the air separation unit.

In [126], the LNG regasification is integrated into an air separation unit with a one-column distillation block. The LNG is vaporized in the main heat exchanger. The utilization of the low-temperature exergy of LNG leads to a decreased power consumption by 38.5 % in comparison to an air separation unit with one-column distillation block without the integration of LNG regasification.

The integration of the LNG regasification into a double-column air separation unit is reported in [127]. This air separation system is enhanced by a power generation cycle using supercritical CO₂. In [128], the air separation unit with LNG regasification is adjusted by a gasification process and CO₂ capture. A thermodynamic and economic analysis for the integration of the LNG regasification into an air separation unit is conducted in [129]. The LNG stream is introduced into the main heat exchanger and leaves it at a temperature of -5 °C. The integration of the LNG regasification leads to a quite small decrease of the power consumption of 8 % compared to values from literature. A comparison of the air separation unit with and without the integration of the LNG regasification shows a decrease of the capital costs of 17 % for the system with LNG regasification.

In [130], an advanced exergetic and an exergoeconomic analysis were applied to an integrated system which consists of an air separation unit, an oxy-fuel carbon dioxide power system, and an LNG regasification unit. The results demonstrate that the main heat exchanger has a high exergy destruction cost rate and a low potential for improvement. The regasification of LNG is integrated into a one-column air separation unit is reported in [131]. The comparison of the one-column air separation unit with and without the integration of LNG regasification shows that the power consumption decreases by 39 %. In addition, an exergetic analysis is applied. The results for the exergetic efficiency are not mentioned, because again an unacceptable definition of the exergetic efficiency is used. The advantages of the integration of the LNG regasification within air separation units were already intensively discussed in [18, 132–135]. In order to evaluate different proposed systems, exergy-based methods were applied.

Chapter 3 Methodology

In this thesis, the proposed systems are evaluated using an energy analysis and exergy-basedmethods. The exergy-based methods are a meaningful tool to understand and analyze energetic or chemical processes which include the following analyses:

- conventional exergetic analysis
- advanced exergetic analysis
- exergoeconomic analysis
- exergoenvironmental analysis
- exergy-risk-hazard analysis

3.1 Energy analysis

Equation 3.1 shows the general energy balance for an open system [136] which has to be fulfilled for each component as well as for the overall system.

$$\frac{\mathrm{d}U + \mathrm{d}KE + \mathrm{d}PE}{\mathrm{d}\tau} = \sum_{j} \dot{Q}_{j} + \sum_{j} \dot{W}_{j} + \sum_{i} (\dot{m}_{i} \cdot (h_{i} + ke_{i} + pe_{i})) - \sum_{o} (\dot{m}_{o} \cdot (h_{o} + ke_{o} + pe_{o}))$$
(3.1)

The differences in kinetic and potential energy are neglected in this thesis. In addition, all systems are analyzed at steady-state conditions. Thus, the energy balance is simplified to the following equation.

$$0 = \sum_{j} \dot{Q}_{j} + \sum_{j} \dot{W}_{j} + \sum_{i} (\dot{m}_{i} \cdot h_{i}) - \sum_{o} (\dot{m}_{o} \cdot h_{o})$$
(3.2)

For the process variables it is defined that a heat or work flow which is supplied to a component or to a system has a positive sign, while a heat or work flow generated by a component or system has a negative sign. For some components, Equation 3.2 is further simplified, for example for adiabatic components no heat flow crosses the system boundaries.

3.2 Conventional exergetic analysis

According to [136, 137], "exergy is defined as the maximum theoretical useful work which is gained if a system is brought into the thermodynamic equilibrium with the thermodynamic environment while it interacts only with the thermodynamic environment". The term exergy consists of four parts: physical, kinetic, potential, and chemical exergy, whereby the kinetic and potential exergy are negligible (Equation 3.3).

$$\dot{E} = \dot{E}^{\rm PH} + \dot{E}^{\rm CH} + \dot{E}^{\rm PE} + \dot{E}^{\rm KE} \tag{3.3}$$

If the temperature of the environment is crossed during a process, the physical exergy has to be split into its mechanical and thermal part [138, 139] as shown in Equations 3.4a and 3.4b. In Equation 3.4b, the state point A is determined at T_0 and p.

$$\dot{E}^{\rm PH} = \dot{E}^{\rm T} + \dot{E}^{\rm M} \tag{3.4a}$$

$$e^{\rm PH} = \underbrace{[(h-h_{\rm A}) - T_0(s-s_{\rm A})]_{p=\rm const.}}_{e^{\rm T}} + \underbrace{[(h_{\rm A} - h_0) - T_0(s_{\rm A} - s_0)]_{T_0=\rm const.}}_{e^{\rm M}}$$
(3.4b)

The conventional exergetic analysis determines the irreversibilities within the components and the overall system and is conducted according to [136]. The general exergy balance [136] is shown in the following equation:

$$\frac{d\dot{E}_{\text{sys}}}{dt} = \sum_{j} \left(1 - \frac{T_0}{T_j} \right) \cdot \dot{Q}_j + \left(\dot{W}_{\text{cv}} - p_0 \frac{dV_{\text{cv}}}{dt} \right) + \sum_{i} \dot{m}_i e_i - \sum_{o} \dot{m}_o e_o - \dot{E}_D$$
(3.5)

The exergy balance can also be formulated using the definition of exergy fuel and exergy product. Equations 3.6 and 3.7 show the exergy balances for the k-th component and for the overall system, respectively.

$$\dot{E}_{\mathrm{F},k} = \dot{E}_{\mathrm{P},k} + \dot{E}_{\mathrm{D},k}$$
 (3.6)

$$\dot{E}_{\rm F,tot} = \dot{E}_{\rm P,tot} + \dot{E}_{\rm D,tot} + \dot{E}_{\rm L,tot}$$
(3.7)

In order to evaluate components and systems, the exergetic efficiencies are calculated using Equation 3.8a and 3.8b [136].

$$\varepsilon_k = \frac{E_{\mathrm{P},k}}{\dot{E}_{\mathrm{F},k}} \tag{3.8a}$$

$$\varepsilon_{\rm tot} = \frac{\dot{E}_{\rm P,tot}}{\dot{E}_{\rm F,tot}} \tag{3.8b}$$

In addition, the exergetic destruction ratios are used for the evaluation of energy or chemical processes which are calculated by Equations 3.9 and 3.10 according to [136]

$$y_{k} = \frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{F,tot}}}$$
(3.9)

$$y_{\rm k}^* = \frac{\dot{E}_{{\rm D},k}}{\dot{E}_{{\rm D},{\rm tot}}} \tag{3.10}$$

3.3 Advanced exergetic analysis

The advanced exergetic analysis gives detailed information about the interactions between the components which cannot be obtained by a conventional exergetic analysis. In addition, this analysis provides information about the potential for improvement of the components.

Therefore, the exergy destruction is divided into unavoidable and avoidable exergy destruction and into exogenous and endogenous exergy destruction [140] as shown in Equations 3.11 and 3.12.

$$\dot{E}_{\mathrm{D},k} = \dot{E}_{\mathrm{D},k}^{\mathrm{UN}} + \dot{E}_{\mathrm{D},k}^{\mathrm{AV}}$$
(3.11)

$$\dot{E}_{\mathrm{D},k} = \dot{E}_{\mathrm{D},k}^{\mathrm{EX}} + \dot{E}_{\mathrm{D},k}^{\mathrm{EN}}$$
 (3.12)

The unavoidable exergy destruction represents the amount of exergy destruction which cannot be further reduced even if the component is at the technological limit. Hence, the avoidable exergy destruction is the part of the total exergy destruction which can be avoided if the components are brought to the technological limitations. Examples for these limitations are: the minimal temperature difference in heat exchangers or the isentropic efficiency in turbomachines. The unavoidable exergy destruction is calculated as given in Equation 3.13.

$$\dot{E}_{\mathrm{D},k}^{\mathrm{UN}} = \dot{E}_{\mathrm{P},k} \cdot \left(\frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{P},k}}\right)^{\mathrm{UN}} \tag{3.13}$$

The endogenous exergy destruction is the part of the total exergy destruction which occurs in a component when this component operates with the same performance as in the real system and all other components assumed to be ideal. Thus, the exogenous exergy destruction is the part which occurs within this component due to irreversibilities within the remaining components.

Several methodologies were developed in order to calculate the endogenous exergy destruction [141] during the last decade. In this thesis, an analytical methodology is applied which will be reported in detail elsewhere.

Finally, the unavoidable, avoidable, endogenous, and exogenous exergy destruction are combined in the resulting variables $\dot{E}_{D,k}^{\text{EN},\text{UN}}$, $\dot{E}_{D,k}^{\text{EN},\text{AV}}$, $\dot{E}_{D,k}^{\text{EN},\text{AV}}$, and $\dot{E}_{D,k}^{\text{EX},\text{AV}}$. The calculation of $\dot{E}_{D,k}^{\text{EN},\text{UN}}$ is shown in Equation 3.14. The equations for the calculation of $\dot{E}_{D,k}^{\text{EN},\text{AV}}$, $\dot{E}_{D,k}^{\text{EX},\text{UN}}$, and $\dot{E}_{D,k}^{\text{EX},\text{AV}}$ are shown in Equations 3.15, 3.16 and 3.17, respectively.

$$\dot{E}_{\mathrm{D},k}^{\mathrm{EN},\mathrm{UN}} = \frac{\dot{E}_{\mathrm{D},k}^{\mathrm{EN}} \cdot \varepsilon_{k}}{1 - \varepsilon_{k}} \cdot \left(\frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{P},k}}\right)^{\mathrm{UN}}$$
(3.14)

$$\dot{E}_{D,k}^{\text{EN,AV}} = \dot{E}_{D,k}^{\text{EN}} - \dot{E}_{D,k}^{\text{EN,UN}}$$
(3.15)

$$\dot{E}_{\mathrm{D},k}^{\mathrm{EX,UN}} = \dot{E}_{\mathrm{D},k}^{\mathrm{UN}} - \dot{E}_{\mathrm{D},k}^{\mathrm{EN,UN}}$$
(3.16)

$$\dot{E}_{\mathrm{D},k}^{\mathrm{EX},\mathrm{AV}} = \dot{E}_{\mathrm{D},k}^{\mathrm{EX}} - \dot{E}_{\mathrm{D},k}^{\mathrm{EX},\mathrm{UN}}$$
(3.17)

The endogenous unavoidable part and the exogenous unavoidable part of the exergy destruction cannot be reduced due to technological limitations within the component itself or the remaining components, respectively. In contrast, the endogenous avoidable and exogenous avoidable part of the exergy destruction can be further reduced by improving the component itself, through structural changes and/or by improving the exergetic efficiency of the remaining components.

3.4 Economic analysis, exergoeconomic analysis, and exergoeconomic optimization

In order to conduct an exergoeconomic analysis and exergoeconomic optimization, an economic analysis has to be applied before.

3.4.1 Economic analysis

The economic analysis is performed according to the total revenue requirement (TRR) method, described in [136]. In order to determine the *TRR*, the purchased equipment cost and the total capital investment has to be estimated.

Estimation of the component costs

The estimation of the purchased equipment costs (*PEC*) and bare module costs (C_{BM}) are based on values from cost graphs or cost correlations. A detailed estimation of the component costs is given in Appendix C whereas a general explanation for the cost estimation is discussed in the following paragraph.

In general, the costs for any component obtained from literature represent the costs for the basic configuration of the component, which means that the component operates at specified pressure and temperature levels and it is built of common materials as for example carbon steel [136]. In order to consider the influence of low or high pressure, low or high temperature and special materials on the cost of the component, the factors f_p , f_T , and f_M are introduced. As an example, the equations for calculating the purchased equipment costs using the modular method could have one of the following forms (Equations 3.18a an 3.18b) [136].

$$PEC_{\rm org} = PEC_{0,\,\rm org} \cdot f_{\rm d}f_{\rm p}f_{\rm T}f_{\rm M} \tag{3.18a}$$

$$PEC_{\text{org}} = PEC_{0, \text{ org}} \cdot (f_{d} + f_{p} + f_{T}) \cdot f_{M}$$
(3.18b)

The entire economic analysis has to be conducted for one reference year. Due to the fact that literature values are available at different years, all values have to be adjusted to the reference year as shown in Equation 3.19 [142]. Therefore, the Chemical Plant Cost Indexes (*CEPCI*) are used which consider the difference in the value of money due to inflation or deflation.

$$PEC_{\rm ref} = PEC_{\rm org} \cdot \frac{CEPCI_{\rm ref}}{CEPCI_{\rm org}}$$
(3.19)

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The bare module costs are calculated using the bare module factor (f_{BM}). The module factor considers all direct and indirect costs related to the installation of the equipment in the process [143]. Independence of the selected equation for the calculation of the purchased equipment costs, the equations for calculating the bare module costs could have one of the following forms (Equations 3.18a an 3.18b) [136]

$$CBM_{\rm ref} = PEC_{0,\,\rm org} \cdot f_{\rm d}f_{\rm p}f_{\rm T}f_{\rm M}f_{\rm BM} \tag{3.20a}$$

$$CBM_{ref} = PEC_{0, org} \cdot [(f_d + f_p + f_T)f_M + f_{BM} - 1]$$
 (3.20b)

Calculation of the fixed and total capital investment

The *FCI* consists of direct and indirect costs, whereas the direct costs are further divided into onsite and offsite costs as shown in Table 3.1. The calculation of the fixed capital investment (*FCI*) is either based on the sum of the purchased equipment costs or on the sum of the bare module costs. If the bare module costs are used in order to calculate the *FCI*, the additional onsite costs for installation, piping, and electrical equipment and the indirect costs for engineering, supervision and construction are already considered with the bare module factor. In case the *PEC* is used for the calculation of the *FCI*, these additional costs are calculated as a percentage value of the *PEC* which depends on the type of the plant. Average values for the onsite costs are shown in Table 3.2. The calculation of the total capital investment is shown in Table 3.3.

Calculation of the total revenue requirement

The total revenue requirement (*TRR*) is calculated as the sum of the levelized carrying charges (*CC*_L), the levelized operating and maintenance costs (*OMC*_L), and the levelized fuel costs (*FC*_L) as shown in Equation 3.21.

$$TRR_{\rm L} = CC_{\rm L} + OMC_{\rm L} + FC_{\rm L} \tag{3.21}$$

Equation 3.22^3 shows the levilization of total capital investment using the capital recovery factor (*CRF*) (Equation 3.23) [136].

 $CC_{\rm L} = TCI \cdot CRF \tag{3.22}$

³taxes are not considered

Table 3.1: Calculation of the fixed capital investment (adopted from [136])

Table 3.2: Percentage values for onsite costs

	[136]	[144]
purchased-equipment installation	20-90 % of PEC	39-47 % of PEC
piping	10-70 % of PEC	16-68 % of PEC
instrumentation and controls	6-40 % of PEC	18-36 % of PEC
electrical equipment and materials	10-15 % of PEC	10-11 % of PEC

$$CRF = \frac{i_{\rm eff} \cdot (1 + i_{\rm eff}^n)}{1 + i_{\rm eff}^n - 1}$$
(3.23)

The *OMC* and *FC* are operational expanses which are due and increase each year. For the levilization of the *OMC* and *FC*, the costs for the first year of operation are multiplied by the so-called constant-escalation levilization factor (*CELF*) [136] whereby either an average general inflation rate (r_g) or an average escalation rate of electricity (r_{el}) is used in order to obtain the *CELF*_g and *CELF*_{el}. Equations 3.25a and 3.25b show the levilization of the *OMC* and *FC*, respectively.

$$CELF_{g} = \frac{k_{g} \cdot (1 - k_{g}^{n})}{1 - g} \cdot CRF \qquad \text{with} \quad k_{g} = \frac{1 + r_{g}}{1 + i_{eff}}$$
(3.24a)

$$CELF_{el} = \frac{k_{el} \cdot (1 - k_{el}^n)}{1 - el} \cdot CRF$$
 with $k_{el} = \frac{1 + r_{el}}{1 + i_{eff}}$ (3.24b)

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total capital investment
plant facility investment 1 (60 % of FCI)
plant facility investment 2 (40 % of FCI)
interest for PFI1
interest for PFI2

Table 3.3: Calculation of the total capital investment

$$OMC_{\rm L} = OMC^{1\rm st} \cdot CELF_{\rm g} \tag{3.25a}$$

 $FC_{\rm L} = FC^{\rm 1st} \cdot CELF_{\rm el} \tag{3.25b}$

3.4.2 Exergoeconomic analysis

The exergoeconomic analysis combines an exergetic and an economic analysis. With this method, a system can be optimized from the cost point of view [136]. The advantage of combining both analyses is that in a process with more than one product, the precise costs for each product are calculated. Thus, this analysis results in values which cannot be obtained by conducting a conventional exergetic and an economic analysis separately.

In the exergoeconomic analysis, a cost rate is assigned to each exergy stream (Equation 3.26). The cost rate associated with each stream consists of three parts: a cost rate associated with thermal exergy, a cost rate associated with mechanical exergy, and a cost rate associated with chemical exergy (Equation 3.27).

$$\dot{C}_j = \dot{E}_j \cdot c_j \tag{3.26}$$

$$\dot{C}_j = \dot{C}_j^{\mathrm{T}} + \dot{C}_j^{\mathrm{M}} + \dot{C}_j^{\mathrm{CH}} \tag{3.27}$$

In order to determine the cost rates for each stream, the cost balances for all components and the overall system have to be fulfilled. Figure 3.1 shows a general component and the associated cost balance is given in Equation 3.28.

$$\sum_{j=1}^{n} (c_j \cdot \dot{E}_j)_{k,\text{in}} + \dot{Z}_k^{\text{CI}} + \dot{Z}_k^{\text{OM}} = \sum_{j=1}^{m} (c_j \cdot \dot{E}_j)_{k,\text{out}}$$
(3.28)

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Figure 3.1: Cost balance of a *k*-th component (adopted from [145])

The cost balances for each component (Equation 3.29) and the overall system (Equation 3.30) can be also formulated using the costs associated with the exergy of fuel and the costs associated with the exergy of product.

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_{k}^{CI} + \dot{Z}_{k}^{OM}$$
(3.29)

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} - \dot{C}_{L,tot}$$
(3.30)

The costs associated with the investment and the operating and maintenance of a component are considered in \dot{Z}_k^{CI} and \dot{Z}_k^{OM} , respectively. Equation 3.31 shows the equations for the calculation of \dot{Z}_k .

$$\dot{Z}_{k} = \frac{CC_{\rm L} + OMC_{\rm L}}{FLH} \cdot \frac{C_{\rm BM,k}}{C_{\rm BM,tot}}$$
(3.31)

In order to solve the cost balances, the costs of streams entering the *k*-th component are known. However, the cost balance is not sufficient to determine the costs of the leaving streams because normally a component has more than one leaving stream, thus, auxiliary equations are required. The number of auxiliary equations is equal to the number of streams leaving the component minus one. The auxiliary equations are divided into either fuel (F) or product (P) auxiliary equations which depend on whether the streams used in the equation are considered in the fuel or product of the component. According to [145], the F equations are defined as "the total cost associated with the removal of exergy from an exergy stream in a component must be equal to the cost at which the removed exergy was supplied to the same stream in upstream components". The P equation is defined according to [145] as "each exergy unit is supplied to any stream associated with the product of a component at the same average specific product costs".

The calculation of the specific product and fuel costs are given in the following equations:

$$c_{\mathrm{P},k} = \frac{\dot{C}_{\mathrm{P},k}}{\dot{E}_{\mathrm{P},k}} \tag{3.32}$$

$$c_{\mathrm{F},k} = \frac{\dot{C}_{\mathrm{F},k}}{\dot{E}_{\mathrm{F},k}} \tag{3.33}$$

According to [136], the cost rate associated with the exergy loss and exergy destruction is calculated using Equations 3.34 and 3.35, respectively.

 $\dot{C}_{\rm L,tot} = c_{\rm F,tot} \cdot \dot{E}_{\rm L,tot} \tag{3.34}$

$$\dot{C}_{\mathrm{D},k} = c_{\mathrm{F},k} \cdot \dot{E}_{\mathrm{D},k} \tag{3.35}$$

For the evaluation of systems, two exergoeconomic variables are used. These are the relative cost difference r_k (Equation 3.36) and the exergoeconomic factor f_k (Equation 3.37) [136].

$$r_k = \frac{c_{\mathrm{P},k} - c_{\mathrm{F},k}}{c_{\mathrm{F},k}}$$
(3.36)

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{\mathrm{D},k}} \tag{3.37}$$

The relative cost difference states the relative increase in the average cost per unit of exergy between the fuel and the product costs of a component [136].

The exergoeconomic factor specifies a relation between the cost rate associated with the investment, maintenance, and operation costs (\dot{Z}_k), and the total costs associated with a component (investment, maintenance, operation costs, and costs associated to the exergy destruction of the component, $\dot{Z}_k + \dot{C}_{D,k}$). This means, for a component with an *f*-factor close to zero, the cost associated with the exergy destruction is predominant and for a component with an *f*-factor close to one, the cost associated with the investment and operating and maintenance predominant. In conclusion, this variable clearly indicates whether a component has to be improved form the thermodynamic or from the economic point of view.

For dissipative components, the cost balances as given in Equations 3.28 and 3.29 cannot be fulfilled because within these components exergy is destroyed without producing a useful effect.

For this reason, the variable $\dot{C}_{\text{diff},k}$ has to be included in the cost balance for dissipative components as shown in Equation 3.38.

$$\sum_{j=1}^{n} (c_j \cdot \dot{E}_j)_{k,i} + \dot{Z}_k^{\text{CI}} + \dot{Z}_k^{\text{OM}} = \sum_{j=1}^{m} (c_j \cdot \dot{E}_j)_{k,o} + \dot{C}_{\text{diff},k}$$
(3.38)

For the analysis of the overall system, $\sum \dot{C}_{\text{diff},k}$ and $\dot{C}_{\text{L,tot}}$ are added to the product costs of the system, because these are additional costs due to irreversibilities which have to be covered. Equation 3.39 shows the equal distribution among the product streams for a system with more than one product stream.

$$\tilde{c}_{j} = \frac{\dot{C}_{j} + (\dot{C}_{\text{L,tot}} + \sum \dot{C}_{\text{diff},k}) \cdot \frac{\dot{E}_{j}}{\dot{E}_{\text{P,tot}}}}{\dot{E}_{j}}$$
(3.39)

3.4.3 Exergoeconomic optimization

The exergoeconomic optimization is conducted in order to decrease the overall product cost by adjusting thermodynamic parameters. The components with the highest $\dot{Z}_k + \dot{C}_{D,k}$ are considered and the respective decision variables are determined. These variables have a high influence on the cost and/or exergetic efficiency of the selected components. One optimization step consists of the following sequence:

Step 1:

In the first step, it is determined whether the investment cost of the component has to be decreased or the exergetic efficiency has to be improved. For this decision, the f-factor is used whereby a high f-factor stands for high investment costs and a low f-factor for high costs associated with the exergy destruction. For dissipative components, the exergy destruction is considered instead of the exergetic efficiency.

Step 2:

The effect of the selected decision variables on the component itself is analyzed for each component. A suggestion on how the decision variables have to be changed in order to fulfill the goal of the component is also provided. This procedure is applied to all components, whereby not all decision variables have an influence on all components.

Step 3:

Finally, all suggestions for the decision variables are considered and an overall decision is made. The decision variables can have opposite effects on the components. Hence, the component with the highest $\dot{Z}_k + \dot{C}_{D,k}$ value determines the direction of the new value of the decision variable. Then, new values for each decision variable are assumed. These values are set in the simulation in order to get the new physical properties.

Step 4:

In order to compare the first iteration with the reference case, the exergetic, economic, and exergoeconomic analyses are conducted one more time. Afterwards, the results from the exergoeconomic analysis are compared with the results from the previous simulation in order to find out if the optimization has been successful. For the overall system, the specific investment cost, the specific cost of the product, and the cost associated with the exergy loss are compared. On a component level it is analyzed if the goals can be achieved. The exergoeconomic optimization is successful when the specific product cost decreases.

3.5 Life cycle assessment and exergoenvironmental analysis

The exergoenvironmental analysis combines an exergetic analysis with a life cycle assessment (LCA) and is conducted in analogy to an exergoeconomic analysis. Instead of the costs associated with the components and inlet streams the environmental impact of the components and streams is analyzed. In order to conduct the exergoenvironmental analysis, the life cycle assessment has to be conducted in advance.

3.5.1 Life cycle assessment

The life cycle assessment identifies the environmental impact during the life time of a component which includes materials and resources for the production and disposal of the component as well as the energy required and additional pollutants during the operation [146]. The LCA is a standardized and widely used method [147] in order to analyze the life cycle of a component.

The LCA has to be conducted for all input streams of the overall systems and for all components within the system. In this thesis, the Eco-indicator 99 life-cycle impact assessment [148, 149] is used.

In general, the environmental impact associated with the *k*-th component consists of the three life-cycle phases construction \dot{Y}_{k}^{CO} , operation and maintenance \dot{Y}_{k}^{OM} , and disposal \dot{Y}_{k}^{DI} (Equation 3.40) [140]. However, in this thesis the environmental impact associated with the components is neglected ($\dot{Y}_{k} = 0$ Pt/h) [150].

$$\dot{Y}_k = \dot{Y}_k^{\rm CO} + \dot{Y}_k^{\rm OM} + \dot{Y}_k^{\rm DI} \tag{3.40}$$

3.5.2 Exergoenvironmental analysis

In the exergoenvironmental analysis, the environmental impact rate \dot{B}_j and the specific environmental impact per unit of exergy are allocated to all streams [151] (Equation 3.41).

$$\dot{B}_j = \dot{E}_j \cdot b_j \tag{3.41}$$

Equation 3.42 shows the exgergoenvironmental balance for the k-th component (analogue to Figure 3.1).

$$\sum_{j=1}^{n} (b_j \cdot \dot{E}_j)_{k,i} + \dot{Y}_k = \sum_{j=1}^{m} (b_j \cdot \dot{E}_j)_{k,o}$$
(3.42)

The exergoenvironmental balance for the k-th component using the definition of the exergy of fuel and exergy of product is shown in the following equation.

$$\dot{B}_{\mathrm{P},k} = \dot{B}_{\mathrm{F},k} + \dot{Y}_k \tag{3.43}$$

For the exergoenvironmental analysis, the auxiliary equations also have to be used in order to calculate the environmental impact of the streams leaving the component. The calculation of the specific environmental impact of the exergy of product and exergy of fuel are given in Equations 3.44 and 3.45, respectively.

$$b_{\mathbf{P},k} = \frac{\dot{B}_{\mathbf{P},k}}{\dot{E}_{\mathbf{P},k}} \tag{3.44}$$

$$b_{\mathrm{F},k} = \frac{\dot{B}_{\mathrm{F},k}}{\dot{E}_{\mathrm{F},k}} \tag{3.45}$$

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The environmental impact rate associated with the exergy loss $\dot{B}_{L,tot}$ and the environmental impact rate associated with the exergy destruction $\dot{B}_{D,k}$ are calculated using Equations 3.46 and 3.47, respectively.

$$\dot{B}_{\rm L,tot} = b_{\rm F,tot} \cdot \dot{E}_{\rm L,tot} \tag{3.46}$$

$$\dot{B}_{\mathrm{D},k} = b_{\mathrm{F},k} \cdot \dot{E}_{\mathrm{D},k} \tag{3.47}$$

For the evaluation of different systems, two exergoenvironmental variables are used. These are the relative environmental impact difference (Equation 3.48) and exergoenvironmental factor (Equation 3.49).

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$$
(3.48)

$$f_{\mathbf{b},k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{\mathbf{D},k}} \tag{3.49}$$

The meaning of the relative environmental impact difference and the exergoenvironmental factor are analogous to the relative cost difference and the exergoeconomic factor.

For the exergoenvironmental analysis, the balance of the environmental impact also has to be adjusted for dissipative components using the difference term $\dot{B}_{\text{diff},k}$ (Equation 3.50).

$$\sum_{j=1}^{n} (b_j \cdot \dot{E}_j)_{k,i} + \dot{Y}_k = \sum_{j=1}^{m} (b_j \cdot \dot{E}_j)_{k,0} + \dot{B}_{\text{diff},k}$$
(3.50)

Analogous to the exergoeconomic analysis, the specific environmental impact of the product streams is adjusted by $\sum \dot{B}_{\text{diff},k}$ and $\dot{B}_{\text{L,tot}}$ (Equation 3.51).

$$\tilde{b}_{j} = \frac{\dot{B}_{j} + (\dot{B}_{\text{L,tot}} + \sum \dot{B}_{\text{diff},k}) \cdot \frac{\dot{E}_{j}}{\dot{E}_{\text{P,tot}}}}{\dot{E}_{j}}$$
(3.51)

3.6 Risk-hazard analysis and exergy-risk-hazard analysis

The combination of a risk-hazard analysis and an exergetic analysis leads to an exergy-risk-hazard analysis. A detailed explanation of the method is published in [152–154].

In general, a hazard is a potential source that poses a harm for life, property, or environment. Several hazard or risk-related studies exist in literature, like the "Hazard and Operability" (HAZOP) and the "Hazard Identification" (HAZID) studies. An often used tool for specifying the risk of process handling with dangerous substances is the "Quantitative Risk Assessment" (QRA) [155], which consists of the following steps according to [156]:

- · Identification of primary events
- Determination of the frequencies of the primary events
- · Determination of the probabilities of the accident scenarios
- · Determination of the impact distanced of the accident scenarios
- Determination of individual risk
- Determination of societal risk
- Result analysis
- Description of measures to reduce the risk

3.6.1 Risk-hazard analysis

The risk is defined as "the product of the frequency and the consequence of hazardous event" [157]. The frequency of an event is determined as the probability of an event with the unit 1/a. The consequence of a fatal accident is the possible number of deaths. The calculation of the risk is given by the general equation in Equation 3.52 [152].

$$R_i = P_i \cdot F_i \tag{3.52}$$

For the calculation of the risk, the fatality and probability have to be estimated. The fatality of a given event is mathematically calculated by using the probit function as shown in Equation 3.53, where according to [158] "Probits accounts for the variation in tolerance to harm for an exposed population". These functions are based on experimental data. Several functions were developed by different researchers over the past years. The detailed transformation of the probit function to the fatality is given in literature [158].

$$Y = k_1 + k_2 \cdot \ln V \tag{3.53}$$

The probability of hazard events is estimated based on generic historical statistics. This is a widespread method for components which are often used in the process industry, for example pipes, vessels, and pumps. In contrast, for components with quite low failure frequencies, historical statistics might not be available. Then, the fault tree or event tree analysis is a recommended approach [157, 159].

3.6.2 Exergy-risk-hazard analysis

The exergy-risk-hazard analysis is conducted in analogy to the exergoeconomic and exergoenvironmental analyses. The cost balance as given in Equation 3.28 is rewritten into a cumulated risk balance for the k-th component (Equation 3.54).

$$\dot{X}_{\mathrm{P},k} = \dot{X}_{\mathrm{F},k} + \dot{R}_k \tag{3.54}$$

The value of \dot{R}_k is the risk of the components which has to be accepted in order to produce the product. It is defined in analogy to the costs associated with the component (\dot{Z}_k) and the environmental impact associated with the component (\dot{Y}_k) .

The specific risk of the exergy of product and exergy of fuel are defined in Equations 3.55 and 3.56, respectively.

$$x_{\mathbf{P},k} = \frac{\dot{X}_{\mathbf{P},k}}{\dot{E}_{\mathbf{P},k}} \tag{3.55}$$

$$x_{\mathrm{F},k} = \frac{\dot{X}_{\mathrm{F},k}}{\dot{E}_{\mathrm{F},k}} \tag{3.56}$$

The risk rate associated with the exergy loss $\dot{X}_{L,tot}$ and the risk rate associated with the exergy destruction $\dot{X}_{D,k}$ are calculated using Equations 3.57 and 3.58, respectively.

$$\dot{X}_{\rm L,tot} = x_{\rm F,tot} \cdot \dot{E}_{\rm L,tot} \tag{3.57}$$

$$\dot{X}_{\mathrm{D},k} = x_{\mathrm{F},k} \cdot \dot{E}_{\mathrm{D}} \tag{3.58}$$

Chapter 4 Process description

Figure 4.1 gives an overview of the evaluated systems. Two different air separations units are considered in this thesis: in Case A the product compression is external whereas in Case B it is internal. In order to analyze the influence of the integration of the LNG regasification into air separation units, different schematics are proposed which vary regarding the complexity of the LNG integration (simple, complex, or safe). The process descriptions of similar systems were previously published in [18, 99, 132–135, 160]. In the following sections, the systems are briefly explained. Detailed information about process parameters, the modeling of the systems, and assumptions are given in the subsequent Chapter 5.



Figure 4.1: Overview of simulated systems



Figure 4.2: Flowsheet of Case A

4.1 Case A

The system Case A (CA) is a conventional air separation unit with two distillation columns, a nitrogen liquefaction block, and external product compression. Its assumptions for the simulation and design are based on [92]. The flowsheet of Case A is shown in Figure 4.2.

The dust-free air is compressed within a two-stage compression process with interstage cooling. In the following pre-purification, the chemical components which will freeze at low temperature have to be removed. These are water and carbon dioxide in particular. After having left the pre-purification block, the air (stream 7) is cooled to the liquefaction temperature within the main heat exchanger (MHE) and gets partially liquid. Afterwards it enters the column block. This block consists of a low- and a high-pressure column (LPC and HPC) which are thermally coupled by the condenser and reboiler.

From the bottom of the high-pressure column an oxygen-enriched stream (stream 11) is withdrawn, throttled and fed to the low-pressure column. In addition, two side-streams (stream 50 and 52) of the high-pressure column also enter the low-pressure column. On the top of the high-pressure column, the leaving vapor stream is split into streams 30 and 64, part of the vapor nitrogen stream (stream 30) is heated in the MHE and fed to the nitrogen liquefaction block. The remaining part
(stream 64) is condensed in the condenser and either returned to the column as a reflux (stream 66) or withdrawn from the condenser (stream 54). The first part of this stream is removed from the system as a liquid product stream (stream 55) and the second part (stream 56) is throttled and enters the LPC. From the top of the low-pressure column, a vapor nitrogen stream (stream 15) is gained and fed to the main heat exchanger. On the bottom of this column, gaseous and liquid oxygen streams (streams 14 and 20) are obtained. The liquid oxygen stream leaves the system and the gaseous oxygen stream is inserted into the main heat exchanger. In addition, a waste nitrogen stream is withdrawn from the low-pressure column. The gaseous streams are heated within the main heat exchanger. Stream 31 leaves the MHE and is fed to the nitrogen liquefaction block. There, it is mixed with stream 44 and stream 47, which are recycled streams within the nitrogen liquefaction block to stream 32. This stream is heated in the heat exchanger 1 and compressed in a three-stage compression process with interstage cooling. After the third nitrogen compressor (NC3), the stream is split into two streams (stream 39 and 45). Stream 39 is further compressed within NC4 and cooled within HE1 (stream 40). Stream 45 is directly fed to the HE1 and is expanded in expander 1 (EXP1) and leaves the EXP1 as stream 47. The nitrogen compressor 3 and 4 are driven by expander 1 and 2, respectively. After leaving the HE1, stream 41 is split into stream 42 and stream 21. Stream 42 is expanded in expander 2 (EXP2), which is connected with nitrogen compressor 4. Stream 21 is cooled in the HE2 by stream 43, which is afterwards mixed with streams 47 and 31. The cooled stream leaves the HE2 as stream 48, is throttled and split into streams 58 and 59. Stream 58 is directly fed to the HPC, while stream 59 is throttled again and then enters the LPC.

The gaseous oxygen and nitrogen streams (streams 17 and 22) leave the MHE and are compressed to the required product pressure. Before leaving the system, the gaseous oxygen is cooled to ambient temperature within interstage cooler oxygen (ICO). The nitrogen stream is used to heat the waste nitrogen within heat exchanger 3 (HE3) and is afterwards cooled to ambient temperature.

4.2 Case A Design 1

The flowsheet of Case A Design 1 (CAD1) is shown in Figure 4.3. In this system, the LNG regasification is integrated wherein the LNG stream is heated within the main heat exchanger and is vaporized within heat exchanger 4. This system represents the simple integration of the LNG regasification.

The LNG enters the system via the LNG pump (stream 60) and is fed to the MHE. By cooling the air to liquefaction temperature, the LNG stream (stream 61) as well as the nitrogen (stream 15), oxygen (stream 20) and a waste nitrogen stream (stream 25) are heated. An additional heat

exchanger (HE4) is required, in order to enable an outlet temperature of 15 °C for the regasified LNG stream. In this heat exchanger, the compressed gaseous nitrogen stream (stream 18) and a nitrogen stream (stream 35) coming from the nitrogen liquefaction block are used to heat the LNG. The air compression and purification block (ACPB) and the column block are not affected by the integration of the LNG stream. Only the stream numbering changed slightly, thus stream 6 (air stream) enters the MHE. The implementation of LNG causes the restructuring of the nitrogen liquefaction block. In Case AD1, the nitrogen liquefaction block consists of three compressors (NC1-NC3), one expander, two heat exchangers (HE1 and HE2), and several mixing and splitting units. The nitrogen compressor 3 (NC3) is still driven by expander 2 (EXP2). The top product of the high-pressure column (gaseous nitrogen, stream 30) is fed to heat exchanger 2 (HE2) of the nitrogen liquefaction block. Stream 31 and stream 44 (stream inside the nitrogen liquefaction block) are mixed into stream 32 which is heated in HE1 and pressurized within NC1. After the NC1, the nitrogen stream is cooled by heating the LNG and waste nitrogen stream (HE3 and HE4). Subsequently, it is fed to the second and third nitrogen compressors, cooled within the HE1 and split into two parts (streams 41 and 42). Stream 42 is expanded in EXP2 where the temperature decreases and reaches the required low-temperature for cooling, together with the incoming stream, stream 41 is cooled within HE2. Stream 48 leaves the nitrogen liquefaction block and is throttled. Stream 49 is split into streams 58 and 59. Stream 58 enters the HPC as a reflux while stream 59 is throttled and fed to the LPC as reflux. The product streams (stream 22 and stream 17) are compressed within OC and NC5. The oxygen stream is cooled within the ICO to ambient temperature. The nitrogen stream is used to vaporize and heat the LNG stream (HE4) and then cooled to ambient temperature within ICN.

4.3 Case A Design 2

The complex integration of the LNG regasification is applied in Case A Design 2 (CAD2). Figure 4.4 shows the flowsheet of this system. The complex integration leads to structural changes in the air compression and purification block and in the nitrogen liquefaction block. The column block is again not affected by the changes.

After being pumped by the LNGP, the LNG stream is split into two streams (stream 41 and 48). Stream 48 is entering the MHE where it is heated, while stream 41 is fed to the nitrogen liquefaction block where it is heated in the HE2. Afterwards, both streams are mixed (stream 43) and further heated in interstage coolers of the air compression block and heat exchanger 4 (HE4) to reach ambient temperature.

The nitrogen liquefaction block only consists of the nitrogen compressors 1 and 2 and heat exchanger 2. The top product of the high-pressure column (gaseous nitrogen, stream 30) enters



Figure 4.3: Flowsheet of Case AD1

the HE2. Within the HE2 the LNG stream and the nitrogen stream are heated. Then, the nitrogen stream is compressed within NC1 and NC2 and is subsequently cooled within the HE2. Stream 34 leaves the nitrogen liquefaction block and is throttled. Finally, it is split into two parts: stream 58 is inserted into the high-pressure column while stream 29 is further throttled and fed to the low-pressure column.

The air compression and purification block contains three air compressors (AC1-AC3), three interstage coolers (IC1-IC3), and the adsorption block (AD). Here, the adsorption block is placed directly after the interstage cooler 1. Water and carbon dioxide are removed and the air is further cooled within the insterstage cooler 2 (IC2). Afterwards, the air is compressed within AC2 and AC3, with cooling taking place in between, in IC3. After having left the MHE, the product streams (stream 18 and 22) are compressed. The nitrogen stream is firstly used to heat the waste nitrogen. Afterwards, both product streams are used to heat the LNG stream within HE4. Before leaving the system, both product streams are cooled to ambient temperature within ICN and ICO.



Figure 4.4: Flowsheet of Case AD2

4.4 Case A Design 2 Safety

The safety concept of CAD2 is named Case A Design 2 Safety (CAD2S) and is shown in Figure 4.5. The objective of this system is the minimization of hazard potentials. The greatest danger arises from the presence of an oxygen or oxygen-enriched stream in conjunction with the LNG stream within components. For this reason, the system is restructured in that manner that the LNG stream is introduced in components where oxygen is not used in parallel.

The pressure of the incoming LNG stream (stream 39) is increased within the LNG pump (LNGP) and then the total LNG stream is fed to HE2 where it is partially vaporized and heated. Afterwards the LNG is completely vaporized and heated to the temperature of the environment within HE5. The column block is again not affected by the structural changes, but the nitrogen liquefaction and air compression as well as purification block differ in comparison to CAD2. The top-product stream of the HPC (stream 30) is again firstly heated within the MHE, and afterwards directly fed to the NC1 and NC2. When leaving the NC2, it is cooled in the HE2 by the LNG stream and throttled (stream 36). This stream is split into streams 37 and 58, which are again used as a reflux for the LPC and HPC, respectively. In the ACPB, a heat transfer medium is used for the cooling of the air to avoid the simultaneous presence of an LNG stream and a stream containing oxygen in the same



Figure 4.5: Flowsheet of Case AD2S

component. Consequently, the heat transfer medium circulates between the HE5, IC2, IC3, IC1, and HE4. The pressure of the heat transfer medium is increased within the water pump (WP) to overcome the pressure drops in the heat exchangers.

4.5 Case B

Case B (CB) represents a modern air separation unit with internal compression of the oxygen product stream. The assumptions for the simulation of Case B are based on [86]. Figure 4.6 shows the flowsheet of this system. The incoming dustless air is compressed in a two-stage compression process with interstage cooling and cleaned in the purification block which is identical with Case A. After the cleaning (stream 10), the air is divided into two parts while the bigger part (stream 11) is fed to the main heat exchanger (MHE), the smaller part (stream 17) is further compressed in the booster air compressor (BAC or AC3). In the MHE, the air streams (streams 12, 14, and 18) are cooled against the product streams which come from the column block. Stream 15 leaves the MHE at an intermediate temperature and is expanded in the expander (EXP1). After the expander, stream 16 enters the low-pressure column (LPC) at an intermediate sieve tray. The air stream at



Figure 4.6: Flowsheet of Case B

high pressure leaves the MHE (stream 19) and is expanded within a throttling valve (stream 20). This stream as well as the second air stream (stream 13) are fed to the high-pressure column (HPC). The high- and low pressure columns are thermally coupled by the condenser/reboiler (CD/REB). The bottom product (stream 21) of the HPC is expanded to the pressure of the low-pressure column and enters it. The top-product of the HPC is gaseous nitrogen which is condensed in the CD/REB. It is assumed that no liquid nitrogen is withdrawn as a product stream, thus the entire liquid nitrogen stream (stream 25) is cooled in the subcooler (SUB) by the top-product of the LPC (stream 34) and is then throttled and fed to the LPC. The bottom-product of the LPC is liquid oxygen which is fed to the oxygen pump while a small amount of the liquid oxygen is withdrawn from the system as a product stream (stream 29). Additionally, a waste nitrogen stream leaves the column block. The liquid oxygen stream vaporizes within the MHE while the nitrogen stream from the top of the LPC and the waste nitrogen stream are heated. The gaseous oxygen (stream 33) leaves the main heat exchanger at ambient temperature. The nitrogen stream (stream 36) is compressed to the consumer's pressure and the resulting high temperature is then used to heat the waste nitrogen stream. Finally, the nitrogen stream (stream 39) is cooled to ambient temperature and leaves the system.

4.6 Case B Design 2 Safety

This system is proposed in analogy to Case AD2S. The LNG stream enters the system with a pump and is then heated within the nitrogen interstage cooler which is divided into two components. The nitrogen interstage cooler (ICN1) is located after the MHE and the second interstage cooler (ICN2) is placed after the nitrogen compressor. The use of the two interstage coolers enables a lower temperature at the inlet of the nitrogen compressor which consequently decreases the power consumption within it. After the two interstage coolers, the LNG is completely vaporized and heated to ambient temperature in the heat exchanger 5 (HE5). Between the HE5, IC2, IC5, and IC1, a heat transfer medium is used in order to avoid the direct contact of oxygen-enriched or oxygen streams and LNG. The heating loop is closed by a pump (WP) to overcome the pressure drops. Thus, in the interstage cooler the cooling water is replaced by the heat transfer medium. The remaining components and the streams are not affected by the integration of the LNG and are the same as in Case B.



Figure 4.7: Flowsheet of Case BD2S

Chapter 5 Modeling and assumptions

5.1 Software

The simulations were conducted using Aspen Plus version V8.6 [161]. Aspen Plus is used for the modeling and simulation of chemical processes. The software includes the property databases and phase equilibrium for conventional chemicals as well as for electrolytes, solid, and polymers. All simulations are conducted at steady-state conditions. In Aspen Plus, the Peng-Robinson-equation was selected as the equation of state. This equation is appropriate for low-temperature applications and was used in several publications [93, 105, 106, 110, 123].

The thermal, mechanical, and chemical exergies are calculated directly from Aspen Plus using Fortran subroutines which were developed by the Institute of Energy Enginnering at the Technische Universität Berlin [162].

The exergy-based methods were conducted using EES (Engineering Equation Solver). EES is a general equation-solving program, which includes thermodynamic property databases of hundreds of substances [163].

Using Mircosoft Excel [164] and Visual Basic for Applications (VBA), the results of the simulation in Aspen Plus were transferred to EES. The evaluation of the results was conducted using Microsoft Excel.

5.2 Assumptions for the modeling

For the modeling of all systems values are assumed, which are shown in Table 5.1. The assumption of the inlet mass flow rate of the air (Case A) is based on the data available in [92]. In Case B, the mass flow rate of the air is determined in order to achieve the same mass flow rates of the oxygen product streams (gaseous and liquid) as in Case A. The isentropic efficiency of the compressors is assumed to be 84 %. In literature, similar values were reported as for example 87 % in [105], 82 %

variable	unit	Case A	Case B
	air		
inlet temperature	°C	15	
inlet pressure	bar	1.0	013
mass flow rate	kg/s	16.39	33.50
composition	mol/mol	$x_{N_2} =$	0.7720
		$x_{O_2} =$	0.2080
		$x_{\rm Ar} =$	0.0905
		$x_{\rm H_2O} =$	0.0102
		$x_{\rm CO_2} =$	0.0003
	LNG		
inlet temperature	°C	-1	62
inlet pressure	bar	1.3	
mass flow rate	kg/s	10.00	10.93
composition	mol/mol	$x_{\rm CH_4} = 0.8698$	
		$x_{C_2H_6} = 0.0935$	
		$x_{C_{3}H_{8}} =$	= 0.0233
		$x_{C_4H_10} = 0.0063$	
		$x_{N_2} =$	0.0071
turbomachines			
isentropic efficiency (compressor)	%	8	34
isentropic efficiency (pump)	%	7	0
isentropic efficiency (expander)	%	9	00
mechanical efficiency	%	99	

 Table 5.1: General assumptions for the modeling of the systems

in [109], 70 % in [111], 89 % in [93], 80 % at normal temperature, and 85 % at low temperature in [110]. For the pump, a slightly lower value of 50 %, in comparison with the assumed value of 70 %, was given in [105]. The isentropic efficiency of the expanders is assumed to be 90 %, in comparison a value of 87 % was reported in [105]. In [109], a mechanical efficiency of 97 % is reported while in this thesis it is assumed to be 99 %.

The product requirements such as mass flow rates, quality, and pressure depend on the consumer. If the air separation plant is located close to an industrial complex, the products are delivered directly to this plant. In contrast, in a standalone air separation unit the products are sold on the market. These facts lead to the varying number of purities and mass flow rates in literature. In [101], an amount of 31.000 m³ gaseous oxygen with a purity of 99.99 mol-% at standard temperature and pressure is stated. Gaseous oxygen with a lower purity of 95 mol-% is reported in [109]. The mass flow rates and purity amount to 10.000 Nm³/h and 93 mol-% and 34.400 Nm³/h and 99 mol-% for the gaseous oxygen are set to 3 kg/s and 0.5 kg/s, respectively. This leads to a production rate of 260 t/d of gaseous oxygen which correspond to a small-scale unit.

In the following paragraphs, the modeling of the separate blocks is described in detail. The explanation is given for the reference case (Case A), all changes for the other systems are given afterwards. Tables 5.2 gives an overview of the components and their respective blocks, whereas splitting units are not assigned to a specific block. The heat exchanger 3 in which the waste nitrogen is heated is assigned to the ACPB.

5.2.1 Air compression and purification block (ACPB)

The air compression and purification block is the first block in the air separation system. In the air compressors (AC1 and AC2), the air is compressed to 6.10 bar. This value is slightly higher in comparison to data available in literature (5.30 bar [109], 4.50 bar [111], and 6 bar [78]) to overcome the pressure drop in the interstage cooler, the adsorption process, and the following main heat exchanger. The pressure between the air compressors 1 and 2 was set in order to minimize the power consumption of AC1 and AC2 which is shown in Equation 5.1 [165].

$$p_{\text{int}} = \sqrt{p_{\text{i},\text{AC1}} \cdot p_{\text{o},\text{AC2}}} \tag{5.1}$$

The air is cooled within the interstage coolers IC1 and IC2 using water, whereby the water stream is not simulated. It is assumed that the air is cooled to a temperature of 35 °C. In [96], the air is cooled to ambient temperature before the purification block. However, here a $\Delta T = 20$ K is assumed. The pre-purification unit, which is based on adsorption, is simulated as a so-called black-box model. Here, impurities which will freeze at cryogenic temperatures are removed. According to [166], a maximum of 0.1 ppm and 1.0 ppm is acceptable for the content of the water vapor and carbon dioxide, respectively. In this thesis, a temperature swing adsorption process is assumed for the removal of water and carbon dioxide. For the desorption of one of the two beds, a waste nitrogen stream is used which is heated to 170 °C in HE3 using the compressed gaseous nitrogen stream. According to [86] and [167], the temperature of the waste nitrogen is between 150 °C and 200 °C.

The pressure drop within all heat-exchangers is assumed to be 3 %. The pre-purification unit also has a pressure drop of 3 %, which corresponds to a pressure drop of 0.1 bar as given in [109, 110].

The air compression and purification block is identical in Case A and Case AD1.

In Case AD2, the air compression block is extended by a third air compressor (AC3) and a further interstage cooler (IC5). Instead of water, the LNG stream is used as cooling medium in the interstage cooler 1,2, and 5. This leads to the relocation of the pre-purification unit. Now, this unit is placed after the first air compressor. The reason for this is, that using the LNG stream as cooling medium, the air can be cooled to a lower temperature in IC2 and IC5 and, thus, the power consumption within the AC2 and AC3 decreases. However, the impurities have to be removed

system	blocks					
	ACPB	MHE	СВ	NLB	PPPB	rest
Case A	AC1, AC2, IC1, IC2, AD, HE3	MHE	HPC, LPC, CD/REB, TV1, TV2, TV5, TV6	HE1, HE2, NC1, NC2, NC3, NC4, IC3, IC4, EXP1,EXP2, MIX1	NC5, OC, ICN, ICO	TV3, TV4
Case AD1	AC1, AC2, IC1, IC2, AD, HE3	MHE	HPC, LPC, CD/REB, TV1, TV2, TV5, TV6	HE1, HE2, NC1, NC2, NC3, EXP2	NC5, OC, ICN, ICO	HE4, TV3, TV4, LNGP
Case AD2	AC1, AC2, AC3 IC1, IC2, IC5, AD, HE3	MHE	HPC, LPC, CD/REB, TV1, TV2, TV5, TV6	HE2, NC1, NC2	NC5, OC, ICN, ICO	HE4, TV3, TV4, LNGP, MIX2
Case AD2S	AC1, AC2, AC3, IC1, IC2, IC5, AD, HE3	MHE	HPC, LPC, CD/REB, TV1, TV2, TV5, TV6	HE1, HE2, NC1, NC2, NC3, EXP2	NC5, OC, ICN, ICO	HE4, HE5, TV3, TV4, LNGP
Case B	AC1, AC2, IC1, IC2, AD, AC3	MHE	HPC, LPC, CD/REB, SUB, TV2, TV3	-	OP, NC5, ICN	EXP1, TV1
Case BD2S	AC1, AC2, IC1, IC2,IC5, AD, AC3	MHE	HPC, LPC, CD/REB, SUB, TV2, TV3	-	OP, NC5, ICN1, ICN2	EXP1, TV1, LNGP, WP, HE5

 Table 5.2: Components included in the different blocks of a system

before the air is cooled to a lower temperature in order to avoid their freezing, thus the adsorption process is placed after air compressor 1. The temperature at the outlet of IC2 and IC5 is set to -20 °C and -10 °C, respectively. The temperature at the outlet of the IC5 cannot be lowered, because otherwise the temperature at the outlet of compressor AC3 is below the temperature of the environment and this can lead to condensation of water vapor on the compressor case.

Since three compressors are used here, Equation 5.1 has to be adjusted to Equations 5.2 and 5.3 in order to get a minimal power consumption within each compressor.

$$p_{\text{int},1} = \sqrt[3]{(p_{\text{i},\text{AC}1})^2 \cdot p_{\text{o},\text{AC}3}}$$
 (5.2)

$$p_{\text{int},2} = \sqrt[3]{p_{\text{i},\text{AC1}} \cdot (p_{\text{o},\text{AC3}})^2}$$
(5.3)

In Case AD2S, a heat transfer medium cools the air in the IC1, IC2, and IC5. A mixture of water and ethylene-glycol ($C_2H_6O_2$) with a molar composition of $x_{H_2O}=0.4$ and $x_{C_2H_6O_2}=0.6$ is used. The heat transfer medium circulates between HE5, IC2, IC5, IC1, and HE4. The mass flow rate (30 kg/s) of this medium is set in order to enable the heating of LNG to ambient temperature.

In Case B, the air compression and purification is identical in comparison to Case A, except one additional air compressor (AC3). According to [86], 30 % of the cleaned air is fed to the AC3 and afterwards to the main heat exchanger. The remaining 70 % are directly cooled within the MHE. In the simulation, a split ratio before AC3 of 27 % is assumed. The air (stream 17) is compressed to 41.2 bar within AC3 and the oxygen vaporizes at 20 bar. The pressure of the air stream is in general higher than the pressure of the vaporizing oxygen stream [78, 86, 97]. In [97], the air is compressed to 73 bar while the typical range for the oxygen pressure is between 30 and 80 bar.

In Case BD2S, a further interstage cooler (IC5) is added to the air compression and purification block in comparison to Case B. Furthermore, the pre-purification block is relocated and placed after the IC1. As already explained for Case AD2S, the reason for this is that the air stream can be cooled to a lower temperature in IC2, because water and carbon dioxide are already removed which decreases the power consumption in the second air compressor. The temperature at the outlet of the IC2 is set to 5 °C. At the outlet of the IC5, the temperature of the air stream (stream 10) is set to 25.8 °C in order to keep the minimal temperature of the main heat exchanger roughly constant. In this system, the same heat transfer medium as in CAD2S is used which circulates between HE5, IC2, IC5, and IC1. The mass flow rate is set to 40 kg/s.

5.2.2 Main heat exchanger (MHE)

The air is liquefied within the main heat exchanger, which is a multi-stream heat exchanger. It is embedded in a so called cold box together with the column block in order to decrease the heat transfer from the environment.

For the main heat exchanger, the model *MHeatX* from AspenPlus [161] is used which can simulate multiple hot and cold streams. According to [111], the air is liquefied at a temperature level of -170 °C to -190 °C. Here, a temperature of -173.4 °C is assumed which is the corresponding saturation temperature at a pressure level of 5.6 bar. For the main heat exchanger, which is a sub-ambient heat exchanger, a pressure drop of 3 % is also assumed. This is equal to a value of 0.168 bar and corresponds to data available in the literature (1-3 % [109] and 0.1 bar [110]). For the minimal temperature difference, several values are available in literature. In [92] the minimal temperature difference amounts to 4.2 K, in [105] an approach temperature of 2.0 K is used, in [106] the minimal temperature difference amounts to 1.7 K after a pinch analysis was conducted. The value can also decrease to 0.4 K as mentioned in [83]. The minimal temperature difference results in 2 K for the systems related to Case A. In all analyzed cases related to Case A, the two gaseous product streams (oxygen and nitrogen) leave the main heat exchanger at ambient temperature.

In Case A, five streams (one hot and four cold streams) are integrated in the main heat exchanger. The hot stream is the inlet air stream which is cooled. The four cold streams are two gaseous nitrogen, one gaseous oxygen, and one waste nitrogen stream. The waste nitrogen stream is heated to 33 °C in order to reach a minimal temperature difference of 2 K.

In Case AD1, the main heat exchanger contains the air stream and one oxygen, one nitrogen, one waste nitrogen, and one LNG stream. Here, also the waste nitrogen stream is heated to 33 °C to reach a minimal temperature difference of 2 K.

In Case AD2, four cold streams (oxygen, nitrogen, waste nitrogen, and LNG) are heated while cooling the inlet air stream. Due to the modified air compression and purification block, the air enters the main heat exchanger with a temperature of 26.8 °C. In order to reach a minimal temperature difference of 2 K, the waste nitrogen stream is heated to a temperature of 24.8 °C.

In Case AD2S, the LNG stream is replaced by a second nitrogen stream which results in one hot stream and four cold streams within the main heat exchanger. The temperature of the waste nitrogen stream is set analog to Case AD2.

In Case B, three hot and three cold streams are fed to the main heat exchanger. The air (stream 11) is divided into two streams within the main heat exchanger. Around 28.1 % of the air mass flow rate leaves the main heat exchanger at a temperature of -120 °C. The share of this mass flow rate is slightly higher in comparison to the data available in literature. As given in [86], a mass portion of 10-20 % at a temperature of -100 to -130 °C is common for this stream. In [111], it is mentioned that the air is split at a temperature level of -140 °C and a part of this stream is fed to the expander.

The gaseous oxygen leaves the MHE at ambient temperature and the waste nitrogen has already been heated to $170 \,^{\circ}\text{C}$ within the MHE. This results in a minimal temperature difference of 2.7 K. The temperature of the nitrogen product streams is not fixed in the simulation. Thus, this stream leaves the MHE with a temperature of approximately 50 $\,^{\circ}\text{C}$.

In Case BD2S, the numbers of streams are equal to Case B. Due to the new interstage cooler in the air compression and purification block, the temperature of the air streams entering the MHE varies in comparison to Case B. Especially the air stream leaving the AC3 (stream 18) has a significantly lower temperature. As already stated in the explanation of the ACPB, the temperatures of stream 12 and 14 are defined in such a way that the minimal temperature difference amounts to 2.7 K. The different inlet temperatures result in a new outlet temperature of the gaseous nitrogen stream of approximately 20 °C.

5.2.3 Column block (CB)

The column block consists of a low- and high-pressure column whereby the condenser of the high-pressure column and the reboiler of the low-pressure column are thermally coupled (condenser/reboiler). The column block produces pure nitrogen and oxygen.

For the simulation of the columns the Aspen Model *RadFrac* is used, which is a rigorous model for the simulation of multistage vapor-liquid separation operations [161]. In contrast to modern plants, both columns are assumed to be sieve tray columns. In order to determine the theoretical stages for each column, a detailed literature review was conducted as shown in Table 5.3.

theoretic	cal stages	literature
LPC	HPC	
54	96	[92]
50	25^{4}	[93]
70	36	[100]
20	7	[101]
60	50	[106]
30	65	[123]
56	51	[168]
56	40	[169]
60	40	[170]

Table 5.3: Overview of the number of theoretical stages of the high- and low-pressure column

⁴equivalent stages, simulated as packed column

For the simulation of the column block in all analyzed cases, the number of theoretical stages was assumed to be 54 and 96 for the high- and low-pressure column, respectively.

The pressure of the high- and low-pressure column is around 5 bar and slightly above atmospheric pressure, respectively [82]. In order to assume a pressure drop, the values given in literature are compared. An overall pressure drop is reported as 0.05 bar and 0.1 bar for the high- and low-pressure column in [109]. In [110] a general pressure drop of 0.1 bar is given. An overall pressure drop of $\Delta p = 0.41$ bar and $\Delta p = 0.06$ bar for the high- and low-pressure columns, respectively, is mentioned in [93]. This leads to a pressure drop of 0.0082 bar per tray for the high-pressure column. The pressure drop of the low-pressure column is very small, because structured packings are used for the analysis. According to [77] and [171] the pressure drop over a sieve tray is between 0.003 bar and 0.005 bar and between 0.003 bar and 0.0065 bar, respectively. For the simulation a pressure drop of 0.003 bar per tray is assumed for the high- and low-pressure column. The temperature difference in the condenser/reboiler depends on the pressure on the top of the HPC and the bottom of the LPC and the corresponding saturation temperatures. In general, this value varies between 1 K and 2 K [77]. In [109] and [101], the minimal temperature amounts 1.5 K and 1 K, respectively. Here, the minimal temperature difference amounts 0.5 K in Cases A and AD1 and 0.49 K in Cases AD2 and AD2S.

In general, the distillate vapor fraction represents the ratio of the stream entering the condenser (stream V3) and the vapor stream leaving the top of the high-pressure column (stream V1). Figure 5.1 shows the vapor streams mentioned. The distillate vapor fraction is set in so that the required heat duty of the reboiler of the low-pressure column is equal to the rejected heat duty of the condenser of the high-pressure column.

parameter	value
high-pressure column	
stages	54
reflux ratio (mass basis)	0.75
distillate vapor fraction (mass basis)	0.65 ⁵ / 0.639 ⁶
low-pressure column	
stages	96
bottoms rate (kg/s)	0.5

Table 5.4: Parameters for the high- and low-pressure column, Cases A, AD1, AD2, AD2S

⁵CA and CAD1



Figure 5.1: Schematic of the top of the high-pressure column

The product streams of oxygen and nitrogen are either withdrawn from the top or bottom of the two columns. The top product of the low-pressure column is gaseous nitrogen with a molar composition of 99 mol-% [109]. The vapor oxygen is withdrawn from the bottom of the low-pressure column, while the liquid oxygen is withdrawn from the condenser/reboiler [100]. The liquid nitrogen stream is withdrawn from the top of the high-pressure column after the condenser [100].

In Case A, AD1, AD2, and AD2S the mass flow rate for the gaseous oxygen is set to 3 kg/s which corresponds to approximately 260 t/d. The mass flow rate of the gained liquid oxygen product stream is set to 0.5 kg/s for the same cases. At the bottom of the high-pressure column an oxygen-enriched liquid stream is withdrawn and fed to the low-pressure column. This stream contains 38 mol-% of oxygen according to [100] or of 35 to 40 mol-% of oxygen according to [170]. In Case A and Case AD1, the stream at the bottom of the high-pressure column consists of 39.8 mol-% and is in the range of the data obtained from literature. This value slightly changes in Case AD2 and AD2S to 39.3 mol-%, which still fits the range. From the high-pressure column two side streams are withdrawn and fed to the low-pressure column (stream 50 and stream 52). In addition, a part of the liquid nitrogen is fed to the low-pressure column as well. All streams which are fed from the lower to the upper column are throttled to the corresponding pressure of the entering trays. The mass flow rate of the waste nitrogen (stream 25) is typically in the range of 10 to 20% of the feed air flow according to [86]. Thus, the mass flow rate of stream 25 is set to 3.28 kg/s which corresponds to 20 % of the inlet air flow. For Cases A, AD1, AD2, and AD2S, all key parameters regarding the stages and the assumed mass flow rates of the streams entering and leaving the high- and low-pressure column are shown in Tables 5.5 and 5.6, respectively.

⁶CAD2 and CAD2S

	AD2S		
parameter	value	unit	
fee	ed stage		
stream 10	54	-	
stream 58	9	-	
prod	uct stage		
stream 11	54	-	
stream 30	1	-	
stream 54	1	-	
stream 52	18	-	
stream 50	16	-	
mass flow rates			
stream 52	0.5	kg/s	
stream 50	2.5	kg/s	

Table 5.5: Feed and product stages, and mass flow rates for the high-pressure column, Cases A, AD1, AD2,

 Table 5.6: Feed and product stages and mass flow rates for the low-pressure column, Cases A, AD1, AD2, AD2S

parameter	value	unit	
feed	stage		
stream 13	39	-	
stream 16/29 ⁷	1	-	
stream 57	1	-	
stream 51	20	-	
stream 53	80	-	
product stage			
stream 15	1	-	
stream 14	96	-	
stream 25	28	-	
stream 20	96	-	
mass flow rates			
stream 25	3.28	kg/s	
stream 20	3	kg/s	

⁷stream 29 in CAD1, CAD2, CAD2S 64

parameter	value	
high-pressure column		
stages	54	
reflux ratio (moll basis)	0.99	
distillate vapor fraction (mass basis)	0	
low-pressure column		
stages	96	
bottoms rate (kg/s)	3.5	

Table 5.7: Parameters for the high- and low-pressure column, Cases B and BD2S

In Case B and BD2S, the amount of produced gaseous and liquid oxygen is also set to 3 kg/s and 0.5 kg/s, respectively, in order to compare both air separation plants. The theoretical number of stages and the pressure drop are assumed to be the same as in Case A. Table 5.7 shows the key parameters for the high- and low-pressure column in Cases B and BD2S. The low- and high-pressure columns are also coupled by the condenser/reboiler, however, the number of side streams changed and, consequently, several parameters. Thus, the minimal temperature in the condenser/reboiler amounts to 0.6 K. The bottom product of the HPC has an oxygen content of 34.6 mol-% which is slightly lower in comparison to the data available in literature (35 to 40 mol-% of oxygen according to [170]). This stream is throttled and fed to the LPC. According to [86], the top product of the HPC is cooled in the subcooler (SUB) and is then throttled and fed to the LPC. The aim of the subcooler is decreasing the liquid fraction of stream 27 after the throttling which in turn increases the liquid nitrogen reflux to the low-pressure column and has a positive effect on the purity of the gaseous nitrogen stream. In the subcooler, the top product stream of the LPC is heated before it is fed to the MHE. The bottom product of the LPC is liquid oxygen which is divided into two streams. A part leaves the system as liquid stream while the remaining stream is fed to the oxygen pump (OP). The mass flow rate of the waste nitrogen amounts to 16.5 kg/s, which represents 49.3 % of the inlet air stream. This value is far higher compared to the given share of 10 to 20 % of the inlet air stream in [86]. However, a lower mass flow rate of the waste nitrogen significantly decreases the purity of the top product stream, and according to [172] the mass flow rate of the waste nitrogen has to be increased in order to get a higher purity. For Case B and BD2S, all key parameters regarding the stages and the assumed mass flow rates of the streams entering and leaving the highand low-pressure column are shown in Tables 5.8 and 5.9, respectively.

parameter	value	unit		
fee	feed stage			
stream 13	54	-		
stream 20	18	-		
prod	uct stage			
stream 21	54	-		
stream 23	1	-		

Table 5.8: Feed and product stages for the high-pressure column, Cases B and BD2S

Table 5.9: Feed and product stages, and mass flow rates for the low-pressure column, Cases B and BD2S

parameter	value	unit		
fee	feed stage			
stream 27	1	-		
stream 16	65	-		
stream 22	17	-		
prod	product stage			
stream 34	1	-		
stream 96	96	-		
stream 4	4	-		
mass	mass flow rates			
stream 37	16.5	kg/s		

5.2.4 Nitrogen liquefaction block (NLB)

The nitrogen liquefaction block is not mandatory for an air separation unit but can be added to an air separation unit in order to increase the amount and purity of the liquid products. According to [92], the nitrogen liquefaction block consists of four compressors with interstage cooling, two heat exchangers, and two expanders.

According to [92], the pressure at the outlet of NC3 and NC4 amounts to 36 bar and 46 bar, respectively. The pressure at the outlet of the according to [92]. Here, it is set to 38 bar, which is related to several facts, that have to be considered in parallel. First, NC3 is driven by EXP1 and NC4 is driven by EXP2, which means that the power generation of the two expanders have to be slightly higher than the consumption of the two compressors. The outlet pressure of EXP1 is fixed to the same pressure as stream 31 in order to decrease the exergy destruction within the mixing unit. Also the outlet pressure of EXP2 is fixed to the pressure of stream 31 plus the pressure drop

within HE2. The second parameter which determines the power generation in both expanders is the mass flow rate which is set by the splitting of stream 38 into stream 39 and 45. These facts together result in a pressure of 38 bar at the outlet of NC3. The inlet pressure of NC3 is set according to [92]. Finally, the pressure at the outlet of NC1 is determined with Equation 5.1, in order to minimize the power consumption of NC1 and NC2.

For HE1 and HE2 the model *MHeatX* is also used and the temperatures of the hot streams in HE1 and HE2 are set to $-130 \,^{\circ}$ C and $-150 \,^{\circ}$ C, respectively.

In Case AD1, the nitrogen liquefaction block only consists of three nitrogen compressors, two heat exchanger, and one expander (EXP2). The incoming stream (stream 30) from the top of the HPC enters directly the NLB instead of passing the MHE. In HE2, this stream is heated and afterwards mixed with a recycling stream (stream 44). The resulting stream is further heated in HE1. The interstage cooler between NC1 and NC2 is removed. The stream leaving the NC1 (stream 34) is instead cooled within HE3 and HE4 and fed back to the NLB. The pressure at the outlet of NC2 is determined in order to reach the same power generation in EXP2 and power consumption in NC3, because NC3 is again driven by EXP2.

In Case AD2, the number of components is even less compared to Case AD1. It consists of two compressors and one heat exchanger. In HE2, stream 30 (nitrogen, top of the HPC) and a part of the LNG stream (stream 41) are heated. The nitrogen stream is compressed to 46 bar within NC1 and NC2. The pressure between both compressors is determined using Equation 5.1.

In Case AD2S, the number of components is the same as in Case AD2 but arrangement of the streams has changed. This is due to the fact that in Case AD2S the entire LNG stream is heated in HE2 while in Case AD2 only a part of the LNG stream is heated. Consequently, the stream 30, is heated in the MHE and is then pressurized within NC1. The outlet pressure is again determined with Equation 5.1, in order to reach minimal power consumption within both compressors.

In Cases B and BD2S, the nitrogen liquefaction block is not included.

5.2.5 Product post-processing block (PPPB)

The product post-processing block contains the compressors for the oxygen and nitrogen product streams and the interstage coolers. These compressors are necessary in order to deliver the gaseous product streams at the required pressure level of the costumer.

The pressure of the gaseous products is set to 20 bar, but, as already mentioned, this value depends on the consumer. For example, in [105] the outlet pressure of oxygen amounts to 48 bar and the pressure of the nitrogen amounts to 1.15 bar, 25 bar, and 88 bar for the low-, medium-, and high-pressure nitrogen stream, respectively. In contrast, in [111], the gaseous product streams are not compressed before leaving the system. Electronic industries require pure nitrogen at a pressure

level of 7-10 bar [173]. In the two interstage coolers ICN and ICO the product streams are cooled to 20 °C as given in [174]. These four components are identical in Cases AD1, AD2, and AD2S.

In Case B, the external compression of the gaseous oxygen is replaced by an internal compression of the liquid oxygen via a pump. Due to the fact that the gaseous oxygen leaves the MHE at ambient temperature, an interstage cooler is not required. The gaseous nitrogen is still compressed in a compressor and afterwards cooled to $20 \,^{\circ}$ C in the interstage cooler.

In Case BD2S, the pressure of the gaseous oxygen is also increased in liquid state using an oxygen pump. The pressure of the gaseous nitrogen is still increased in the nitrogen compressor. Due to the integration of LNG regasification, an additional nitrogen interstage cooler is introduced. The gaseous nitrogen stream, leaving the MHE, is consequently first cooled in the ICN1 in order to decrease the power consumption in the NC5. Afterwards, the stream is compressed to 20 bar and cooled within ICN2 to a temperature of 20 °C using the LNG stream.

5.2.6 Additional components

In all systems, several additional components which cannot be assigned to one of the above mentioned blocks are used.

In Case AD1, an LNG pump is added to the system, where the LNG stream is pressurized to 20 bar. The LNG is compressed to the required pressure before it is regasified in order to keep the power consumption as low as possible. According to [48], the power consumption will be 20 times higher if the natural gas will be compressed after the regasification. The pressure of the regasified natural gas depends on the pressure of the gas grid and ranges from 30 bar, as given in [53], and between 50 to 100 bar, as given in [29]. For the Italian natural gas grid a pressure in the range of 70 bar is given in [48].

In order to vaporize and heat the LNG stream to ambient temperature an additional heat exchanger is required (HE4). Therefore, the outlet streams of NC5 and HE3 (stream 18 and stream 35) are used.

In Case AD2, an LNG pump and a heat exchanger (HE4) are also new components in comparison to Case A. In HE4, both gaseous product streams are used to vaporize and heat the LNG to ambient temperature.

In Case AD2S, a water pump and a heat exchanger (HE5) are added to the system in comparison to CAD2. The water pump is required to cover the pressure drops of the heat transfer medium in the heat exchangers. HE5 is added in order to vaporize and heat the LNG stream using the heat transfer medium.

In order to analyze the effect of the LNG pressure, a sensitivity analysis is conducted in Case AD2S. Due to the fact that a supercritical pressure of the LNG enables an improved heat transfer, different regasification pressure levels (of 20 bar, 40 bar, 60 bar, and 100 bar) are assumed.

In Case BD2S, an LNG pump is added to the system. Furthermore, a water pump and a heat exchanger (HE5) are required as in Case AD2S. The water pump overcomes the pressure drop of the heat transfer medium. For this system, the influence of the LNG pressure is also analyzed and the same pressure levels as in Case AD2S are assumed.

5.3 Assumptions for the exergy-based methods

To conduct the exergy-based methods presented in Chapter 3, several assumptions were set.

5.3.1 Conventional and advanced exergetic analysis

For the exergetic analysis, the temperature and pressure of the environment have to be defined. In this thesis, average European conditions are assumed and set to $T_0 = 15$ °C and $p_0 = 1.013$ bar. The model of Szargut is used [175] for the calculation of the chemical exergy.

For the advanced exergetic analysis, the technological limitations in order to determine the unavoidable exergy destruction were assumed for the turbomachines and heat exchangers. For the compressors and expanders, a value of the isentropic efficiency of 90% was selected as technological limitation. An isentropic efficiency of 80% was assumed as technological limitation for the pumps. For the heat exchangers the parameter that identifies the technological limitations is the minimal temperature difference in each heat exchanger, which was assumed to be 0.5 K. For the compressors, expanders, and heat exchangers the same technological limitations were reported in [130]. Dissipative components, throttling valves as well as the two columns are not considered for the advanced exergetic analysis.

5.3.2 Economic and exergoeconomic analysis

In order to conduct an economic analysis several general assumptions were set which are given in Table 5.10. Detailed assumptions for the estimation of the component costs are given in the Appendix C. In this thesis, all cost values are given in US \$ and refer to the year 2015.

The full load hours and plant life are set to 8,000 h/a and 20 a, which are also given in [106, 176]. In [177], it is given that the revision of air separation units accounts for 5 % of the year which is equal to a full load hour of 8,322 h/a. In [178], it is stated, that a brief shut down for inspection is

parameter	value
reference year	2015
full load hours (FLH)	8000 h/a
plant life	20 a
annual interest rate	10%
electricity costs	0.09 \$/kWh
LNG costs	0.005 \$/MJ
average general inflation rate (nominal)	0.025 1/a
average nominal escalation rate of electricity	0.035 1/a

Table 5.10: General assumptions for the economic analysis

done every year and a shut down of two weeks is done every five years for air separation plants. Both data are in the range of the assumed value of 8,000 h/a.

The estimation of the operating and maintenance costs is based on the total capital investment. For the first year, it is assumed that the operating and maintenance costs amount to 4% of the *FCI*.

The electricity costs are assumed based on data in [179–181]. The electricity costs for industry consumers for several European countries ranges from $0.079 \notin k$ Wh to $0.102 \notin k$ Wh depending on the annual electricity consumption. In [181], the electricity costs for the chemical industry are given in different European countries which ranges from $0.060 \notin k$ Wh to $0.165 \notin k$ Wh for gas processing manufactures. Beside the energy procurement costs also taxes, transportation, and distribution costs, and levies for renewable energies highly influence the overall electricity costs. These additional costs depends on the total annual power consumption and the legislation in the countries. A detail analysis of the additional fees especially for the chemical industry is also conducted in [181] which vary between $0.003 \notin k$ Wh and $0.093 \notin k$ Wh.

Finally, a value of 0.090 €/kWh is assumed which is equal to 0.090 \$/kWh ⁸. In [106], electricity costs of 0.150 \$/kWh (year 2015) are chosen, which is close to the assumed value. The costs for the LNG stream are taken from [3]. Here, LNG costs for the different market regions are mention which vary between 2.50 \$/mmBtu and 8.00 \$mmBtu. Thus, an average value of 5.25 \$/mmBtu is assumed which is equal to 0.005 \$/MJ.

5.3.3 Life cycle assessment and exergoenvironmental analysis

In order to conduct an exergoenvironmental analysis, the environmental impact of all streams entering the system as well as the component-related environmental impact have to be determined. According to [148], the environmental impact of the electricity is assumed to be 26 mPt/kWh. This

⁸exchange rate (2016): $1 \in \approx 1 \text{ US }$ \$

impact varies regarding the power mix of the country, where the ASU is located. The environmental impact of the entering LNG stream is obtained from [182] and amounts to 5.483 Pt/GJ. In order to solve the equations, the values are converted to a uniform unit and amounts to 7.22 mPt/MJ and 5.48 mPt/MJ for the electricity and LNG stream, respectively. The environmental impact associated with the entering air is set to 0 mPt/MJ.

The component-related environmental impact (\dot{Y}_k) is not considered in this thesis and consequently set to 0 mPt/h.

5.3.4 Risk-hazard and exergy-risk-hazard analysis

Due to the lack of data for the calculation of the risk related to oxygen-enriched streams, streams with low temperatures and oxygen deficient atmospheres, the exergy-risk-hazard analysis is not conducted for the air separation units. The general hazards related to ASUs are discussed in Section 6.1. Thus, the risk is only calculated for components which includes LNG streams. The following hazards related to LNG are considered in this thesis: jet fire, flash fire, and explosion.

In general, a fire might be possible if a a fuel and oxygen are present in a certain mixture and they are exposed to heat or an ignition source as shown in Figure 5.2. For natural gas ⁹, the combustible range amounts from 5 to 15 vol-% in the air [183]. In case of a spill of LNG a fire can result, whereby it is distinguished in either pool fire, jet fire or flash fire. The occurrence of the different fires depends on the type of ignition, the type of release and the pressure of the LNG stream [17]. Several possible scenarios are shown in the event-tree in Figure 5.3. According to this figure, a jet fire would occur if an LNG stream will be released under pressure. This can either take place in liquefaction or regasification plants. In case of an LNG spill, the released LNG would rapidly evaporate and this will result in a vapor cloud. In case the cloud reaches an ignition source, a flash fire will occur. In the event, that a flash fire burns up and downwind, and goes back to the LNG spill, a pool fire will result. A second possibility for a pool fire is the direct ignition of the LNG pool. Further hazards of an LNG spill are cryogenic burns or asphyxiation.



Figure 5.2: Fire triangle

9100 % methane



Figure 5.3: Event-tree for the release of LNG at atmospheric and elevated pressure (adopted from [184])

In this thesis, the specific risk associated with the incoming LNG stream, the air, and the electricity are set to 0 inj/MJ, because the analysis focuses on the risk associated with the process itself.

Probability of jet fire, flash fire, and explosion

The probability of a jet fire is the product of the probability of a leakage and the probability of ignition as shown in Equation 5.4. A flash fire or explosion occurs when a fluid leaves the system through a leakage which stays undetected and then the leaked fluid is ignited. The probability of flash fire and explosion are equal, thus a factor of 0.5 has to be considered. The estimation of the probability of a flash fire and a explosion is shown Equation 5.5. The probability of ignition for LNG amounts to $3 \cdot 10^{-5}$ 1/a [157], whereas for the probability of the late ignition a value of 0.1 1/a is given in [185].

The probability of leakage for several components is given in [157]. For the analysis a leak with a diameter higher than 1 mm is assumed. The probabilities are given for different diameter of the

pipeline. For all components, it is assumed that the diameter of the pipes amounts to 6" ($\hat{=}15$ cm) because a diameter of 5" to 11" and 11" to 17" is commonly used in the European gas network according to [186]. A more detailed design for gas pipelines is given in [187].

$$P_{\rm jf} = P_{\rm leak} \cdot P_{\rm ignition} \tag{5.4}$$

$$P_{\rm ff} = P_{\rm ex} = 0.5 \cdot P_{\rm leak} \cdot P_{\rm late-ignition} \cdot P_{\rm ignition} \tag{5.5}$$

Fatality of jet fire, flash fire and explosion

In order to estimate the fatality of a jet fire, flash fire, and explosion a mathematical model was developed in [188]. There the fatalities for the three accident scenarios are determined as a function of the distance of the accident scenario. The estimation of all three fatalities is based on the maximum distance, where one of the three mentioned accidents will cause injures.

For the estimation of the fatalities caused by a jet fire, the causative entity has to be determined which corresponds to the thermal radiation. The thermal radiation depends on the heat flow, the distance from the heat source, and the fraction of heat not absorbed by the atmosphere. In addition, it has to be assumed that the combustion of the jet fire is incomplete which leads to the use of a factor for the efficiency of the combustion. The efficiency varies from 19% to 34% for natural gas as given in [189]. In order to analysis the presence and absence of oxygen streams two different efficiency are assumed. For those component, where no oxygen is present in parallel to an LNG stream, an efficiency of 19% is assumed. In contrast, the efficiency increase to 34% if oxygen and LNG are placed within the same component. Using the Probit function of a jet fire and the Probit transformation given in [190], the fatality is determined.

In order to estimate the fatality of a flash fire, the amount of ignited gas from the leaked gas has to be determined. If gas is leaked, it can only form in a certain concentration a flash fire. Again, a mathematical model was developed [188] in order to determine the radiation and consequently the fatality using the Probit function.

For the estimation of the fatality of an explosion due to overpressure, first the amount of the ignited mass from the leaked mass is determined. The fatality is once again calculated using the Probit function for explosion as given in [190].

Chapter 6 Results and discussion

6.1 Air separation units

The stream data as well as the results of the exergetic, exergoeconomic, and exergoenvironmental analysis of all streams for Cases A and B are given in the Appendix A in Tables A.1 and A.2, respectively.

Energy analysis

The results obtained from the energy analysis are shown in Table 6.2. The total power consumption of Cases A and B amounts to 17.5 MW and 15.9 MW, respectively. Thus, the total power consumption decreases by 8.8 % from Case A to B. The specific power consumption per gaseous oxygen is $2.31 \text{ kWh/Nm}_{GOX}^3$ in Case A whereas it increases to $2.11 \text{ kWh/Nm}_{GOX}^3$ in Case B.

For both cases, the specific power consumption is higher in comparison to the data available in literature, as shown in Table 6.1, where the average value amounts to $0.35 \text{ kWh/Nm}_{GOX}^3$. The large difference between the data given and the results for Cases A and B has several reasons. First of all, for data given in literature it is not clearly stated whether the oxygen leaves the air separation unit at elevated pressure or at atmospheric pressure. Solely in [103] it is mentioned that the oxygen leaves the air separation unit with atmospheric pressure. Furthermore, in some publications the specific power consumption is reported per produced oxygen which also includes the liquid oxygen but it is not specified in detail. Another reason for the difference in the specific power consumption is the purity of the oxygen which may differ between 95 mol-% and 99.9 mol-%. The production of the liquid products also has a huge influence on the power consumption. In [105], the typical specific power consumption for the production of gaseous products is given as $6-7.5 \text{ kJ/mol}_{air}$. This value amounts to $30.8 \text{ kJ/mol}_{air}$ and $13.7 \text{ kJ/mol}_{air}$ in Cases A and B, respectively. A comparison of these data shows a large difference which is in particular related to the production of additional liquid products. Especially in Case A the power consumption is influenced by the refrigeration cycle

specific power consumption kWh/Nm $_{O_2}^3$	literature
0.28 - 0.30	[83]
0.464 - 0.639	[102]
0.25	$[103]^{10}$
0.253	[104]
0.36 - 0.50	[111]
0.238	[177]
0.35 - 0.57	[191]

Table 6.1: Specific power consumption values obtained from literature

Table 6.2: Results obtained from the energy analysis of the overall system, Cases A and B

system	$\dot{W}_{ m tot}$ MW	^W GOX kWh/kg _{GOX}	^W GOX kWh/Nm ³ _{GOX}
Case A	17.5 MW	1.62	2.31
Case B	15.9 MW	1.48	2.11

(nitrogen liquefaction block) which is used in order to increase the purity and the amount of liquid products. Finally, the production scale of the air separation plant influences the specific power consumption. Both simulated air separation units are a small-scale system which results in a higher specific power consumption. If only the power consumption associated with the air compressors (AC1 and AC2) is considered, the specific power consumption would amount to $0.467 \text{ kWh/Nm}_{GOX}^3$ in Case A. This value is close to the values in literature.

Another factor which influences the specific power consumption is the delivery pressure which is also discussed in [93]. Here it is mentioned that up to 59 % of the total power consumption is used for product compression. In Case A, the product compression requires 22.7 %, the air compression requires 20.2 %, and the nitrogen liquefaction block requires 57.1 % of the total power consumption. In Case B, the product compression amounts to 40 % which is caused by the high mass flow rate of gaseous nitrogen.

The mass flow rates of the product streams and their purities for Cases A and B are given in Table 6.3 and Figure 6.2, respectively. As already mentioned, the amount of gaseous and liquid oxygen is fixed for all simulations. In Case A, the liquid nitrogen is set to be 70 % of the condensed stream leaving the HPC. The remaining 30 % enters the LPC. The comparison of the product streams shows an increase of the gaseous nitrogen stream by a factor of two in Case B, but the inlet air stream was also doubled. The purities for the four product streams range from 97.0 mol-% to



Figure 6.1: Power consumption/generation, Cases A and B

system	<i>ṁ</i> GOX	<i>ṁ</i> GAN	<i>ṁ</i> LOX	<i>ṁ</i> LN
	kg/s	kg/s	kg/s	kg/s
Case A	3.00	6.85	0.50	2.65
Case B	3.00	13.27	0.50	0.00

Table 6.3: Mass flow rates of the product streams, Cases A and B

98.0 mol-% for the oxygen streams, and are 99.0 mol-% for the nitrogen product streams in Case A. In Case B, the purities for the liquid and gaseous oxygen stream amount to 99.9 mol-%. The gaseous nitrogen stream has a molar composition of 98.5 mol-%. The comparison of the purities shows an increase in the purity for the two oxygen streams and a small decrease of the purity for the gaseous nitrogen stream. The increase of molar composition of the oxygen stream is equal to 3%. Even if this seems to be a small increase, it has a huge influence on the further usage of the oxygen, because high quality oxygen is used for other applications as oxygen with a purity of 97 mol-% due to the different requirements for the quality.

Conventional exergetic analysis and advanced exergetic analysis

The results obtained from the exergetic analysis for the overall system are shown in Table 6.4. The exergetic efficiency of Case A amounts to 28.4 % while it increased to 31.1 % in Case B. The comparison of the exergetic efficiency exhibits an increase of 9.5 % from Case A to Case B. This



Figure 6.2: Purity of the product streams, Cases A and B

is related to the structural changes of the different product compression units and the associated thermodynamic parameters. An exergetic efficiency of a single air separation unit of 26.6 % is reported in [110] which is in the same range as the exergetic efficiencies of Cases A and B. The exergy of product is almost equal in Cases A and B, which means that the double amount of the gaseous nitrogen compensates the product stream of the liquid nitrogen which is not available. Comparing the exergy destruction of the overall system, it can be stated that the exergy destruction is lower in Case B. The higher exergy loss in Case B in comparison with Case A is related to the significantly increased mass flow rate of the waste nitrogen in order to archive gaseous nitrogen with high purity. For the improvement of air separation units new opportunities for the use of the waste nitrogen are of particular interest, which are discussed in [109].

In [130], the exergetic efficiency for some components of the integrated air separation and power generation cycle is given. However, from the ASU only an exergetic efficiency of 57.2% for the MHE is reported. In contrast, an exergetic efficiency of 94.3% for the MHE is given in [110]. In Cases A and B, it amounts to 73.1% and 78.1% respectively. The results obtained for Cases A and B are in the range of the two mentioned values in literature. The specific exergy destruction within the cold box which includes the MHE, the HPC, the LPC, and the TVs between the two columns typically lies in the range between 1.6 kJ/mol_{air} and 2 kJ/mol_{air} according to [105]. The specific exergy destruction within the cold section is calculated for both cases and amounts to 2.8 kJ/mol_{air} and 2.9 kJ/mol_{air} for Cases A and B, respectively. The difference can be led back to



Table 6.4: Results obtained from the exergetic analysis of the overall system, Cases A and B

Figure 6.3: Exergy destruction within the components, Cases A and B

the different sizes of air separation plants and the consequently higher specific exergy destruction for a small-scale system.

Figure 6.3 shows the exergy destruction within the selected components. In Case A, the IC3, HE1, MHE, and ICN have the highest exergy destruction. The IC3 and HE1 are both located in the nitrogen liquefaction block. Consequently, the nitrogen liquefaction block has the highest exergy destruction among all other blocks of components as shown in Figure 6.4, where the exergy destruction ratio amounts to 60.1 %. The exergy destruction ratio of the other blocks varies between 4.8 % and 12.0 %. In Case B, the ICN has the highest exergy destruction, followed by the LPC and the MHE. The block with the highest exergy destruction ratio is the product post-processing block which also contains the ICN.

Figure 6.4 shows typical ranges for the exergy destruction ratio obtained from data available in [92, 105, 106, 109, 111, 192]. For the evaluation of this diagram, it is important to mention that the exergy destruction within the components and, consequently, the exergy destruction ratios are affected by the production scale and the structure of air separation units. Nevertheless, this figure gives an overview of the lowest and highest value for the exergy destruction ratio of the component blocks and the results of Cases A and B. The results of both systems for the main heat exchanger and column block are within the range or close to the minimum values. For the product post-processing block and the nitrogen liquefaction block, each value was only reported in one paper ([105] and [92]). In Figure 6.4, the results for Case A and the data obtained from literature are close to each other, because the air separation system proposed by [92] is the base for the simulation of Case A. For the air compression and purification block, the exergy destruction ratio in Case A is significantly lower than the lowest value obtained from literature. In contrast, for Case B, the exergy destruction ratio for the air compression and purification block is close to the minimal value. The exergy destruction ratio of the product-post processing block is significantly higher than the value obtained from literature. However, only one literature source reported the exergy destruction ratio of the product-post processing block, hence it is not meaningful. A comparison of the exergy destruction ratios of the component blocks shows the high influence of the system's structure. In Case A, the ACPB has an exergy destruction ratio of 10.5 % whereas it increased to 26.1 % in Case B. The lowest value obtained from literature amounts to 31.0 %. This demonstrates that the increased air pressure, the additional air compressor, and the higher feed air stream result in a higher exergy destruction ratio which is closer to the value reported in literature.

Figure 6.5 shows the results obtained from the advanced exergetic analysis (Section 5.3). Dissipative components, throttling valves as well as the two columns are not considered for this analysis.

In Case A, the HE1, which is the component with the highest exergy destruction, has only a small potential for improvement. The share of the avoidable exergy destruction represents 15%. In contrast, the share of the avoidable exergy destruction of the main heat exchanger amounts to 43.3%. HE3 has the largest potential for improvement with a share of the avoidable exergy destruction of 78.6%. The reason for this is related to the function of the HE3. This heat exchanger is required for heating the waste nitrogen stream to 170 °C, but the nitrogen stream used has a temperature of 420 °C. Thus, in general the waste nitrogen can be heated to a higher temperature to improve the performance of this heat exchanger. Due to the fact, that the share of the avoidable exogenous exergy destruction of the HE3 amounts to 55.1%, especially the improvement of the other components would lead to a reduction of the exergy destruction within this heat exchanger. In addition, the results of the advanced exergetic analysis of the HE2 are important. Even if this component has only the fourth highest exergy destruction, it has a share of the avoidable exergy



Figure 6.4: Exergy destruction ratio within the component blocks in Cases A and B in comparison to data available in literature

destruction of 62% whereby more than 40% of it can be avoided if the parameters within the remaining components are adjusted. The turbo-machines have a share of the avoidable exergy destruction of around 35%. For all components in Case A, the avoidable exogenous exergy destruction is higher than the avoidable endogenous exergy destruction which means that in order to reduce the exergy destruction within a component particularly the remaining components have to be improved. In Case B, the main heat exchanger, which is by far the component with the highest exergy destruction, has only a share of the avoidable exergy destruction amounts to 43%. In order to reduce the exergy destruction within the main heat exchanger, the remaining components have to be improved, because the part of the avoidable exergy destruction is higher than the avoidable exergy destruction is higher than the avoidable exogenous exergy destruction amounts to 43%. In order to reduce the exergy destruction within the main heat exchanger, the remaining components have to be improved, because the part of the avoidable exogenous exergy destruction is higher than the avoidable exogenous exergy destruction is higher than the exoidable exogenous exergy destruction is higher than the avoidable endogenous exergy destruction. The results of the advanced exergetic analysis of the turbo-machines show similar results for Case B as for Case A. In Case B, the share of the avoidable exergy destruction also amounts to 35%.



Figure 6.5: Results obtained from the advanced exergetic analysis, Cases A and B

Economic analysis and exergoeconomic analysis

A detailed estimation of the component costs is given in the Appendix C.

Table 6.5 shows the results of the bare module costs for the component blocks. The percentage shares are graphically shown in Figure 6.6 for Cases A and B. The total bare module costs amount to around $29 \cdot 10^6$ \$ in both cases. The distribution of the costs demonstrate that the column block accounts for 45 % of the total bare module costs in Case A. The nitrogen liquefaction block is responsible for one third of the total bare module costs. The air compression and purification block, the product post-processing, and the main heat exchanger have a significant lower share. In Case B, the share of the cost for the column block increases and accounts to 63.9 % of the total component costs, followed by the air compression and purification block with a share of 17.4 %.

A comparison of the results obtained from the economic analysis in Cases A and B shows an increase of the total capital investment of 1.8 %. A more detailed comparison on the component level shows that the costs of the main heat exchanger increased significantly in Case B and are twice as high as in Case A. The main reason for the increased costs of the main heat exchanger are related to the higher heat duty in Case B, and, consequently the higher heat transfer area. In Case B, the bare module costs of the air compression and purification block and column block increased by around 70 % and 45 %, respectively. Especially the third air compressor within the air compression block is responsible for the increased costs. The bare module costs for the column are higher for Case B, because the diameter of the column shell increased slightly due to the higher mass flow rates in Case B.


Table 6.5: Bare module costs for the component blocks, Cases A and B

Figure 6.6: Distribution of the bare module costs among the component blocks, Cases A and B

Table 6.6 shows the results for the *FCI*, *TCI*, and the specific investment costs per exergy of product for Cases A and B. Detailed calculations of the fixed capital investment for Cases A and B are given in Appendix C in Tables C.36 and C.37, respectively. Tables C.38 and C.39 show the detailed calculations of the total capital investment for Cases A and B, respectively.

The specific investment costs amounts to $8.97 \cdot 10^3$ \$/kW_{*E*_p} and $9.14 \cdot 10^3$ \$/kW_{*E*_p} in Cases A and B, respectively, as given in Table 6.6. In order to compare the results obtained from the economic analysis with data available in literature, the specific investment costs per gaseous oxygen are calculated for both systems. These values amount to $0.173 \cdot 10^6$ \$/t_{GOX}/d and $0.176 \cdot 10^6$ \$/t_{GOX}/d for Cases A and B, respectively. Both values are close to the curve shown in Figure 6.7 which shows the specific investment costs of some air separation units for the reference year 2015. The specific investment costs decrease significantly with increasing production rate of gaseous oxygen which correspond to the economies of scale. For a small-scale plant with approximately 200 t/d, the costs are ten times higher compared to a plant with an oxygen production of 2,000 t/d.

The levelized carrying charges, the operating and maintenance costs, the fuel costs, and the total revenue requirement are given in Table 6.7.



Table 6.6: Fixed and total capital investment costs, Cases A and B

Figure 6.7: Specific investment costs depending on the oxygen production (values obtained from (A) [193], (B) [194], (C) [195], (D) [196], (E) [197], (F) [198], (G) [199])

 Table 6.7: Levelized carrying charges, operating and maintenance costs, fuel costs, and total revenue requirement, Cases A and B

	<i>СС</i> _L 10 ³ \$/а	<i>ОМС</i> _L 10 ³ \$/а	<i>FC</i> _L 10 ³ \$/a	<i>TRR</i> 10 ³ \$/a
Case A	5,256	1,864	17,771	24,891
Case B	5,352	1,898	16,182	23,432

Table 6.8: Results obtained from the exergoeconomic analysis of the overall system, Cases A and B

	Ċ _{F,tot} \$/h	Ċ _{P,tot} \$/h	Ċ _{D,tot} \$/h	Ż _{tot} \$/h	Ċ _{L,tot} ¹¹ \$/h	с _F \$/МЈ	с _Р \$/МЈ	r _{tot}	f _{tot}
Case A	2,223	2,976	1,566	890	136	0.035	0.173	3.92	0.36
Case B	2,555	2,766	1,613	906	696	0.044	0.193	2.49	0.36

¹¹are already included in costs associated with the exergy of the overall product



Figure 6.8: Specific costs of the product streams, Cases A and B

The results of the economic analysis are used in order to conduct the exergoeconomic analysis. Table 6.8 shows the results for the overall systems obtained from the exergoeconomic analysis. The total specific product costs amount to 0.173 \$/MJ and 0.193 \$/MJ in Cases A and B, respectively. A comparison shows an increase of the specific product costs of 11 % from Case A to Case B. A reason for this increase is the huge increase of the cost rate associated with the exergy loss in Case B. While this value amounts to 136 \$/h in Case A, it increases to 696 \$/h in Case B, due to the large mass flow rate of the waste nitrogen stream.

The specific costs of the product streams are given in Figure 6.8. In both cases, the specific costs of the gaseous nitrogen stream are the lowest costs, followed by the specific costs of the gaseous oxygen. The specific costs for the liquid product streams are significantly higher. In Case A, the costs of the liquid oxygen and nitrogen are 31 % and 40 % higher than the gaseous products, respectively. The specific costs of the liquid oxygen are twice as high as the specific costs of the gaseous oxygen in Case B. A comparison of both systems shows that the specific costs of the gaseous nitrogen and the liquid oxygen are close to each other. In contrast, the specific costs of the gaseous oxygen are approximately one third higher in Case B than in Case A.

Only a few publications mention costs, which complicates the validation of the results obtained from the exergoeconomic analysis. In [106], costs of 0.050 \$/kg and 0.020 \$/kg are assumed for the



Figure 6.9: Costs of oxygen depending on the size of the plant size (adopted from [201])

oxygen and nitrogen, respectively. General production costs in the range of 0.040 \$/kg to 0.070 \$/kg are given in [178]. The product costs of the gaseous streams are close to these ranges. In general, it has to be considered that the costs of the products highly depend on the size and location of the plant, thus, for small amounts of liquid nitrogen the costs can easily increase to approximately 1.2 \$/kg [200]. The influence of the size of the plant is also shown in Figure 6.9 where a range of 0.027 to 0.034 \$/kg is given for an air separation plant with a production rate of 200 t/d. Even if these data are already a few years old, they can be used in order to get the magnitude of the costs.

Figure 6.10 shows typical ranges for the costs of the gaseous and liquid products [200] and the results obtained from the exergoeconomic analysis of Cases A and B. The results are except for the liquid oxygen in the range or close to the range of the given data.

The cost rates associated with the eight most important components are shown in Figure 6.11 for Cases A and B. In Case A, the HE1 is the component with the highest cost rate while especially the cost rate associated with the exergy destruction outweigh. The MHE and the IC3 have the second and third highest cost rates. For these two components, the cost rates associated with the exergy destruction are also significantly higher as the cost rate associated with the investment and operating and maintenance costs. For the improvement of the system it can be concluded that all three heat exchangers have to be improved from the thermodynamic point of view in order to decrease the cost rates associated with the exergy destruction. Only for the two columns, the cost



Figure 6.10: Specific costs of the product stream in Cases A and B in comparison to data available in literature

rates associated with the investment and operating and maintenance costs are higher than the cost rates associated with the exergy destruction.

In Case B, the main heat exchanger has the highest cost rate, followed by the nitrogen interstage cooler and the two columns. For the two heat exchangers, the cost rates associated with the exergy destruction outweigh, while for the two columns the costs associated with the investment, maintenance, and operation are higher. These relations are also indicated by the given exergoeconomic factor on top of each column.

For the exergoeconomic analysis, two sensitivity analyses are conducted to evaluate the effect of (a) the costs associated with the components (\dot{Z}_k), and (b) the cost of electricity (c_{el}). In both analyses the lower value is assumed to be 70 % of the basic value which represents an overestimation of the basic value. The higher value is assumed to be 130 % of the basic value which represents an underestimation approach. Figure 6.12 show the results of the sensitivity analyses for the product streams for Cases A and B. The difference on a percentage basis between the basic value (\dot{Z}_{ref} or $c_{el,ref}$) and the overestimation and underestimation approach are shown in Table 6.9. The specific product costs of the overall systems are more effected by the electricity costs than by the investment costs. For both systems, the specific product costs increase by approximately 20 % if the electricity costs are underestimated by 30 %. An underestimation of the investment costs by 30 % solely results in an increase of approximately 8 % of the specific product costs. As shown in Figure 6.12, the gaseous nitrogen is mostly affected by the electricity costs in Case A. The specific product costs

Chapter 6 Results and discussion



Figure 6.11: Total cost rates associated with the components, Cases A and B (on top of each column the corresponding f value is given)

increase or decrease by 22.4,% in the case of an underestimation or overestimation of the electricity costs by 30%.

In Case B, the specific product costs of the gaseous nitrogen are 23 % higher in case the electricity costs are underestimated by 30 %. An increase of the cost rate associated with the investment, maintenance and operation by 30 % results in higher product costs of the gaseous nitrogen by 7 %. For the two oxygen streams, the specific product costs decrease by approximately 21 %, in case the electricity costs are overestimated by 30 %. An underestimation of the electricity costs by 30 % leads to an increase of the specific product costs of 21 %. In contrast, a varying cost rate associated with the investment, maintenance and operation by 30 % affects the specific product of the oxygen streams by 9.3 %.

A comparison of the results obtained of the sensitivity analysis for the exergoeconomic analysis shows similar results for Cases A and B. In both systems, the effect of an under- or overestimation of the electricity costs has a significantly higher influence on the product costs than the cost rate associated with the investment, maintenance and operation. As given in [82], 33 % to 59 % of the operational expenses (sum of operating and maintenance costs and fuel costs) are caused by the fuel costs. The dependency of the oxygen costs on the capital investment and the fuel costs is also shown in Figure 6.13. For an air separation plant with an oxygen production rate of approximately 200 t/d, the costs of the oxygen are composed by 45 % of the fuel costs, by 30 % of investment costs, and by 35 % of other costs. For air separation plants with higher capacity the influence of



Figure 6.12: Sensitivity analysis - Specific costs of the product streams, Cases A and B

	$\Delta c_{ m GOX} \ \%$		Δc_{q}	$\Delta c_{ m GAN} \ \%$		$\Delta c_{ m LOX} \ \%$		N
	CA	CB	CA	CB	CA	CB	CA	CB
70 % of Ż _{ref}	-9.1	-9.4	-7.6	-7.0	-9.7	-9.2	-8.8	-
130 % of Ż _{ref}	9.2	9.4	7.5	7.0	9.7	9.1	8.8	
70 % of $c_{el,ref}$	-20.8	-20.6	-22.5	-23.0	-20.3	-20.8	-21.2	-
130 % of $c_{el,ref}$	20.9	20.6	22.4	23.0	20.3	20.8	21.2	

Table 6.9: Sensitivity analysis - Difference in the costs of the product streams, Cases A and B

the fuel costs is even higher and increase to a share of 70% if the oxygen production amounts to 2,000 t/d. Also in [172], the total capital investment costs make 30 to 40% of the final product costs, which also demonstrates that the remaining 70% to 60% of the product costs are caused by the fuel costs and other costs whereby the cost associated with power consumption significantly outweigh.

Life cycle analysis and exergoenvironmental analysis

The environmental impact of air separation units is discussed in [202]. Due to the fact that the feedstock of an air separation system is ambient air and no chemical reaction occurs within the plant, the waste and purge streams solely consists of components which were originally present in



Figure 6.13: Distribution of the oxygen costs depending on the oxygen production rate (adopted from [201])

the air. The most important environmental impact is associated with the electricity consumption since air separation units are an energy-intensive process. Furthermore, impacts include the use of cooling water and oil as well as the noise of compressors, pumps, and venting of tanks.

Table 6.10 shows the results for the overall system obtained from the exergoenvironmental analysis. The specific environmental impact associated with the exergy of the overall product amounts to 25.3 mPt/MJ in Case A and 29.1 mPt/MJ in Case B. The environmental impact of the four product streams is given in Figure 6.14. The liquid product streams have the most significant environmental impacts which amount to 21.4 mPt/kg for the liquid oxygen and 19.0 mPt/kg for the liquid nitrogen in Case A. In the same system, the environmental impact of the gaseous streams is significantly lower. The gaseous oxygen stream has an impact of 8.2 mPt/kg. Thus, the environmental impact of the gaseous oxygen decreases by 62 % in comparison to the environmental impact of the liquid oxygen. The comparison of the environmental impact of the nitrogen streams shows a decrease of 68.6 % from the liquid nitrogen stream to the gaseous nitrogen stream. In Case B, the gaseous nitrogen has the lowest environmental impact which accounts to 7.2 mPt/kg. The environmental impact of the liquid oxygen is twice as high as the gaseous oxygen.

In [148], the environmental impacts for oxygen as well as nitrogen amount to 12 mPt/kg. A comparison of these values with the data obtained from Case A shows that the environmental impact for the gaseous oxygen is 32 % lower in Case A as given in [148]. The value for gaseous nitrogen is twice as high as the value given in [148]. The environmental impact of the two liquid products is significantly higher. The impact of the liquid oxygen and nitrogen increases by 58 % and 78 %, respectively.

A comparison with data obtained from [148] with the results of Case B shows, that the environmental impact of the gaseous oxygen exactly matches this value. The environmental impact of the gaseous nitrogen is slightly lower than the value given in literature, in contrast the environmental impact of the liquid oxygen is significantly higher.

A comparison of the environmental impact of Cases A and B demonstrates that the environmental impact of the product streams is higher for Case B. While the environmental impact of the liquid oxygen increased by 15 % for Case B, the environmental impact of the gaseous nitrogen increased by 20%. The highest rise is obtained for the gaseous oxygen which amounts to 54%.

Table 6.1	0: Results	obtained	from th	e exergoe	environ	mental anal	ysis of the c	overall syste	m, Cases	s A and B
		<i>İ</i> B _{F,tot} Pt/h	<i>B</i> _{P,tot} Pt/h	<i>B</i> _{D,tot} Pt/h	Ÿ _{tot} Pt∕h	$\dot{B}_{\rm L,tot} \stackrel{12}{}_{\rm Pt/h}$	b _F mPt/MJ	b _P mPt/MJ	r _{b,tot}	
	Case A Case B	455 523	455 523	321 330	0 0	19 98	7.2 9.1	25.3 29.1	2.52 1.62	



Figure 6.14: Specific environmental impact of the product streams, Cases A and B

¹²are already included in environmental impact associated with the exergy of the overall product

Risk-hazard analysis

As already mentioned, the exergy-risk-hazard analysis cannot be applied to the air separation units. However, general hazards related to air separation units are discussed in order to emphasize the importance of this kind of analysis.

In general, air separation units have different potential hazards due to the presence of pure oxygen or oxygen-enriched streams at low temperature. According to [203], the main hazards are rapid oxidation, embrittlement, pressure excursions due to vaporizing liquids, and oxygen-enriched or deficient atmospheres. In [178], the hazards related to liquid air, oxygen, and nitrogen are distinguished in three different areas (physiological, physical, and chemical). Hazards like frostbite or asphyxiation belong to the physiological hazards. Physical hazards are related to low temperature, high pressure, and oxygen enrichment, while the chemical hazards include oxidation, flammability, fire, and explosion. In [96, 204] the trace contaminants of air are classified into different categories of problems. These problems are plugging, flammable or reactive, and corrosive contaminants of the air. Water, carbon dioxide and nitrous oxide belong to the plugging contaminants. At low temperature, these components form solid particles and can partially or totally block components which can lead to serious hazards. The next group contains reactive components which are in particular hydrocarbons, as for example CH₄, C₂H₂, C₂H₄. Components as for example SO₂, SO₃, H_2S , Cl_2 belong to the group of corrosive components which can react with the process equipment and can lead to serious hazards. Even if these particles have a concentration of less than 1 vppm in industrial air, they can be responsible for dangerous problems and cannot be ignored for the operation of an air separation plant.

In the pre-purification unit of an air separation unit, most of these components are in general removed by 100% [96]. In case contaminants, especially hydrocarbons, enter the column block of the ASU, they concentrate in the liquid oxygen in the sump of the low-pressure column. To avoid a high concentration of these impurities in the LOX, a mass flow rate of 0.1% to 0.2% of the incoming air of liquid oxygen must be withdrawn from the reboiler, even if liquid products are not required [204]. In [77] it is mentioned, that 0.5% of the generated liquid oxygen have to be continuously withdrawn to avoid the accumulation of hydrocarbons in the liquid phase.

Another hazard is represented by the oxygen compressor in air separation units with external compression unit. In this component, pure oxygen is compressed to high pressure and the moving parts of the compressor might be an ignition source. In addition, oxygen compressors require special lubricants which are non-flammable. Usually, mineral oil and grease are composed of hydrocarbons which could oxidize with the oxygen. This in turn could lead to high temperatures and a self-ignition. For this reason, the lubricant for oxygen compressor must be oil and grease-free [205]. According to [206], the lubricants used for oxygen compressors are halogenated fluids.

effects
normal
some adverse physiological effects occur, which are not noticeable
increased pulse and breathing rate, impaired thinking and attention, reduced coordination
abnormal fatigue upon exertion, emotional upset, faulty coordina- tion, poor judgment
very poor judgment and coordination, impaired respiration that may cause permanent heart damage, nausea and vomiting
inability to perform various movements, loss of consciousness, convulsions, death

Table 6.11: Effects of oxygen-deficient atmosphere on the human body (data adopted from [202])

As already mentioned, other risks related to air separation plants are an oxygen concentration below or above the acceptable range for humans and the consequences of a frostbite. Table 6.11 shows the effect on the oxygen deficient concentration on the human body. Nitrogen itself is non-toxic and will not burn or explode, but it is risky if it is present in high concentrations which reduces the oxygen levels within a space. The minimum acceptable concentration of oxygen in a room is 18 %.

The data available for hazards that take place in air separation units is quite unsatisfactory. A survey of accidents in air separation units in Japan [207] classified the hazard potential into explosion, bursting, burn, frostbite, and suffocation. The study was conducted for the time period between 1930 and 1963 where in total 48 accidents happened. As reported in the study, the component that exhibits the highest probability for accidents is the reboiler with 50% of the accidents, followed by the main heat exchanger with 12.5 %. The reboiler has such a high risk of accidents because, as already mentioned, liquid oxygen is boiled and hydrocarbons are accumulated in the liquid oxygen. In the 1950s, several accidents like small fires or even fatal explosions happened. This led to an increase in safety considerations and, finally, to the formation of several gas associations which offer detailed explanations about the safety related to air separation units (European Gas Association [202]). In 1997, an explosion happened in an air separation unit in Malaysia which is discussed in detail in [208]. This plant supplies oxygen to the nearest Shell gasification plant. The cause for this explosion were airborne particulates which passed the main air purification system. These combustible substances accumulated in the vaporizer of the distillation column and led to an aluminum combustion which was detected after some fragments were analyzed. This accident caused 12 injuries, but none were serious.

According to [78], Case B would have a lower risk due to the replacement of the oxygen compressor by the oxygen pump. The oxygen compressor used in Case A has quite a high potential for hazards, because the increase of the pressure results in a significantly lower ignition temperature of steel or iron.

6.2 LNG regasification integrated into air separation units

The stream data as well as the results of the exergetic, exergoeconomic, and exergoenvironmental analysis of all streams for Cases AD1, AD2, AD2S, and BD2S are given in Appendix A in Tables A.3, A.4 A.5, and A.6 respectively. The results obtained from the exergy-risk-hazard analysis of all streams for Cases AD1, AD2, AD2S, and BD2S are given in Tables A.7, A.8 A.9, and A.10, respectively.

Energy analysis

The results obtained from the energy analysis of Cases AD1, AD2, AD2S, and BD2S are shown in Table 6.12. The power consumption amounts to 13.4 MW, 8.6 MW, and 8.7 MW, for Cases AD1, AD2, and AD2S, respectively. In comparison to Case A, the power consumption decreases by approximately 22 % in Case AD1. In Case AD2 and AD2S, the power consumption decreases by 51 % and 50 %, respectively. These values correspond to the data available in literature, where a decrease of the power consumption of around 50 % [9, 178] to 66 % [115] is given. However, a significantly lower value of the power reduction of 8 % was reported in [129]. Due to the constant amount of gaseous oxygen production, the specific power consumption also decreases in Cases AD1, AD2, and AD2S.

Case BD2S has a total power consumption of 11.6 MW which corresponds to a decrease of 27 % of the power consumption compared to Case B. Thus, this integrated system shows a lower reduction in the power consumption than Case AD2S.

system	$\dot{W}_{ m tot}$ MW	^W GOX kWh/kg _{GOX}	^W GOX kWh/Nm ³ _{GOX}
Case AD1	13.6	1.26	1.80
Case AD2	8.6	0.79	1.13
Case AD2S	8.7	0.81	1.15
Case BD2S	11.6	1.07	1.54

Table 6.12: Results obtained from the energy analysis, Cases AD1, AD2, AD2S, and BD2S

Figure 6.15 shows the power consumption and generation of selected components within the four discussed systems. The results of the three air compressors show a decrease of the power consumption of AC1 and AC2 in Cases AD2 and AD2S. The decrease of the power consumption in AC1 and AC2 is a consequence of the changed arrangement of the air compression and purification block and the integration of the LNG stream within the interstage coolers of the air. In Cases AD2 and AD2S, the purification block is directly located after the IC1 which means that water and carbon dioxide are already removed before the air enters the IC2. Consequently, the air is cooled to a lower temperature in IC2 and IC3 which leads to a lower power consumption in AC2 and AC3. The rearrangement of the nitrogen liquefaction block leads to a significant decrease of the power consumption of NC1 and NC2 in Cases AD2/S in comparison with Case AD1.

In Case BD2S, the structural changes related to the integration of the LNG stream also lead to a decrease in the power consumption of the AC2 and AC3. The highest decrease in the power consumption of more than 60 % is reached in the NC5. This is also related to the integrated LNG stream and the new interstage cooler (ICN1) which is located before the compressor in order to decrease the power consumption.

A comparison of Cases AD2S and BD2S shows a significantly higher power consumption within the air compressors in Case BD2S. This is caused by two facts, first of all the feed air stream in Case BD2S is twice as much as in Case AD2S. Secondly, the outlet pressure of the AC3 amounts to 41.2 bar in Case BD2S while the air is compressed to 5.7 bar in Case AD2S. However, the different outlet pressures are related to the two configuration of air separation units (Case A and B) which are used as a base for the LNG integration.

The mass flow rates of the product streams as well as their purities are given in Table 6.13 and Figure 6.16. Table 6.13 also includes the mass flow rate of the regasified LNG. The product streams of the gaseous and liquid oxygen are set constant for all systems, as already mentioned in Chapter 5. The mass flow rate of the gaseous nitrogen is slightly higher for Cases AD2 and AD2S in comparison with Case AD1. This small increase is responsible for the slightly higher power consumption of NC5 in Cases AD2 and AD2S in comparison with Case AD1. The higher feed air stream leads to an increase of the gaseous nitrogen stream which is twice as high in Case B than in the systems related to Case A. In Case BD2S, the amount of regasified LNG increases by approximately 1 kg/s in comparison to the systems related to Case A. In neither case, the purity of the product streams is affected by the integration of the LNG regasification. Thus, the differences in the purity are solely affected by the two varying configurations of air separation units.



Figure 6.15: Power consumption/generation, Cases AD1, AD2, AD2S, and BD2S



Figure 6.16: Purity of the product streams in Cases AD1, AD2, AD2S, and BD2S

system	<i>ṁ</i> GOX kg/s	<i>ṁ</i> GAN kg/s	<i>ṁ</i> LOX kg/s	<i>ṁ</i> LN kg/s	<i>ṁ</i> LNG
Case AD1	3.00	6.85	0.50	2.70	10.00
Case AD2	3.00	7.25	0.50	2.70	10.00
Case AD2S	3.00	7.25	0.50	2.70	10.00
Case BD2S	3.00	13.27	0.50	-	10.93

Table 6.13: Mass flow rates of the products streams, Cases AD1, AD2, AD2S, and BD2S

Conventional exergetic analysis and advanced exergetic analysis

The results of the exergetic analysis of the overall systems for Cases AD1, AD2, AD2S, and BD2S are shown in Table 6.14. The exergetic efficiency amounts to 37.8 %, 47.7 % and 49 % in Cases AD1, AD2, and AD2S, respectively. In comparison to Case A, the exergetic efficiency increased in Case AD1 by 33 %, in Case AD2 by 68 %, and in Case AD2S by 72.4%. This increase is mainly related to the decreased power consumption for the systems with the integration of LNG regasification. For Case BD2S, the exergetic efficiency increased by 33 % from Case B and results in 41.4 %. A comparison with the systems related to Case A shows that Case BD2S has a higher exergetic efficiency than Case AD1, but a lower values than Cases AD2 and AD2S.

In order to determine the available low-temperature exergy of the LNG stream, the released heat rate and the thermodynamic mean temperature are required (Equation 6.2).

$$\dot{E}_{\dot{Q}} = \left| \left(1 - \frac{T_0}{T_{\rm m}} \right) \cdot \dot{Q} \right| \tag{6.1}$$

$$T_{\rm m} = \frac{h_{\rm o} - h_{\rm i}}{s_{\rm o} - s_{\rm i}} \tag{6.2}$$

The regasification of LNG from a temperature level of $-160 \,^{\circ}$ C to an ambient temperature of 15 $^{\circ}$ C results in a specific heat rate of 0.84 MJ/kg_{LNG}. The specific low-temperature exergy amounts to 0.51 MJ/kg_{LNG} which is used as a fuel in the integrated systems.

In [209], two different air separation units with the integration of LNG regasification are compared from the exergetic point of view. These two systems have an exergetic efficiency of 38.2 % and 66.4 %. An increase of the exergetic efficiency of 50.5 % was reported in [131] if the LNG regasification is integrated into an air separation unit. The proposed system is a one-column air separation system. In comparison, the increase of the exergetic efficiency from Case AD1 to Case AD2 corresponds to 26 %. The difference between the values reported in literature and the results obtained in this thesis have many causes, as for example different structure, different scale, and different integration possibilities of LNG.

system	Ė _{F,tot} MW	Ė _{P,tot} MW	Ė _{D,tot} MW	Ė _{L,tot} MW	€ _{tot} %
Case AD1	22.2	8.4	13.4	0.44	37.8
Case AD2	17.1	8.2	8.8	0.18	47.7
Case AD2S	17.3	8.5	8.6	0.18	49.0
Case BD2S	21.1	8.7	11.4	0.93	41.4

Table 6.14: Results obtained from the exergetic analysis, Cases AD1, AD2, AD2S, and BD2S

The exergy destruction within selected components is graphically shown in Figure 6.17. The component with by far the highest exergy destruction is HE4 in Case AD1. The components with the highest exergy destruction in Case AD2 are HE4, HE2, MHE, and IC5. In Case AD2S, HE5, HE2, and HE4 have the highest exergy destruction.

The rearrangement of the adsorption block and the consequent lower temperature of the air entering AC2 and AC3 also decreases the exergy destruction within AC2 and AC3 in Case AD2 in comparison to Case AD1. A disadvantage of the rearrangement of the adsorption block is the increased exergy destruction of the IC1 and IC2 in Case AD2 in comparison to AD1. The increased exergy destruction is related to the huge temperature difference within the interstage cooler between the air and the LNG stream. In Case AD2S, the exergy destruction within the IC1, IC2, and IC5 decreases significantly by using a heat transfer medium instead of LNG. The reason therefore is the lower temperature difference within the interstage coolers and, consequently, an improved heat transfer.

The exergy destruction within the main heat exchanger slightly decreases from Case AD1 to AD2 and AD2S. Due to the fact that the minimal temperature difference is kept constant in all cases, the lower exergy destruction is a result of the lower heat transfer rate within the MHE in Cases AD2 and AD2S. In Cases AD2 and AD2S, the heat transfer rate slightly decreases because the air enters the MHE with a lower temperature in comparison to Case AD1.

A comparison of the values for the exergy destruction for Cases B and BD2S shows a significantly lower exergy destruction within the IC2 in Case BD2S. However, the IC5 is introduced in Case BD2S which has a relatively high exergy destruction. The exergy destruction within ICN1 and ICN2 (Case BD2S) decreases significantly and amounts to the half of the exergy destruction within ICN (Case B). In Case BD2S, the HE5 is the component with the highest exergy destruction. The exergy destruction of the remaining components is only slightly affected by the structural changes of the systems.

A comparison of the exergy destruction within the Cases AD1, AD2, AD2S and Case BD2S shows a higher exergy destruction within the MHE and LPC for Case BD2S. The exergy destruction within HE5 is slightly higher in Case BD2S than in Case AD2S.



Figure 6.17: Exergy destruction within the components in Cases AD1, AD2, AD2S, and BD2S

Figure 6.18 shows the exergy destruction ratio of the component blocks for Cases AD1, AD2, AD2S, and BD2S. In Case AD1, the remaining components have the highest exergy destruction ratio with a value of 54 %. This high value is caused by the heating of the LNG stream in the HE4. For Cases AD2 and AD2S, the remaining components also cause a high share of exergy destruction, because in these systems the additional heat exchanger (HE5) for the LNG heating is also assigned with the remaining components. The value of the NLB decreases for all three cases (AD1, AD2, and AD2S) to an exergy destruction ratio of around 17 %. In Case A, the NLB has the highest exergy destruction ratio with a value of approximately 60 % (Figure 6.4). Thus, the new structure of the NLB significantly affects the exergy destruction. The effect of the rearrangement of the adsorption block in Case AD2 is also shown by the exergy destruction ratio. This value increases to 32 % in Case AD2 in comparison to 10 % in Case AD1. This is led back to the increased temperature difference in the interstage cooler by using LNG as cooling medium. The change from LNG to water-ethylene-glycol as cooling medium deceases the exergy destruction ratio from 32 % in Case AD2 to 15.8 % in Cases AD2S. The exergy destruction ratio of the MHE slightly increases from Case AD1 to AD2S while the exergy destruction ratio of the product post-processing block slightly decreases.

Case BD2S shows a significantly higher exergy destruction ratio for the air compression and purification block in comparison to Case AD2S. The exergy destruction ratio of the MHE increases





Figure 6.18: Exergy destruction ratio within the components, Cases AD1, AD2, AD2S, and BD2S

slightly in Case BD2S while the exergy destruction ratio of the product post-processing block is three times higher than in Case AD2S.

The results of the advanced exergetic analysis for Cases AD1, AD2, AD2S, and BD2S are shown in Figure 6.19.

In Case AD1, the main heat exchanger has the highest exergy destruction. The share of avoidable exergy destruction makes up to 12% of the exergy destruction of this component which results in a low potential for improvement. The component with the second highest exergy destruction is the HE3 which has the highest share of the avoidable exergy destruction. In order to improve this component, particularly, the remaining components have to be considered because the share of the avoidable exogenous exergy destruction is higher than the share of the avoidable endogenous exergy destruction.

The HE3, MHE, and IC5 are the components with the highest exergy destruction in Case AD2. The share of the avoidable exergy destruction of the MHE accounts for 18% while the IC5 and HE3 have a share of 95% and 79%, respectively. Thus, the MHE has a low potential for improvement. In order to improve the IC5 or HE3, either the component itself or the remaining components have to be improved. For both components (IC5 and HE3) the share of the avoidable exogenous and avoidable endogenous exergy destruction amounts to half of the share of the avoidable exergy destruction. The large potential for improvement of these components is related to the fact that within HE3 the waste nitrogen stream is heated which is limited by the required temperature for this

stream whereby the nitrogen stream used for the heating offers a significantly higher temperature. In IC5, the same behavior occurs, here the temperature of the air stream is limited at the outlet of the IC5.

In Case AD2S, HE5, HE2, and MHE are the components with the highest exergy destruction. For the MHE, a reduction of the exergy destruction by around half is feasible. For the HE2, the share of the avoidable exergy destruction accounts for 30 % while the HE5 has a share of just 5 %. Thus, the potential for improvement is quite low for the HE5. For all three components, the share of the avoidable endogenous and avoidable exogenous exergy destruction amounts for half of the exergy destruction.

The three components with the highest exergy destruction are HE5, MHE, and ICN1 in Case BD2S. However, the share of the avoidable exergy destruction amounts to 5% of the exergy destruction which results in a low potential for improvement for this component. For the MHE and ICN1, the share of the avoidable exergy destruction is slightly higher and accounts for 16% for both components. As already demonstrated for the other systems, the share of the avoidable endogenous and the avoidable exergy destruction is half in each case.

The share of the avoidable exergy destruction within the turbomachines amounts to around 39 % in Cases AD1, AD2, AD2S, and BD2S, however the exergy destruction of these components is significantly lower and consequently their improvement is less important.

In [130], an advanced exergetic analysis is applied to the LNG regasification integrated into an air separation unit with a power cycle using the same assumptions for the technological limit for compressors, expanders, and heat exchangers. The results reported in this paper show a share of the unavoidable exergy destruction of the MHE of 99 % which is significantly higher in comparison to the results obtained in this thesis. The share of the avoidable exergy destruction for the air compressor accounts for 65 % as reported in [130] which is higher in comparison to a share of 38 % obtained in this thesis.

It is possible to conclude that all analyzed systems have very strong interdependencies between the components. The improvement of any of the components and/or the structure of the system will significantly affect the effectiveness of the remaining components.

Economic analysis, exergoeconomic analysis, and exergoeconomic optimization

A detailed estimation of the cost of the components for Cases AD1, AD2, AD2S, and BD2S are given in Appendix C in Tables C.5 to C.35.

The results of the bar module costs for the component groups are shown in Table 6.15. The percentage shares of the component blocks are graphically shown in Figure 6.20 for Cases AD1, AD2, AD2S, and BD2S.



Figure 6.19: Results obtained from the advanced exergetic analysis, Case AD1, AD2, AD2S, and BD2S

Case AD2 has the lowest total bare module costs. In order to increase the safety of the system, the bare module costs from Case AD2 to AD2S increase by 17%. In Case AD1, the bar module costs are slightly lower than in Case AD2S. The bare module costs for Case BD2S are significantly higher and amount to approximately $31.4 \cdot 10^3$ \$. A comparison of the single air separation units with the integrated systems demonstrates a decrease of the bare module costs for all LNG systems related to Case A which is in the range of 12% to 25%. In contrast, the bare module costs increases by 8% for Case BD2S in comparison with Case B.

A comparison of the costs on a component level shows that the column block has the highest investment costs within all systems which at least amounts to half of the total component costs. A comparison of the results obtained for Cases AD2S and BD2S shows a high increase in the costs of the MHE due to a higher heat transfer which is associated with the increased mass flow rate of the feed air stream.

Table 6.16 shows the fixed and total capital investment costs as well as the specific investment costs of Cases AD1, AD2, AD2S, and BD2S. The total capital investment costs from Case AD1 to AD2 decrease by 12%, while from Case AD2 to AD2S they increase by 17%. The decrease and increase are related to the varying bare module costs. Thus, in order to decrease the hazard potential of the system, higher investment costs have to be accepted. This leads to an increase of the specific investment costs from Case AD2 to AD2S. A comparison of the two safety concepts shows an increase of the *TCI* by 26\% from Case AD2S to Case BD2S.

A comparison of the integrated systems (Case AD1, AD2, and AD2S) and Case A shows a reduction of the total capital investment which is in the range of 12 % to 25 %. This range is close to the values given in [118, 129] where a reduction of the investment costs of 10 % and 17 % are mentioned if the LNG regasification is integrated into an air separation unit. In contrast, the total capital investment costs increases by 8 % from Case B to Case BD2S.

The levelized carrying charges, operating and maintenance costs, fuel costs, and the total revenue requirement are given in Table 6.17. The fuel costs decrease significantly from Case AD1 to AD2, which, consequently, leads to a lower *TRR* by 30 %. For Case AD2S the *TRR* decreases by 24 % in comparison to Case AD1. The *TRR* increases from Cases AD2S to BD2S by 31 %.

1,tot ³ \$
347
281
937
367

Table 6.15: Bare module costs for the component blocks, Cases AD1, AD2, AD2S, and BD2S



Figure 6.20: Distribution of the bare module costs among the component blocks, Case AD1, AD2, AD2S, and BD2S

	<i>FCI</i> 10 ⁶ \$	<i>TCI</i> 10 ⁶ \$	specific investment costs 10^3 \$/kW _{$\dot{E}_P$}
Case AD1	32.9	38.3	4.57
Case AD2	28.7	33.5	4.10
Case AD2S	33.7	39.3	4.64
Case BD2S	42.3	49.4	5.67

Table 6.16: Fixed and total capital investment costs, Cases AD1, AD2, AD2S, and BD2S

 Table 6.17: Levelized carrying charges, operating and maintenance costs, fuel costs and total revenue requirements, Cases AD1, AD2, AD2S, and BD2S

	CC_{L}	<i>OMC</i> _L	$FC_{\rm L}$	TRR
	10 ³ \$/a	10 ³ \$/a	10 ³ \$/a	10 ³ \$/a
Case AD1	4,502	1,596	13,861	19,959
Case AD2	3,935	1,395	8,705	14,035
Case AD2S	4,611	1,635	8,841	15,087
Case BD2S	5,800	2,057	11,833	19,689

 Table 6.18: Results obtained from the exergoeconomic analysis of the overall system, Cases AD1, AD2, AD2S, and BD2S

	Ċ _{F,tot} \$/h	Ċ _{P,tot} \$/h	Ċ _{D,tot} \$/h	Ż _{tot} \$/h	Ċ _{L,tot} ¹³ \$/h	c _{F,tot} \$/MJ	c _{P,tot} \$/MJ	r _{tot} -	f _{tot}
Case AD1	1,849	2,612	1,104	762	199	0.023	0.086	2.69	0.41
Case AD2	1,241	1,908	636	666	94	0.020	0.065	2.22	0.51
Case AD2S	1,258	2,039	630	781	87	0.020	0.067	2.31	0.55
Case BD2S	1,514	2,496	820	982	561	0.020	0.080	2.99	0.54

The results obtained from the exergoeconomic analysis of Cases AD1, AD2, AD2S, and BD2S are shown in Table 6.18. The costs associated with exergy destruction almost decrease by a factor of two from Case AD1 to Cases AD2 and from Case AD1 to Case AD2S. The costs associated with the exergy loss also decrease in the same range from Case AD1 to AD2. For Case AD2S, the decrease of the costs associated with the exergy loss is even higher. The overall specific product costs are 25 % lower in Case AD2 in comparison to Case AD1. If the safety aspects are considered, the specific product costs increases by 3 % (from Case AD2 to AD2S). In Case BD2S, the costs associated with the exergy loss are slightly higher as for Cases AD2 and AD2S. The costs associated with the exergy loss are slightly lower in Case BD2S than in Case AD1. A

¹³are already included in the costs associated with the exergy of the overall product



Figure 6.21: Specific costs of the product streams, Case AD1, AD2, AD2S, and BD2S

comparison of the air separation units (Cases A and B) with the systems with integration of LNG regasification shows a decrease of the overall product costs which ranges from 50% to 61%. As given in [178], the product costs of an air separation unit can be decreased by almost half if the ASU is combined with an LNG receiving terminal. Thus, the results of the LNG systems are in the range of the data given in literature.

The specific costs of the four product streams for Cases AD1, AD2, AD2S, and BD2S are shown in Figure 6.21. In order to highlight the huge decrease of the product costs, the specific costs of the product streams of the conventional air separation units (Cases A and B) are additionally shown. A comparison of the results for Case A and Case AD2S shows that the specific costs of all four streams decrease by half. The specific costs of the product streams for Cases AD2 and AD2S are almost equal. The product costs of the product stream decreases by 34 % to 39 % from Case B to Case BD2S, whereby the highest decrease is reached for the gaseous nitrogen stream.

The cost rates associated with the components for Cases AD1, AD2, AD2S, and BD2S are given in Figure 6.22. The figure only shows the eight components with the highest cost rates. On top of each column the respective f value is given. In all four systems at least one heat exchanger and the two columns belong to the components with the highest cost rates. For the two columns, the cost rate associated with the investment costs predominant the total cost rates. For the heat exchangers it is the other way around. Here, the cost rates associated with exergy destruction are significantly higher. Especially the HE4 in Case AD2S has a high cost rate associated with exergy destruction and, consequently, a low exergoeconomic factor which amounts to 0.008. In all cases, the cost rates for the following components are significantly lower and only half as large.

In order to evaluate the dependency of the product costs on the electricity costs and the investment costs, the sensitivity analyses are also conducted for Cases AD1, AD2, AD2S and BD2S whereby the results are given in Figure 6.23.

In Case AD1, an increase or decrease of the electricity costs of 30%, results in an increase or decrease of the product costs of approximately of 19%. In contrast, the product costs increase by 10% in case the investment costs are underestimated by 30%. In Case AD2 and AD2S, an increase or decrease of the electricity costs by 30% results in an increase or decrease of the product costs by approximately 17%. The product costs increase or decreases by 12% if the investment costs are increased or decreased by 30%. In Case BD2S, the product costs increase or decrease of a decrease by approximately 18% if the cost of the electricity increases or decreases by 30%. An increase or a decrease of the investment costs by 30% results in an increase or decrease of the product costs by approximately 18% if the cost of the electricity increases or decrease by 30%. An increase or a decrease of the investment costs by 30% results in an increase or decrease of the product costs by around 12%. As already discussed for the single air separation units, the product costs are more affected by the electricity costs than by the investment costs which also arise for the integrated systems.

Furthermore, an exergoeconomic optimization is applied for Cases AD2 and AD2S. The most important components from the exergoeconomic point of view are already given in Figures 6.23b and 6.23c for Cases AD2 and AD2S, respectively. In both systems the HPC and LPC are not considered for the exergoeconomic optimization. In addition, in Case AD2 the TV3 and MIX2 are not taken into account, whereas in Case AD2S the HE5 is ignored, because this component already has an exergoeconomic factor of 0.465 which is close to the exergoeconomic optimum. The decision variables and the corresponding old and new values for the selected decision variables are given in Table 6.19 and 6.20 for Cases AD2 and AD2S, respectively.

Tables 6.21 and 6.22 show selected results obtained from the exergoeconomic optimization of Case AD2 which are required in order to determine if the iteration step was successful or unsuccessful. The specific investment costs and the costs associated with the exergy loss increase for the iteration step while the specific product costs remain constant. The exergetic efficiency of the overall systems decreases from 47.7 % to 47.6 %. A comparison of the molar composition of the product streams shows a slight increase for all four products while the specific product costs of all streams also remain constant. The results on the component level (Table 6.22) show that for all components except for the NC1 the goal was reached. The exergoeconomic optimization is successful if the specific product costs decrease. In this iteration step, the specific product costs are constant, but the purity of the products increases. Thus, the product streams of the optimized systems are more valuable because they have a higher purity and the same specific product costs.



Figure 6.22: Total cost rates associated with the component, Case AD1, AD2, AD2S, and BD2S (on top of each column the corresponding *f* value is given)

108



Figure 6.23: Sensitivity analysis - Specific costs of the product streams, Case AD1, AD2, AD2S, and BD2S

Table 0.19. Excegoceonomic optimization, Case AD2									
	$\dot{Z}_{k} + \dot{C}_{\mathrm{D},k}$ \$/h	f -	$\begin{array}{c} \text{goal} \\ \dot{Z}_k \downarrow \text{ or} \\ \boldsymbol{\varepsilon}_k \uparrow / \dot{E}_{\mathrm{D},k} \downarrow \end{array}$	<i>T</i> ₁₀ °C	<i>T</i> ₃₄ °C	$\eta_{ m is,NC5}\ \%$	$\eta_{ m is,NC1} \ \%$		
MHE	212	0.1294	$\mathcal{E}_{\mathrm{k}}\uparrow$	\downarrow					
HE2	127	0.1417	$oldsymbol{arepsilon}_{\mathrm{k}}\uparrow$		\downarrow				
NC5	77	0.6044	$\dot{Z}_k\downarrow$			\uparrow			
NC1	56	0.8398	$\dot{Z}_k\downarrow$				\uparrow		
			final	\downarrow	\downarrow	\uparrow	\uparrow		
			decision						
			initial	-173.40	-150	84	84		
			new	-173.45	-152	85	85		

Table 6.19: Exergoeconomic optimization, Case AD2

Table 6.20: Exergoeconomic optimization, Case AD2S

	$\dot{Z}_k + \dot{C}_{D,k}$	f	goal	<i>T</i> ₄₈	T_{10}	$\eta_{ m is,NC1}$	$\eta_{ m is,NC5}$	$\eta_{ m is,NC1}$
	\$/h	-	$Z_k \downarrow \text{ or }$	°C	°C	%	%	%
			$\varepsilon_{\mathrm{k}}\uparrow/E_{\mathrm{D,k}}\downarrow$					
HE4	273	0.0077	$\dot{E}_{\mathrm{D,k}}\downarrow$	\downarrow				
MHE	248	0.1270	$oldsymbol{arepsilon}_{\mathrm{k}}\uparrow$		\downarrow			
NC2	92	0.8561	$\dot{Z}_k\downarrow$			\uparrow		
NC5	77	0.5932	$\dot{Z}_k\downarrow$				\uparrow	
NC1	65	0.8335	$\dot{Z}_k\downarrow$					\uparrow
			final	\uparrow	\downarrow	\uparrow	\uparrow	\uparrow
			decision					
			initial	15	-173.40	84	84	84
			new	18	-173.45	85	85	85

For the exergoeconomic optimization of Case AD2S the objective whether to increase the exergetic efficiency or to decrease the costs associated with the component is reached for all components as shown in Tables 6.23 and 6.24. However, the specific investment costs as well as the costs associated with the exergy loss increase while the exergetic efficiency decreases. A comparison of the purity of the product streams shows that the purity for the gaseous nitrogen and the liquid oxygen remains constant. The purity of the gaseous oxygen slightly decreases while the purity of the liquid nitrogen slightly increases. The specific costs increase for all streams except the gaseous nitrogen which remains constant. The first iteration step demonstrates that even if the goal for all components is fulfilled, the overall product costs cannot be decreased.

	initial system	iteration	satisfied
specific investment costs in $kW_{\dot{E}_{p}}$	4,096	4,166	X
$c_{\rm p}$ in \$/MJ	0.065	0.065	=
<i>Ċ</i> _L in \$/h	94	108	х
\mathcal{E}_{tot} in %	47.7	47.6	Х
molar composition	on in kmol/kmol		
GOX	0.9717	0.9718	\checkmark
GAN	0.9900	0.9920	\checkmark
LOX	0.9801	0.9802	\checkmark
LN	0.9992	0.9993	\checkmark
specific produc	t costs in \$/kg		
GOX	0.095	0.095	=
GAN	0.084	0.084	=
LOX	0.109	0.109	=
LN	0.097	0.097	=

Table 6.21: Exergoeconomic optimization - Prove of results, part I, Case AD2

Table 6.22: Exergoeconomic optimization - Prove of results, part II, Case AD2

	goal	initial system	iteration	satisfied
		\dot{Z}_k in \$/h or	\dot{Z}_k in \$/h or	
		ε in % / $\dot{E}_{\mathrm{D,k}}$ in MW	ε in %/ $\dot{E}_{\mathrm{D,k}}$ in MW	
MHE	$\mathbf{\epsilon}_{\mathrm{k}}\uparrow$	73.2	75.2	\checkmark
HE2	$\mathbf{\epsilon}_{\mathrm{k}}\uparrow$	55.0	56.9	\checkmark
NC5	$\dot{Z}_k\downarrow$	45.9	44.5	\checkmark
NC1	$\dot{Z}_k\downarrow$	37.8	38.5	Х

Exergoenvironmental analysis

The results obtained from the exergoenvironmental analysis are shown in Table 6.25. The specific environmental impact associated with the exergy of the overall product from Case AD1 to Case AD2 decreases by 22 %, and from Case AD1 to AD2S by 24 %. A comparison of the results obtained for Case A and the integrated LNG systems shows a decrease of the specific environmental impact associated with the exergy of product in the range of 33 % to 49 %.

In Case BD2S, the specific environmental impact associated with the exergy of product reaches the lowest value which amounts to 9.88 mPt/MJ. These values correspond to a decrease of 66.1 % in comparison with Case B.

	initial system	iteration	satisfied
specific investment costs in $kW_{\dot{E}_{p}}$	4,644	4,657	X
$c_{\rm p}$ in \$/MJ	0.067	0.067	=
<i>Ċ</i> _L in \$/h	87	91	х
\mathcal{E}_{tot} in %	49.0	48.8	Х
molar composition	on in kmol/kmol		
GOX	0.9717	0.9711	X
GAN	0.9900	0.9900	=
LOX	0.9801	0.9797	=
LN	0.9992	0.9993	\checkmark
specific produc	t costs in \$/kg		
GOX	0.096	0.097	X
GAN	0.086	0.086	=
LOX	0.108	0.109	Х
LN	0.098	0.099	Х

Table 6.23: Exergoeconomic optimization - Prove of results, part I, Case AD2S

	goal	initial system Ż _k in \$/h or ε in % / Ė _{D,k} in MW	iteration \dot{Z}_k in \$/h or ε in %/ $\dot{E}_{D,k}$ in MW	satisfied
HE4	$\dot{E}_{\mathrm{D,k}}\downarrow$	1260	1226	\checkmark
MHE	$\boldsymbol{arepsilon}_{\mathrm{k}}\uparrow$	73.9	76.5	\checkmark
NC2	$\dot{Z}_k\downarrow$	78.9	77.0	\checkmark
NC5	$\dot{Z}_k\downarrow$	45.9	45.1	\checkmark
NC1	$\dot{Z}_k\downarrow$	54.4	53.2	\checkmark

Table 6.24: Exergoeconomic optimization - Prove of results, part II, Case AD2S

The specific environmental impact of the four product streams is shown in Figure 6.24. In order to simplify the analysis and comparison, the values obtained for Cases A and B are also given in this figure. The specific environmental impact of all product streams decreases for the air separation units with integrated LNG regasification. This decrease is mainly relate to the lower power consumption of the systems with LNG regasification. The environmental impact of the product streams was halved for all product streams in Cases AD2S and BD2S in comparison to Cases A and B.

Table 6.25: Results obtained from the exergoenvironmental analysis of the overall system, Cases AD1,AD2, AD2S, and BD2S

	<i>B</i> _{F,tot} Pt/h	<i>B</i> _{P,tot} Pt/h	<i>B</i> _{D,tot} Pt/h	Ý _{tot} Pt∕h	$\dot{B}_{\rm L,tot}^{14}$ Pt/h	b _{F,tot} Pt/MJ	b _{P,tot} Pt/MJ	r _{b,tot}
Case AD1	515	515	308	0	29	6.53	17.06	1.61
Case AD2	391	390	200	0	15	6.33	13.27	1.10
Case AD2S	394	394	197	0	14	6.34	12.95	1.04
Case BD2S	310	310	168	0	68	4.09	9.88	1.42



Figure 6.24: Specific environmental impact of product streams, Cases A, AD1, AD2, AD2S, B, and BD2S

¹⁴are already included in the environmental impact associated with the exergy of the overall product

Risk-hazard analysis and exergy-risk-hazard-analysis

LNG systems are exposed to several hazards which are related to liquid leakages under pressure, liquid leakages from storage tanks (at atmospheric pressure), rollover in an LNG storage tank, and liquid pools evaporating to form a flammable vapor plume whereby the kind of hazard depends on the step of the LNG chain. Leaks under pressure, for example, can occur in liquefaction and regasification plants as well as during the transfer of LNG from storage tank to carriers and in the opposite direction [157].

Hazards and risks related to the LNG chain are intensively discussed and analyzed in several studies where the main focus is an LNG spill over water during marine LNG transportation [184, 210, 211]. The analyses focus on the transportation by ship because weather conditions (for example high waves) or the collision with other ships causes major problems. In [212], the hazard potential related to the loading and unloading are discussed.

For the exergy-risk-hazard-analysis only components which include LNG are considered, as given in Table 6.26. The risks associated with the components are influenced by the mass flow rate of LNG and the presence or absence of oxygen which is also given in Table 6.26. The risks associated with the components are given in Figure 6.26, for Case AD1, AD2, AD2S, and BD2S. In all components, the risk associated with a jet fire is the lowest.

In Case AD1, the MHE has the highest risk because the entire LNG stream is fed to this component and, in parallel an oxygen stream is presence. The risk associated with the HE4 is slightly lower, because in this heat exchanger no oxygen is present. The HE4 has the highest risk in Case AD2, followed by the MHE and HE2. In the safety systems (Cases AD2S and BD2S), HE5 has the highest risk associated with the component. The risk for the overall system amounts to $18.2 \cdot 10^{-4}$ inj/a, $27.5 \cdot 10^{-4}$ inj/a, $16.5 \cdot 10^{-4}$ inj/a and $13.0 \cdot 10^{-4}$ inj/a for Cases AD1, AD2, AD2S, and BD2S, respectively. Figure 6.25 shows the ALARP triangle which stands for "as low as reasonable possible". This diagram shows a classification for the risk which ranges from acceptable ($\dot{R} = 3 \cdot 10^{-7}$ inj/a) to intolerable ($\dot{R} = 10^{-4}$ inj/a) [213, 214]. The ALRAP area is considered as a tolerable risk. In order to compare these ranges, the risk of everyday events are given in [214], for example, the risk of death by lightning which amounts to 10^{-7} inj/a or the risk of death in a traffic accident which amounts to 10^{-4} inj/a.

The risk values of the overall systems are higher than the acceptable range. However, all components would need to cause problems at the same time which is quite unlikely. The risk of the single components ranges from $1 \cdot 10^{-5}$ inj/a to $8.4 \cdot 10^{-5}$ inj/a and is in the limit of a tolerable risk. This means the operators of the process have to accept this risk in order to generate the products.



Figure 6.25: ALARP triangle (adopted from [213])

		112	, 1, 11D2, 1	1D20, un				
System		IC ¹⁵	MHE	HE2	HE4	HE5	LNGP	ICN ¹⁶
Case AD1	<i>m</i> _{LNG} in kg/s	0	10	0	10	na	10	na
Case AD1	oxygen present?	no	yes	no	yes	no	no	na
		10	~	-	10		10	
Case AD2	$m_{\rm LNG}$ in kg/s	10	5	5	10	na	10	na
	oxygen present?	yes	yes	no	yes	na	no	na
	$\dot{m}_{\rm ING}$ in kg/s	0	0	10	0	10	10	na
Case AD2S								
	oxygen present?	no	no	no	no	no	no	na
	man in ka/a	0	0	0	0	10.02	10.02	10.02
Case BD2S	m _{LNG} III Kg/s	0	0	0	U	10.95	10.95	10.95
	oxygen present?	no	no	no	no	no	no	no

 Table 6.26: Mass flow rate of LNG within selected components for the exergy-risk-hazard-analysis, Cases AD1, AD2, AD2S, and BD2S

Table 6.27 shows the risks associated with the exergy of the overall product, the risk of the overall systems, and the specific risk per exergy of product for Cases AD1, AD2, AD2S, and BD2S. The risk of the overall system increases from Case AD1 to AD2 by 50%. The introduction of the safety concepts (Cases AD2S and BD2S) leads to a significant decrease of the risk. It decreases by 40% from AD2 to AD2S. The increase from AD1 to AD2 is associated with the integration of the LNG in almost all heat exchangers whereby most of them also contain an oxygen stream. Case BD2S has the lowest risk for the overall system which is even 21% lower than the risk of Case AD2S. The use of a water-ethylene-glycol mixture significantly decreases the risk of the safety related systems, because a direct contact of LNG and oxygen or oxygen-enriched streams is

¹⁵includes the IC1, IC2, and IC5

¹⁶includes the ICN1 and ICN2



Figure 6.26: Risk associated with the components, Cases AD1, AD2, AD2S, and BD2S

avoided. This concept is also used in a real air separation plants with LNG regasification in China [43] where the LNG is used in order to cool glycol which is then used for the cooling of air in the interstage cooler of the air separation unit.

Figure 6.27 shows the total risk rates associated with the six most important components for Cases AD1, AD2, AD2S, and BD2S. For all components, the risk rates associated with the component itself are significantly higher than the risk rates associated with the exergy destruction.

AD25, and BD25							
<i>R</i> _{tot} 10 ^{−5} inj/a	Ż _{P,tot} 10 ^{−5} inj/a	$\dot{X}_{\rm L,tot}^{17}$ 10 ⁻⁵ inj/a	10^{-3} inj/MJ				
18.19	18.19	0.60	6.88				
27.48	27.48	0.57	10.66				
16.53	16.53	0.36	6.20				
13.03	13.03	0.0002	4.74				
	$\begin{array}{r} \dot{R}_{\rm tot} \\ 10^{-5} \text{ inj/a} \\ 18.19 \\ 27.48 \\ 16.53 \\ 13.03 \end{array}$	\dot{R}_{tot} $\dot{X}_{P,tot}$ 10^{-5} inj/a 10^{-5} inj/a 18.19 18.19 27.48 27.48 16.53 16.53 13.03 13.03	\dot{R}_{tot} $\dot{X}_{P,tot}$ $\dot{X}_{L,tot}^{17}$ 10^{-5} inj/a 10^{-5} inj/a 10^{-5} inj/a 18.19 18.19 0.60 27.48 27.48 0.57 16.53 16.53 0.36 13.03 13.03 0.0002				

Table 6.27: Results obtained from the exergy-risk-hazard analysis of the overall system, Cases AD1, AD2,
AD2S, and BD2S

The specific risks of the product streams are given in Figure 6.28. The specific risk of all streams is extremely low. However, a comparison shows that the specific risk associated with the liquid product streams is significantly higher than the specific risk of the gaseous product streams. In Case AD2S, the gaseous nitrogen has the lowest specific risk, while the gaseous and liquid oxygen have the lowest specific risk in Case BD2S. In Case AD2, all streams have the highest specific risk because the LNG is integrated in all heat exchangers which significantly increases the potential for hazards.

Sensitivity analysis - LNG pressure for Cases AD2S and BD2S

For Cases AD2S and BD2S, a sensitivity analysis is conducted in order to analyze the effect of the LNG pressure on the overall systems. For these systems an energetic, exergetic, economic, and exergoeconomic analysis are applied.

Energy analysis

The increase of the LNG pressure to 100 bar, results in a 2.8 % higher power consumption for both cases as shown in Table 6.28. In both systems, this is related to the increased power consumption of the LNG pump. In Case BD2S, the power consumption is slightly higher than in Case AD2S due to

¹⁷are already included in the risk associated with the exergy of the overall product



Figure 6.27: Total risk rates associated with the component, Cases AD1, AD2, AD2S, and BD2S

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Figure 6.28: Specific risks of the product streams, Cases AD1, AD2, AD2S, and BD2S

the increased mass flow rate of LNG. In Case BD2S, the mass flow rate of the LNG increases by approximately 4 % if the LNG pressure is increased by 20 bar. The increasing mass flow rate of LNG as a function of the LNG pressure is also reported in [126].

Conventional exergetic analysis

Table 6.29 shows the results of the exergetic analysis for the overall systems at four different pressure levels. For both systems, the exergetic efficiency increases if the LNG pumped to 100 bar instead of 20 bar. In Case A, the exergetic efficiency increases by 19.6 % and in Case B, the increase of the exergetic efficiency is even higher and amounts to 22.7 %. These increases are related to the improved heat transfer in the heat exchangers and the resulting lower exergy destruction. The improved heat transfer by increasing the LNG pressure is also reported in [48].

Figures 6.29 and 6.30 show the $T, \Delta \dot{H}$ -diagrams for the HE5 in Cases AD2S and BD2S for an LNG pressure of 20 bar and 100 bar, respectively. In both diagrams, the curve for the hot stream is not affected by the variation of the LNG pressure. In Case AD2S solely the transferred heat rate decreases if the LNG is pumped to 100 bar. In both figures, the curve for the cold stream for an LNG pressure of 100 bar is much closer to the curve of the hot stream than the curve of the cold stream for an LNG pressure of 20 bar. The differences in the curve of the cold stream are related

system	<i>p</i> LNG bar	<i>ṁ</i> LNG kg/s	$\dot{W}_{ m tot}$ MW	w _{LNG} kJ/kg _{LNG}
Case AD2S	20	10.0	8.70	870.3
	40	10.0	8.77	876.5
	60	10.0	8.83	882.6
	100	10.0	8.95	895.0
Case BD2S	20	10.9	11.65	1,068.6
	40	11.4	11.72	1,028.1
	60	11.8	11.80	999.8
	100	12.9	11.98	928.3

 Table 6.28: Results obtained from the energy analysis at varying LNG pressure levels, Cases AD2S and BD2S

 Table 6.29: Results obtained from the exergetic analysis at varying LNG pressure levels, Cases AD2S and BD2S

system	<i>p</i> _{LNG} bar	Ė _{F,tot} MW	Ė _{P,tot} MW	Ė _{D,tot} MW	Ė _{L,tot} MW	$rac{arepsilon_{ m tot}}{\%}$
	20	17.3	8.5	8.6	0.18	49.0
Casa AD29	40	17.3	9.3	7.9	0.18	53.5
Case AD25	60	17.4	9.7	7.5	0.18	56.0
	100	17.5	10.3	7.1	0.18	58.6
	20	21.1	8.7	11.4	0.93	41.4
Cose DD19	40	21.5	9.8	10.8	0.93	45.6
Case DD25	60	22.0	10.5	10.5	0.93	47.9
	100	23.1	11.7	10.4	0.93	50.8

to the regasification of LNG below and above the critical point. For pure methane, the critical point amounts to 45 bar, thus, for an LNG pressure of 100 bar the evaporation takes place above the critical point. The area between the curves for the hot and cold stream is an evaluation criteria for the irreversibilities within a heat exchanger and, thus, shows a decrease of the exergy destruction within HE5 in both cases.

The exergy destruction within the selected components is shown in Figure 6.31. As already mentioned, the value of the LNG pressure affects the exergy destruction within heat exchangers. The highest decrease of the exergy destruction is reached within HE5 where it decreases by 66 % and 48 % for Cases AD2S and BD2S, respectively. In Case AD2S, the exergy destruction also decreases within HE2 and HE4 if the LNG is pumped to 100 bar. In Case BD2S, the exergy destruction is reduced by approximately half in HE4 and by one fifth in HE2.



Figure 6.29: $T, \Delta \dot{H}$ -diagram for HE5 at different pressure levels of LNG, Case AD2S



Figure 6.30: $T, \Delta \dot{H}$ -diagram for HE5 at different pressure levels of LNG, Case BD2S



Figure 6.31: Exergy destruction within the components for different pressure levels of LNG, Cases AD2S and BD2S

Economic and exergoeconomic analysis

Table 6.30 shows the bare module costs for Cases AD2S and BD2S at LNG pressures of 20 bar and 100 bar. For Cases AD2S and BD2S, the bare module costs of the overall system for an LNG pressure of 100 bar increase by 2.3 % and 2.5 %, respectively. In both cases, the costs of the main heat exchanger and the column block are not affected by the increased pressure of the LNG stream. In Case BD2S, the bare module costs of the air compression and purification block additionally remain constant. The results for the fixed and total capital investment costs, as well as the specific investment costs are given in Table 6.31. Table 6.32 includes the results for the carrying charges, operating and maintenance costs, fuel costs and total revenue requirement. Due to an increase in the bare module costs, the total capital investment as well as the total revenue requirement also increases.

The results obtained from the exergoeconomic analysis at varying pressure level of LNG for Cases AD2S and BD2S are shown in Table 6.33. The specific product costs for both systems decrease if the LNG pressure is increased to 100 bar. These decreases amount to 16 % and 24 % in Case AD2S and BD2S, respectively. The costs associated with the exergy loss are not affected by

the increased pressure of the LNG pressure. The exergoeconomic factor for both systems increases for an LNG pressure of 100 bar in comparison to 20 bar. This is related to the fact that the costs associated with the exergy destruction decrease more for an LNG pressure of 100 bar than the costs associated with the investment, maintenance, and operating costs increase. The effect of the varying LNG pressure on the specific costs of the four product streams is shown in Figure 6.32. The costs of the product streams for the systems with an LNG pressure of 100 bar are lower in comparison to the systems with an LNG pressure of 20 bar. The decreases range from 4.2% to 5% and from 2.9% to 4.6%, in Cases AD2S and BD2S, respectively. In both cases, the highest decrease of the specific costs is obtained for the gaseous nitrogen stream. Consequently, the sensitivity analysis demonstrates the high influence of the LNG pressure on the overall system and the positive effects on the exergetic efficiency and the specific product costs.

 Table 6.30: Bare module costs for the component blocks at varying LNG pressure levels, Cases AD2S and BD2S

				55	-5			
	<i>p</i> _{LNG} bar	$\begin{array}{c} C_{\rm BM,\ ACPB} \\ 10^3 \$ \end{array}$	$\begin{array}{c} C_{\rm BM,MHE} \\ 10^3 \$ \end{array}$	$C_{\rm BM,CB} \ 10^3 $	$\begin{array}{c} C_{\rm BM,NLB} \\ 10^3 \$ \end{array}$	$\begin{array}{c} C_{\rm BM,PPP} \\ 10^3 \$ \end{array}$	$C_{\rm BM,rest}$ 10 ³ \$	$\begin{array}{c} C_{\rm BM,tot} \\ 10^3 \$ \end{array}$
Casa AD29	, 20	3,070	1,005	12,800	4,463	2,481	1,118	24,937
Case AD23) 100	3,122	1,005	12,800	4,528	2,531	1,522	25,507
Casa DD20	, 20	4,666	3,303	18,490	0	3,364	1,544	31,367
Case BD25) 100	4,666	3,303	18,490	0	3,487	2.202	32,147

Table 6.31: Fixed and total capital investment costs at varying LNG pressure levels, Cases AD2S and BD2S

	<i>p</i> _{LNG} bar	<i>FCI</i> 10 ⁶ \$	<i>TCI</i> 10 ⁶ \$	specific investment costs $10^3/kW_{\dot{E}_P}$
Case AD2S	20	33.7	39.3	4.64
Case AD25	100	34.4	40.2	3.91
Case PD2S	20	42.3	49.4	5.67
	100	43.4	50.6	4.32

 Table 6.32: Levelized carrying charges, operating and maintenance costs, fuel costs and total revenue requirement at varying LNG pressure levels, Cases AD2S and BD2S

	p_{LNG}	CC_{L}	$OMC_{\rm L}$	$FC_{\rm L}$	TRR 10^3 \$/a
	Dai	10 \$/a	10 \$/a	10 \$/a	10 \$/a
Casa AD2S	20	4,611	1,635	8.841	15.087
Case AD25	100	4,716	1,673	9,092	15,481
Case DD20	20	5,800	2,057	11,833	19,689
Case BD25	100	5,944	2,108	12,165	20,217

			pre	ssure iev	cis, casea		1 DD25			
	<i>p</i> LNG bar	Ċ _{F,tot} \$/h	Ċ _{P,tot} \$/h	Ċ _{D,tot} \$/h	Ż _{tot} \$/h	Ċ _{L,tot} ¹⁸ \$/h	c _{F,tot} \$/MJ	c _{P,tot} \$/MJ	r _{tot} -	f _{tot}
Casa AD2S	20	1,258	2,039	630	781	87	0.020	0.067	2.31	0.55
Case AD25	100	1,290	2,088	522	799	87	0.020	0.057	1.77	0.61
Core DD29	20	1,514	1,935	820	982	561	0.020	0.080	2.99	0.54
Case BD2S	100	1,555	2,001	702	1,006	561	0.019	0.061	2.30	0.60

 Table 6.33: Results obtained from the exergoeconomic analysis of the overall systems at varying LNG pressure levels, Cases AD2S and BD2S



Figure 6.32: Specific costs of the product streams, Cases AD2S and BD2S

¹⁸are already included in the cost associated with the exergy of the overall product

Chapter 7 Conclusion and outlook

This thesis evaluates the integration of LNG regasification into air separation units. As a base two different air separation units are analyzed which differ regarding the kind of product compression. In Case A, an external product compression unit is used in order to increase the pressure of the gaseous oxygen stream while in Case B, the liquid oxygen stream is pumped to a higher pressure (internal compression) and evaporates afterwards. The change of the product compression decreases the specific power consumption and enhances the safety of the system.

The results of the exergetic analysis show that the exergetic efficiency of Case B is slightly higher while keeping the production of gaseous oxygen and nitrogen and liquid oxygen constant in both air separation plants. In contrast, the total capital investment costs are approximately 2% higher in Case B than in Case A, which results in lower specific costs of the product streams in Case A. Especially, the specific costs of the gaseous oxygen are significantly lower in Case A than in Case B. A comparison of the results with data obtained from literature shows that the costs of the gaseous product streams are in the range of the published data. Sensitivity analyses regarding the electricity costs and the investment, operating and maintenance costs lead to the result that the costs of the product streams are much more affected by the electricity costs as by investment costs. A comparison of the results obtained from the exergoenvironmental analysis shows that the environmental impact of the gaseous products is close to the data given in literature. Unfortunately, the exergy-risk-hazard analysis could not be applied to the single air separation units. Solely, potential hazards related to air separation units are discussed in general and suggestions for major reduction of the hazard potentials of air separation units are proposed.

Four different systems with the integration of the LNG regasification are evaluated within this thesis, which differ regarding the complexity of the LNG insertion. Two of these systems have been developed with the intention to reduce the hazard potential. The results demonstrate the advantages of the use of the low-temperature exergy of LNG within air separation units. The results from the energy analysis show a decrease in the power consumption by approximately 50 % while the amount and purity of the gaseous and liquid products remain constant (exception: the amount of gaseous nitrogen even increases in Case AD2 and AD2S). The large decrease of the power consumption is

also reported in literature. The overall exergetic efficiency increases in the best case (Case AD2S) by 72 % in comparison to a single air separation unit which is mainly related to the decreased power consumption. From the economic point of view, it can be concluded that the system with the LNG integration in all heat exchangers (complex integration) has the lowest total capital investment costs, but the highest risk as demonstrated by the exergy-risk-hazard analysis. In contrast, the products generated by this system have the lowest specific costs and the lowest environmental impact. The environmental impact associated with the exergy of the overall product reduces significantly for the processes with integration of LNG regasification due to the lower power consumption and the associated decrease in the emissions of carbon dioxide. In addition, cooling water is saved due to the use of LNG as cooling medium in Case AD2 which is not considered within the calculation but is reported in [43].

The results of the analyses demonstrate the advantages of the integration of the LNG regasification into air separation units. Due to the use of the available low-temperature exergy of LNG, part of the exergy invested for the liquefaction process is recovered by decreasing the power consumption of the air separation unit.

For further investigations, existing industrial air separation units can be analyzed with and without the integration of LNG regasification. The evaluation of these plants using the exergybased methods would demonstrate the real potential for improving the air separation unit from the thermodynamic, the economic, the environmental, and the risk point of view. A further advantage is the reduction of the start-up time of air separation units due to the utilization of low-temperature exergy of LNG (shortly reported in [124]). In addition, dynamic analyses can be conducted to get a deeper understanding of the influence of the electricity market, as well as the LNG shipping market and LNG delivery.

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Appendix A Stream data

					Ta	able A.1:	Stream	data, Cas	se A						
stream number	ṁ	р	Т	e ^{CH}	e^{M}	e^{T}	Ė	$c^{\rm CH}$	c ^M	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	B
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	16.4	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
2	16.4	2.5	113.1	3.8	73.1	14.0	1.5	0.000	0.044	0.044	226.7	0.00	8.31	8.31	42.7
3	16.4	2.4	35.0	3.8	70.7	0.8	1.2	0.000	0.044	0.044	186.0	0.00	8.31	8.31	35.0
4	16.4	6.1	147.5	3.8	148.1	24.6	2.9	0.000	0.044	0.044	446.5	0.00	8.26	8.22	84.1
5	16.4	5.9	35.0	3.8	145.7	1.0	2.5	0.000	0.044	0.044	379.4	0.00	8.26	8.22	71.5
7	16.3	5.8	35.0	5.3	143.4	0.7	2.4	0.174	0.044	0.044	423.5	5.84	8.26	8.22	71.5
10	16.3	5.6	-173.4	5.3	141.2	134.4	4.6	0.174	0.044	0.232	2244.0	5.84	8.26	31.61	319.1
11	8.2	5.5	-173.7	13.0	135.4	456.2	4.9	0.352	0.047	0.186	2815.0	37.21	8.73	24.86	382.5
13	8.2	1.4	-189.0	13.0	26.8	547.7	4.8	0.352	0.047	0.162	2781.0	37.21	8.73	22.15	377.9
14	0.5	1.6	-178.7	120.9	33.3	539.3	0.3	0.227	0.127	0.160	212.8	27.09	17.83	21.46	27.8
15	6.8	1.3	-193.3	22.7	21.3	170.8	1.5	0.557	0.114	0.164	1062.0	64.65	17.53	22.73	140.9
17	6.8	1.3	15.0	22.7	18.6	0.0	0.3	0.557	0.114	0.164	363.7	64.65	17.53	22.73	44.2
18	6.8	20.0	419.4	22.7	253.8	163.0	3.0	0.557	0.048	0.043	784.2	64.65	8.55	7.84	121.1
19	6.8	19.4	357.9	22.7	251.2	125.0	2.7	0.557	0.048	0.043	741.1	64.65	8.55	7.84	113.2
20	3.0	1.6	-178.7	120.4	33.2	116.7	0.8	0.227	0.127	0.160	543.3	27.09	17.83	21.46	68.6
21	6.6	44.6	-130.0	25.5	322.0	86.8	2.9	0.272	0.046	0.205	940.9	30.43	8.67	32.44	151.4
22	3.0	1.5	15.0	120.4	31.1	0.0	0.5	0.227	0.127	0.160	338.4	27.09	17.83	21.46	41.2
23	3.0	20.0	366.8	120.4	220.3	118.1	1.4	0.227	0.058	0.046	491.7	27.09	9.29	7.89	67.4
24	3.0	19.4	20.0	120.4	218.1	0.0	1.0	0.227	0.058	0.046	431.4	27.09	9.29	7.89	57.1
25	3.3	1.4	-190.7	8.9	26.0	160.4	0.6	0.603	0.121	0.164	411.6	69.85	17.68	22.73	55.8
27	3.3	1.3	33.0	8.9	19.6	0.5	0.1	0.603	0.121	0.164	92.6	69.85	17.68	22.73	11.6
28	3.3	1.2	170.0	8.9	17.0	31.7	0.2	0.603	0.121	0.130	136.3	69.85	17.68	22.91	19.5
29	6.8	19.4	20.0	22.7	251.2	0.0	1.9	0.557	0.048	0.043	609.1	64.65	8.55	7.84	89.1
30	6.6	5.3	-178.3	25.5	141.3	141.4	2.0	0.272	0.049	0.184	947.3	30.43	9.00	25.98	135.8
31	6.6	5.1	-63.6	25.5	138.7	13.9	1.2	0.272	0.049	0.184	388.3	30.43	9.00	25.98	56.6
32	42.0	5.3	-166.9	25.5	141.3	115.9	11.9	0.272	0.045	0.139	4452.0	30.43	8.47	22.76	696.5
33	42.0	5.0	46.2	25.5	136.2	1.7	6.9	0.272	0.045	0.139	2015.0	30.43	8.47	22.76	297.2
34	42.0	14.0	176.2	25.5	224.0	35.1	11.9	0.272	0.044	0.047	2784.0	30.43	8.35	8.84	446.6
35	42.0	13.6	20.0	25.5	221.4	0.0	10.4	0.272	0.044	0.047	2520.0	30.43	8.35	8.84	396.5
36	42.0	32.0	117.1	25.5	294.0	15.9	14.1	0.272	0.044	0.043	3097.0	30.43	8.33	8.30	507.3
37	42.0	31.0	20.0	25.5	291.4	0.0	13.3	0.272	0.044	0.043	2977.0	30.43	8.33	8.30	484.2

stream number	ṁ	р	Т	e ^{CH}	e^{M}	e^{T}	Ė	c ^{CH}	c^{M}	e^{T}	Ċ	b ^{CH}	b^{M}	b^{T}	
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
	-														
38	42.0	37.3	38.9	25.5	306.9	1.0	14.0	0.272	0.045	0.067	3146.0	30.43	8.50	11.49	513.1
39	20.0	37.3	38.9	25.5	306.9	1.0	6.7	0.272	0.045	0.067	1498.0	30.43	8.50	11.49	244.3
40	20.0	46.0	61.9	25.5	324.6	3.8	7.1	0.272	0.046	0.068	1598.0	30.43	8.67	11.52	261.3
41	20.0	44.6	-130.0	25.5	322.0	86.8	8.7	0.272	0.046	0.205	2851.0	30.43	8.67	32.44	458.9
42	13.4	44.6	-130.0	25.5	322.0	86.8	5.8	0.272	0.046	0.205	1910.0	30.43	8.67	32.44	307.5
43	13.4	5.3	-178.3	25.5	141.3	209.7	5.0	0.272	0.046	0.117	1834.0	30.43	8.67	19.19	290.3
44	13.4	5.1	-164.8	25.5	138.7	111.6	3.7	0.272	0.046	0.117	1274.0	30.43	8.67	19.19	198.5
45	22.0	37.3	38.9	25.5	306.9	1.0	7.3	0.272	0.045	0.067	1648.0	30.43	8.50	11.49	268.8
46	22.0	36.9	-130.0	25.5	305.9	79.1	9.0	0.272	0.045	0.205	2924.0	30.43	8.50	32.44	470.4
47	22.0	5.1	-178.7	25.5	138.7	186.5	7.7	0.272	0.045	0.118	2790.0	30.43	8.50	19.41	441.3
48	6.6	43.3	-150.0	25.5	319.4	208.2	3.6	0.272	0.046	0.200	1504.0	30.43	8.67	32.20	243.2
49	6.6	5.6	-177.6	25.5	146.0	338.6	3.4	0.272	0.046	0.147	1504.0	30.43	8.67	24.24	243.2
50	2.5	5.3	-177.2	8.8	139.2	482.1	1.6	0.431	0.047	0.186	900.6	43.89	8.78	24.78	122.0
51	2.5	1.4	-192.2	8.8	24.5	586.1	1.5	0.431	0.047	0.162	900.6	43.89	8.78	22.11	122.0
52	0.5	5.4	-176.1	9.3	139.7	133.5	0.1	0.417	0.048	0.184	63.1	42.75	8.83	25.98	9.2
53	0.5	1.5	-182.9	9.3	35.0	141.8	0.1	0.417	0.048	0.208	63.1	42.75	8.83	30.97	9.2
54	3.8	5.3	-178.3	25.3	141.3	494.3	2.5	0.272	0.049	0.169	1326.0	30.43	9.00	22.87	182.1
55	2.7	5.3	-178.3	25.3	141.3	494.3	1.8	0.272	0.049	0.169	928.2	30.43	9.00	22.87	127.5
56	1.1	5.3	-178.3	25.3	141.3	494.3	0.8	0.272	0.049	0.169	397.8	30.43	9.00	22.87	54.6
57	1.1	1.3	-193.5	25.3	21.3	602.7	0.7	0.272	0.049	0.148	397.8	30.43	9.00	20.55	54.6
58	5.3	5.6	-177.6	25.5	146.0	338.6	2.7	0.272	0.046	0.147	1203.0	30.43	8.67	24.24	194.6
59	1.3	5.6	-177.6	25.5	146.0	338.6	0.7	0.272	0.046	0.147	300.8	30.43	8.67	24.24	48.7
63	18.2	5.3	-178.3	25.4	141.3	141.3	5.6	0.272	0.049	0.184	2608.0	30.43	9.00	25.98	373.9
64	11.6	5.3	-178.3	25.4	141.3	141.3	3.6	0.272	0.049	0.184	1662.0	30.43	9.00	25.98	238.2
65	11.6	5.3	-178.3	25.4	141.3	494.3	7.7	0.272	0.049	0.169	4051.0	30.43	9.00	22.87	556.4
66	7.8	5.3	-178.3	25.1	141.3	494.2	5.1	0.272	0.049	0.169	2722.0	30.43	9.00	22.87	374.0
67	10.3	1.6	-178.8	120.4	33.1	538.2	7.1	0.227	0.127	0.160	4359.0	27.09	17.83	21.46	569.5
68	9.8	1.6	-178.8	120.4	33.1	538.2	6.8	0.227	0.127	0.160	4147.0	27.09	17.83	21.46	541.8
69	9.8	1.6	-178.8	120.4	33.1	116.7	2.6	0.227	0.127	0.160	1770.0	27.09	17.83	21.46	223.6
70	6.8	1.6	-178.8	119.9	33.0	116.1	1.8	0.227	0.127	0.160	1225.0	27.09	17.83	21.46	154.8

	Table A.2: Stream data, Case B T CH M T CH M T CH M T CH M T T <th <="" colspan="2" th=""></th>														
stream number	ṁ	р	Т	$e^{\rm CH}$	e^{M}	e^{T}	Ė	c^{CH}	c^{M}	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	B
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	33.5	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
2	33.5	2.5	113.1	3.8	73.1	14.0	3.0	0.000	0.043	0.043	451.5	0.00	8.31	8.31	87.3
3	33.5	2.4	35.0	3.8	70.7	0.8	2.5	0.000	0.043	0.043	370.6	0.00	8.31	8.31	71.6
4	33.5	6.3	151.7	3.8	150.7	26.0	6.0	0.000	0.043	0.042	908.4	0.00	8.25	8.21	175.7
5	33.5	6.1	35.0	3.8	148.2	1.0	5.1	0.000	0.043	0.042	767.7	0.00	8.25	8.21	148.5
7	0.0	5.9	35.0	50.0	0.6	3.0	0.0	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
12	17.5	5.9	35.0	5.3	145.8	0.7	2.7	0.094	0.043	0.042	425.3	5.94	8.25	8.21	78.2
13	17.5	5.8	-173.1	5.3	143.4	141.9	5.1	0.094	0.043	0.193	2142.0	5.94	8.25	27.35	321.4
14	6.9	5.9	35.0	5.3	145.8	0.7	1.0	0.094	0.043	0.042	166.9	5.94	8.25	8.21	30.7
15	6.9	5.8	-120.0	5.3	143.4	48.8	1.4	0.094	0.043	0.193	396.4	5.94	8.25	27.35	63.1
16	6.9	1.5	-162.7	5.3	31.7	100.2	0.9	0.094	0.043	0.124	353.0	5.94	8.25	18.52	53.2
17	8.9	5.9	35.0	5.3	145.8	0.7	1.3	0.094	0.043	0.042	215.2	5.94	8.25	8.21	39.6
18	8.9	41.2	302.9	5.3	304.7	93.0	3.6	0.094	0.076	0.106	1066.0	5.94	14.73	20.57	205.4
19	8.9	40.0	-150.0	5.3	302.2	219.5	4.7	0.094	0.076	0.193	2098.0	5.94	14.73	27.35	334.8
20	8.9	5.8	-174.6	5.3	143.4	346.5	4.4	0.094	0.076	0.157	2098.0	5.94	14.73	24.07	334.8
21	16.1	5.5	-174.3	9.8	136.3	460.0	9.8	0.216	0.057	0.172	5159.0	24.24	11.04	23.40	726.0
22	16.1	1.4	-189.6	9.8	27.0	559.2	9.6	0.216	0.057	0.152	5159.0	24.24	11.04	21.41	726.0
23	10.3	5.3	-178.2	22.7	141.1	493.4	6.7	0.194	0.060	0.162	3429.0	23.14	11.30	22.19	483.0
26	10.3	5.3	-179.0	22.7	141.1	497.0	6.8	0.194	0.060	0.162	3455.0	23.14	11.30	22.23	486.7
27	10.3	1.3	-193.4	22.7	21.3	606.3	6.7	0.194	0.060	0.145	3455.0	23.14	11.30	20.46	486.7
28	3.5	1.6	-178.6	124.1	33.5	542.6	2.5	0.221	0.138	0.156	1467.0	27.81	20.24	21.05	195.9
29	0.5	1.6	-178.6	124.1	33.5	542.6	0.4	0.221	0.138	0.156	209.6	27.81	20.24	21.05	28.0
30	3.0	1.6	-178.6	124.1	33.5	542.6	2.1	0.221	0.138	0.156	1258.0	27.81	20.24	21.05	167.9
31	3.0	20.0	-177.7	124.1	221.8	353.8	2.1	0.221	0.154	0.156	1260.0	27.81	21.04	21.05	168.1
33	3.0	19.4	20.0	124.1	219.6	0.0	1.0	0.221	0.154	0.156	662.5	27.81	21.04	21.05	87.2
34	13.3	13	-193.2	20.8	21.3	170.2	2.8	0.548	0.128	0.155	1936.0	67.92	20.51	21.80	265.5
35	13.3	13	-191.9	20.8	21.3	166.6	2.8	0.548	0.128	0.155	1910.0	67.92	20.51	21.81	261.9
36	13.3	13	48.1	20.0	18.7	1 8	0.5	0.548	0.128	0.193	674.1	67.92	20.51	27.35	88.1
37	16.5	1.3	-189.0	5.6	21.1	152.8	3.0	0.594	0.128	0.155	1767.0	73 57	20.51	21.35	248 1
38	16.5	1.3	170.0	5.6	18.7	31.2	0.9	0.594	0.128	0.193	695.0	73 57	20.52	27.35	97.0
39	13.3	20.0	493.9	20.8	253.5	212.7	6.5	0.548	0.048	0.123	1553.0	67.92	8 72	7 95	253.8

stream number	ṁ	р	Т	e^{CH}	e^{M}	e^{T}	Ė	$c^{\rm CH}$	c^{M}	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	<i>B</i>
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
40	13.3	19.4	20.0	20.8	250.9	0.0	3.6	0.548	0.048	0.043	1115.0	67.92	8.72	7.95	172.0
44	20.4	5.3	-178.1	22.7	141.1	140.6	6.2	0.194	0.060	0.168	2691.0	23.14	11.30	24.06	404.8
46	20.4	5.3	-178.2	22.7	141.1	493.3	13.4	0.194	0.060	0.162	6823.0	23.14	11.30	22.19	961.2
47	10.2	5.3	-178.1	20.0	140.8	492.1	6.6	0.194	0.060	0.162	3364.0	23.14	11.30	22.19	474.2
48	20.8	1.6	-178.7	124.1	33.3	542.8	14.6	0.221	0.138	0.156	8721.0	27.81	20.24	21.05	1164.0
49	17.3	1.6	-178.7	124.1	33.3	542.8	12.1	0.221	0.138	0.156	7254.0	27.81	20.24	21.05	968.3
50	17.3	1.6	-178.7	124.1	33.3	118.3	4.8	0.221	0.138	0.156	3143.0	27.81	20.24	21.05	412.0
51	17.3	1.6	-178.7	124.0	33.3	118.3	4.8	0.221	0.138	0.156	3142.0	27.81	20.24	21.05	411.9

	Table A.3: Stream data, Case AD1 ream number \dot{m} p T e^{CH} e^{CH} e^{T} \dot{C} b^{CH} b^{M} b^{T} \dot{B}														
stream number	ṁ	р	Т	e^{CH}	e^{M}	e^{T}	Ė	c^{CH}	c^{M}	e^{T}	Ċ	b^{CH}	b^{M}	b^{T}	B
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	16.4	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
2	16.4	2.5	113.1	3.8	73.1	14.0	1.5	0.000	0.044	0.044	226.7	0.00	8.31	8.31	42.7
3	16.4	2.4	35.0	3.8	70.7	0.8	1.2	0.000	0.044	0.044	186.0	0.00	8.31	8.31	35.0
4	16.4	6.1	147.5	3.8	148.1	24.6	2.9	0.000	0.044	0.044	446.5	0.00	8.26	8.22	84.1
5	16.4	5.9	35.0	3.8	145.7	1.0	2.5	0.000	0.044	0.044	379.4	0.00	8.26	8.22	71.5
6	16.3	5.8	35.0	5.3	143.4	0.7	2.4	0.174	0.044	0.044	423.5	5.84	8.26	8.22	71.5
10	16.3	5.6	-173.4	5.3	141.2	134.4	4.6	0.174	0.044	0.078	1033.0	5.84	8.26	12.72	170.4
11	8.2	5.5	-173.7	13.0	135.4	456.2	4.9	0.226	0.047	0.096	1556.0	20.14	8.63	12.65	211.8
13	8.2	1.4	-189.0	13.0	26.8	547.7	4.8	0.226	0.047	0.088	1537.0	20.14	8.63	12.09	209.2
14	0.5	1.6	-178.7	120.9	33.3	539.3	0.3	0.140	0.092	0.091	124.8	15.09	12.88	11.98	15.7
15	6.8	1.3	-193.3	22.7	21.3	170.8	1.5	0.338	0.091	0.091	620.3	34.79	14.31	12.67	80.3
17	6.8	1.3	15.0	22.7	18.6	0.0	0.3	0.338	0.091	0.091	230.6	34.79	14.31	12.67	26.0
18	6.8	20.0	419.4	22.7	253.8	163.0	3.0	0.338	0.046	0.043	651.1	34.79	8.32	7.84	102.9
19	6.8	19.4	244.6	22.7	251.2	64.5	2.3	0.338	0.046	0.043	544.3	34.79	8.32	7.84	83.4
20	3.0	1.6	-178.7	120.4	33.2	116.7	0.8	0.140	0.092	0.091	330.3	15.09	12.88	11.98	39.3
22	3.0	1.5	15.0	120.4	31.1	0.0	0.5	0.140	0.092	0.091	255.3	15.09	12.88	11.98	29.9
23	3.0	20.0	366.8	120.4	220.3	118.1	1.4	0.140	0.062	0.047	364.9	15.09	9.64	8.00	48.5
24	3.0	19.4	20.0	120.4	218.0	0.0	1.0	0.140	0.062	0.047	328.4	15.09	9.64	8.00	42.3
25	3.3	1.4	-190.7	8.9	26.0	160.4	0.6	0.375	0.092	0.091	240.3	38.62	13.59	12.67	32.2
26	3.3	3.0	33.0	8.9	91.0	0.6	0.3	0.375	0.092	0.091	138.4	38.62	13.59	12.67	18.7
27	3.3	3.0	170.0	8.9	91.0	31.8	0.4	0.375	0.092	0.162	198.6	38.62	13.59	27.39	28.9
28	6.8	18.8	20.0	22.7	248.5	0.0	1.9	0.338	0.046	0.043	473.0	34.79	8.32	7.84	70.4
29	1.3	1.3	-193.5	25.5	21.3	406.5	0.6	0.167	0.047	0.091	201.1	16.11	8.55	14.89	31.6
30	6.6	5.3	-178.3	25.5	141.3	141.4	2.0	0.167	0.048	0.089	560.4	16.11	8.69	13.20	83.2
31	6.6	5.1	-122.2	25.5	138.7	52.5	14	0.167	0.048	0.089	368.9	16.11	8 69	13.20	54.8
32	20.0	5.1	-122.2	25.5	138.7	52.5	43	0.167	0.047	0.081	1083.0	16.11	8.60	12.63	163.0
33	20.0	5.0	152.2	25.5	136.7	26.2	3.8	0.167	0.047	0.118	990.9	16.11	8.60	17.32	146.3
34	20.0	1/1 0	333.3	25.5	220.0	110.8	73	0.167	0.047	0.060	1527.0	16.11	8 37	10.13	247.2
35	20.0	14.2	312.0	25.5	229.0	08.8	7.0	0.167	0.045	0.000	1/68 0	16.11	8 32	10.13	277.3
36	20.0	14.0	20.0	25.5	220.5	0.0	5.0	0.167	0.045	0.000	1033.0	16.11	8 32	10.13	163.6
20	20.0	25.2	125.7	25.5	202.2	19.5	5.0	0.107	0.045	0.000	1240.0	16.11	0.52 9.21	0.15	221.1

kg/sbar°CkJ/kgkJ/kgMWS/MJS/MJS/MJS/hmP/MJmp/mJmm/mJmm/ms/ms/ms/ms/ms/ms/ms/ms/	stream number	ṁ	р	Т	e^{CH}	e^{M}	e^{T}	Ė	c^{CH}	c^{M}	e^{T}	Ċ	b^{CH}	b^{M}	b^{T}	<i>B</i>
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$																
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	39	20.0	46.0	163.0	25.5	324.6	31.2	7.6	0.167	0.047	0.058	1536.0	16.11	8.55	9.75	251.1
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	40	20.0	44.7	-90.0	25.5	322.1	32.1	7.6	0.167	0.047	0.118	1671.0	16.11	8.55	17.32	267.7
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	41	6.6	44.7	-90.0	25.5	322.1	32.1	2.5	0.167	0.047	0.118	551.5	16.11	8.55	17.32	88.4
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	42	13.4	44.7	-90.0	25.5	322.1	32.1	5.1	0.167	0.047	0.118	1120.0	16.11	8.55	17.32	179.4
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	43	13.4	5.3	-168.7	25.5	141.3	119.7	3.8	0.167	0.047	0.077	969.0	16.11	8.55	12.34	149.2
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	44	13.4	5.1	-122.2	25.5	138.7	52.5	2.9	0.167	0.047	0.077	714.4	16.11	8.55	12.34	108.2
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	46	1.0	1.0	120.0	50.0	0.0	598.9	0.6	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	49	6.6	5.6	-177.6	25.5	146.0	338.7	3.4	0.167	0.047	0.092	1005.0	16.11	8.55	14.72	157.8
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	50	2.5	5.3	-177.2	8.8	139.2	482.2	1.6	0.285	0.047	0.096	498.3	24.11	8.64	12.61	67.5
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	51	2.5	1.4	-192.2	8.8	24.5	586.1	1.5	0.285	0.047	0.088	498.3	24.11	8.64	12.07	67.5
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	52	0.5	5.4	-176.1	9.3	139.7	133.5	0.1	0.275	0.047	0.089	37.9	23.43	8.65	13.20	5.7
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	53	0.5	1.5	-182.9	9.3	35.0	141.8	0.1	0.275	0.047	0.119	37.9	23.43	8.65	18.81	5.7
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	54	3.8	5.3	-178.3	25.3	141.3	494.3	2.5	0.167	0.048	0.092	769.8	16.11	8.69	12.40	105.9
561.1 5.3 -178.3 25.3 141.3 494.3 0.8 0.167 0.048 0.092 230.9 16.11 8.69 12.40 33.57 57 1.11.3 -193.5 25.3 21.3 602.7 0.7 0.167 0.048 0.085 230.9 16.11 8.69 11.90 33.56 58 5.3 5.6 -177.6 25.5 146.0 338.7 2.7 0.167 0.047 0.092 804.4 16.11 8.55 14.72 33.56 59 1.3 5.6 -177.6 25.5 146.0 338.7 0.7 0.167 0.047 0.092 201.1 16.11 8.55 14.72 33.66 60 10.0 1.3 -162.0 50654.0 32.4 850.1 515.4 0.005 0.005 9277.0 5.48 5.48 5.48 10.66 61 10.0 20.0 -160.9 50654.0 374.6 395.7 514.3 0.005 0.006 0.005 9287.0 5.48 5.59 5.48 10.66 62 10.0 19.4 -134.8 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9267.0 5.48 5.59 5.48 10.0 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 10.0 <t< td=""><td>55</td><td>2.7</td><td>5.3</td><td>-178.3</td><td>25.3</td><td>141.3</td><td>494.3</td><td>1.8</td><td>0.167</td><td>0.048</td><td>0.092</td><td>538.9</td><td>16.11</td><td>8.69</td><td>12.40</td><td>74.2</td></t<>	55	2.7	5.3	-178.3	25.3	141.3	494.3	1.8	0.167	0.048	0.092	538.9	16.11	8.69	12.40	74.2
57 1.1 1.3 -193.5 25.3 21.3 602.7 0.7 0.167 0.048 0.085 230.9 16.11 8.69 11.90 33 58 5.3 5.6 -177.6 25.5 146.0 338.7 2.7 0.167 0.047 0.092 804.4 16.11 8.55 14.72 13 59 1.3 5.6 -177.6 25.5 146.0 338.7 0.7 0.167 0.047 0.092 201.1 16.11 8.55 14.72 33 60 10.0 1.3 -162.0 50654.0 32.4 850.1 515.4 0.005 0.005 9277.0 5.48 5.48 5.48 10 61 10.0 20.0 -160.9 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9267.0 5.48 5.59 5.48 10 62 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 10	56	1.1	5.3	-178.3	25.3	141.3	494.3	0.8	0.167	0.048	0.092	230.9	16.11	8.69	12.40	31.8
58 5.3 5.6 -177.6 25.5 146.0 338.7 2.7 0.167 0.047 0.092 804.4 16.11 8.55 14.72 11 59 1.3 5.6 -177.6 25.5 146.0 338.7 0.7 0.167 0.047 0.092 201.1 16.11 8.55 14.72 33 60 10.0 1.3 -162.0 50654.0 32.4 850.1 515.4 0.005 0.005 0.005 9277.0 5.48 5.48 5.48 5.48 10 61 10.0 20.0 -160.9 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9287.0 5.48 5.59 5.48 10 62 10.0 19.4 -134.8 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 916.0 5.48 5.59 5.48 10 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.5	57	1.1	1.3	-193.5	25.3	21.3	602.7	0.7	0.167	0.048	0.085	230.9	16.11	8.69	11.90	31.8
59 1.3 5.6 -177.6 25.5 146.0 338.7 0.7 0.167 0.047 0.092 201.1 16.11 8.55 14.72 33 60 10.0 1.3 -162.0 50654.0 32.4 850.1 515.4 0.005 0.005 9277.0 5.48 5.48 5.48 5.48 10 61 10.0 20.0 -160.9 50654.0 381.3 501.4 515.4 0.005 0.006 0.005 9287.0 5.48 5.59 5.48 10 62 10.0 19.4 -134.8 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9287.0 5.48 5.59 5.48 10 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 100 66 18.2 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.092 2352.0 16.11 8.69 1	58	5.3	5.6	-177.6	25.5	146.0	338.7	2.7	0.167	0.047	0.092	804.4	16.11	8.55	14.72	126.2
60 10.0 1.3 -162.0 50654.0 32.4 850.1 515.4 0.005 0.005 9277.0 5.48 5.48 5.48 10 61 10.0 20.0 -160.9 50654.0 381.3 501.4 515.4 0.005 0.005 9287.0 5.48 5.59 5.48 10 62 10.0 19.4 -134.8 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9267.0 5.48 5.59 5.48 10 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 100 66 18.2 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14.40 33.6 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33.20 14.43 344.3 7.7 0.167 0.048 0.092 2352.0 16.11 <td>59</td> <td>1.3</td> <td>5.6</td> <td>-177.6</td> <td>25.5</td> <td>146.0</td> <td>338.7</td> <td>0.7</td> <td>0.167</td> <td>0.047</td> <td>0.092</td> <td>201.1</td> <td>16.11</td> <td>8.55</td> <td>14.72</td> <td>31.6</td>	59	1.3	5.6	-177.6	25.5	146.0	338.7	0.7	0.167	0.047	0.092	201.1	16.11	8.55	14.72	31.6
61 10.0 20.0 -160.9 50654.0 381.3 501.4 515.4 0.005 0.006 0.005 9287.0 5.48 5.59 5.48 10 62 10.0 19.4 -134.8 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9267.0 5.48 5.59 5.48 10 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 100 66 18.2 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14.0 67 11.6 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.092 2352.0 16.11 8.69 13.20 14.0 33.0 68 11.6 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 <	60	10.0	1.3	-162.0	50654.0	32.4	850.1	515.4	0.005	0.005	0.005	9277.0	5.48	5.48	5.48	10170.0
62 10.0 19.4 -134.8 50654.0 377.6 395.7 514.3 0.005 0.006 0.005 9267.0 5.48 5.59 5.48 10 63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 100 66 18.2 5.3 -178.3 25.4 141.3 141.3 5.6 0.167 0.048 0.089 1543.0 16.11 8.69 13.20 14.3 67 11.6 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14.4 68 11.6 5.3 -178.3 25.4 141.3 494.3 7.7 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33.4 69 7.8 5.3 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 <td< td=""><td>61</td><td>10.0</td><td>20.0</td><td>-160.9</td><td>50654.0</td><td>381.3</td><td>501.4</td><td>515.4</td><td>0.005</td><td>0.006</td><td>0.005</td><td>9287.0</td><td>5.48</td><td>5.59</td><td>5.48</td><td>10170.0</td></td<>	61	10.0	20.0	-160.9	50654.0	381.3	501.4	515.4	0.005	0.006	0.005	9287.0	5.48	5.59	5.48	10170.0
63 10.0 18.8 15.0 50654.0 374.0 0.0 510.3 0.005 0.006 0.005 9196.0 5.48 5.59 5.48 100 66 18.2 5.3 -178.3 25.4 141.3 141.3 5.6 0.167 0.048 0.089 1543.0 16.11 8.69 13.20 22 67 11.6 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14 68 11.6 5.3 -178.3 25.4 141.3 494.3 7.7 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33 69 7.8 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 8.69 12.40 33 70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 <td>62</td> <td>10.0</td> <td>19.4</td> <td>-134.8</td> <td>50654.0</td> <td>377.6</td> <td>395.7</td> <td>514.3</td> <td>0.005</td> <td>0.006</td> <td>0.005</td> <td>9267.0</td> <td>5.48</td> <td>5.59</td> <td>5.48</td> <td>10150.0</td>	62	10.0	19.4	-134.8	50654.0	377.6	395.7	514.3	0.005	0.006	0.005	9267.0	5.48	5.59	5.48	10150.0
66 18.2 5.3 -178.3 25.4 141.3 141.3 5.6 0.167 0.048 0.089 1543.0 16.11 8.69 13.20 22 67 11.6 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14 68 11.6 5.3 -178.3 25.4 141.3 494.3 7.7 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33 69 7.8 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 8.69 12.40 23 70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 11.98 33 71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98	63	10.0	18.8	15.0	50654.0	374.0	0.0	510.3	0.005	0.006	0.005	9196.0	5.48	5.59	5.48	10070.0
67 11.6 5.3 -178.3 25.4 141.3 141.3 3.6 0.167 0.048 0.089 983.1 16.11 8.69 13.20 14 68 11.6 5.3 -178.3 25.4 141.3 494.3 7.7 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33 69 7.8 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 8.69 12.40 2 70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 11.98 33 71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 33 72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 1076.0 15.09 12.88 11.98	66	18.2	5.3	-178.3	25.4	141.3	141.3	5.6	0.167	0.048	0.089	1543.0	16.11	8.69	13.20	229.1
68 11.6 5.3 -178.3 25.4 141.3 494.3 7.7 0.167 0.048 0.092 2352.0 16.11 8.69 12.40 33 69 7.8 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 8.69 12.40 2 70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 11.98 33 71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 33 72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 33 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 1076.0 15.09 12.88 11.98	67	11.6	5.3	-178.3	25.4	141.3	141.3	3.6	0.167	0.048	0.089	983.1	16.11	8.69	13.20	146.0
69 7.8 5.3 -178.3 25.1 141.3 494.2 5.1 0.167 0.048 0.092 1580.0 16.11 8.69 12.40 2 70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 11.98 33 71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 33 72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 12.09 12.88 11.98 33 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 133 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 745.0 15.09 12.88 11.98 88	68	11.6	5.3	-178.3	25.4	141.3	494.3	7.7	0.167	0.048	0.092	2352.0	16.11	8.69	12.40	323.6
70 10.3 1.6 -178.8 120.4 33.1 538.2 7.1 0.140 0.092 0.091 2557.0 15.09 12.88 11.98 33.1 71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 33.1 72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 11.98 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 11.98	69	7.8	5.3	-178.3	25.1	141.3	494.2	5.1	0.167	0.048	0.092	1580.0	16.11	8.69	12.40	217.5
71 9.8 1.6 -178.8 120.4 33.1 538.2 6.8 0.140 0.092 0.091 2433.0 15.09 12.88 11.98 30 72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 11 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 745.0 15.09 12.88 11.98 88	70	10.3	1.6	-178.8	120.4	33.1	538.2	7.1	0.140	0.092	0.091	2557.0	15.09	12.88	11.98	321.4
72 9.8 1.6 -178.8 120.4 33.1 116.7 2.6 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 12 73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 1076.0 15.09 12.88 11.98 12	71	9.8	1.6	-178.8	120.4	33.1	538.2	6.8	0.140	0.092	0.091	2433.0	15.09	12.88	11.98	305.8
73 6.8 1.6 -178.8 119.9 33.0 116.1 1.8 0.140 0.092 0.091 745.0 15.09 12.88 11.98 8	72	9.8	1.6	-178.8	120.4	33.1	116.7	2.6	0.140	0.092	0.091	1076.0	15.09	12.88	11.98	128.1
	73	6.8	1.6	-178.8	119.9	33.0	116.1	1.8	0.140	0.092	0.091	745.0	15.09	12.88	11.98	88.7

					Та	ble A.4:	Stream	data, Cas	e AD2						
stream number	ṁ	р	Т	$e^{\rm CH}$	e^{M}	e^{T}	Ė	$c^{\rm CH}$	с ^М	e^{T}	Ċ	b^{CH}	b^{M}	b^{T}	Ė
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	16.4	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.0	0.0	0.0	0.0
2	16.4	2.0	88.4	3.8	56.3	8.2	1.1	0.000	0.045	0.045	170.9	0.0	8.4	8.4	31.9
3	16.4	1.9	35.0	3.8	53.8	0.7	1.0	0.000	0.045	0.045	144.5	0.0	8.4	8.4	27.0
5	16.3	1.9	35.0	5.3	51.1	0.7	0.9	0.170	0.045	0.045	188.5	5.1	8.4	8.4	27.0
6	16.3	1.8	-20.0	5.3	48.4	2.3	0.9	0.170	0.045	0.160	201.6	5.1	8.4	101.7	39.2
7	16.3	4.0	56.2	5.3	113.4	2.7	2.0	0.170	0.048	0.050	376.3	5.1	10.3	11.7	71.9
8	16.3	3.9	-10.0	5.3	110.9	1.2	1.9	0.170	0.048	0.420	390.1	5.1	10.3	237.3	84.7
9	16.3	5.7	26.8	5.3	142.9	0.2	2.4	0.170	0.051	0.061	477.5	5.1	11.8	16.9	100.4
10	16.3	5.6	-173.4	5.3	141.2	132.9	4.5	0.170	0.051	0.092	1185.0	5.1	11.8	17.0	231.2
11	8.2	5.5	-173.7	13.0	135.4	456.2	4.9	0.219	0.055	0.091	1528.0	23.3	11.9	15.1	258.6
13	8.2	1.4	-189.0	13.0	26.8	547.7	4.8	0.219	0.055	0.086	1510.0	23.3	11.9	14.7	255.5
14	0.5	1.6	-178.7	121.0	33.3	539.4	0.3	0.135	0.096	0.088	120.6	17.9	16.6	14.4	18.9
15	7.2	1.3	-193.3	22.3	21.3	170.6	1.6	0.339	0.100	0.088	643.6	42.8	18.9	15.3	103.4
18	7.2	1.3	15.0	22.3	18.6	0.0	0.3	0.339	0.100	0.088	245.9	42.8	18.9	15.3	34.1
19	7.2	20.0	419.4	22.3	253.7	162.9	3.2	0.339	0.047	0.043	689.5	42.8	8.7	7.8	115.6
20	3.0	1.6	-178.7	120.4	33.2	116.7	0.8	0.135	0.096	0.088	321.0	17.9	16.6	14.4	47.4
21	7.2	19.4	365.2	22.3	251.1	129.3	2.9	0.339	0.047	0.043	648.9	42.8	8.7	7.8	108.1
22	3.0	1.5	15.0	120.4	31.1	0.0	0.5	0.135	0.096	0.088	207.8	17.9	16.6	14.4	28.9
23	3.0	20.0	366.7	120.4	220.3	118.1	1.4	0.135	0.053	0.046	361.1	17.9	9.1	7.9	55.1
24	3.0	19.4	97.1	120.4	218.1	9.2	1.0	0.135	0.053	0.046	305.5	17.9	9.1	7.9	45.6
25	2.9	1.4	-190.6	8.6	25.9	160.0	0.6	0.364	0.098	0.088	205.5	45.9	17.7	15.3	34.3
26	2.9	1.3	24.8	8.6	19.6	0.2	0.1	0.364	0.098	0.092	52.8	45.9	17.7	17.0	7.8
27	2.9	1.2	170.0	8.6	16.9	31.7	0.2	0.364	0.098	0.134	94.0	45.9	17.7	24.2	15.2
28	3.0	18.8	20.0	120.4	215.9	0.0	1.0	0.135	0.053	0.046	299.6	17.9	9.1	7.9	44.6
29	1.3	1.3	-193.5	25.5	21.3	408.2	0.6	0.161	0.059	0.072	165.8	18.9	10.8	15.8	34.4
30	6.7	5.3	-178.3	25.5	141.3	141.4	2.1	0.161	0.056	0.085	573.9	18.9	12.0	15.7	105.2
31	6.7	5.1	-99.1	25.5	138.7	33.1	1.3	0.161	0.056	0.085	350.8	18.9	12.0	15.7	63.8
32	6.7	16.0	-19.1	25.5	235.3	2.4	1.8	0.161	0.063	0.085	457.8	18.9	11.6	15.7	77.9
33	6.7	46.0	88.1	25.5	324.5	8.8	2.4	0.161	0.059	0.049	568.8	18.9	10.8	8.6	97.2
34	6.7	44.6	-150.0	25.5	322.0	207.1	3.7	0.161	0.059	0.055	829.2	18.9	10.8	15.6	172.1
36	7.2	18.3	20.0	22.3	246.0	0.0	1.9	0.339	0.047	0.043	498.5	42.8	8.7	7.8	80.5
stream number	ṁ	р	Т	e^{CH}	e^{M}	e^{T}	Ė	$c^{\rm CH}$	c^{M}	e^{T}	Ċ	b^{CH}	b^{M}	b^{T}	Ė
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	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
37	6.7	5.6	-177.6	25.5	146.0	340.0	3.4	0.161	0.059	0.064	829.2	18.9	10.8	15.1	172.1
38	1.3	5.6	-177.6	25.5	146.0	340.0	0.7	0.161	0.059	0.064	165.8	18.9	10.8	15.1	34.4
39	10.0	1.3	-162.0	50654.0	32.4	850.1	515.4	0.005	0.005	0.005	9277.0	5.5	5.5	5.5	10170.0
40	10.0	20.0	-160.9	50654.0	381.3	501.4	515.4	0.005	0.006	0.005	9287.0	5.5	5.6	5.5	10170.0
41	5.0	20.0	-160.9	50654.0	381.3	501.4	257.7	0.005	0.006	0.005	4644.0	5.5	5.6	5.5	5087.0
42	5.0	19.4	-99.1	50654.0	377.6	166.4	256.0	0.005	0.006	0.005	4613.0	5.5	5.6	5.5	5054.0
43	10.0	19.4	-103.5	50654.0	377.6	249.2	512.8	0.005	0.006	0.005	9242.0	5.5	5.6	5.6	10120.0
44	10.0	18.8	-101.6	50654.0	373.9	190.5	512.2	0.005	0.006	0.005	9230.0	5.5	5.6	5.6	10110.0
45	10.0	18.3	-96.1	50654.0	370.1	132.9	511.6	0.005	0.006	0.005	9219.0	5.5	5.6	5.6	10100.0
46	10.0	17.7	-80.0	50654.0	366.4	72.6	510.9	0.005	0.006	0.005	9207.0	5.5	5.6	5.6	10090.0
47	10.0	15.0	15.0	50654.0	345.8	0.0	510.0	0.005	0.006	0.005	9190.0	5.5	5.6	5.6	10070.0
48	5.0	20.0	-160.9	50654.0	381.3	501.4	257.7	0.005	0.006	0.005	4644.0	5.5	5.6	5.5	5087.0
49	5.0	19.4	-117.6	50654.0	377.6	338.9	256.9	0.005	0.006	0.005	4629.0	5.5	5.6	5.5	5071.0
50	2.5	5.3	-177.2	9.2	139.4	482.7	1.6	0.268	0.055	0.092	489.8	27.1	11.9	15.0	82.4
51	2.5	1.4	-192.3	9.2	24.5	586.8	1.6	0.268	0.055	0.086	489.8	27.1	11.9	14.7	82.4
52	0.5	5.4	-176.2	9.6	139.7	133.9	0.1	0.260	0.055	0.085	38.8	26.5	11.9	15.7	7.2
53	0.5	1.5	-183.0	9.6	35.0	142.2	0.1	0.260	0.055	0.120	38.8	26.5	11.9	23.5	7.2
54	3.8	5.3	-178.3	25.3	141.3	494.4	2.5	0.161	0.056	0.088	752.4	18.9	12.0	14.8	128.8
55	2.6	5.3	-178.3	25.3	141.3	494.4	1.7	0.161	0.056	0.088	526.7	18.9	12.0	14.8	90.2
56	1.1	5.3	-178.3	25.3	141.3	494.4	0.7	0.161	0.056	0.088	225.7	18.9	12.0	14.8	38.6
57	1.1	1.3	-193.5	25.3	21.3	602.7	0.7	0.161	0.056	0.083	225.7	18.9	12.0	14.6	38.6
58	5.3	5.6	-177.6	25.5	146.0	340.0	2.7	0.161	0.059	0.064	663.3	18.9	10.8	15.1	137.6
64	18.3	5.3	-178.3	25.4	141.3	141.3	5.6	0.161	0.056	0.085	1571.0	18.9	12.0	15.7	287.9
65	11.6	5.3	-178.3	25.4	141.3	141.3	3.6	0.161	0.056	0.085	997.1	18.9	12.0	15.7	182.8
66	11.6	5.3	-178.3	25.4	141.3	494.3	7.7	0.161	0.056	0.088	2316.0	18.9	12.0	14.8	396.4
67	7.8	5.3	-178.3	25.1	141.3	494.2	5.2	0.161	0.056	0.088	1562.0	18.9	12.0	14.8	267.4
68	10.3	1.6	-178.8	120.4	33.1	538.3	7.1	0.135	0.096	0.088	2474.0	17.9	16.6	14.4	386.9
69	9.8	1.6	-178.8	120.4	33.1	538.3	6.8	0.135	0.096	0.088	2353.0	17.9	16.6	14.4	368.1
70	9.8	1.6	-178.8	120.4	33.1	116.8	2.6	0.135	0.096	0.088	1046.0	17.9	16.6	14.4	154.5
71	6.8	1.6	-178.8	120.0	33.0	116.1	1.8	0.135	0.096	0.088	724.7	17.9	16.6	14.4	107.0

	Table A.5: Stream data, Case AD2S														
stream number	ṁ	р	Т	e^{CH}	e^{M}	e^{T}	Ė	$c^{\rm CH}$	c^{M}	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	16.4	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
2	16.4	2.0	88.4	3.8	56.3	8.2	1.1	0.000	0.045	0.045	170.9	0.00	8.38	8.38	31.9
3	16.4	1.9	35.0	3.8	53.8	0.7	1.0	0.000	0.045	0.045	144.5	0.00	8.38	8.38	27.0
5	16.3	1.9	35.0	5.3	51.1	0.7	0.9	0.170	0.045	0.045	188.5	5.05	8.38	8.38	27.0
6	16.3	1.8	-20.0	5.3	48.4	2.3	0.9	0.170	0.045	0.280	218.0	5.05	8.38	133.00	43.5
7	16.3	4.0	56.2	5.3	113.4	2.7	2.0	0.170	0.050	0.054	392.7	5.05	10.91	12.80	76.1
8	16.3	3.9	-10.0	5.3	110.9	1.2	1.9	0.170	0.050	0.635	420.2	5.05	10.91	273.10	91.1
9	16.3	5.7	26.8	5.3	142.9	0.2	2.4	0.170	0.054	0.069	507.5	5.05	12.54	18.20	106.9
10	16.3	5.6	-173.4	5.3	141.2	132.9	4.5	0.170	0.054	0.110	1361.0	5.05	12.54	16.93	237.2
11	8.2	5.5	-173.7	13.0	135.4	456.2	4.9	0.136	0.051	0.085	1396.0	11.94	10.77	12.41	214.2
13	8.2	1.4	-189.0	13.0	26.8	547.7	4.8	0.136	0.051	0.080	1379.0	11.94	10.77	12.31	211.6
14	0.5	1.6	-178.7	121.0	33.3	539.4	0.3	0.114	0.088	0.080	107.4	13.52	13.91	11.69	15.1
15	7.2	1.3	-193.3	22.3	21.3	170.6	1.6	0.259	0.091	0.079	554.0	29.32	16.13	12.42	81.3
16	7.2	1.3	15.0	22.3	18.6	0.0	0.3	0.259	0.091	0.079	195.3	29.32	16.13	12.42	24.9
17	7.2	20.0	419.4	22.3	253.7	162.9	3.2	0.259	0.046	0.043	638.9	29.32	8.45	7.84	106.3
18	7.2	19.4	365.2	22.3	251.1	129.3	2.9	0.259	0.046	0.043	598.3	29.32	8.45	7.84	98.9
19	7.2	18.8	114.7	22.3	248.5	15.0	2.1	0.259	0.046	0.043	467.8	29.32	8.45	7.84	74.9
20	3.0	1.6	-178.7	120.4	33.2	116.7	0.8	0.114	0.088	0.080	280.1	13.52	13.91	11.69	37.3
21	3.0	1.5	15.0	120.4	31.1	0.0	0.5	0.114	0.088	0.080	177.7	13.52	13.91	11.69	22.2
22	3.0	20.0	366.7	120.4	220.3	118.1	1.4	0.114	0.052	0.046	331.0	13.52	8.74	7.89	48.4
23	3.0	19.4	114.7	120.4	218.1	13.2	1.1	0.114	0.052	0.046	277.4	13.52	8.74	7.89	39.3
24	3.0	18.3	20.0	120.4	213.6	0.0	1.0	0.114	0.052	0.046	268.3	13.52	8.74	7.89	37.7
25	2.9	1.4	-190.6	8.6	25.9	160.0	0.6	0.277	0.089	0.079	181.0	31.28	15.01	12.42	27.6
26	2.9	1.3	24.8	8.6	22.1	0.2	0.1	0.277	0.089	0.110	45.6	31.28	15.01	16.93	6.3
27	2.9	1.2	170.0	8.6	16.9	31.7	0.2	0.277	0.089	0.140	86.8	31.28	15.01	25.13	13.7
28	7.2	18.3	20.0	22.3	246.0	0.0	1.9	0.259	0.046	0.043	448.1	29.32	8.45	7.84	71.3
29	1.3	1.3	-193.5	25.5	21.3	408.2	0.6	0.000	0.036	0.036	73.5	0.00	4.28	8.89	17.8
30	6.7	5.3	-178.3	25.5	141.3	141.4	2.1	0.115	0.052	0.078	511.8	11.82	10.79	12.94	87.7
32	6.7	5.2	-81.9	25.5	138.8	22.5	1.2	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
33	6.7	16.0	5.7	25.5	235.3	0.2	1.7	0.000	0.023	0.000	130.8	0.00	2.77	0.00	15.6
34	6.7	46.0	123.1	25.5	324.5	17.9	2.5	0.000	0.036	0.071	313.4	0.00	4.28	8.27	36.9

stream number	ṁ	p	Т	e^{CH}	e ^M	e^{T}	Ė	c^{CH}	c^{M}	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	Ė
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
35	67	44.6	-150.0	25.5	322.0	207.1	37	0.000	0.036	0.018	367.6	0.00	4 28	11 30	89.2
36	67	53	-178.2	25.5	141 7	342.6	3.4	0.000	0.036	0.030	367.6	0.00	4.20	9.08	89.2
37	13	53	-178.2	25.5	141.7	342.6	0.7	0.000	0.036	0.030	73.5	0.00	4 28	9.08	17.8
39	10.0	13	-162.0	50654.0	32.4	850.1	515.4	0.005	0.005	0.005	9277.0	5.48	5.48	5.48	10170.0
40	10.0	20.0	-160.9	50654.0	381.3	501.4	515.4	0.005	0.006	0.005	9287.0	5.48	5.59	5.48	10170.0
41	10.0	19.4	-103.2	50654.0	377.7	240.0	512.7	0.005	0.006	0.005	9240.0	5.48	5.59	5.48	10120.0
42	10.0	18.9	15.0	50654.0	374.0	0.0	510.3	0.005	0.006	0.005	9196.0	5.48	5.59	5.48	10070.0
43	30.0	1.5	20.0	0.0	0.1	0.1	0.0	0.000	0.467	0.037	3.2	0.00	8.86	24.60	0.4
44	30.0	1.5	-39.2	0.0	0.0	18.2	0.5	0.000	0.467	0.037	75.9	0.00	8.86	24.60	48.5
45	30.0	1.4	-29.6	0.0	0.0	12.0	0.4	0.000	0.467	0.037	50.7	0.00	8.86	24.60	32.0
46	30.0	1.4	-17.9	0.0	0.0	6.4	0.2	0.000	0.467	0.037	27.8	0.00	8.86	24.60	17.0
47	30.0	1.4	-8.5	0.0	0.0	3.2	0.1	0.000	0.467	0.037	14.7	0.00	8.86	24.60	8.4
48	30.0	1.4	20.0	0.0	0.0	0.1	0.0	0.000	0.467	0.037	2.4	0.00	8.86	24.60	0.4
49	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
50	2.5	5.3	-177.2	9.2	139.4	482.7	1.6	0.153	0.052	0.085	447.8	12.05	10.77	12.37	68.2
51	2.5	1.4	-192.3	9.2	24.5	586.8	1.6	0.153	0.052	0.080	447.8	12.05	10.77	12.28	68.2
52	0.5	5.4	-176.2	9.6	139.7	133.9	0.1	0.150	0.052	0.078	34.4	12.03	10.78	12.94	6.0
53	0.5	1.5	-183.0	9.6	35.0	142.2	0.1	0.150	0.052	0.112	34.4	12.03	10.78	20.12	6.0
54	3.8	5.3	-178.3	25.3	141.3	494.4	2.5	0.115	0.052	0.080	677.2	11.82	10.79	12.12	105.9
55	2.6	5.3	-178.3	25.3	141.3	494.4	1.7	0.115	0.052	0.080	474.1	11.82	10.79	12.12	74.1
56	1.1	5.3	-178.3	25.3	141.3	494.4	0.7	0.115	0.052	0.080	203.2	11.82	10.79	12.12	31.8
57	1.1	1.3	-193.5	25.3	21.3	602.7	0.7	0.115	0.052	0.076	203.2	11.82	10.79	12.09	31.8
58	5.3	5.3	-178.2	25.5	141.7	342.6	2.7	0.000	0.036	0.030	294.1	0.00	4.28	9.08	71.4
62	18.3	5.3	-178.3	25.4	141.3	141.3	5.6	0.115	0.052	0.078	1401.0	11.82	10.79	12.94	240.0
63	11.6	5.3	-178.3	25.4	141.3	141.3	3.6	0.115	0.052	0.078	889.3	11.82	10.79	12.94	152.4
64	11.6	5.3	-178.3	25.4	141.3	494.3	7.7	0.115	0.052	0.080	2084.0	11.82	10.79	12.12	326.0
65	7.8	5.3	-178.3	25.1	141.3	494.2	5.2	0.115	0.052	0.080	1406.0	11.82	10.79	12.12	220.0
66	10.3	1.6	-178.8	120.4	33.1	538.3	7.1	0.114	0.088	0.080	2203.0	13.52	13.91	11.69	310.3
67	9.8	1.6	-178.8	120.4	33.1	538.3	6.8	0.114	0.088	0.080	2096.0	13.52	13.91	11.69	295.2
68	9.8	1.6	-178.8	120.4	33.1	116.8	2.6	0.114	0.088	0.080	913.3	13.52	13.91	11.69	121.6
69	6.8	1.6	-178.8	120.0	33.0	116.1	1.8	0.114	0.088	0.080	632.5	13.52	13.91	11.69	84.2

	Table A.6: Stream data, Case BD2S														
stream number	ṁ	р	Т	$e^{\rm CH}$	e^{M}	e^{T}	Ė	c^{CH}	с ^М	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	Ė
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
1	33.5	1.0	15.0	3.8	0.0	0.0	0.1	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
2	33.5	2.5	113.0	3.8	73.1	14.0	3.0	0.000	0.043	0.043	451.4	0.00	8.31	8.31	87.3
3	33.5	2.4	35.0	3.8	70.6	0.8	2.5	0.000	0.043	0.043	369.9	0.00	8.31	8.31	71.5
5	33.3	2.3	35.0	5.3	68.0	0.7	2.5	0.090	0.043	0.043	409.7	5.14	8.31	8.31	71.5
6	33.3	2.2	5.0	5.3	65.5	0.2	2.4	0.090	0.043	0.043	394.2	5.14	8.31	8.31	68.5
7	33.3	6.1	114.8	5.3	148.3	14.3	5.6	0.090	0.046	0.013	891.6	5.14	8.86	2.58	165.0
10	33.3	5.9	25.8	5.3	145.8	0.2	5.0	0.090	0.046	0.013	855.5	5.14	8.86	2.58	158.0
11	24.4	5.9	25.8	5.3	145.8	0.2	3.7	0.090	0.046	0.013	627.5	5.14	8.86	2.58	115.9
12	17.5	5.9	25.8	5.3	145.8	0.2	2.7	0.090	0.046	0.013	450.6	5.14	8.86	2.58	83.2
13	17.5	5.8	-173.1	5.3	143.4	141.9	5.1	0.090	0.046	0.150	1788.0	5.14	8.86	17.68	240.1
14	6.9	5.9	25.8	5.3	145.8	0.2	1.0	0.090	0.046	0.013	176.9	5.14	8.86	2.58	32.7
15	6.9	5.8	-120.0	5.3	143.4	48.8	1.4	0.090	0.046	0.150	355.4	5.14	8.86	17.68	53.5
16	6.9	1.5	-162.7	5.3	31.7	100.2	0.9	0.090	0.046	0.105	308.2	5.14	8.86	14.20	42.8
17	8.9	5.9	25.8	5.3	145.8	0.2	1.3	0.090	0.046	0.013	228.1	5.14	8.86	2.59	42.1
18	8.9	41.2	286.3	5.3	304.7	84.4	3.5	0.090	0.045	0.044	570.1	5.14	8.40	7.96	104.0
19	8.9	40.0	-150.0	5.3	302.2	219.5	4.7	0.090	0.045	0.150	1501.0	5.14	8.40	17.68	205.9
20	8.9	5.8	-174.6	5.3	143.4	346.5	4.4	0.090	0.045	0.116	1501.0	5.14	8.40	15.05	205.9
21	16.1	5.5	-174.3	9.8	136.3	460.0	9.8	0.180	0.049	0.135	4088.0	16.36	9.18	15.24	488.9
22	16.1	1.4	-189.6	9.8	27.0	559.2	9.6	0.180	0.049	0.120	4088.0	16.36	9.18	14.33	488.9
23	10.3	5.3	-178.2	22.7	141.1	493.4	6.7	0.158	0.051	0.129	2752.0	15.28	9.30	14.91	333.3
26	10.3	5.3	-179.0	22.7	141.1	497.0	6.8	0.158	0.051	0.129	2773.0	15.28	9.30	14.94	335.8
27	10.3	1.3	-193.4	22.7	21.3	606.3	6.7	0.158	0.051	0.116	2773.0	15.28	9.30	14.09	335.8
28	3.5	1.6	-178.6	124.1	33.5	542.6	2.5	0.181	0.116	0.125	1188.0	18.90	15.38	14.32	133.9
29	0.5	1.6	-178.6	124.1	33.5	542.6	0.4	0.181	0.116	0.125	169.7	18.90	15.38	14.32	19.1
30	3.0	1.6	-178.6	124.1	33.5	542.6	2.1	0.181	0.116	0.125	1018.0	18.90	15.38	14.32	114.8
31	3.0	20.0	-177.7	124.1	221.8	353.8	2.1	0.181	0.125	0.125	1021.0	18.90	14.58	14.32	115.0
33	3.0	19.4	20.0	124.1	219.6	0.0	1.0	0.181	0.125	0.125	539.3	18.90	14.58	14.32	59.9
34	13.3	1.3	-193.2	20.8	21.3	170.2	2.8	0.449	0.109	0.124	1563.0	46.07	16.48	14.84	183.1
35	13.3	1.3	-191.9	20.8	21.3	166.6	2.8	0.449	0.109	0.124	1542.0	46.07	16.48	14.84	180.6
36	13.3	1.3	20.3	20.8	18.7	0.1	0.5	0.449	0.109	0.150	542.9	46.07	16.48	17.68	60.4
37	16.5	1.3	-189.0	5.6	21.1	152.8	3.0	0.487	0.109	0.124	1423.0	49.90	16.50	14.84	172.0

stream number	ṁ	р	Т	e ^{CH}	e^{M}	e^{T}	Ė	c ^{CH}	c ^M	e^{T}	Ċ	$b^{\rm CH}$	b^{M}	b^{T}	Ė
	kg/s	bar	°C	kJ/kg	kJ/kg	kJ/kg	MW	\$/MJ	\$/MJ	\$/MJ	\$/h	mPt/MJ	mPt/MJ	mPt/MJ	Pt/h
38	16.5	1.3	170.0	5.6	18.7	31.2	0.9	0.487	0.109	0.150	560.8	49.90	16.50	17.68	67.6
39	13.3	1.2	-153.0	20.8	15.8	87.8	1.7	0.449	0.109	0.016	595.3	46.07	16.48	12.06	108.8
40	13.3	20.0	23.7	20.8	253.5	0.1	3.6	0.449	0.045	0.011	995.4	46.07	10.36	2.76	171.2
41	13.3	19.4	20.0	20.8	250.9	0.0	3.6	0.449	0.045	0.011	989.7	46.07	10.36	2.76	169.9
42	1.0	1.0	120.0	50.0	0.0	598.9	0.6	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
43	1.0	1.0	120.0	50.0	0.0	598.9	0.6	0.000	0.000	0.000	0.0	0.00	0.00	0.00	0.0
44	20.4	5.3	-178.1	22.7	141.1	140.6	6.2	0.158	0.051	0.131	2146.0	15.28	9.30	15.72	284.6
46	20.4	5.3	-178.2	22.7	141.1	493.3	13.4	0.158	0.051	0.129	5475.0	15.28	9.30	14.91	663.1
47	10.2	5.3	-178.1	20.0	140.8	492.1	6.6	0.158	0.051	0.129	2699.0	15.28	9.30	14.91	327.3
48	20.8	1.6	-178.7	124.1	33.3	542.8	14.6	0.181	0.116	0.125	7059.0	18.90	15.38	14.32	795.9
49	17.3	1.6	-178.7	124.1	33.3	542.8	12.1	0.181	0.116	0.125	5871.0	18.90	15.38	14.32	661.9
51	17.3	1.6	-178.7	124.0	33.3	118.3	4.8	0.181	0.116	0.125	2562.0	18.90	15.38	14.32	283.4
54	10.9	1.3	-162.0	50654.0	32.4	850.1	563.3	0.005	0.005	0.005	10139.0	5.48	5.48	5.48	11120.0
55	10.9	20.0	-160.9	50654.0	381.3	501.4	563.3	0.005	0.006	0.005	10151.0	5.48	5.59	5.48	11120.0
56	10.9	19.4	-104.6	50654.0	377.6	281.1	560.8	0.005	0.006	0.005	10107.0	5.48	5.59	5.48	11070.0
57	10.9	18.8	-105.3	50654.0	373.9	281.0	560.8	0.005	0.006	0.005	10106.0	5.48	5.59	5.48	11070.0
58	10.9	18.3	15.0	50654.0	370.1	0.0	557.7	0.005	0.006	0.052	10050.0	5.48	5.59	36.72	11010.0
59	40.0	1.5	20.1	0.0	0.1	0.2	0.0	0.000	0.366	0.052	4.0	0.00	8.31	36.72	0.9
60	40.0	1.5	-26.3	0.0	0.0	11.8	0.5	0.000	0.366	0.052	90.6	0.00	8.31	36.72	62.4
61	40.0	1.4	-19.3	0.0	0.0	8.0	0.3	0.000	0.366	0.052	61.9	0.00	8.31	36.72	42.2
62	40.0	1.4	1.6	0.0	0.0	1.2	0.0	0.000	0.366	0.052	10.7	0.00	8.31	36.72	6.1
63	40.0	1.3	20.1	0.0	0.0	0.2	0.0	0.000	0.366	0.052	3.1	0.00	8.31	36.72	0.9

stream number	x ^{CH}	x ^M	x ^T	Ż
	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-10} inj/h
	5		5	
1	0.00	0.00	0.00	0.0
1	0.00	0.00	0.00	0.0
2	0.00	0.00	0.00	0.0
3	0.00	0.00	0.00	0.0
4	0.00	0.00	0.00	0.0
5	0.00	0.00	0.00	0.0
0	0.00	0.00	19.92	0.0
10	0.00	0.00	18.82	148.5
11	13.70	0.08	9.79	106.9
15	13.70	0.08	8.07	105.2
14	9.45	3.88	7.30	9.4
13	22.20	2.31	7.78	40.3
17	22.26	2.51	7.78	10.6
18	22.26	0.18	0.00	10.6
19	22.26	0.18	0.00	10.6
20	9.45	3.88	7.36	23.0
22	9.45	3.88	7.36	15.4
23	9.45	1.30	0.00	15.4
24	9.45	1.30	0.00	15.3
25	24.71	3.21	7.78	18.3
26	24.71	3.21	7.78	6.1
27	24.71	3.21	2.17	6.9
28	22.26	0.18	0.00	10.6
29	11.49	0.05	2.92	7.0
30	11.49	0.24	10.25	42.2
31	11.49	0.24	10.25	20.5
32	11.49	0.12	4.08	37.6
33	11.49	0.12	3.70	29.2
34	11.49	0.07	0.87	29.2
35	11.49	0.07	0.87	28.4
36	11.49	0.07	0.87	22.2
38	11.49	0.05	0.00	22.2
39	11.49	0.05	0.03	22.4
40	11.49	0.05	3.70	30.8
41	11.49	0.05	3.70	10.2
42	11.49	0.05	3.70	20.7
43	11.49	0.05	1.04	20.5
44	11.49	0.05	1.04	17.1
46	0.00	0.00	0.00	0.0
49	11.49	0.05	3.49	35.2
50	15.88	0.11	9.76	43.7
51	15.88	0.11	8.05	43.7
52	15.51	0.14	10.25	2.8
53	15.51	0.14	9.75	2.8
54	11.49	0.24	8.23	59.9
55	11.49	0.24	8.23	42.0
56	11.49	0.24	8.23	18.0

 Table A.7: Stream results obtained from the exergy-risk-hazard analysis, Case AD1

stream number	x ^{CH}	x ^M	x^{T}	Ż
	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-10} inj/h
57	11.49	0.24	6.80	18.0
58	11.49	0.05	3.49	28.1
59	11.49	0.05	3.49	7.0
60	0.00	0.00	0.00	0.0
61	0.00	1.96	0.00	26.9
62	0.00	1.96	0.00	26.6
63	0.00	1.96	0.00	26.4
66	11.49	0.24	10.25	116.1
67	11.49	0.24	10.25	73.9
68	11.49	0.24	8.23	183.1
69	11.49	0.24	8.23	123.0
70	9.45	3.88	7.36	193.3
71	9.45	3.88	7.36	183.9
72	9.45	3.88	7.36	74.8
73	9.45	3.88	7.36	51.8

 Table A.8: Stream results obtained from the exergy-risk-hazard analysis, Case AD2

stream number	x ^{CH}	x ^M	x ^T	Ż
	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-13} inj/MJ	10^{-10} inj/h
1	0.00	0.00	0.00	0.0
2	0.00	0.00	0.00	0.0
3	0.00	0.00	0.00	0.0
5	0.00	0.00	0.00	0.0
6	0.00	0.00	130.00	17.8
7	0.00	2.57	4.48	17.8
8	0.00	2.57	276.10	35.6
9	0.00	4.23	9.98	35.6
10	0.00	4.23	24.47	225.6
11	25.07	4.35	17.80	266.0
13	25.07	4.35	15.48	262.7
14	18.65	10.98	14.84	19.1
15	44.93	10.03	15.73	101.8
18	44.93	10.03	15.73	31.0
19	44.93	0.74	0.00	31.0
20	18.65	10.98	14.84	46.9
21	44.93	0.74	0.00	31.0
22	18.65	10.98	14.84	27.9
23	18.65	1.55	0.00	27.9
24	18.65	1.55	0.00	27.9
25	48.18	10.51	15.73	33.4
26	48.18	10.51	24.47	6.5
27	48.18	10.51	1.16	6.5
28	18.65	1.55	0.00	27.9

Appendix A	Stream	data
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stream number	x ^{CH}	x ^M	x^{T}	Ż
	10 ⁻¹³ inj/MJ	10 ⁻¹³ inj/MJ	10 ⁻¹³ inj/MJ	10 ⁻¹⁰ inj/h
20	21.00	2.04	14.54	21.4
29	21.00	3.84	14.54	31.4
30	21.00	4.57	18.56	91.3
31	21.00	4.57	18.56	42.8
32	21.00	5.12	18.56	42.8
33	21.00	3.84	0.45	42.8
34	21.00	3.84	23.08	157.2
36	44.93	0.74	0.00	30.9
37	21.00	3.84	16.05	157.2
38	21.00	3.84	16.05	31.3
39	0.00	0.00	0.00	0.0
40	0.00	1.96	0.00	26.9
41	0.00	1.96	0.00	13.5
42	0.00	1.96	0.00	13.3
43	0.00	1.96	0.00	26.6
44	0.00	1.96	0.00	26.4
45	0.00	1.96	0.00	26.1
46	0.00	1.96	0.00	25.8
47	0.00	1.96	0.00	24.4
48	0.00	1.96	0.00	13.5
49	0.00	1.96	0.00	13.3
50	28.51	4.40	17.74	85.0
51	28.51	4.40	15.46	85.0
52	27.96	4.44	18.56	6.1
53	27.96	4.44	20.74	6.1
54	21.00	4.57	15.99	123.1
55	21.00	4.57	15.99	86.2
56	21.00	4.57	15.99	36.9
57	21.00	4.57	14.03	36.9
58	21.00	3.84	16.05	125.7
64	21.00	4.57	18.56	249.9
65	21.00	4.57	18.56	158.6
66	21.00	4.57	15.99	379.0
67	21.00	4.57	15.99	255.6
68	18.65	10.98	14.84	392.3
69	18.65	10.98	14.84	373.2
70	18.65	10.98	14.84	152.9
71	18 65	10.08	14.84	105.0

stream number	x ^{CH}	x ^M	x^{T}	Ż
	10 ⁻¹³ inj/MJ	10 ⁻¹³ inj/MJ	10 ⁻¹³ inj/MJ	10 ⁻¹⁰ inj/h
1	0.00	0.00	0.00	0.0
2	0.00	0.00	0.00	0.0
2	0.00	0.00	0.00	0.0
5	0.00	0.00	0.00	0.0
5	0.00	0.00	215 70	20.5
0	0.00	0.00	7.42	29.5
7	0.00	4.20	/.43	29.3
0	0.00	4.20	410.30	56.3
9	0.00	6.69	13.12	156.8
10	0.00	5.09	10.11	150.8
11	8.40 8.46	5.20	0.22	157.8
13	8.40 10.22	5.20 8.25	9.53	11.4
14	21.07	8.23	8.90	11.4 50.7
15	21.97	8.65	9.45	59.7
18	21.97	0.63	0.00	17.0
19	21.97	0.63	0.00	16.9
20	10.22	8.25	8.90	27.5
21	10.22	8.25	8.90	16.1
22	10.22	1.16	0.00	16.1
23	10.22	1.16	0.00	16.0
24	10.22	1.16	0.00	16.0
25	23.43	8.45	9.45	20.1
26	23.43	8.45	13.03	4.1
27	23.43	8.45	1.59	4.1
28	21.97	0.63	0.00	16.9
29	0.00	0.04	7.85	15.4
30	8.97	5.28	10.56	59.2
31	8.97	5.28	10.56	28.8
32	0.00	0.00	0.00	0
33	0.00	0.05	0.00	0.3
34	0.00	0.04	0.00	0.3
36	0.00	0.04	9.33	76.8
37	0.00	0.04	9.33	15.4
38	0.00	0.00	0.00	0.0
39	0.00	0.00	0.00	0.0
40	0.00	1.96	0.00	26.9
41	0.00	1.96	0.00	26.6
42	0.00	1.96	0.00	26.4
43	0.00	0.00	43.87	0.6
44	0.00	0.00	43.87	86.4
45	0.00	0.00	43.87	56.9
46	0.00	0.00	43.87	30.2
47	0.00	0.00	43.87	15.0
48	0.00	0.00	43.87	0.6
49	0.00	0.00	0.00	0.0
50	8.03	5.22	10.08	51.0
51	8.03	5.22	9.31	51.0

Table A.9: Stream results obtained from the exergy-risk-hazard analysis, Case AD2S

stream number	x ^{CH}	x^{M}	x^{T}	Ż
	10^{-13} inj/MJ	10 ⁻¹³ inj/MJ	10^{-13} inj/MJ	10 ⁻¹⁰ inj/h
52	8.10	5.23	10.56	4.0
53	8.10	5.23	13.79	4.0
54	8.97	5.28	9.42	76.3
55	8.97	5.28	9.42	53.4
56	8.97	5.28	9.42	22.9
57	8.97	5.28	8.78	22.9
58	0.00	0.04	9.33	61.5
62	8.97	5.28	10.56	162.0
63	8.97	5.28	10.56	102.9
64	8.97	5.28	9.42	234.9
65	8.97	5.28	9.42	158.5
66	10.22	8.25	8.90	232.9
67	10.22	8.25	8.90	221.6
68	10.22	8.25	8.90	89.5
69	10.22	8.25	8.90	62.0

Table A.10: Stream results obtained from the exergy-risk-hazard analysis, Case BD2S

stream number	x ^{CH}	x ^M	x^{T}	Ż
	10^{-15} inj/MJ	10^{-15} inj/MJ	10^{-15} inj/MJ	10^{-13} inj/h
1	0.00	0.00	0.00	0.0
2	0.00	0.00	0.00	0.0
3	0.00	0.00	0.00	0.0
5	1.69	0.00	0.00	0.0
6	1.69	0.00	0.00	10.7
7	1.69	0.00	0.00	10.7
10	1.69	0.00	0.00	10.7
11	1.69	0.00	0.00	7.8
12	1.69	0.00	0.00	5.6
13	1.69	0.00	0.02	7.6
14	1.69	0.00	0.00	2.2
15	1.69	0.00	0.02	2.5
16	1.69	0.00	0.01	2.5
17	1.69	0.00	0.00	2.8
18	1.69	0.00	0.00	2.8
19	1.69	0.00	0.02	4.4
20	1.69	0.00	0.01	4.4
21	0.88	0.00	0.02	10.3
22	0.88	0.00	0.02	10.3
23	0.39	0.00	0.02	7.6
26	0.39	0.00	0.02	7.6
27	0.39	0.00	0.02	7.6
28	0.11	0.02	0.02	3.5
29	0.11	0.02	0.02	0.5

stream number	x ^{CH}	x ^M	x^{T}	Ż
	10 ⁻¹⁵ inj/MJ	10^{-15} inj/MJ	10^{-15} inj/MJ	10^{-13} inj/h
30	0.11	0.02	0.02	3.0
31	0.11	0.02	0.02	3.0
33	0.11	0.02	0.02	2.1
34	0.52	0.01	0.02	6.8
35	0.52	0.01	0.02	6.7
36	0.52	0.01	0.02	5.2
37	0.57	0.01	0.02	3.8
38	0.57	0.01	0.02	2.4
39	0.52	0.01	393.90	16,540.0
40	0.52	136.50	40.44	16,540.0
41	0.52	136.50	40.44	16,370.0
42	0.00	0.00	0.00	0.0
43	0.00	0.00	0.00	0.0
44	0.39	0.00	0.02	8.7
46	0.39	0.00	0.02	15.1
47	0.39	0.00	0.02	7.1
48	0.11	0.02	0.02	20.9
49	0.11	0.02	0.02	17.4
51	0.11	0.02	0.02	11.0
54	0.00	0.00	0.00	0.0
55	0.00	185.40	0.00	27,810.0
56	0.00	185.40	0.00	27,540.0
57	0.00	185.40	0.00	27,270.0
58	0.00	185.40	5302.00	27,000.0
59	0.00	0.00	5302.00	1,215.0
60	0.00	0.00	5302.00	89,960.0
61	0.00	0.00	5302.00	60,910.0
62	0.00	0.00	5302.00	8,777.0
63	0.00	0.00	5302.00	1,215.0

Appendix B

Exergy-based methods

High- and low-pressure column

Tables B.2, B.3, B.4, B.5, B.6, and B.7 show the definitions of the exergy of fuel and exergy of product for selected components for the Cases A, B, AD1, AD2, AD2S, and BD2S, respectively.

For the definition of the exergy of the fuel and exergy of product of the two columns the mixer PMHPC and PMLPC are introduced. Both columns have several inlet streams which have to be combined to one inlet stream for the definitions. Figure B.1 shows a schematic of the two mixer. The corresponding stream numbers for all Cases are given in Table B.1. The auxiliary equations for each component for the exergoeconomic (and for exergoenvironmental and exergy-risk-hazard analysis) are given in Tables B.8, B.9, B.10, B.11, B.12, and B.13, respectively.



Figure B.1: Schematic of the PMHPC and PMLPC

stream	Case A	Case AD1	Case AD2	Case AD2S	Case B	Case BD2S
А	10	10	10	10	13	13
В	58	58	58	58	20	20
С	66	69	67	65	47	47
D	61	65	63	61	52	52
Е	51	51	51	51	22	22
F	13	13	13	13	NA	NA
G	16	29	29	29	16	16
Н	57	57	57	57	NA	NA
Ι	53	53	53	53	27	27
J	60	64	62	60	53	53

 Table B.1: Stream numbers for the PMHPC and PMLPC

	Table B.2: Definition of exergy of fuel and exergy of product, Case A		
component	$\dot{E}_{\mathrm{F},k}$	Ė _{P,k}	
AC1	Ŵ _{AC1}	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$	
IC1	dissipative component: $\dot{E}_{D,IC1} = \dot{E}_3 - \dot{E}_2$	-	
AC2	Ŵ _{AC2}	$\dot{E}_4^{\mathrm{M}}-\dot{E}_3^{\mathrm{M}}+\dot{E}_4^{\mathrm{T}}-\dot{E}_3^{\mathrm{T}}$	
IC2	dissipative component: $\dot{E}_{\rm D,IC1} = \dot{E}_4 - \dot{E}_5$	-	
MHE	$\dot{E}_{15}^{\rm PH} - \dot{E}_{17}^{\rm PH} + \dot{E}_{20}^{\rm PH} - \dot{E}_{22}^{\rm PH} + \dot{E}_{30}^{\rm PH} - \dot{E}_{31}^{\rm PH} + \dot{E}_{25}^{\rm PH} - \dot{E}_{27}^{\rm PH} + \dot{E}_{7}^{\rm M} - \dot{E}_{10}^{\rm M} + \dot{E}_{7}^{\rm T}$	$\dot{E}_{10}^{\mathrm{T}}$	
AD	$\dot{E}_{5}^{ m M}-\dot{E}_{7}^{ m M}+\dot{E}_{5}^{ m T}-\dot{E}_{7}^{ m T}$	$\dot{E}_7^{ m CH}-\dot{E}_5^{ m CH}$	
HE3	$\dot{E}_{27}^{ m M}-\dot{E}_{28}^{ m M}+\dot{E}_{18}^{ m M}-\dot{E}_{19}^{ m M}+\dot{E}_{18}^{ m T}-\dot{E}_{19}^{ m T}$	$\dot{E}_{28}^{\mathrm{T}}-\dot{E}_{27}^{\mathrm{T}}$	
NC5	Ŵ _{NC5}	$\dot{E}^{\mathrm{M}}_{18} - \dot{E}^{\mathrm{M}}_{17} + \dot{E}^{\mathrm{T}}_{18} - \dot{E}^{\mathrm{M}}_{17}$	
OC	Ŵ _{OC}	$\dot{E}^{ m M}_{23}-\dot{E}^{ m M}_{22}+\dot{E}^{ m T}_{23}-\dot{E}^{ m T}_{22}$	
HPC	$\dot{m}_{63} \cdot (e_{61}^{\mathrm{T}} - e_{63}^{\mathrm{T}}) + \dot{m}_{52} \cdot (e_{61}^{\mathrm{T}} - e_{52}^{\mathrm{T}}) + \dot{m}_{11} \cdot (e_{61}^{\mathrm{M}} - e_{11}^{\mathrm{M}})$	$ \begin{split} & \dot{m}_{63} \cdot (e^{\rm CH}_{63} - e^{\rm CH}_{61}) + \dot{m}_{50} \cdot (e^{\rm CH}_{50} - e^{\rm CH}_{61}) + \dot{m}_{52} \cdot (e^{\rm CH}_{52} - e^{\rm CH}_{61}) + \dot{m}_{11} \cdot (e^{\rm CH}_{11} - e^{\rm CH}_{61}) + \dot{m}_{50} \cdot (e^{\rm CH}_{50} - e^{\rm CH}_{61}) + \dot{m}_{11} \cdot (e^{\rm CH}_{11} - e^{\rm CH}_{61}) + \dot{m}_{50} \cdot (e^{\rm CH}_{63} - e^{\rm M}_{61}) + \dot{m}_{52} \cdot (e^{\rm M}_{52} - e^{\rm M}_{61}) + \dot{m}_{50} \cdot (e^{\rm M}_{50} - e^{\rm M}_{61}) \\ \end{split} $	
LPC	$\dot{m}_{25} \cdot (e_{60}^{\rm T} - e_{25}^{\rm T}) + \dot{m}_{15} \cdot (e_{60}^{\rm T} - e_{15}^{\rm T}) + \dot{m}_{25} \cdot (e_{60}^{\rm CH} - e_{25}^{\rm CH})$	$ \begin{split} \dot{m}_{15} \cdot (e^{\rm M}_{15} - e^{\rm M}_{60}) + \dot{m}_{15} \cdot (e^{\rm CH}_{15} - e^{\rm CH}_{60}) + \dot{m}_{25} \cdot (e^{\rm M}_{25} - e^{\rm M}_{60}) + \dot{m}_{67} \cdot (e^{\rm T}_{67} - e^{\rm T}_{60}) + \dot{m}_{67} \cdot (e^{\rm M}_{67} - e^{\rm M}_{60}) \\ e^{\rm M}_{60} + \dot{m}_{67} \cdot (e^{\rm CH}_{67} - e^{\rm CH}_{60}) \end{split} $	
HE2	$\dot{E}_{43}^{\mathrm{M}} - \dot{E}_{44}^{\mathrm{M}} + \dot{E}_{21}^{\mathrm{M}} - \dot{E}_{48}^{\mathrm{M}} + \dot{E}_{43}^{\mathrm{T}} - \dot{E}_{44}^{\mathrm{T}}$	$\dot{E}_{48}^{\mathrm{T}}-\dot{E}_{21}^{\mathrm{T}}$	
EXP2	$\dot{E}_{42}^{ m M}-\dot{E}_{43}^{ m M}$	$\dot{E}_{43}^{\mathrm{T}}-\dot{E}_{42}^{\mathrm{T}}+\dot{W}_{\mathrm{EXP2}}$	
EXP1	$\dot{E}_{46}^{ m M}-\dot{E}_{47}^{ m M}$	$\dot{E}_{47}^{\mathrm{T}}-\dot{E}_{46}^{\mathrm{T}}+\dot{W}_{\mathrm{EXP1}}$	
NC1	Ŵ _{NC1}	$\dot{E}^{\mathrm{M}}_{34} - \dot{E}^{\mathrm{M}}_{33} + \dot{E}^{\mathrm{T}}_{34} - \dot{E}^{\mathrm{T}}_{33}$	
IC3	dissipative component: $\dot{E}_{D,IC3} = \dot{E}_{34} - \dot{E}_{35}$	-	
NC2	W _{NC2}	$\dot{E}^{\mathrm{M}}_{36}-\dot{E}^{\mathrm{M}}_{35}+\dot{E}^{\mathrm{T}}_{36}-\dot{E}^{\mathrm{T}}_{35}$	
IC4	dissipative component: $\dot{E}_{D,IC4} = \dot{E}_{36} - \dot{E}_{37}$		
NC3	Ŵ _{NC1}	$\dot{E}^{ m M}_{38}-\dot{E}^{ m M}_{37}+\dot{E}^{ m T}_{38}-\dot{E}^{ m T}_{37}$	
NC4	$\dot{W}_{ m NC4}$	$\dot{E}^{ m M}_{40}-\dot{E}^{ m M}_{39}+\dot{E}^{ m T}_{40}-\dot{E}^{ m T}_{39}$	
HE1	$\dot{E}_{32}^{\mathrm{M}} - \dot{E}_{33}^{\mathrm{M}} + \dot{E}_{40}^{\mathrm{M}} - \dot{E}_{41}^{\mathrm{M}} + \dot{E}_{45}^{\mathrm{M}} - \dot{E}_{46}^{\mathrm{M}} + \dot{E}_{40}^{\mathrm{T}} + \dot{E}_{45}^{\mathrm{T}} + \dot{E}_{32}^{\mathrm{T}}$	$\dot{E}_{41}^{ m T}+\dot{E}_{46}^{ m T}+\dot{E}_{33}^{ m T}$	
TV3	$\dot{E}^{ m M}_{48} - \dot{E}^{ m M}_{49}$	$\dot{E}_{49}^{\mathrm{T}}-\dot{E}_{48}^{\mathrm{T}}$	
TV4	$\dot{E}_{59}^{ m M}-\dot{E}_{16}^{ m M}$	$\dot{E}_{16}^{ m T} - \dot{E}_{59}^{ m T}$	

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
ICO	dissipative component: $\dot{E}_{D,ICO} = \dot{E}_{23} - \dot{E}_{24}$	-
ICN	dissipative component: $\dot{E}_{D,ICN} = \dot{E}_{19} - \dot{E}_{29}$	-
TV1	$\dot{E}_{56}^{ m M} - \dot{E}_{57}^{ m M}$	$\dot{E}_{57}^{\mathrm{T}}-\dot{E}_{56}^{\mathrm{T}}$
TV6	$\dot{E}_{52}^{\rm M} - \dot{E}_{53}^{\rm M}$	$\dot{E}_{53}^{\mathrm{T}}-\dot{E}_{52}^{\mathrm{T}}$
TV5	$\dot{E}_{50}^{\rm M} - \dot{E}_{51}^{\rm M}$	$\dot{E}_{51}^{\mathrm{T}}-\dot{E}_{50}^{\mathrm{T}}$
TV2	$\dot{E}_{11}^{ m M} - \dot{E}_{13}^{ m M}$	$\dot{E}_{13}^{ m T} - \dot{E}_{11}^{ m T}$
CDREB	$\dot{E}^{\mathrm{M}}_{64} - \dot{E}^{\mathrm{M}}_{64} + \dot{E}^{\mathrm{T}}_{68} - \dot{E}^{\mathrm{T}}_{69} + \dot{E}^{\mathrm{M}}_{68} - \dot{E}^{\mathrm{M}}_{69}$	$\dot{E}_{64}^{ m T}-\dot{E}_{65}^{ m T}$
PMHPC	$\dot{E}_{58} + \dot{E}_{10} + \dot{E}_{69}$	\dot{E}_{65}
PMLPC	$\dot{E}_{29} + \dot{E}_{51} + \dot{E}_{13} + \dot{E}_{57} + \dot{E}_{70} + \dot{E}_{53}$	\dot{E}_{64}
tot	$\dot{E}_1 + \dot{W}_{\mathrm{tot}} + \dot{E}_{60}^{\mathrm{T}} - \dot{E}_{63}^{\mathrm{T}} + \dot{E}_{60}^{\mathrm{CH}} - \dot{E}_{63}^{\mathrm{CH}}$	$\dot{E}_{14} + \dot{E}_{55} + \dot{E}_{28} + \dot{E}_{24} + \dot{E}_{63}^{\mathrm{T}} - \dot{E}_{60}^{\mathrm{M}}$

	Table B.3: Definition of exergy of fuel and exergy of product, Case B		
component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$	
AC1	Ψ _{AC1}	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$	
IC1	dissipative component: $\dot{E}_{D,IC1} = \dot{E}_3 - \dot{E}_2$	-	
AC2	$\dot{W}_{ m AC2}$	$\dot{E}_4^{\mathrm{M}}-\dot{E}_3^{\mathrm{M}}+\dot{E}_4^{\mathrm{T}}-\dot{E}_3^{\mathrm{T}}$	
IC2	dissipative component: $\dot{E}_{D,IC1} = \dot{E}_4 - \dot{E}_5$	-	
AD	$\dot{E}_5^{ m M} - \dot{E}_{10}^{ m M} + \dot{E}_5^{ m T} - \dot{E}_{10}^{ m T}$	$\dot{E}_{10}^{ m CH}-\dot{E}_{5}^{ m CH}+\dot{E}_{8}+\dot{E}_{9}+\dot{E}_{7}$	
AC3	$\dot{W}_{ m AC3}$	$\dot{E}^{ m M}_{17} - \dot{E}^{ m M}_{18} + \dot{E}^{ m T}_{17} - \dot{E}^{ m T}_{18}$	
MHE	$ \begin{split} \dot{E}^{\rm PH}_{32} - \dot{E}^{\rm PH}_{33} + \dot{E}^{\rm M}_{35} - \dot{E}^{\rm M}_{36} + \dot{E}^{\rm M}_{18} - \dot{E}^{\rm M}_{19} + \dot{E}^{\rm M}_{12} - \dot{E}^{\rm M}_{13} + \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{15} + \dot{E}^{\rm M}_{37} - \dot{E}^{\rm M}_{38} + \\ \dot{E}^{\rm T}_{35} + \dot{E}^{\rm T}_{37} + \dot{E}^{\rm T}_{18} + \dot{E}^{\rm T}_{12} + \dot{E}^{\rm T}_{14} \end{split} $	$\dot{E}_{36}^{\mathrm{T}} + \dot{E}_{38}^{\mathrm{T}} + \dot{E}_{19}^{\mathrm{T}} + \dot{E}_{13}^{\mathrm{T}} + \dot{E}_{15}^{\mathrm{T}}$	
HPC	$\dot{m}_{44} \cdot (e_{52}^{\mathrm{T}} - e_{44}^{\mathrm{T}}) + \dot{m}_{21} \cdot (e_{52}^{\mathrm{M}} - e_{21}^{\mathrm{M}})$	$\dot{m}_{44} \cdot (e^{\text{CH}}_{44} - e^{\text{CH}}_{52}) + \dot{m}_{44} \cdot (e^{\text{M}}_{44} - e^{\text{M}}_{52}) + \dot{m}_{21} \cdot (e^{\text{CH}}_{21} - e^{\text{CH}}_{52}) + \dot{m}_{21} \cdot (e^{\text{T}}_{21} - e^{\text{T}}_{52})$	
LPC	$\dot{m}_{37} \cdot (e_{53}^{\text{CH}} - e_{37}^{\text{CH}}) + \dot{m}_{37} \cdot (e_{53}^{\text{T}} - e_{37}^{\text{T}}) + \dot{m}_{34} \cdot (e_{53}^{\text{T}} - e_{34}^{\text{T}})$	$ \begin{split} \dot{m}_{48} \cdot (e^{\rm CH}_{48} - e^{\rm CH}_{53}) + \dot{m}_{34} \cdot (e^{\rm CH}_{34} - e^{\rm CH}_{53}) + \dot{m}_{48} \cdot (e^{\rm M}_{48} - e^{\rm M}_{53}) + \dot{m}_{37} \cdot (e^{\rm M}_{37} - e^{\rm T}_{53}) + \dot{m}_{34} \cdot (e^{\rm M}_{34} - e^{\rm M}_{53}) + \dot{m}_{48} \cdot (e^{\rm M}_{48} - e^{\rm T}_{53}) + \dot{m}_{48} \cdot ($	
OP	$\dot{W}_{ m OP}+\dot{E}_{ m 30}^{ m T}-\dot{E}_{ m 31}^{ m T}$	$\dot{E}_{31}^{ m M} - \dot{E}_{30}^{ m M}$	
EXP1	$\dot{E}_{15}^{ m M} - \dot{E}_{16}^{ m M}$	$\dot{E}_{16}^{\mathrm{T}} - \dot{E}_{15}^{\mathrm{T}} + \dot{W}_{\mathrm{EXP1}}$	
NC5	Ŵ _{NC5}	$\dot{E}_{39}^{ m PH} - \dot{E}_{36}^{ m PH}$	
ICN	dissipative component: $\dot{E}_{D,ICN} = \dot{E}_{39} - \dot{E}_{40}$	-	
TV3	$\dot{E}_{21}^{\rm M} - \dot{E}_{22}^{\rm M}$	$\dot{E}_{22}^{\mathrm{T}} - \dot{E}_{21}^{\mathrm{T}}$	
CDREB	$\dot{E}^{\mathrm{M}}_{45} - \dot{E}^{\mathrm{M}}_{46} + \dot{E}^{\mathrm{T}}_{49} - \dot{E}^{\mathrm{T}}_{50} + \dot{E}^{\mathrm{M}}_{49} - \dot{E}^{\mathrm{M}}_{50}$	$\dot{E}_{45}^{\mathrm{T}}-\dot{E}_{46}^{\mathrm{T}}$	
TV1	$\dot{E}_{19}^{ m M} - \dot{E}_{20}^{ m M}$	$\dot{E}_{20}^{\mathrm{T}}-\dot{E}_{19}^{\mathrm{T}}$	
SUB	$\dot{E}_{25}^{\mathrm{M}} - \dot{E}_{26}^{\mathrm{M}} + \dot{E}_{34}^{\mathrm{M}} - \dot{E}_{35}^{\mathrm{M}} + \dot{E}_{34}^{\mathrm{T}} - \dot{E}_{35}^{\mathrm{T}}$	$\dot{E}_{26}^{\mathrm{T}}-\dot{E}_{25}^{\mathrm{T}}$	
TV2	$\dot{E}_{26}^{\rm M} - \dot{E}_{27}^{\rm M}$	$\dot{E}_{27}^{\mathrm{T}}-\dot{E}_{26}^{\mathrm{T}}$	
tot	$\dot{E}_1 + \dot{W}_{ m tot}$	$\dot{E}_{33}+\dot{E}_{40}+\dot{E}_{29}+\dot{E}_{24}$	

component	Ė.,	Ė.,
	L _{F,k}	L _{P,k}
AC1	Ŵ _{AC1}	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$
IC1	dissipative component: $\dot{E}_{\rm D,IC1} = \dot{E}_3 - \dot{E}_2$	-
AC2	W _{AC2}	$\dot{E}_4^{\mathrm{M}}-\dot{E}_3^{\mathrm{M}}+\dot{E}_4^{\mathrm{T}}-\dot{E}_3^{\mathrm{T}}$
IC2	dissipative component: $\dot{E}_{\rm D,IC1} = \dot{E}_4 - \dot{E}_5$	-
MHE	$\dot{E}_{15}^{\rm PH} - \dot{E}_{17}^{\rm PH} + \dot{E}_{20}^{\rm PH} - \dot{E}_{22}^{\rm PH} + \dot{E}_{25}^{\rm PH} - \dot{E}_{26}^{\rm PH} + \dot{E}_{6}^{\rm M} - \dot{E}_{10}^{\rm M} + \dot{E}_{6}^{\rm T} + \dot{E}_{61}^{\rm PH} - \dot{E}_{62}^{\rm PH}$	$\dot{E}_{10}^{ m T}$
AD	$\dot{E}_{5}^{\mathrm{M}}-\dot{E}_{6}^{\mathrm{M}}+\dot{E}_{5}^{\mathrm{T}}-\dot{E}_{6}^{\mathrm{T}}$	$\dot{E}_6^{ m CH}-\dot{E}_5^{ m CH}$
HE3	$\dot{E}_{26}^{ m M}-\dot{E}_{27}^{ m M}+\dot{E}_{34}^{ m M}-\dot{E}_{35}^{ m M}+\dot{E}_{34}^{ m T}-\dot{E}_{35}^{ m T}$	$\dot{E}_{27}^{\mathrm{T}}-\dot{E}_{26}^{\mathrm{T}}$
NC5	Ŵ _{NC5}	$\dot{E}^{ ext{M}}_{18}-\dot{E}^{ ext{M}}_{17}+\dot{E}^{ ext{T}}_{18}-\dot{E}^{ ext{T}}_{17}$
OC	Ŵ _{OC}	$\dot{E}^{ m M}_{23}-\dot{E}^{ m M}_{22}+\dot{E}^{ m T}_{23}-\dot{E}^{ m T}_{22}$
HPC	$\dot{m}_{66} \cdot (e_{65}^{\mathrm{T}} - e_{66}^{\mathrm{T}}) + \dot{m}_{52} \cdot (e_{65}^{\mathrm{T}} - e_{52}^{\mathrm{T}}) + \dot{m}_{11} \cdot (e_{65}^{\mathrm{M}} - e_{11}^{\mathrm{M}})$	$ \begin{split} \dot{m}_{66} \cdot (e^{\rm CH}_{66} - e^{\rm CH}_{65}) + \dot{m}_{66} \cdot (e^{\rm M}_{66} - e^{\rm M}_{65}) + \dot{m}_{52} \cdot (e^{\rm CH}_{52} - e^{\rm CH}_{65}) + \dot{m}_{52} \cdot (e^{\rm M}_{52} - e^{\rm M}_{65}) + \dot{m}_{50} \cdot (e^{\rm CH}_{50} - e^{\rm CH}_{65}) + \dot{m}_{50} \cdot (e^{\rm M}_{50} - e^{\rm CH}_{65}) + \dot{m}_{50} \cdot (e^{\rm M}_{50} - e^{\rm CH}_{65}) + \dot{m}_{11} \cdot (e^{\rm CH}_{11} - e^{\rm CH}_{65}) + \dot{m}_{11} \cdot (e^{\rm H}_{11} - e^{\rm H}_{65}) + m$
LPC	$\dot{m}_{25} \cdot (e_{64}^{\rm CH} - e_{25}^{\rm CH}) + \dot{m}_{15} \cdot (e_{64}^{\rm T} - e_{15}^{\rm T}) + \dot{m}_{25} \cdot (e_{64}^{\rm T} - e_{25}^{\rm T})$	$ \begin{split} \dot{m}_{15} \cdot (e^{\rm CH}_{15} - e^{\rm CH}_{64}) + \dot{m}_{70} \cdot (e^{\rm CH}_{70} - e^{\rm CH}_{64}) + \dot{m}_{15} \cdot (e^{\rm M}_{15} - e^{\rm M}_{64}) + \dot{m}_{25} \cdot (e^{\rm M}_{25} - e^{\rm M}_{64}) + \dot{m}_{70} \cdot (e^{\rm M}_{70} - e^{\rm M}_{70}) + \dot{m}_{70} \cdot ($
HE2	$\dot{E}^{\mathrm{M}}_{41} - \dot{E}^{\mathrm{M}}_{48} + \dot{E}^{\mathrm{M}}_{43} - \dot{E}^{\mathrm{M}}_{44} + \dot{E}^{\mathrm{M}}_{30} - \dot{E}^{\mathrm{M}}_{31} + \dot{E}^{\mathrm{T}}_{43} - \dot{E}^{\mathrm{T}}_{44} + \dot{E}^{\mathrm{T}}_{30} - \dot{E}^{\mathrm{T}}_{31}$	$\dot{E}_{48}^{\mathrm{T}}-\dot{E}_{41}^{\mathrm{T}}$
EXP2	$\dot{E}_{42}^{ m M}-\dot{E}_{43}^{ m M}$	$\dot{E}_{43}^{\mathrm{T}}-\dot{E}_{42}^{\mathrm{T}}+\dot{W}_{\mathrm{EXP2}}$
EXP1	$\dot{E}_{42}^{ m M}-\dot{E}_{43}^{ m M}$	$\dot{E}_{43}^{\mathrm{T}}-\dot{E}_{42}^{\mathrm{T}}+\dot{W}_{\mathrm{EXPl}}$
NC1	Ŵ _{NC1}	$\dot{E}^{ m M}_{ m 34}-\dot{E}^{ m M}_{ m 33}+\dot{E}^{ m T}_{ m 34}-\dot{E}^{ m T}_{ m 33}$
NC2	Ŵ _{NC2}	$\dot{E}^{ m M}_{ m 38}-\dot{E}^{ m M}_{ m 36}+\dot{E}^{ m T}_{ m 38}-\dot{E}^{ m T}_{ m 36}$
NC3	$\dot{W}_{ m NC1}$	$\dot{E}^{ m M}_{ m 39}-\dot{E}^{ m M}_{ m 38}+\dot{E}^{ m T}_{ m 39}-\dot{E}^{ m T}_{ m 38}$
HE1	$\dot{E}_{32}^{\mathrm{M}} - \dot{E}_{33}^{\mathrm{M}} + \dot{E}_{39}^{\mathrm{M}} - \dot{E}_{40}^{\mathrm{M}} + \dot{E}_{39}^{\mathrm{T}} + \dot{E}_{32}^{\mathrm{T}}$	$\dot{E}_{40}^{\mathrm{T}}+\dot{E}_{33}^{\mathrm{T}}$
TV3	$\dot{E}^{ m M}_{48} - \dot{E}^{ m M}_{49}$	$\dot{E}_{49}^{\mathrm{T}}-\dot{E}_{48}^{\mathrm{T}}$
TV4	$\dot{E}_{59}^{ m M} - \dot{E}_{21}^{ m M}$	$\dot{E}_{21}^{\mathrm{T}}-\dot{E}_{59}^{\mathrm{T}}$
ICO	dissipative component: $\dot{E}_{\rm D,ICO} = \dot{E}_{23} - \dot{E}_{24}$	-
ICN	dissipative component: $\dot{E}_{\rm D,ICN} = \dot{E}_{19} - \dot{E}_{28}$	-
TV1	$\dot{E}_{56}^{ m M} - \dot{E}_{57}^{ m M}$	$\dot{E}_{57}^{\mathrm{T}}-\dot{E}_{56}^{\mathrm{T}}$

Table B.4: Definition of exergy of fuel and exergy of product, Case AD1

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
TV6	$\dot{E}_{52}^{ m M} - \dot{E}_{53}^{ m M}$	$\dot{E}_{53}^{\mathrm{T}}-\dot{E}_{52}^{\mathrm{T}}$
TV5	$\dot{E}_{50}^{\rm M} - \dot{E}_{51}^{\rm M}$	$\dot{E}_{51}^{\mathrm{T}}-\dot{E}_{50}^{\mathrm{T}}$
TV2	$\dot{E}_{11}^{ m M} - \dot{E}_{13}^{ m M}$	$\dot{E}_{13}^{\mathrm{T}}-\dot{E}_{11}^{\mathrm{T}}$
CDREB	$\dot{E}^{\mathrm{M}}_{68} - \dot{E}^{\mathrm{M}}_{69} + \dot{E}^{\mathrm{T}}_{68} - \dot{E}^{\mathrm{T}}_{69} + \dot{E}^{\mathrm{M}}_{64} - \dot{E}^{\mathrm{M}}_{65}$	$\dot{E}_{65}^{\mathrm{T}}-\dot{E}_{64}^{\mathrm{T}}$
PMHPC	$\dot{E}_{58} + \dot{E}_{10} + \dot{E}_{66}$	\dot{E}_{61}
PMLPC	$\dot{E}_{13} + \dot{E}_{51} + \dot{E}_{53} + \dot{E}_{57} + \dot{E}_{70} + \dot{E}_{16}$	\dot{E}_{60}
LNGP	$\dot{W}_{\mathrm{LNG}} + \dot{E}_{60}^{\mathrm{T}} - \dot{E}_{61}^{\mathrm{T}}$	$\dot{E}_{61}^{ m M} - \dot{E}_{60}^{ m M}$
HE4	dissipative component: $\dot{E}_{D,HE4} = \dot{E}_{62} - \dot{E}_{63} + \dot{E}_{35} - \dot{E}_{36} + \dot{E}_{18} - \dot{E}_{19}$	-
tot	$\dot{E}_1 + \dot{W}_{ m tot}$	$\dot{E}_{14} + \dot{E}_{29} + \dot{E}_{24} + \dot{E}_{55}$

	Table B.5: Definition of exergy of fuel and exergy of product, Case AD2		
component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$	
AC1	Ŵ _{AC1}	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$	
IC1	$\dot{E}_{3}^{\mathrm{M}}-\dot{E}_{2}^{\mathrm{M}}+\dot{E}_{43}^{\mathrm{M}}-\dot{E}_{44}^{\mathrm{M}}+\dot{E}_{43}^{\mathrm{T}}-\dot{E}_{44}^{\mathrm{T}}+\dot{E}_{2}^{\mathrm{T}}$	$\dot{E}_3^{ m T}$	
AD	$\dot{E}_{3}^{\rm M} - \dot{E}_{5}^{\rm M} + \dot{E}_{3}^{\rm T} - \dot{E}_{5}^{\rm T}$	$\dot{E}_{5}^{\mathrm{CH}} - \dot{E}_{3}^{\mathrm{CH}}$	
IC2	$\dot{E}_{5}^{\rm M} - \dot{E}_{6}^{\rm M} + \dot{E}_{44}^{\rm M} - \dot{E}_{45}^{\rm M} + \dot{E}_{44}^{\rm T} - \dot{E}_{45}^{\rm T} + \dot{E}_{5}^{\rm T}$	\dot{E}_{6}^{T}	
AC2	Ŵ _{AC2}	$\dot{E}_{7}^{\rm M} - \dot{E}_{6}^{\rm M} + \dot{E}_{7}^{\rm T} - \dot{E}_{8}^{\rm T}$	
IC5	$\dot{E}_7^{ m M}-\dot{E}_8^{ m M}+\dot{E}_{45}^{ m M}-\dot{E}_{46}^{ m M}+\dot{E}_{45}^{ m T}-\dot{E}_{46}^{ m T}+\dot{E}_7^{ m T}$	$\dot{E}_8^{ m T}$	
AC3	$\dot{W}_{\mathrm{AC3}} + \dot{E}_8^{\mathrm{T}}$	$\dot{E}_9^{\mathrm{M}}-\dot{E}_8^{\mathrm{M}}+\dot{E}_9^{\mathrm{T}}$	
MHE	$\dot{E}_{15}^{\rm PH} - \dot{E}_{18}^{\rm PH} + \dot{E}_{20}^{\rm PH} - \dot{E}_{22}^{\rm PH} + \dot{E}_{25}^{\rm PH} - \dot{E}_{26}^{\rm PH} + \dot{E}_{9}^{\rm M} - \dot{E}_{10}^{\rm M} + \dot{E}_{9}^{\rm T} + \dot{E}_{25}^{\rm T} + \dot{E}_{48}^{\rm PH} - \dot{E}_{49}^{\rm PH}$	$\dot{E}_{10}^{\mathrm{T}} + \dot{E}_{26}^{\mathrm{T}}$	
HE3	$\dot{E}_{26}^{\rm M} - \dot{E}_{27}^{\rm M} + \dot{E}_{19}^{\rm M} - \dot{E}_{21}^{\rm M} + \dot{E}_{19}^{\rm T} - \dot{E}_{21}^{\rm T}$	$\dot{E}_{27}^{\mathrm{T}}-\dot{E}_{26}^{\mathrm{T}}$	
NC5	Ŵ _{NC5}	$\dot{E}^{\mathrm{M}}_{18} - \dot{E}^{\mathrm{M}}_{17} + \dot{E}^{\mathrm{T}}_{18} - \dot{E}^{\mathrm{T}}_{17}$	
OC	Ŵ _{OC}	$\dot{E}^{\mathrm{M}}_{23} - \dot{E}^{\mathrm{M}}_{22} + \dot{E}^{\mathrm{T}}_{23} - \dot{E}^{\mathrm{T}}_{22}$	
HPC	$\dot{m}_{11} \cdot (e_{63}^{\rm T} - e_{11}^{\rm T}) + \dot{m}_{52} \cdot (e_{63}^{\rm T} - e_{52}^{\rm T}) + \dot{m}_{64} \cdot (e_{63}^{\rm T} - e_{64}^{\rm T})$	$ \begin{split} \dot{m}_{11} \cdot (e_{11}^{\text{CH}} - e_{63}^{\text{CH}}) + \dot{m}_{50} \cdot (e_{50}^{\text{CH}} - e_{63}^{\text{CH}}) + \dot{m}_{52} \cdot (e_{52}^{\text{CH}} - e_{63}^{\text{CH}}) + \dot{m}_{64} \cdot (e_{64}^{\text{CH}} - e_{63}^{\text{CH}}) + \dot{m}_{50} \cdot (e_{50}^{\text{M}} - e_{63}^{\text{M}}) + \dot{m}_{52} \cdot (e_{52}^{\text{CH}} - e_{63}^{\text{CH}}) + \dot{m}_{64} \cdot (e_{64}^{\text{M}} - e_{63}^{\text{CH}}) + \dot{m}_{11} \cdot (e_{11}^{\text{T}} - e_{63}^{\text{T}}) + \dot{m}_{50} \cdot (e_{50}^{\text{T}} - e_{63}^{\text{T}}) \\ \end{split} $	
LPC	$\dot{m}_{25} \cdot (e_{62}^{\text{CH}} - e_{25}^{\text{CH}}) + \dot{m}_{15} \cdot (e_{62}^{\text{T}} - e_{15}^{\text{T}}) + \dot{m}_{25} \cdot (e_{62}^{\text{T}} - e_{25}^{\text{T}})$	$ \begin{split} \dot{m}_{68} \cdot (e^{\rm CH}_{68} - e^{\rm CH}_{62}) + \dot{m}_{15} \cdot (e^{\rm CH}_{15} - e^{\rm CH}_{62}) + \dot{m}_{68} \cdot (e^{\rm M}_{68} - e^{\rm M}_{62}) + \dot{m}_{15} \cdot (e^{\rm M}_{15} - e^{\rm M}_{62}) + \dot{m}_{25} \cdot (e^{\rm M}_{25} - e^{\rm M}_{62}) + \dot{m}_{68} \cdot (e^{\rm T}_{68} - e^{\rm T}_{62}) + \dot{m}_{68} \cdot (e^{\rm T}_{68} - e^{\rm T}_{68}) + \dot{m}_{68} \cdot ($	
HE2	$\dot{E}_{33}^{\mathrm{M}} - \dot{E}_{34}^{\mathrm{M}} + \dot{E}_{41}^{\mathrm{PH}} - \dot{E}_{42}^{\mathrm{PH}} + \dot{E}_{30}^{\mathrm{PH}} - \dot{E}_{31}^{\mathrm{PH}} + \dot{E}_{33}^{\mathrm{PH}}$	$\dot{E}_{34}^{ m T}$	
NC1	$\dot{W}_{\mathrm{NC1}} + \dot{E}_{31}^{\mathrm{T}} - \dot{E}_{32}^{\mathrm{T}}$	$\dot{E}_{32}^{M} - \dot{E}_{31}^{M}$	
NC2	$\dot{W}_{ m NC2}+\dot{E}_{ m 32}^{ m T}$	$\dot{E}^{ m M}_{33}-\dot{E}^{ m M}_{32}+\dot{E}^{ m T}_{33}$	
TV3	$\dot{E}_{34}^{ m M}-\dot{E}_{37}^{ m M}$	$\dot{E}_{37}^{\mathrm{T}}-\dot{E}_{34}^{\mathrm{T}}$	
TV4	$\dot{E}_{38}^{ m M}-\dot{E}_{29}^{ m M}$	$\dot{E}_{29}^{\mathrm{T}}-\dot{E}_{38}^{\mathrm{T}}$	
ICO	dissipative component: $\dot{E}_{\rm D,ICO} = \dot{E}_{24} - \dot{E}_{28}$	-	
ICN	dissipative component: $\dot{E}_{\rm D,ICN} = \dot{E}_{35} - \dot{E}_{36}$	-	
TV1	$\dot{E}_{56}^{ m M}-\dot{E}_{57}^{ m M}$	$\dot{E}_{57}^{\mathrm{T}}-\dot{E}_{56}^{\mathrm{T}}$	
TV6	$\dot{E}_{52}^{ m M} - \dot{E}_{53}^{ m M}$	$\dot{E}_{53}^{\mathrm{T}}-\dot{E}_{52}^{\mathrm{T}}$	
TV5	$\dot{E}_{50}^{ m M}-\dot{E}_{51}^{ m M}$	$\dot{E}_{51}^{\mathrm{T}}-\dot{E}_{50}^{\mathrm{T}}$	

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174	component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
	TV2	$\dot{E}_{11}^{\rm M} - \dot{E}_{12}^{\rm M}$	$\dot{E}_{12}^{\mathrm{T}} - \dot{E}_{11}^{\mathrm{T}}$
	CDREB	$\dot{E}^{\mathrm{M}}_{69} - \dot{E}^{\mathrm{M}}_{70} + \dot{E}^{\mathrm{T}}_{69} - \dot{E}^{\mathrm{T}}_{70} + \dot{E}^{\mathrm{M}}_{65} - \dot{E}^{\mathrm{M}}_{66}$	$\dot{E}_{66}^{ m T}-\dot{E}_{65}^{ m T}$
	PMHPC	$\dot{E}_{58} + \dot{E}_{10} + \dot{E}_{67}$	\dot{E}_{63}
	PMLPC	$\dot{E}_{13} + \dot{E}_{51} + \dot{E}_{53} + \dot{E}_{57} + \dot{E}_{71} + \dot{E}_{29}$	\dot{E}_{62}
	HE4	dissipative component: $\dot{E}_{D,HE4} = \dot{E}_{23} - \dot{E}_{24} + \dot{E}_{21} - \dot{E}_{35} + \dot{E}_{46} - \dot{E}_{47}$	-
	LNGP	$\dot{W}_{ ext{LNG}} + \dot{E}_{39}^{ ext{T}} - \dot{E}_{40}^{ ext{T}}$	$\dot{E}_{40}^{ m M}-\dot{E}_{39}^{ m M}$
	tot	$\dot{E}_1 + \dot{W}_{ m tot} + \dot{E}_{39}^{ m T} - \dot{E}_{47}^{ m M} + \dot{E}_{39}^{ m CH} - \dot{E}_{47}^{ m CH}$	$\dot{E}_{14} + \dot{E}_{55} + \dot{E}_{36} + \dot{E}_{28} + \dot{E}^{\mathrm{M}}_{47} - \dot{E}^{\mathrm{M}}_{39}$

	Table B.6: Definition of exergy of fuel and exergy of product, Case AD2S		
component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$	
AC1	Ŵ _{AC1}	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$	
IC1	dissipative component: $\dot{E}_{\text{D,IC1}} = \dot{E}_2^{\text{PH}} - \dot{E}_3^{\text{PH}} + \dot{E}_{46}^{\text{PH}} - \dot{E}_{47}^{\text{PH}}$	-	
AD	$\dot{E}_{3}^{\mathrm{M}} - \dot{E}_{5}^{\mathrm{M}} + \dot{E}_{3}^{\mathrm{T}} - \dot{E}_{5}^{\mathrm{T}}$	$\dot{E}_5^{ m CH}-\dot{E}_3^{ m CH}$	
IC2	$\dot{E}_5^{\rm M} - \dot{E}_6^{\rm M} + \dot{E}_{44}^{\rm M} - \dot{E}_{45}^{\rm M} + \dot{E}_{44}^{\rm T} - \dot{E}_{45}^{\rm T} + \dot{E}_5^{\rm T}$	$\dot{E}_6^{ m T}$	
AC2	$\dot{W}_{ m AC2} + \dot{E}_6^{ m T}$	$\dot{E}_7^{\mathrm{M}}-\dot{E}_6^{\mathrm{M}}+-\dot{E}_7^{\mathrm{T}}$	
IC5	$\dot{E}_7^{\mathrm{M}} - \dot{E}_8^{\mathrm{M}} + \dot{E}_{45}^{\mathrm{M}} - \dot{E}_{46}^{\mathrm{M}} + \dot{E}_{45}^{\mathrm{T}} - \dot{E}_{46}^{\mathrm{T}} + \dot{E}_7^{\mathrm{T}}$	$\dot{E}_8^{ m T}$	
AC3	$\dot{W}_{ m AC3}+\dot{E}_8^{ m T}$	$\dot{E}_9^{ m M}-\dot{E}_8^{ m M}+\dot{E}_9^{ m T}$	
MHE	$\dot{E}_{15}^{\rm PH} - \dot{E}_{16}^{\rm PH} + \dot{E}_{20}^{\rm PH} - \dot{E}_{21}^{\rm PH} + \dot{E}_{25}^{\rm PH} - \dot{E}_{26}^{\rm PH} + \dot{E}_{9}^{\rm M} - \dot{E}_{10}^{\rm M} + \dot{E}_{9}^{\rm T} + \dot{E}_{25}^{\rm T}$	$\dot{E}_{10}^{\mathrm{T}}+\dot{E}_{26}^{\mathrm{T}}$	
HE3	$\dot{E}_{26}^{\mathrm{M}} - \dot{E}_{27}^{\mathrm{M}} + \dot{E}_{17}^{\mathrm{M}} - \dot{E}_{18}^{\mathrm{M}} + \dot{E}_{17}^{\mathrm{T}} - \dot{E}_{18}^{\mathrm{T}}$	$\dot{E}_{27}^{\mathrm{T}}-\dot{E}_{26}^{\mathrm{T}}$	
NC5	Ŵ _{NC5}	$\dot{E}^{ m M}_{17} - \dot{E}^{ m M}_{16} + \dot{E}^{ m T}_{17} - \dot{E}^{ m T}_{16}$	
OC	Ŵ _{OC}	$\dot{E}^{ m M}_{23} - \dot{E}^{ m M}_{21} + \dot{E}^{ m T}_{23} - \dot{E}^{ m T}_{21}$	
HPC	$\dot{m}_{11} \cdot \left(e_{61}^{\rm M} - e_{11}^{\rm M} \right) + \dot{m}_{52} \cdot \left(e_{61}^{\rm T} - e_{52}^{\rm T} \right) + \dot{m}_{62} \cdot \left(e_{61}^{\rm T} - e_{62}^{\rm T} \right)$	$ \begin{split} \dot{m}_{11} \cdot (e_{11}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{50} \cdot (e_{50}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{52} \cdot (e_{52}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{62} \cdot (e_{62}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{62} \cdot (e_{52}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{52} \cdot (e_{52}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{52} \cdot (e_{52}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{51} \cdot (e_{52}^{\mathrm{T}} - e_{61}^{\mathrm{CH}}) + \dot{m}_{50} \cdot (e_{52}^{\mathrm{T}} - e_{61}^{\mathrm{T}}) + \dot{m}_{50} \cdot (e_{50}^{\mathrm{T}} - e_{50}^{\mathrm{T}}) + \dot{m}_{50} \cdot (e_{50}^{\mathrm{T}} - e_{50}^{\mathrm{T}}) + $	
LPC	$\dot{m}_{25} \cdot (e_{60}^{\rm CH} - e_{25}^{\rm CH}) + \dot{m}_{15} \cdot (e_{60}^{\rm T} - e_{15}^{\rm T}) + \dot{m}_{25} \cdot (e_{60}^{\rm T} - e_{25}^{\rm T})$	$ \begin{split} \dot{m}_{66} \cdot (e^{\rm CH}_{66} - e^{\rm CH}_{60}) + \dot{m}_{15} \cdot (e^{\rm CH}_{15} - e^{\rm CH}_{60}) + \dot{m}_{66} \cdot (e^{\rm M}_{66} - e^{\rm M}_{60}) + \dot{m}_{15} \cdot (e^{\rm M}_{15} - e^{\rm M}_{60}) + \dot{m}_{25} \cdot (e^{\rm M}_{25} - e^{\rm M}_{60}) + \dot{m}_{66} \cdot (e^{\rm H}_{66} - e^{\rm H}_{60}) + \dot{m}_{66} \cdot ($	
HE2	$\dot{E}_{34}^{\mathrm{M}} - \dot{E}_{35}^{\mathrm{M}} + \dot{E}_{40}^{\mathrm{PH}} - \dot{E}_{41}^{\mathrm{PH}} + \dot{E}_{34}^{\mathrm{T}}$	$\dot{E}_{35}^{ m T}$	
NC1	$\dot{W}_{\rm NC1} + \dot{E}_{32}^{\rm T} - \dot{E}_{33}^{\rm T}$	$\dot{E}_{33}^{\rm M} - \dot{E}_{32}^{\rm M}$	
NC2	$\dot{W}_{ m NC2} + \dot{E}_{ m 33}^{ m T}$	$\dot{E}^{\mathrm{M}}_{34}-\dot{E}^{\mathrm{M}}_{33}+\dot{E}^{\mathrm{T}}_{34}$	
TV3	$\dot{E}_{35}^{ m M} - \dot{E}_{36}^{ m M}$	$\dot{E}_{36}^{\mathrm{T}}-\dot{E}_{35}^{\mathrm{T}}$	
TV4	$\dot{E}_{37}^{ m M} - \dot{E}_{29}^{ m M}$	$\dot{E}_{29}^{\mathrm{T}}-\dot{E}_{37}^{\mathrm{T}}$	
ICO	dissipative component: $\dot{E}_{D,ICO} = \dot{E}_{23} - \dot{E}_{24}$	-	
ICN	dissipative component: $\dot{E}_{\rm D,ICN} = \dot{E}_{19} - \dot{E}_{28}$	-	
TV1	$\dot{E}_{56}^{ m M}-\dot{E}_{57}^{ m M}$	$\dot{E}_{57}^{\mathrm{T}}-\dot{E}_{56}^{\mathrm{T}}$	
TV6	$\dot{E}_{52}^{ m M} - \dot{E}_{53}^{ m M}$	$\dot{E}_{53}^{\mathrm{T}}-\dot{E}_{52}^{\mathrm{T}}$	
TV5	$\dot{E}_{50}^{\rm M} - \dot{E}_{51}^{\rm M}$	$\dot{E}_{51}^{\mathrm{T}}-\dot{E}_{50}^{\mathrm{T}}$	

Table D (Definition of a of final and a comprised and that Case AD26

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
TV2	$\dot{E}_{11}^{ m M} - \dot{E}_{12}^{ m M}$	$\dot{E}_{12}^{ m T} - \dot{E}_{11}^{ m T}$
CDREB	$\dot{E}_{67}^{ m M}-\dot{E}_{68}^{ m M}+\dot{E}_{68}^{ m T}-\dot{E}_{67}^{ m M}+\dot{E}_{63}^{ m M}-\dot{E}_{64}^{ m M}$	$\dot{E}_{64}^{ m T}-\dot{E}_{63}^{ m T}$
PMHPC	$\dot{E}_{58} + \dot{E}_{10} + \dot{E}_{65}$	\dot{E}_{61}
PMLPC	$\dot{E}_{13} + \dot{E}_{51} + \dot{E}_{53} + \dot{E}_{57} + \dot{E}_{69} + \dot{E}_{29}$	\dot{E}_{60}
HE5	$\dot{E}^{\mathrm{M}}_{43} - \dot{E}^{\mathrm{M}}_{44} + \dot{E}^{\mathrm{M}}_{41} - \dot{E}^{\mathrm{M}}_{42} + \dot{E}^{\mathrm{T}}_{43} + \dot{E}^{\mathrm{T}}_{41}$	$\dot{E}_{44}^{\mathrm{M}}+\dot{E}_{42}^{\mathrm{M}}$
WP	$\dot{W}_{ m WP}$	$\dot{E}^{ m M}_{43}-\dot{E}^{ m M}_{48}+\dot{E}^{ m T}_{43}-\dot{E}^{ m T}_{48}$
LNGP	$\dot{W}_{ m LNGP}+\dot{E}_{ m 39}^{ m T}-\dot{E}_{ m 40}^{ m T}$	$\dot{E}_{40}^{ m M}-\dot{E}_{39}^{ m M}$
HE4	dissipative component: $\dot{E}_{D,HE4} = \dot{E}_{47} - \dot{E}_{48} + \dot{E}_{22} - \dot{E}_{23} + \dot{E}_{18} - \dot{E}_{19}$	-
tot	$\dot{E}_1 + \dot{W}_{\text{tot}} + \dot{E}_{39}^{\text{T}} - \dot{E}_{42}^{\text{T}} + \dot{E}_{39}^{\text{CH}} - \dot{E}_{42}^{\text{CH}}$	$\dot{E}_{14}+\dot{E}_{55}+\dot{E}_{24}+\dot{E}_{28}+\dot{E}^{\mathrm{M}}_{42}-\dot{E}^{\mathrm{M}}_{39}$

	Table B.7: Definition of exergy of fuel and exergy of product, Case BD2S			
component	Ė _{F,k}	Ė _{P,k}		
AC1	$\dot{W}_{ m AC1}$	$\dot{E}_2^{\mathrm{M}}-\dot{E}_1^{\mathrm{M}}+\dot{E}_2^{\mathrm{T}}-\dot{E}_1^{\mathrm{T}}$		
IC1	dissipative component: $\dot{E}_{D,IC1} = \dot{E}_{62} - \dot{E}_{63} + \dot{E}_2 - \dot{E}_3$	-		
AD	$\dot{E}_3^{\mathrm{M}}-\dot{E}_5^{\mathrm{M}}+\dot{E}_3^{\mathrm{T}}-\dot{E}_5^{\mathrm{T}}$	$\dot{E}_5^{ m CH}-\dot{E}_3^{ m CH}\dot{E}_8+\dot{E}_9+\dot{E}_{64}$		
IC2	dissipative component: $\dot{E}_{\rm D,IC2} = \dot{E}_{60} - \dot{E}_{61} + \dot{E}_5 - \dot{E}_6$	-		
AC2	$\dot{W}_{ m AC2}+\dot{E}_{ m 6}^{ m T}$	$\dot{E}_7^{\mathbf{M}}-\dot{E}_6^{\mathbf{M}}+\dot{E}_7^{\mathrm{T}}$		
IC5	dissipative component: $\dot{E}_{\text{D,IC5}} = \dot{E}_7 - \dot{E}_{10} + \dot{E}_{61} - \dot{E}_{62}$	-		
AC3	Ŵ _{AC3}	$\dot{E}^{ m M}_{17} - \dot{E}^{ m M}_{18} + \dot{E}^{ m T}_{17} - \dot{E}^{ m T}_{18}$		
MHE	$ \dot{E}^{\rm PH}_{32} - \dot{E}^{\rm PH}_{33} + \dot{E}^{\rm M}_{35} - \dot{E}^{\rm M}_{36} + \dot{E}^{\rm M}_{18} - \dot{E}^{\rm M}_{19} + \dot{E}^{\rm M}_{12} - \dot{E}^{\rm M}_{13} + \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{15} + \dot{E}^{\rm M}_{37} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{35} + \dot{E}^{\rm M}_{37} + \dot{E}^{\rm M}_{18} + \dot{E}^{\rm M}_{12} + \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{15} + \dot{E}^{\rm M}_{37} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{35} + \dot{E}^{\rm M}_{37} + \dot{E}^{\rm M}_{18} + \dot{E}^{\rm M}_{12} + \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{14} - \dot{E}^{\rm M}_{15} + \dot{E}^{\rm M}_{37} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm M}_{38} - \dot{E}^{\rm M}_{38} + \dot{E}^{\rm$	$\dot{E}_{36}^{\mathrm{T}}+\dot{E}_{38}^{\mathrm{T}}+\dot{E}_{19}^{\mathrm{T}}+\dot{E}_{13}^{\mathrm{T}}+\dot{E}_{15}^{\mathrm{T}}$		
HPC	$\dot{m}_{44} \cdot (e_{52}^{\mathrm{T}} - e_{44}^{\mathrm{T}}) + \dot{m}_{21} \cdot (e_{52}^{\mathrm{M}} - e_{21}^{\mathrm{M}})$	$\dot{m}_{44} \cdot (e^{\text{CH}}_{44} - e^{\text{CH}}_{52}) + \dot{m}_{44} \cdot (e^{\text{M}}_{44} - e^{\text{M}}_{52}) + \dot{m}_{21} \cdot (e^{\text{CH}}_{21} - e^{\text{CH}}_{52}) + \dot{m}_{21} \cdot (e^{\text{T}}_{21} - e^{\text{T}}_{52})$		
LPC	$\dot{m}_{37} \cdot (e_{53}^{\text{CH}} - e_{37}^{\text{CH}}) + \dot{m}_{37} \cdot (e_{53}^{\text{T}} - e_{37}^{\text{T}}) + \dot{m}_{34} \cdot (e_{53}^{\text{T}} - e_{34}^{\text{T}})$	$ \begin{split} \dot{m}_{48} \cdot (e^{\rm CH}_{48} - e^{\rm CH}_{53}) + \dot{m}_{34} \cdot (e^{\rm CH}_{34} - e^{\rm CH}_{53}) + \dot{m}_{48} \cdot (e^{\rm M}_{48} - e^{\rm M}_{53}) + \dot{m}_{37} \cdot (e^{\rm M}_{37} - e^{\rm T}_{53}) + \dot{m}_{34} \cdot (e^{\rm M}_{34} - e^{\rm M}_{53}) + \dot{m}_{48} \cdot (e^{\rm H}_{48} - e^{\rm T}_{53}) + \dot{m}_{48} \cdot (e^{\rm H}_{48} - e^{\rm T}_{53}) + \dot{m}_{48} \cdot (e^{\rm H}_{48} - e^{\rm T}_{53}) + \dot{m}_{48} \cdot (e^{\rm H}_{48} - e^{\rm H}_{53}) + \dot{m}_{48} \cdot ($		
OP	$\dot{W}_{ m OP} + \dot{E}_{ m 30}^{ m T} - \dot{E}_{ m 31}^{ m T}$	$\dot{E}_{31}^{ m M} - \dot{E}_{30}^{ m M}$		
EXP1	$\dot{E}_{15}^{\rm M} - \dot{E}_{16}^{\rm M}$	$\dot{E}_{16}^{\mathrm{T}} - \dot{E}_{15}^{\mathrm{T}} + \dot{W}_{\mathrm{EXP1}}$		
ICN1	$\dot{E}_{36}^{\rm M} - \dot{E}_{39}^{\rm M} + \dot{E}_{55}^{\rm M} - \dot{E}_{56}^{\rm M} + \dot{E}_{55}^{\rm T} - \dot{E}_{56}^{\rm T} + \dot{E}_{36}^{\rm T}$	$\dot{E}_{39}^{ m T}$		
NC5	$\dot{W}_{ m NC5}+\dot{E}_{ m 36}^{ m T}$	$\dot{E}^{ m M}_{40} - \dot{E}^{ m M}_{39} + \dot{E}^{ m T}_{40}$		
ICN2	dissipative component: $\dot{E}_{D,ICN2} = \dot{E}_{40} - \dot{E}_{41} + \dot{E}_{56} - \dot{E}_{57}$	-		
CDREB	$\dot{E}_{45}^{\mathrm{M}} - \dot{E}_{46}^{\mathrm{M}} + \dot{E}_{49}^{\mathrm{T}} - \dot{E}_{50}^{\mathrm{T}} + \dot{E}_{49}^{\mathrm{M}} - \dot{E}_{50}^{\mathrm{M}}$	$\dot{E}_{46}^{\mathrm{T}}-\dot{E}_{45}^{\mathrm{T}}$		
TV1	$\dot{E}_{19}^{ m M}-\dot{E}_{20}^{ m M}$	$\dot{E}_{20}^{\mathrm{T}}-\dot{E}_{19}^{\mathrm{T}}$		
SUB	$\dot{E}_{25}^{\mathrm{M}} - \dot{E}_{26}^{\mathrm{M}} + \dot{E}_{34}^{\mathrm{M}} - \dot{E}_{35}^{\mathrm{M}} + \dot{E}_{34}^{\mathrm{T}} - \dot{E}_{35}^{\mathrm{T}}$	$\dot{E}_{26}^{\mathrm{T}}-\dot{E}_{25}^{\mathrm{T}}$		
TV2	$\dot{E}_{26}^{\rm M} - \dot{E}_{27}^{\rm M}$	$\dot{E}_{27}^{\mathrm{T}}-\dot{E}_{26}^{\mathrm{T}}$		

<u> </u>			
178	component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
	TV3	$\dot{E}_{21}^{M} - \dot{E}_{22}^{M}$	$\dot{E}_{22}^{\mathrm{T}} - \dot{E}_{21}^{\mathrm{T}}$
	LNGP	$\dot{W}_{\mathrm{LNGP}} + \dot{E}_{54}^{\mathrm{T}} - \dot{E}_{55}^{\mathrm{T}}$	$\dot{E}_{55}^{ m M} - \dot{E}_{54}^{ m M}$
	WP	Ŵ _{WP}	$\dot{E}^{\mathrm{M}}_{59} - \dot{E}^{\mathrm{M}}_{63} + \dot{E}^{\mathrm{T}}_{59} - \dot{E}^{\mathrm{T}}_{63}$
	HE5	$\dot{E}^{\rm M}_{59} - \dot{E}^{\rm M}_{60} + \dot{E}^{\rm M}_{57} - \dot{E}^{\rm M}_{58} + \dot{E}^{\rm T}_{57} - \dot{E}^{\rm T}_{58} + \dot{E}^{\rm T}_{59}$	$\dot{E}_{60}^{\mathrm{T}}$
	tot	$\dot{E}_1 + \dot{W}_{ m tot} + \dot{E}_{54}^{ m CH} - \dot{E}_{58}^{ m CH} + \dot{E}_{54}^{ m T} - \dot{E}_{58}^{ m T}$	$\dot{E}_{33} + \dot{E}_{40} + \dot{E}_{29} + \dot{E}_{24} + \dot{E}_{58}^{\mathrm{M}} - \dot{E}_{54}^{\mathrm{M}}$

Table B.8: Definition of the auxiliary equations (F and P rule), Case A			
component	F-rule	P-rule	
AC1	$c_1^{\rm CH}=c_2^{\rm CH}$	$rac{\dot{C}^{\mathbf{M}}_{\mathbf{M}}-\dot{C}^{\mathbf{M}}_{\mathbf{M}}}{E_{2}^{\mathbf{M}}-E_{1}^{\mathbf{M}}}=rac{\dot{C}_{1}^{2}-\dot{C}_{1}^{T}}{E_{2}^{2}-E_{1}^{T}}$	
IC1	dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}, c_2^{\text{M}} = c_3^{\text{M}}, c_2^{\text{T}} = c_3^{\text{T}}$		
AC2	$c_3^{\rm CH} = c_4^{\rm CH}$	$rac{\dot{C}_{3}^{A}-\dot{C}_{4}^{M}}{\dot{E}_{3}^{A}-\dot{E}_{4}^{M}}=rac{C_{3}^{-}-\dot{C}_{4}^{-}}{\dot{E}_{3}^{-}-\dot{E}_{4}^{-}}$	
IC2	dissipative component: $c_4^{\text{CH}} = c_5^{\text{CH}}, c_4^{\text{M}} = c_5^{\text{M}}, c_4^{\text{T}} = c_5^{\text{T}}$	-	
MHE	$ \begin{split} c^{\rm CH}_{15} &= c^{\rm CH}_{17}, c^{\rm CH}_{25} = c^{\rm CH}_{27}, c^{\rm CH}_{30} = c^{\rm CH}_{31}, c^{\rm CH}_{20} = c^{\rm CH}_{22}, c^{\rm CH}_{7} = c^{\rm CH}_{10}, \\ c^{\rm M}_{15} &= c^{\rm M}_{17}, c^{\rm M}_{25} = c^{\rm M}_{27}, c^{\rm M}_{30} = c^{\rm M}_{31}, c^{\rm M}_{20} = c^{\rm M}_{22}, c^{\rm M}_{7} = c^{\rm M}_{10}, c^{\rm T}_{15} = c^{\rm T}_{17}, \\ c^{\rm T}_{25} &= c^{\rm T}_{27}, c^{\rm T}_{30} = c^{\rm T}_{31}, c^{\rm T}_{20} = c^{\rm T}_{22} \end{split} $	-	
AD	$c_5^{\mathrm{T}} = c_7^{\mathrm{T}}, c_5^{\mathrm{M}} = c_7^{\mathrm{M}}$	-	
HE3	$c_{27}^{\text{CH}} = c_{28}^{\text{CH}}, c_{18}^{\text{CH}} = c_{19}^{\text{CH}}, c_{18}^{\text{M}} = c_{19}^{\text{M}}, c_{27}^{\text{M}} = c_{28}^{\text{M}}, c_{18}^{\text{T}} = c_{19}^{\text{T}}$	-	
NC5	$c_{18}^{\rm CH} = c_{17}^{\rm CH}$	$\frac{C_{18}^{m}-C_{17}^{m}}{E_{19}^{m}-E_{17}^{m}}=\frac{C_{18}^{m}-C_{17}^{m}}{E_{19}^{m}-E_{17}^{m}}$	
OC	$c_{23}^{\rm CH} = c_{22}^{\rm CH}$	$rac{C_{23}^{\rm M_3}-C_{22}^{\rm M_2}}{E_{23}^{\rm M_3}-E_{22}^{\rm M_2}}=rac{C_{23}^{\rm T}-C_{22}^{\rm T}}{E_{23}^{\rm T}-E_{22}^{\rm T}}$	
HPC	$c_{61}^{\mathrm{T}} = c_{63}^{\mathrm{T}}, c_{61}^{\mathrm{T}} = c_{52}^{\mathrm{T}}, c_{61}^{\mathrm{M}} = c_{11}^{\mathrm{M}}$	$ \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{50}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{52} \cdot (e_{52}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{52} \cdot (e_{52}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{53} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{52} \cdot (e_{52}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{52} \cdot (e_{52}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{50}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{53} \cdot (e_{51}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{53} \cdot (e_{51}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}, \frac{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{CH} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{T} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{T} - e_{61}^{CH} - e_{61}^{CH})} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{T} - e_{61}^{CH} - e_{61}^{CH})}} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{63} \cdot (e_{63}^{T} - e_{61}^{CH} - e_{61}^{CH})}} = \frac{m_{50} \cdot (e_{50}^{T} - e_{61}^{CH} - e_{61}^{CH})}{m_{50} \cdot (e_{63}^{T} - e_{61}^{CH})}}$	
LPC	$c_{60}^{\mathrm{T}} = c_{25}^{\mathrm{T}}, c_{60}^{\mathrm{T}} = c_{15}^{\mathrm{T}}, c_{60}^{\mathrm{CH}} = c_{25}^{\mathrm{CH}}$	$\frac{\frac{m_{15} \cdot (e_{15}^{H} \cdot e_{15}^{H} - e_{00}^{H} \cdot e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{15} \cdot (e_{15}^{H} \cdot e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{15} \cdot (e_{15}^{H} \cdot e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{25} \cdot (e_{25}^{H} \cdot e_{25}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{25} \cdot (e_{25}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})} = \frac{\frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})} = \frac{m_{25} \cdot (e_{15}^{H} - e_{00}^{H})}{\hat{m}_{15} \cdot (e_{15}^{H} - e_{00}^{H})}$	
HE2	$c_{21}^{\rm CH} = c_{48}^{\rm CH}, c_{43}^{\rm CH} = c_{44}^{\rm CH}, c_{21}^{\rm M} = c_{48}^{\rm M}, c_{43}^{\rm M} = c_{44}^{\rm M}, c_{43}^{\rm T} = c_{44}^{\rm T}$	-	
EXP2	$c_{42}^{\rm CH} = c_{43}^{\rm CH}, c_{42}^{\rm M} = c_{43}^{\rm M}$	$rac{C_{43}^{-}-C_{42}^{-}}{E_{43}^{+}-E_{42}^{-}}=rac{\psi_{\mathrm{EXP2}}}{\psi_{\mathrm{EXP2}}}$	
EXP1	$c_{46}^{\rm CH} = c_{47}^{\rm CH}, c_{46}^{\rm M} = c_{47}^{\rm M}$	$rac{C_{47}^{-}-C_{46}^{-}}{E_{47}^{-}-E_{46}^{-}}=rac{W_{\mathrm{EXP1}}}{W_{\mathrm{EXP1}}}$	

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
NC1	$c_{34}^{ m CH}=c_{33}^{ m CH}$	$rac{C_{34}^4-C_{33}^3}{E_{34}^M-E_{33}^4}=rac{C_{34}^4-C_{13}^3}{E_{34}^7-E_{13}^3}$
IC3	dissipative component: $c_{34}^{CH} = c_{35}^{CH}$, $c_{34}^{M} = c_{35}^{M}$, $c_{34}^{T} = c_{35}^{T}$	-
NC2	$c_{36}^{\rm CH} = c_{35}^{\rm CH}$	$\frac{\dot{c}_{35}^{\rm ob}-\dot{c}_{35}^{\rm ob}}{E_{36}^{\rm ob}-\dot{E}_{35}^{\rm ob}}=\frac{\dot{c}_{35}^{\rm ob}-\dot{c}_{35}^{\rm ob}}{E_{36}^{\rm ob}-\dot{E}_{35}^{\rm ob}}$
IC4	dissipative component: $c_{36}^{CH} = c_{37}^{CH}, c_{36}^{M} = c_{37}^{M}, c_{36}^{T} = c_{37}^{T}$	-
NC3	$c_{38}^{ m CH} = c_{37}^{ m CH}$	$rac{C_{33}^{ m M}-C_{37}^{ m M}}{E_{33}^{ m M}-E_{37}^{ m M}}=rac{C_{33}^{ m M}-C_{37}^{ m M}}{E_{33}^{ m M}-E_{37}^{ m M}}$
NC4	$c_{40}^{\rm CH}=c_{39}^{\rm CH}$	$rac{\dot{C}_{40}^{M}-\dot{C}_{39}^{M}}{E_{40}^{M}-E_{39}^{M}}=rac{\dot{C}_{40}^{T}-\dot{C}_{39}^{T}}{E_{40}^{T}-E_{39}^{T}}$
HE1	$\begin{split} c^{\rm CH}_{45} &= c^{\rm CH}_{46}, c^{\rm CH}_{40} = c^{\rm CH}_{41}, c^{\rm CH}_{32} = c^{\rm CH}_{33}, c^{\rm M}_{45} = c^{\rm M}_{46}, c^{\rm M}_{40} = c^{\rm M}_{41}, \\ c^{\rm M}_{32} &= c^{\rm M}_{33}, c^{\rm M}_{32} = c^{\rm M}_{33} \end{split}$	$c_{41}^{\mathrm{T}} = c_{46}^{\mathrm{T}}$
TV3	$c_{49}^{\rm CH}=c_{48}^{\rm CH}, c_{49}^{\rm M}=c_{48}^{\rm M}$	-
TV4	$c_{59}^{\rm CH} = c_{16}^{\rm CH}, c_{59}^{\rm M} = c_{16}^{\rm M}$	-
ICO	dissipative component: $c_{23}^{CH} = c_{24}^{CH}, c_{23}^{M} = c_{24}^{M}, c_{23}^{T} = c_{24}^{T}$	-
ICN	dissipative component: $c_{19}^{\text{CH}} = c_{29}^{\text{CH}}, c_{19}^{\text{M}} = c_{29}^{\text{M}}, c_{19}^{\text{T}} = c_{29}^{\text{T}}$	-
TV1	$c_{56}^{\rm CH} = c_{57}^{\rm CH}, c_{56}^{\rm M} = c_{57}^{\rm M}$	-
TV6	$c_{52}^{\rm CH} = c_{53}^{\rm CH}, c_{52}^{\rm M} = c_{53}^{\rm M}$	-
TV5	$c_{50}^{\rm CH} = c_{51}^{\rm CH}, c_{50}^{\rm M} = c_{51}^{\rm M}$	
TV2	$c_{11}^{\text{CH}} = c_{13}^{\text{CH}}, c_{11}^{\text{M}} = c_{13}^{\text{M}}$	-
CDREB	$c_{64}^{\rm CH} = c_{65}^{\rm CH}, c_{68}^{\rm CH} = c_{69}^{\rm CH}, c_{64}^{\rm M} = c_{65}^{\rm M}, c_{68}^{\rm M} = c_{69}^{\rm M}, c_{68}^{\rm T} = c_{69}^{\rm T}$	-
PMHPC	$c_{61}^{\mathrm{T}} = rac{C_{58}^{\mathrm{T}} + C_{66}^{\mathrm{T}} + C_{10}^{\mathrm{T}}}{E_{61}^{\mathrm{T}}}, c_{61}^{\mathrm{M}} = rac{C_{58}^{\mathrm{M}} + C_{60}^{\mathrm{M}} + C_{10}^{\mathrm{M}}}{E_{61}^{\mathrm{M}}}$	-
PMLPC	$ \begin{split} c^{\mathrm{T}}_{60} &= \frac{\dot{c}^{\mathrm{T}}_{13} + \dot{c}^{\mathrm{T}}_{51} + \dot{c}^{\mathrm{T}}_{53} + \dot{c}^{\mathrm{T}}_{16} + \dot{c}^{\mathrm{T}}_{57} + \dot{c}^{\mathrm{T}}_{70}}{\dot{E}^{\mathrm{T}}_{60}}, \\ c^{\mathrm{M}}_{60} &= \frac{\dot{c}^{\mathrm{M}}_{13} + \dot{c}^{\mathrm{M}}_{51} + \dot{c}^{\mathrm{M}}_{53} + \dot{c}^{\mathrm{M}}_{16} + \dot{c}^{\mathrm{M}}_{57} + \dot{c}^{\mathrm{M}}_{70}}{\dot{E}^{\mathrm{M}}_{60}} \end{split} $	-

Table B.9: Definition of the auxiliary equations (F and P rule), Case B		
component	F-rule	P-rule
AC1	$c_1^{\rm CH} = c_2^{\rm CH}$	$rac{C_{\mathrm{M}}^{\mathrm{M}}-C_{\mathrm{M}}^{\mathrm{M}}}{E_{\mathrm{M}}^{\mathrm{M}}-E_{\mathrm{M}}^{\mathrm{M}}}=rac{C_{\mathrm{M}}^{\mathrm{T}}-C_{\mathrm{M}}^{\mathrm{T}}}{E_{\mathrm{M}}^{\mathrm{T}}-E_{\mathrm{M}}^{\mathrm{T}}}$
IC1	dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}$, $c_2^{\text{M}} = c_3^{\text{M}}$, $c_2^{\text{T}} = c_3^{\text{T}}$	
AC2	$c_3^{\text{CH}} = c_4^{\text{CH}}$	$rac{\dot{C}_3^{-1}-\dot{C}_4^{-1}}{\dot{E}_3^{-1}-\dot{E}_4^{-1}}=rac{\dot{C}_3^{-1}-\dot{C}_4^{-1}}{\dot{E}_3^{-1}-\dot{E}_4^{-1}}$
IC2	dissipative component: $c_4^{\text{CH}} = c_5^{\text{CH}}, c_4^{\text{M}} = c_5^{\text{M}}, c_4^{\text{T}} = c_5^{\text{T}}$	-
AD	$c_5^{\rm T} = c_{10}^{\rm T}, c_5^{\rm M} = c_{10}^{\rm M}, c_8^{\rm CH} = 0$	-
AC3	$c_{17}^{\rm CH}=c_{18}^{\rm CH}$	$rac{C_{17}^{ m m}-C_{18}^{ m m}}{E_{17}^{ m m}-E_{18}^{ m m}}=rac{C_{17}^{ m m}-C_{18}^{ m m}}{E_{17}^{ m m}-E_{18}^{ m m}}$
MHE	$c_{32}^{\text{CH}} = c_{33}^{\text{CH}}, c_{18}^{\text{CH}} = c_{19}^{\text{CH}}, c_{12}^{\text{CH}} = c_{13}^{\text{CH}}, c_{14}^{\text{CH}} = c_{15}^{\text{CH}}, c_{35}^{\text{CH}} = c_{36}^{\text{CH}},$	$c_{36}^{T} = c_{38}^{T}, c_{36}^{T} = c_{19}^{T}, c_{36}^{T} = c_{13}^{T}, c_{36}^{T} = c_{15}^{T}$
	$ c_{37}^{CH} = c_{38}^{CH}, \\ c_{32}^{M} = c_{33}^{M}, c_{18}^{M} = c_{19}^{M}, c_{12}^{M} = c_{13}^{M}, c_{14}^{M} = c_{15}^{M}, c_{35}^{M} = c_{36}^{M}, c_{37}^{M} = c_{38}^{M}, \\ c_{32}^{T} = c_{33}^{T}, $	
HPC	$c_{52}^{\mathrm{T}} = c_{44}^{\mathrm{T}}, c_{52}^{\mathrm{M}} = c_{21}^{\mathrm{M}}$	$\frac{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}}\cdot e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}}\cdot e_{52}^{\mathrm{CH}})}{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})} = \frac{\dot{m}_{440}\cdot(e_{44}^{\mathrm{CH}}\cdot e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}}\cdot e_{52}^{\mathrm{CH}})}{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}, \\ \frac{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})} = \frac{\dot{m}_{21}\cdot(e_{21}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}{\dot{m}_{21}\cdot(e_{21}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}, \\ \frac{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}{\dot{m}_{44}\cdot(e_{44}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})} = \frac{\dot{m}_{21}\cdot(e_{21}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}{\dot{m}_{21}\cdot(e_{21}^{\mathrm{CH}} - e_{52}^{\mathrm{CH}})}, $
LPC	$c_{53}^{\text{CH}} = c_{37}^{\text{CH}}, c_{53}^{\text{T}} = c_{37}^{\text{T}}, c_{53}^{\text{T}} = c_{34}^{\text{T}}$	$\frac{m_{44}(e_{44}^{cH}-e_{53}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH}-e_{53}^{cH})} = \frac{m_{34}(e_{34}^{cH}-e_{53}^{cH}+e_{53}^{cH})}{m_{34}(e_{34}^{cH}-e_{53}^{cH}-e_{53}^{cH})}, \\ \frac{m_{48}(e_{48}^{cH}-e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{34}(e_{34}^{cH}-e_{53}^{cH}+e_{53}^{cH})}{m_{34}(e_{54}^{cH}-e_{53}^{cH})}, \\ \frac{m_{48}(e_{48}^{cH}-e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{37}(e_{37}^{cH}-e_{37}^{cH}+e_{53}^{cH})}{m_{37}(e_{37}^{cH}-e_{37}^{cH}+e_{33}^{cH})}, \\ \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH}+e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{34}(e_{34}^{cH}-e_{53}^{cH})}, \\ \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})}, \\ \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})} = \frac{m_{48}(e_{48}^{cH}-e_{53}^{cH})}{m_{48}(e_{48}^{cH}-e_{53}^{cH})}$
OP	$c_{31}^{\text{CH}} = c_{30}^{\text{CH}}$, $c_{31}^{\text{T}} = c_{30}^{\text{T}}$	-
EXP1	$c_{15}^{\rm CH} = c_{16}^{\rm CH}, c_{15}^{\rm M} = c_{16}^{\rm M}$	$\frac{\dot{C}_{16}^{-}-\dot{C}_{15}^{T}}{\dot{E}_{16}^{+}-\dot{E}_{15}^{T}}=\frac{\dot{W}_{\rm EXP1}}{\dot{W}_{\rm EXP1}}$
NC5	$c_{36}^{\rm CH} = c_{39}^{\rm CH}$	$rac{\dot{C}_{16}^{7}}{E_{39}^{7}} = rac{\dot{C}_{40}^{40} - \dot{C}_{36}^{M}}{E_{40}^{40} - \dot{E}_{36}^{M}}$
ICN	$c_{39}^{\rm CH} = c_{40}^{\rm CH}, c_{39}^{\rm M} = c_{40}^{\rm M}, c_{39}^{\rm T} = c_{40}^{\rm T}$	-
TV3	$c_{21}^{\text{CH}} = c_{22}^{\text{CH}}, c_{21}^{\text{M}} = c_{22}^{\text{M}}$	-
CDREB	$c_{49}^{\text{CH}} = c_{50}^{\text{CH}}, c_{45}^{\text{CH}} = c_{46}^{\text{CH}}, c_{49}^{\text{M}} = c_{50}^{\text{M}}, c_{45}^{\text{M}} = c_{46}^{\text{M}}, c_{49}^{\text{T}} = c_{50}^{\text{T}}$	-

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
TV1	$c_{19}^{\rm CH} = c_{20}^{\rm CH}, c_{19}^{\rm M} = c_{20}^{\rm M}$	-
SUB	$c_{25}^{\mathrm{CH}} = c_{26}^{\mathrm{CH}}, c_{34}^{\mathrm{CH}} = c_{35}^{\mathrm{CH}}, c_{25}^{\mathrm{M}} = c_{26}^{\mathrm{M}}, c_{34}^{\mathrm{M}} = c_{35}^{\mathrm{M}}, c_{34}^{\mathrm{T}} = c_{35}^{\mathrm{T}}$	-
TV2	$c_{26}^{\rm CH} = c_{27}^{\rm CH}, c_{26}^{\rm M} = c_{27}^{\rm M}$	-
PMHPC	$c_{52}^{\mathrm{T}} = \frac{c_{20}^{\mathrm{T}} + c_{13}^{\mathrm{T}} + c_{47}^{\mathrm{T}}}{E_{52}^{\mathrm{T}}}, c_{52}^{\mathrm{M}} = \frac{c_{20}^{\mathrm{M}} + c_{41}^{\mathrm{M}} + c_{47}^{\mathrm{M}}}{E_{52}^{\mathrm{M}}}$	-
PMLPC	$c_{53}^{\mathrm{T}} = \frac{\dot{c}_{16}^{\mathrm{T}} + \dot{c}_{51}^{\mathrm{T}} + \dot{c}_{22}^{\mathrm{T}} + \dot{c}_{21}^{\mathrm{T}}}{\dot{E}_{53}^{\mathrm{T}}}, c_{53}^{\mathrm{M}} = \frac{\dot{c}_{16}^{\mathrm{M}} + \dot{c}_{51}^{\mathrm{M}} + \dot{c}_{21}^{\mathrm{M}} + \dot{c}_{21}^{\mathrm{M}}}{\dot{E}_{53}^{\mathrm{M}}}$	-

Table B.10: Definition of the auxiliary equations (F and P rule), Case AD1			
component	F-rule	P-rule	
AC1	$c_1^{\rm CH} = c_2^{\rm CH}$	$\frac{\dot{C}_{2}^{\mathrm{M}}-\dot{C}_{1}^{\mathrm{M}}}{\dot{E}_{2}^{\mathrm{M}}-\dot{E}_{1}^{\mathrm{M}}}=\frac{\dot{C}_{2}^{\mathrm{T}}-\dot{C}_{1}^{\mathrm{T}}}{\dot{E}_{2}^{\mathrm{T}}-\dot{E}_{1}^{\mathrm{T}}}$	
IC1	dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}, c_2^{\text{M}} = c_3^{\text{M}}, c_2^{\text{T}} = c_3^{\text{T}}$	-	
AC2	$c_3^{\rm CH} = c_4^{\rm CH}$	$rac{\dot{C}_3^{-}-\dot{C}_4^{-}}{\dot{E}_3^{-}-\dot{E}_4^{+}}=rac{\dot{C}_3^{-}-\dot{C}_4^{-}}{\dot{E}_3^{-}-\dot{E}_4^{+}}$	
IC2	dissipative component: $c_4^{\text{CH}} = c_5^{\text{CH}}, c_4^{\text{M}} = c_5^{\text{M}}, c_4^{\text{T}} = c_5^{\text{T}}$	-	
MHE	$ \begin{split} c^{\rm CH}_{15} &= c^{\rm CH}_{17}, c^{\rm CH}_{25} = c^{\rm CH}_{27}, c^{\rm CH}_{61} = c^{\rm CH}_{62}, c^{\rm CH}_{20} = c^{\rm CH}_{22}, c^{\rm CH}_{6} = c^{\rm CH}_{10}, \\ c^{\rm CH}_{15} &= c^{\rm H}_{17}, c^{\rm SH}_{25} = c^{\rm M}_{27}, c^{\rm CH}_{61} = c^{\rm M}_{62}, c^{\rm M}_{20} = c^{\rm M}_{22}, c^{\rm M}_{7} = c^{\rm M}_{10}, c^{\rm T}_{15} = c^{\rm T}_{17}, \\ c^{\rm T}_{25} &= c^{\rm T}_{27}, c^{\rm T}_{61} = c^{\rm T}_{62}, c^{\rm M}_{20} = c^{\rm T}_{22} \end{split} $	-	
AD	$c_5^{\mathrm{T}} = c_6^{\mathrm{T}}, c_5^{\mathrm{M}} = c_6^{\mathrm{M}},$ -		
HE3	$c_{26}^{\text{CH}} = c_{27}^{\text{CH}}, c_{34}^{\text{CH}} = c_{35}^{\text{CH}}, c_{26}^{\text{M}} = c_{27}^{\text{M}}, c_{34}^{\text{M}} = c_{35}^{\text{M}}, c_{34}^{\text{T}} = c_{35}^{\text{T}}$	-	
NC5	$c_{18}^{\rm CH} = c_{17}^{\rm CH}$	$rac{C_{18}^{\mathrm{m}}-C_{17}^{\mathrm{m}}}{E_{18}^{\mathrm{m}}-E_{17}^{\mathrm{m}}}=rac{C_{18}^{\mathrm{m}}-C_{17}^{\mathrm{m}}}{E_{18}^{\mathrm{m}}-E_{17}^{\mathrm{m}}}$	
OC	$c_{23}^{\rm CH} = c_{22}^{\rm CH}$	$\frac{C_{23}^{en} - C_{23}^{en}}{E_{23}^{en} - E_{23}^{en}} = \frac{C_{23}^{en} - C_{22}^{en}}{E_{12}^{en} - E_{12}^{en}}$	
HPC	$c_{65}^{\mathrm{T}} = c_{66}^{\mathrm{T}}, c_{65}^{\mathrm{T}} = c_{52}^{\mathrm{T}}, c_{65}^{\mathrm{M}} = c_{11}^{\mathrm{M}}$	$\frac{\frac{m_{66} \cdot (e_{66}^{\text{CH}} \cdot e_{66}^{\text{CH}} - e_{65}^{\text{CH}} \cdot e_{65}^{\text{CH}})}{m_{66} \cdot (e_{66}^{\text{CH}} - e_{65}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{66} \cdot (e_{66}^{\text{CH}} - e_{65}^{\text{CH}} \cdot e_{55}^{\text{CH}})}{m_{66} \cdot (e_{66}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{52} \cdot (e_{52}^{\text{CH}} - e_{55}^{\text{CH}} + e_{55}^{\text{CH}})}{m_{66} \cdot (e_{66}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{52} \cdot (e_{52}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{51} \cdot (e_{51}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{11} \cdot (e_{11}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}, \frac{\frac{m_{66} \cdot (e_{66}^{\text{CH}} - e_{65}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{66} \cdot (e_{66}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{51} \cdot (e_{51}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{11} \cdot (e_{11}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}, \frac{\frac{m_{66} \cdot (e_{66}^{\text{CH}} - e_{65}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{66} \cdot (e_{66}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})}} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{\frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})} = \frac{m_{50} \cdot (e_{50}^{\text{CH}} - e_{55}^{\text{CH}})}{m_{50} \cdot (e_{50}^{\text{CH}} - e_$	
LPC	$c_{64}^{\rm T} = c_{25}^{\rm T}, c_{64}^{\rm T} = c_{15}^{\rm T}, c_{64}^{\rm CH} = c_{25}^{\rm CH}$	$\frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H} - e_{14}^{H} - e_{14}^{H})}{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}, \frac{\frac{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}{m_{15} \cdot (e_{15}^{H} - e_{14}^{H})}}$	
HE2	$ \begin{split} c^{\rm CH}_{41} &= c^{\rm CH}_{46}, c^{\rm CH}_{43} = c^{\rm CH}_{44}, c^{\rm CH}_{30} = c^{\rm CH}_{31}, c^{\rm M}_{41} = c^{\rm M}_{46}, c^{\rm M}_{43} = c^{\rm M}_{44}, \\ c^{\rm M}_{30} &= c^{\rm M}_{31}, c^{\rm T}_{43} = c^{\rm T}_{44}, c^{\rm M}_{30} = c^{\rm T}_{31} \end{split} $	-	
EXP2	$c_{42}^{\rm CH} = c_{43}^{\rm CH}, c_{42}^{\rm M} = c_{43}^{\rm M}$	$rac{\dot{C}_{43}^{-}-\dot{C}_{42}^{-}}{E_{43}^{-}-\dot{E}_{42}^{-}}=rac{W_{\mathrm{EXP2}}}{W_{\mathrm{EXP2}}}$	

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
NC1	$c_{34}^{\rm CH}=c_{33}^{\rm CH}$	$rac{C_{34}^{\mathrm{M}}-C_{33}^{\mathrm{M}}}{\dot{E}_{34}^{\mathrm{M}}-\dot{E}_{33}^{\mathrm{M}}}=rac{C_{34}^{\mathrm{T}}-C_{33}^{\mathrm{T}}}{\dot{E}_{34}^{\mathrm{T}}-\dot{E}_{33}^{\mathrm{T}}}$
NC2	$c_{36}^{\rm CH}=c_{38}^{\rm CH}$	$\frac{\dot{C}_{38}^{M} - \dot{C}_{36}^{M}}{\dot{E}_{38}^{M} - \dot{E}_{36}^{M}} = \frac{\dot{C}_{38}^{T} - \dot{C}_{36}^{T}}{\dot{E}_{38}^{T} - \dot{E}_{36}^{T}}$
NC3	$c_{39}^{ m CH}=c_{38}^{ m CH}$	$\frac{\frac{\dot{C}_{39}^{\rm M} - \dot{C}_{38}^{\rm M}}{\dot{E}_{39}^{\rm M} - \dot{E}_{38}^{\rm M}}}{\dot{E}_{39}^{\rm M} - \dot{E}_{38}^{\rm M}} = \frac{\dot{C}_{39}^{\rm T} - \dot{C}_{38}^{\rm T}}{\dot{E}_{39}^{\rm T} - \dot{E}_{38}^{\rm T}}$
HE1	$c_{39}^{\text{CH}} = c_{40}^{\text{CH}}, c_{32}^{\text{CH}} = c_{33}^{\text{CH}}, c_{39}^{\text{M}} = c_{40}^{\text{M}}, c_{32}^{\text{M}} = c_{33}^{\text{M}}$	$c_{40}^{\mathrm{T}} = c_{33}^{\mathrm{T}}$
TV3	$c_{46}^{\rm CH}=c_{49}^{\rm CH},c_{46}^{\rm M}=c_{49}^{\rm M}$	-
TV4	$c_{59}^{\rm CH} = c_{29}^{\rm CH}, c_{59}^{\rm M} = c_{29}^{\rm M}$	-
ICO	dissipative component: $c_{23}^{CH} = c_{24}^{CH}, c_{23}^{M} = c_{24}^{M}, c_{23}^{T} = c_{24}^{T}$	-
ICN	dissipative component: $c_{19}^{\text{CH}} = c_{28}^{\text{CH}}, c_{19}^{\text{M}} = c_{28}^{\text{M}}, c_{19}^{\text{T}} = c_{28}^{\text{T}}$	-
TV1	$c_{56}^{\rm CH} = c_{57}^{\rm CH}, c_{56}^{\rm M} = c_{57}^{\rm M}$	-
TV6	$c_{52}^{\rm CH} = c_{53}^{\rm CH}, c_{52}^{\rm M} = c_{53}^{\rm M}$	-
TV5	$c_{50}^{\rm CH} = c_{51}^{\rm CH}, c_{50}^{\rm M} = c_{51}^{\rm M}$	
TV2	$c_{11}^{\rm CH} = c_{13}^{\rm CH}, c_{11}^{\rm M} = c_{13}^{\rm M}$	-
CDREB	$c_{64}^{\rm CH} = c_{65}^{\rm CH}, c_{68}^{\rm CH} = c_{69}^{\rm CH}, c_{64}^{\rm M} = c_{65}^{\rm M}, c_{68}^{\rm M} = c_{69}^{\rm M}, c_{68}^{\rm T} = c_{69}^{\rm T}$	-
PMHPC	$c_{61}^{\mathrm{T}} = rac{C_{58}^{\mathrm{T}} + C_{66}^{\mathrm{T}} + C_{10}^{\mathrm{T}}}{E_{61}^{\mathrm{T}}}, c_{61}^{\mathrm{M}} = rac{C_{58}^{\mathrm{M}} + C_{64}^{\mathrm{M}} + C_{10}^{\mathrm{M}}}{E_{61}^{\mathrm{M}}}$	-
PMLPC	$c_{60}^{\mathrm{T}} = rac{\dot{c}_{13}^{\mathrm{T}} + \dot{c}_{51}^{\mathrm{T}} + \dot{c}_{53}^{\mathrm{T}} + \dot{c}_{16}^{\mathrm{T}} + \dot{c}_{57}^{\mathrm{T}} + \dot{c}_{70}^{\mathrm{T}}}{\dot{k}_{50}^{\mathrm{T}}},$	-
	$c_{60}^{\rm M} = \frac{\dot{c}_{13}^{\rm M} + \dot{c}_{51}^{\rm M} + \dot{c}_{33}^{\rm M} + \dot{c}_{16}^{\rm M} + \dot{c}_{57}^{\rm M} + \dot{c}_{70}^{\rm M}}{\dot{E}_{61}^{\rm M}}$	
LNGP	$c_{60}^{\rm CH} = c_{61}^{\rm CH}, c_{60}^{\rm T} = c_{61}^{\rm T}$	
HE4	dissipative component: $c_{62}^{CH} = c_{63}^{CH}, c_{35}^{CH} = c_{36}^{CH}, c_{18}^{CH} = c_{19}^{CH}, c_{62}^{CH} = c_{63}^{CH}, c_{35}^{CH} = c_{36}^{CH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{35}^{TH} = c_{36}^{TH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{35}^{TH} = c_{36}^{TH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{35}^{TH} = c_{36}^{TH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{35}^{TH} = c_{36}^{TH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{18}^{TH} = c_{19}^{TH}, c_{62}^{TH} = c_{63}^{TH}, c_{18}^{TH} = c_{18}^{TH}, c_{18}^{TH} = c_{18}^{T$	-

Table B.11: Definition of the auxiliary equations (F and P rule), Case AD2		
component	F-rule	P-rule
AC1	$c_1^{\rm CH} = c_2^{\rm CH}$	$\frac{\dot{c}_{2}^{N}-\dot{c}_{1}^{M}}{E_{2}^{N}-\dot{E}_{1}^{M}}=\frac{\dot{c}_{2}^{T}-\dot{c}_{1}^{T}}{E_{2}^{T}-E_{1}^{T}}$
IC1	dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}, c_2^{\text{M}} = c_3^{\text{M}}, c_2^{\text{T}} = c_3^{\text{T}}, c_{43}^{\text{CH}} = c_{44}^{\text{CH}}, c_{43}^{\text{M}} = c_{44}^{\text{M}}, c_{43}^{\text{T}} = c_{44}^{\text{T}}$	-
AD	$c_3^{\mathrm{T}} = c_5^{\mathrm{T}}, c_3^{\mathrm{M}} = c_5^{\mathrm{M}},$ -	
IC2	$c_5^{\rm CH} = c_6^{\rm CH}, c_5^{\rm M} = c_6^{\rm M}, c_{44}^{\rm CH} = c_{45}^{\rm CH}, c_{44}^{\rm M} = c_{45}^{\rm M}, c_{44}^{\rm T} = c_{45}^{\rm T}$	-
AC2	$c_6^{\rm CH} = c_7^{\rm CH}$	$rac{C_7^{\rm N}-C_6^{\rm M}}{E_7^{\rm N}-E_6^{\rm M}}=rac{\dot{C}_7^{\rm T}}{E_7^{\rm T}}$
IC5	$c_7^{\rm CH} = c_8^{\rm CH}, c_7^{\rm M} = c_8^{\rm M}, c_{45}^{\rm CH} = c_{46}^{\rm CH}, c_{45}^{\rm M} = c_{46}^{\rm M}, c_{45}^{\rm T} = c_{46}^{\rm T}$	-
AC3	$c_8^{\rm CH}=c_9^{\rm CH}$	$rac{\dot{C}_{9}^{0}-\dot{C}_{8}^{M}}{\dot{E}_{9}^{0}-\dot{E}_{8}^{M}}=rac{\dot{C}_{9}^{0}}{\dot{E}_{9}^{1}}$
MHE	$ \begin{split} c^{\rm CH}_{15} &= c^{\rm CH}_{18}, c^{\rm CH}_{25} = c^{\rm CH}_{26}, c^{\rm CH}_{48} = c^{\rm CH}_{49}, c^{\rm CH}_{20} = c^{\rm CH}_{22}, c^{\rm CH}_{9} = c^{\rm CH}_{10}, \\ c^{\rm CH}_{15} &= c^{\rm R}_{18}, c^{\rm SH}_{25} = c^{\rm SH}_{26}, c^{\rm AH}_{48} = c^{\rm AH}_{49}, c^{\rm SH}_{20} = c^{\rm M}_{22}, c^{\rm M}_{9} = c^{\rm M}_{10}, c^{\rm T}_{15} = c^{\rm T}_{18}, \\ c^{\rm T}_{25} &= c^{\rm T}_{26}, c^{\rm T}_{48} = c^{\rm T}_{49}, c^{\rm T}_{20} = c^{\rm T}_{22} \end{split} $	$c_{10}^{\mathrm{T}} = c_{26}^{\mathrm{T}}$
HE3	$c_{26}^{\text{CH}} = c_{27}^{\text{CH}}, c_{19}^{\text{CH}} = c_{21}^{\text{CH}}, c_{19}^{\text{M}} = c_{21}^{\text{M}}, c_{26}^{\text{M}} = c_{27}^{\text{M}}, c_{19}^{\text{T}} = c_{21}^{\text{T}}$	-
NC5	$c_{19}^{\rm CH} = c_{18}^{\rm CH}$	$\frac{\dot{C}_{19}^{\rm H}-\dot{C}_{18}^{\rm H}}{\dot{E}_{19}^{\rm H}-\dot{E}_{18}^{\rm H}}=\frac{\dot{C}_{19}^{\rm H}-\dot{C}_{18}^{\rm H}}{\dot{E}_{19}^{\rm H}-\dot{E}_{18}^{\rm H}}$
OC	$c_{22}^{\rm CH} = c_{23}^{\rm CH}$	$rac{C_{23}^{\rm M}-C_{23}^{\rm M}}{E_{23}^{\rm M}-E_{22}^{\rm M}}=rac{C_{23}^{\rm T}-C_{22}^{\rm T}}{E_{23}^{\rm T}-E_{22}^{\rm T}}$

HPC $c_{12}^{T} = c_{13}^{T}, c_{13}^{T} = c_{12}^{T}, c_{23}^{T} = c_{11}^{T}$ $\frac{\theta_{24} - c_{21}^{T} - c_{21}^{T} - c_{12}^{T} - c_$	component	$\dot{E}_{\mathrm{F},k}$	Ė _{P,k}
$\frac{\frac{1}{10} \frac{1}{10}	HPC LPC	$c_{63}^{\mathrm{T}} = c_{64}^{\mathrm{T}}, c_{63}^{\mathrm{T}} = c_{52}^{\mathrm{T}}, c_{63}^{\mathrm{M}} = c_{11}^{\mathrm{M}}$ $c_{62}^{\mathrm{T}} = c_{25}^{\mathrm{T}}, c_{62}^{\mathrm{T}} = c_{15}^{\mathrm{T}}, c_{62}^{\mathrm{CH}} = c_{25}^{\mathrm{CH}}$	$\begin{aligned} \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{63}^{CH} - c_{63}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} &= \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{63}^{CH} - c_{63}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)}{\dot{m}_{11} \left(c_{11}^{CH} - c_{14}^{CH} - c_{64}^{CH} - c_{63}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{63}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{63}^{CH}\right)}{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{63}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{63}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{64} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{65} \left(c_{64}^{CH} - c_{64}^{CH} - c_{64}^{CH}\right)} \\ \frac{\dot{m}_{55} \left(c_{15}^{CH} - c_{64}$
NC1 $c_{31}^{CH} = c_{32}^{CH}, c_{31}^{T} = c_{32}^{CH}$ -NC2 $c_{32}^{CH} = c_{33}^{CH}$ $\frac{c_{33}^{M} - c_{32}^{M}}{E_{33}^{M} - E_{32}^{M}} = \frac{c_{13}^{T}}{E_{33}^{T}}$ TV3 $c_{34}^{CH} = c_{37}^{CH}, c_{34}^{M} = c_{37}^{M}$ -TV4 $c_{34}^{CH} = c_{29}^{CH}, c_{38}^{M} = c_{29}^{M}$ -IC0dissipative component: $c_{24}^{CH} = c_{28}^{CH}, c_{24}^{M} = c_{28}^{M}, c_{14}^{T} = c_{18}^{T}$ -ICNdissipative component: $c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T}$ -TV1 $c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M}$ -	HE2	$c_{41}^{\text{CH}} = c_{42}^{\text{CH}}, c_{33}^{\text{CH}} = c_{34}^{\text{CH}}, c_{30}^{\text{CH}} = c_{31}^{\text{CH}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{30}^{\text{M}} = c_{31}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{30}^{\text{M}} = c_{31}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{34}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{34}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{34}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{42}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^{\text{M}}, c_{33}^{\text{M}} = c_{42}^{\text{M}}, c_{41}^{\text{M}} = c_{42}^$	$\frac{m_{15} \cdot (e_{15}^{\rm M} - e_{62}^{\rm M})}{\dot{m}_{68} \cdot (e_{68}^{\rm CH} - e_{62}^{\rm CH})} = \frac{m_{68} \cdot (e_{68}^{\rm CH} - e_{62}^{\rm CH})}{\dot{m}_{68} \cdot (e_{68}^{\rm CH} - e_{62}^{\rm CH})}$
NC2 $c_{33}^{CH} = c_{33}^{CH}$ $c_{33}^{CH} - c_{32}^{CH} = c_{33}^{T}$ TV3 $c_{34}^{CH} = c_{37}^{CH}, c_{34}^{M} = c_{37}^{M}$ -TV4 $c_{38}^{CH} = c_{29}^{CH}, c_{38}^{M} = c_{29}^{M}$ -IC0dissipative component: $c_{24}^{CH} = c_{28}^{CH}, c_{24}^{M} = c_{28}^{M}, c_{24}^{T} = c_{28}^{T}$ -ICNdissipative component: $c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T}$ -TV1 $c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M}$ -	NC1	$c_{31}^{\text{CH}} = c_{32}^{\text{CH}}, c_{31}^{\text{CH}} = c_{32}^{\text{CH}}$	<u>-</u>
$c_{33}^{CH} = c_{37}^{CH}, c_{34}^{M} = c_{37}^{M} \qquad -$ $TV4 \qquad c_{38}^{CH} = c_{29}^{CH}, c_{38}^{M} = c_{29}^{M} \qquad -$ $IC0 \qquad \text{dissipative component: } c_{24}^{CH} = c_{28}^{CH}, c_{24}^{M} = c_{28}^{M}, c_{24}^{T} = c_{28}^{T} \qquad -$ $ICN \qquad \text{dissipative component: } c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T} \qquad -$ $TV1 \qquad c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M} \qquad -$	NC2	$c_{32}^{\text{CH}} = c_{33}^{\text{CH}}$	$rac{\dot{c}_{33}^{M}-\dot{c}_{23}^{M}}{c_{M}^{M}-c_{M}^{M}}=rac{\dot{c}_{33}^{T}}{c_{11}^{M}-c_{11}^{M}}$
TV4 $c_{38}^{CH} = c_{29}^{CH}, c_{38}^{M} = c_{29}^{M}$ - IC0 dissipative component: $c_{24}^{CH} = c_{28}^{CH}, c_{24}^{M} = c_{28}^{M}, c_{24}^{T} = c_{28}^{T}$ - ICN dissipative component: $c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T}$ - TV1 $c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M}$ -	TV3	$c_{34}^{ m CH}=c_{37}^{ m CH}, c_{34}^{ m M}=c_{37}^{ m M}$	-
ICO dissipative component: $c_{24}^{CH} = c_{28}^{CH}$, $c_{24}^{M} = c_{28}^{M}$, $c_{14}^{T} = c_{28}^{T}$ - ICN dissipative component: $c_{35}^{CH} = c_{36}^{CH}$, $c_{35}^{M} = c_{36}^{M}$, $c_{35}^{T} = c_{36}^{T}$ - TV1 $c_{56}^{CH} = c_{57}^{CH}$, $c_{56}^{M} = c_{57}^{M}$ -	TV4	$c_{38}^{ m CH}=c_{29}^{ m CH},c_{38}^{ m M}=c_{29}^{ m M}$	-
ICNdissipative component: $c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T}$ -TV1 $c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M}$ -	ICO	dissipative component: $c_{24}^{CH} = c_{28}^{CH}, c_{24}^{M} = c_{28}^{M}, c_{24}^{T} = c_{28}^{T}$	-
TV1 $c_{56}^{CH} = c_{57}^{CH}, c_{56}^{M} = c_{57}^{M}$	ICN	dissipative component: $c_{35}^{CH} = c_{36}^{CH}, c_{35}^{M} = c_{36}^{M}, c_{35}^{T} = c_{36}^{T}$	-
	TV1	$c_{56}^{\rm CH} = c_{57}^{\rm CH}$, $c_{56}^{\rm M} = c_{57}^{\rm M}$	-

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathrm{P},k}$
TV6	$c_{52}^{\rm CH} = c_{53}^{\rm CH}, c_{52}^{\rm M} = c_{53}^{\rm M}$	-
TV5	$c_{50}^{\rm CH} = c_{51}^{\rm CH}, c_{50}^{\rm M} = c_{51}^{\rm M}$	
TV2	$c_{11}^{\rm CH} = c_{13}^{\rm CH}, c_{11}^{\rm M} = c_{13}^{\rm M}$	-
CDREB	$c^{\rm CH}_{65} = c^{\rm CH}_{66}, c^{\rm CH}_{69} = c^{\rm CH}_{70}, c^{\rm M}_{65} = c^{\rm M}_{66}, c^{\rm M}_{69} = c^{\rm M}_{70}, c^{\rm T}_{69} = c^{\rm T}_{70}$	-
PMHPC	$c_{63}^{\mathrm{T}} = rac{C_{58}^{\mathrm{T}} + C_{67}^{\mathrm{T}} + C_{10}^{\mathrm{T}}}{E_{63}^{\mathrm{T}}}, c_{63}^{\mathrm{M}} = rac{C_{58}^{\mathrm{M}} + C_{67}^{\mathrm{M}} + C_{10}^{\mathrm{M}}}{E_{63}^{\mathrm{M}}}$	-
PMLPC	$c_{62}^{\mathrm{T}} = \frac{\dot{c}_{13}^{\mathrm{T}} + \dot{c}_{51}^{\mathrm{T}} + \dot{c}_{53}^{\mathrm{T}} + \dot{c}_{57}^{\mathrm{T}} + \dot{c}_{71}^{\mathrm{T}}}{\dot{E}_{57}^{\mathrm{T}} + \dot{c}_{71}^{\mathrm{T}}},$	-
	$c_{62}^{\rm M} = \frac{\dot{c}_{13}^{\rm M} + \dot{c}_{51}^{\rm M} + \dot{c}_{53}^{\rm M} + \dot{c}_{129}^{\rm M} + \dot{c}_{57}^{\rm M} + \dot{c}_{71}^{\rm M}}{\dot{k}_{62}^{\rm M}}$	
HE4	dissipative component: $c_{46}^{CH} = c_{47}^{CH}$, $c_{21}^{CH} = c_{35}^{CH}$, $c_{23}^{CH} = c_{24}^{CH}$,	-
	$c_{46}^{M} = c_{47}^{M}, c_{21}^{M} = c_{35}^{M}, c_{23}^{M} = c_{24}^{M}, c_{46}^{T} = c_{47}^{T}, c_{21}^{T} = c_{35}^{T}, c_{23}^{T} = c_{24}^{T},$	
LNGP	$c_{39}^{\rm CH} = c_{40}^{\rm CH}, c_{39}^{\rm T} = c_{40}^{\rm T}$	

Table B.12: Definition of the auxiliary equations (F and P rule), Case AD2S			
F-rule	P-rule		
$c_1^{\rm CH}=c_2^{\rm CH}$	$rac{\dot{C}_2^{\rm M}-\dot{C}_1^{\rm M}}{E_2^{\rm M}-E_1^{\rm M}}=rac{\dot{C}_2^{\rm T}-\dot{C}_1^{\rm T}}{E_2^{\rm T}-\dot{E}_1^{\rm T}}$		
dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}, c_2^{\text{M}} = c_3^{\text{M}}, c_2^{\text{T}} = c_3^{\text{T}}, c_{47}^{\text{T}} = 0, c_{46}^{\text{M}} = c_{47}^{\text{M}}, c_{46}^{\text{T}} = c_{47}^{\text{T}}$	-		
$c_3^{\rm T} = c_5^{\rm T}, c_3^{\rm M} = c_5^{\rm M},$ -			
$c_5^{\rm CH} = c_6^{\rm CH}, c_5^{\rm M} = c_6^{\rm M}, c_{45}^{\rm CH} = 0, c_{44}^{\rm M} = c_{45}^{\rm M}, c_{44}^{\rm T} = c_{45}^{\rm T}$	-		
$c_6^{\rm CH}=c_7^{\rm CH}$	$\frac{\frac{C_1^M - \mathcal{C}_0^M}{E_1^M - \mathcal{E}_0^M}}{E_1^M - \mathcal{E}_1^M} = \frac{\dot{C}_1^T}{E_1^T}$		
$c_7^{\text{CH}} = c_8^{\text{CH}}, c_7^{\text{M}} = c_8^{\text{M}}, c_{46}^{\text{CH}} = 0, c_{45}^{\text{M}} = c_{46}^{\text{M}}, c_{45}^{\text{T}} = c_{46}^{\text{T}}$	-		
$c_8^{\rm CH}=c_9^{\rm CH}$	$rac{\dot{C}_{9}^{0}-\dot{C}_{8}^{0}}{\dot{E}_{9}^{0}-\dot{E}_{8}^{0}}=rac{\dot{C}_{9}^{0}}{\dot{E}_{9}^{1}}$		
$\begin{split} c^{\rm CH}_{15} &= c^{\rm CH}_{16}, c^{\rm CH}_{25} = c^{\rm CH}_{26}, c^{\rm CH}_{30} = c^{\rm CH}_{31}, c^{\rm CH}_{20} = c^{\rm CH}_{21}, c^{\rm CH}_{9} = c^{\rm CH}_{10}, \\ c^{\rm H}_{15} &= c^{\rm H}_{16}, c^{\rm M}_{25} = c^{\rm M}_{26}, c^{\rm M}_{30} = c^{\rm M}_{31}, c^{\rm M}_{20} = c^{\rm M}_{22}, c^{\rm M}_{9} = c^{\rm M}_{10}, c^{\rm H}_{15} = c^{\rm H}_{16}, \\ c^{\rm T}_{25} &= c^{\rm T}_{26}, c^{\rm T}_{30} = c^{\rm T}_{31}, c^{\rm T}_{20} = c^{\rm T}_{22} \end{split}$	$c_{10}^{\mathrm{T}} = c_{26}^{\mathrm{T}}$		
$c_{26}^{\mathrm{CH}} = c_{27}^{\mathrm{CH}}, c_{17}^{\mathrm{CH}} = c_{18}^{\mathrm{CH}}, c_{17}^{\mathrm{M}} = c_{18}^{\mathrm{M}}, c_{26}^{\mathrm{M}} = c_{27}^{\mathrm{M}}, c_{17}^{\mathrm{T}} = c_{18}^{\mathrm{T}}$	-		
$c_{16}^{\rm CH}=c_{17}^{\rm CH}$	$\frac{C_{17}^{\rm H} - C_{16}^{\rm H}}{E_{17}^{\rm H} - E_{16}^{\rm H}} = \frac{C_{17}^{\rm T} - C_{16}^{\rm H}}{E_{17}^{\rm T} - E_{16}^{\rm H}}$		
$c_{21}^{\rm CH} = c_{22}^{\rm CH}$	$\frac{C_{22}^{\rm M} - C_{21}^{\rm M}}{E_{22}^{\rm M} - \tilde{E}_{21}^{\rm M}} = \frac{C_{22}^{\rm T} - C_{21}^{\rm T}}{\tilde{E}_{22}^{\rm T} - \tilde{E}_{21}^{\rm T}}$		

component

AC1 IC1

AD IC2 AC2 IC5 AC3 MHE

HE3

NC5

OC

HPC	$c_{61}^{T} = c_{62}^{T}, c_{61}^{T} = c_{52}^{T}, c_{61}^{M} = c_{11}^{M}$	$\frac{\dot{m}_{62} \cdot (e_{62}^{\mathrm{CH}} \cdot c_{62}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}} \cdot c_{61}^{\mathrm{CH}})}{\dot{m}_{62} \cdot (e_{62}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}} - e_{61}^{\mathrm{CH}})} = \frac{\dot{m}_{62} \cdot (e_{62}^{\mathrm{M}} \cdot c_{62}^{\mathrm{M}} - e_{61}^{\mathrm{M}} \cdot c_{61}^{\mathrm{M}})}{\dot{m}_{62} \cdot (e_{62}^{\mathrm{M}} - e_{61}^{\mathrm{M}})},$
		$\frac{\dot{m}_{62} \cdot (e_{62}^{\text{CH}} \cdot c_{62}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})}{\dot{m}_{52} \cdot (e_{52}^{\text{CH}} \cdot c_{52}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})} = \frac{\dot{m}_{52} \cdot (e_{52}^{\text{CH}} \cdot c_{52}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})}{\dot{m}_{52} \cdot (e_{52}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})},$
		$\frac{m_{62} \cdot (e_{62}^{\text{CH}} - e_{61}^{\text{CH}})}{m_{62} \cdot (e_{62}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}})} = \frac{m_{52} \cdot (e_{52}^{\text{CH}} - e_{61}^{\text{CH}})}{m_{11} \cdot (e_{11}^{\text{CH}} - e_{11}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}})}$
		$m_{62} \cdot (e_{62}^{CH} - e_{61}^{CH}) - m_{11} \cdot (e_{11}^{CH} - e_{61}^{CH})$, $m_{62} \cdot (e_{62}^{CH} - e_{61}^{CH} - e_{61}^{CH}) - m_{62} \cdot (e_{61}^{T} - e_{61}^{T} - e_{61}^{T} - e_{61}^{T})$
		$\frac{\frac{m_{62}\cdot(e_{62}-e_{61}-e_{61})}{m_{62}\cdot(e_{62}-e_{61})}}{\frac{m_{50}\cdot(e_{50}-e_{50}-e_{61}-e_{61})}{m_{50}\cdot(e_{50}-e_{61})},$
		$\frac{\dot{m}_{62} \cdot (e_{62}^{\text{CH}} \cdot c_{61}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})}{\dot{m}_{11} \cdot (e_{11}^{\text{T}} \cdot e_{11}^{\text{T}} - e_{61}^{\text{T}} \cdot c_{61}^{\text{T}})} = \frac{\dot{m}_{11} \cdot (e_{11}^{\text{T}} \cdot e_{11}^{\text{T}} - e_{61}^{\text{T}} \cdot c_{61}^{\text{T}})}{\dot{m}_{11} \cdot (e_{11}^{\text{T}} - e_{11}^{\text{T}} - e_{61}^{\text{T}} \cdot c_{61}^{\text{T}})},$
		$m_{62} \cdot (e_{62}^{\text{CH}} - e_{61}^{\text{CH}}) = m_{11} \cdot (e_{11}^{-} - e_{61}^{\text{CH}})$ $m_{61} \cdot (e_{50}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}}) = m_{61} \cdot (e_{50}^{\text{CH}} - e_{50}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}})$
		$\frac{1}{m_{62} \cdot (e_{62}^{CH} - e_{61}^{CH})} - \frac{1}{m_{61} \cdot (e_{50}^{CH} - e_{61}^{CH})},$
		$\frac{\frac{m_{62} \cdot (e_{62} \cdot e_{62} - e_{61} \cdot e_{61})}{m_{62} \cdot (e_{62}^{CH} - e_{61}^{CH})} = \frac{\frac{m_{52} \cdot (e_{52} \cdot e_{52} - e_{61} \cdot e_{61})}{m_{52} \cdot (e_{52}^{M} - e_{61}^{M})},$
		$\frac{\dot{m}_{62} \cdot (e_{62}^{\text{CH}} \cdot c_{62}^{\text{CH}} - e_{61}^{\text{CH}} \cdot c_{61}^{\text{CH}})}{\dot{m}_{51} \cdot (e_{51}^{\text{CH}} - e_{61}^{\text{CH}} - e_{61}^{\text{CH}})} = \frac{\dot{m}_{50} \cdot (e_{50}^{\text{M}} \cdot e_{50}^{\text{M}} - e_{61}^{\text{M}} \cdot e_{61}^{\text{M}})}{\dot{m}_{52} \cdot (e_{50}^{\text{M}} - e_{61}^{\text{M}} - e_{61}^{\text{M}})}$
LDC	T T T T CH CH	$\begin{array}{cccc} m_{62} \cdot (e_{62} - e_{61}) & m_{50} \cdot (e_{50} - e_{61}) \\ m_{15} \cdot (e_{15}^{\rm M} \cdot c_{15}^{\rm M} - e_{60}^{\rm M} \cdot c_{60}^{\rm M}) & m_{15} \cdot (e_{15}^{\rm CH} \cdot c_{15}^{\rm CH} - e_{60}^{\rm CH} \cdot c_{60}^{\rm CH}) \end{array}$
LFC	$c_{62} - c_{25}, c_{60} - c_{15}, c_{60} - c_{25}$	$\frac{\dot{m}_{15} \cdot (e_{15}^{\mathrm{M}} - e_{60}^{\mathrm{M}})}{(M - M - M - M)} = \frac{\dot{m}_{15} \cdot (e_{15}^{\mathrm{CH}} - e_{60}^{\mathrm{CH}})}{(M - M - M - M)},$
		$\frac{\frac{m_{15} \cdot (e_{15} \cdot c_{15} - e_{60} \cdot c_{60})}{m_{15} \cdot (e_{15}^{\rm M} - e_{60}^{\rm M})} = \frac{\frac{m_{25} \cdot (e_{25} \cdot e_{25} - e_{60} \cdot c_{60})}{m_{25} \cdot (e_{25}^{\rm M} - e_{60}^{\rm M})},$
		$\frac{\dot{m}_{15} \cdot (e_{15}^{M} \cdot e_{15}^{M} - e_{60}^{M} \cdot e_{60}^{M})}{\dot{m}_{e_{1}} \cdot (e_{15}^{M} - e_{10}^{M} - e_{10}^{M})} = \frac{\dot{m}_{66} \cdot (e_{15}^{K} \cdot e_{16}^{T} - e_{10}^{K} \cdot e_{10}^{T})}{\dot{m}_{e_{1}} \cdot (e_{15}^{T} - e_{10}^{T} - e_{10}^{T})},$
		$\frac{m_{15} \cdot (e_{15} - e_{60})}{m_{15} \cdot (e_{15}^{M} - e_{60}^{M} \cdot e_{60}^{M})} = \frac{m_{25} \cdot (e_{66}^{M} \cdot e_{60}^{M} - e_{60}^{M} \cdot e_{60}^{M})}{m_{25} \cdot (e_{66}^{M} \cdot e_{60}^{M} - e_{60}^{M} \cdot e_{60}^{M})}$
		$\begin{array}{ccc} \dot{m}_{15} \cdot (e_{15}^{\rm M} - e_{60}^{\rm M}) & m_{66} \cdot (e_{66}^{\rm M} - e_{60}^{\rm M}) & , \\ \dot{m}_{15} \cdot (e_{15}^{\rm M} - e_{15}^{\rm M} - e_{15}^{\rm M} + e_{15}^{\rm M}) & m_{66} \cdot (e_{60}^{\rm CH} - e_{60}^{\rm CH} + e_{60}^{\rm CH}) & , \end{array}$
		$\frac{\frac{m_{15} \cdot (r_{15} - c_{60} - c_{60})}{\dot{m}_{15} \cdot (r_{15}^{\rm M} - c_{60}^{\rm M})} = \frac{\frac{m_{60} \cdot (r_{66} - c_{60} - c_{60} - c_{60})}{\dot{m}_{66} \cdot (r_{66}^{\rm CH} - r_{60}^{\rm CH})}$
HE2	$c^{\rm CH}_{40} = c^{\rm CH}_{41}, c^{\rm CH}_{34} = c^{\rm CH}_{35}, c^{\rm M}_{40} = c^{\rm M}_{41}, c^{\rm M}_{34} = c^{\rm M}_{35}, c^{\rm T}_{40} = c^{\rm T}_{41}$	-
NC1	$c_{32}^{\rm CH} = c_{33}^{\rm CH}, c_{32}^{\rm T} = c_{33}^{\rm CH}$	-
NC2	$c_{32}^{\rm CH} = c_{33}^{\rm CH}$	$\frac{\frac{C_{33}^{\mathrm{M}} - C_{32}^{\mathrm{M}}}{E_{33}^{\mathrm{M}} - E_{32}^{\mathrm{M}}} = \frac{\frac{C_{33}^{\mathrm{T}}}{E_{32}^{\mathrm{T}}}$
TV3	$c_{35}^{\rm CH} = c_{36}^{\rm CH}, c_{35}^{\rm M} = c_{36}^{\rm M}$	-
TV4	$c_{37}^{\rm CH} = c_{29}^{\rm CH}, c_{37}^{\rm M} = c_{29}^{\rm M}$	-
ICO	dissipative component: $c_{23}^{CH} = c_{24}^{CH}$, $c_{23}^{M} = c_{24}^{M}$, $c_{23}^{T} = c_{24}^{T}$	-
ICN	dissipative component: $c_{19}^{CH} = c_{28}^{CH}$, $c_{19}^{M} = c_{28}^{M}$, $c_{29}^{T} = c_{28}^{T}$	-
TV1	$c_{56}^{\rm CH} = c_{57}^{\rm CH}, c_{56}^{\rm M} = c_{57}^{\rm M}$	-
TV6	$c_{52}^{\rm CH} = c_{53}^{\rm CH}$, $c_{52}^{\rm M} = c_{53}^{\rm M}$	-

component	$\dot{E}_{\mathrm{F},k}$
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$\dot{E}_{\mathrm{P},k}$

TV5	$c_{50}^{\rm CH} = c_{51}^{\rm CH}, c_{50}^{\rm M} = c_{51}^{\rm M}$	
TV2	$c_{11}^{\rm CH} = c_{13}^{\rm CH}, c_{11}^{\rm M} = c_{13}^{\rm M}$	-
CDREB	$c^{\rm CH}_{63} = c^{\rm CH}_{64}, c^{\rm CH}_{67} = c^{\rm CH}_{68}, c^{\rm M}_{63} = c^{\rm M}_{64}, c^{\rm M}_{67} = c^{\rm M}_{68}, c^{\rm T}_{67} = c^{\rm T}_{68}$	-
PMHPC	$c_{61}^{\mathrm{T}} = \frac{C_{58}^{\mathrm{T}} + C_{65}^{\mathrm{T}} + C_{10}^{\mathrm{T}}}{E_{61}^{\mathrm{T}}}, c_{61}^{\mathrm{M}} = \frac{C_{58}^{\mathrm{M}} + C_{65}^{\mathrm{M}} + C_{10}^{\mathrm{M}}}{E_{61}^{\mathrm{M}}}$	-
PMLPC	$c_{60}^{\mathrm{T}} = rac{\dot{c}_{13}^{\mathrm{T}} + \dot{c}_{51}^{\mathrm{T}} + \dot{c}_{53}^{\mathrm{T}} + \dot{c}_{29}^{\mathrm{T}} + \dot{c}_{57}^{\mathrm{T}} + \dot{c}_{69}^{\mathrm{T}}}{\dot{E}_{50}^{\mathrm{T}}},$	-
	$c^{\rm M}_{60} = \frac{\dot{c}^{\rm M}_{13} + \dot{c}^{\rm M}_{51} + \dot{c}^{\rm M}_{33} + \dot{c}^{\rm M}_{129} + \dot{c}^{\rm M}_{57} + \dot{c}^{\rm M}_{69}}{E^{\rm M}_{60}}$	
HE5	$c^{\rm CH}_{41} = c^{\rm CH}_{42}, c^{\rm CH}_{44} = 0, c^{\rm M}_{41} = c^{\rm M}_{42}, c^{\rm M}_{43} = c^{\rm M}_{44}, c^{\rm T}_{41} = c^{\rm T}_{42}$	
WP	$c^{\rm CH}_{43}=0, c^{\rm T}_{48}=c^{\rm T}_{43}$	
LNGP	$c^{\rm CH}_{39} = c^{\rm CH}_{40}, c^{\rm T}_{39} = c^{\rm T}_{40}$	
HE4	dissipative component: $c_{48}^{\text{CH}} = 0$, $c_{22}^{\text{CH}} = c_{23}^{\text{CH}}$, $c_{18}^{\text{CH}} = c_{19}^{\text{CH}}$, $c_{47}^{\text{M}} = c_{48}^{\text{M}}$, $c_{22}^{\text{M}} = c_{23}^{\text{M}}$, $c_{18}^{\text{M}} = c_{19}^{\text{H}}$, $c_{12}^{\text{T}} = c_{23}^{\text{T}}$, $c_{47}^{\text{T}} = c_{48}^{\text{T}}$,	-
component	F-rule	P-rule
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AC1	$c_1^{\rm CH} = c_2^{\rm CH}$	$\frac{\dot{c}_{2}^{v} - \dot{c}_{1}^{u}}{E_{2}^{v} - \dot{e}_{1}^{u}} = \frac{\dot{c}_{2}^{v} - \dot{c}_{1}^{v}}{E_{2}^{v} - E_{1}^{u}}$
IC1	dissipative component: $c_2^{\text{CH}} = c_3^{\text{CH}}$, $c_2^{\text{M}} = c_3^{\text{M}}$, $c_2^{\text{T}} = c_3^{\text{T}}$	-
AD	$c_3^{\rm T} = c_5^{\rm T}, c_3^{\rm M} = c_5^{\rm M}$	-
IC2	dissipative component: $c_5^{\text{CH}} = c_6^{\text{CH}}$, $c_{61}^{\text{CH}} = 0$, $c_5^{\text{M}} = c_6^{\text{M}}$, $c_{60}^{\text{M}} = c_{61}^{\text{M}}$, $c_5^{\text{T}} = c_6^{\text{T}}$, $c_{60}^{\text{T}} = c_{61}^{\text{T}}$,	-
AC2	$c_3^{ m CH}=c_4^{ m CH}$	$rac{\dot{C}_{1}^{7}}{E_{1}^{7}}=rac{C_{3}^{3}-C_{4}^{M}}{E_{3}^{M}-E_{4}^{M}}$
IC5	dissipative component: $c_7^{\text{CH}} = c_{10}^{\text{CH}}, c_{62}^{\text{CH}} = 0, c_7^{\text{M}} = c_{10}^{\text{M}}, c_{61}^{\text{M}} = c_{62}^{\text{M}}, c_7^{\text{T}} = c_{10}^{\text{T}}, c_{61}^{\text{T}} = c_{62}^{\text{T}}$	
AC3	$c_{17}^{\rm CH}=c_{18}^{\rm CH}$	$\frac{\frac{C_{17}}{E_{17}} - \frac{C_{18}}{E_{17}}}{\frac{E_{17}}{E_{18}}} = \frac{\frac{C_{17}}{E_{17}} - \frac{C_{18}}{E_{17}}}{\frac{E_{17}}{E_{18}} - \frac{E_{18}}{E_{18}}}$
MHE	$ \begin{split} c^{\rm CH}_{32} &= c^{\rm CH}_{33}, c^{\rm CH}_{18} = c^{\rm CH}_{19}, c^{\rm CH}_{12} = c^{\rm CH}_{13}, c^{\rm CH}_{14} = c^{\rm CH}_{15}, c^{\rm CH}_{35} = c^{\rm CH}_{36}, c^{\rm CH}_{37} = c^{\rm CH}_{38}, \\ c^{\rm S2}_{32} &= c^{\rm S3}_{33}, c^{\rm H}_{18} = c^{\rm M}_{19}, c^{\rm H}_{12} = c^{\rm M}_{13}, c^{\rm H}_{14} = c^{\rm M}_{15}, c^{\rm S4}_{35} = c^{\rm M}_{36}, c^{\rm S4}_{37} = c^{\rm M}_{38}, \\ \end{split} $	$c_{36}^{\mathrm{T}} = c_{38}^{\mathrm{T}}, c_{36}^{\mathrm{T}} = c_{19}^{\mathrm{T}}, c_{36}^{\mathrm{T}} = c_{13}^{\mathrm{T}}, c_{36}^{\mathrm{T}} = c_{15}^{\mathrm{T}}$
HPC	$c_{52}^{\rm T} = c_{44}^{\rm T}, c_{52}^{\rm M} = c_{21}^{\rm M}$	$\frac{\dot{m}_{44}\cdot(e_{44}^{\rm cH}\cdot e_{44}^{\rm CH}-e_{55}^{\rm CH}\cdot c_{51}^{\rm CH})}{\dot{m}_{44}\cdot(e_{44}^{\rm cH}-e_{55}^{\rm CH})} = \frac{\dot{m}_{440}\cdot(e_{44}^{\rm cH}\cdot e_{44}^{\rm cH}-e_{55}^{\rm CH}, e_{51}^{\rm CH})}{\dot{m}_{44}\cdot(e_{44}^{\rm cH}-e_{52}^{\rm CH})},$
		$\frac{m_{44}\cdot(e_{44}^{cH}-e_{52}^{cH}-e_{52}^{cH})}{m_{44}\cdot(e_{44}^{cH}-e_{52}^{cH})} = \frac{m_{21}\cdot(e_{21}^{cH}-e_{21}^{cH}-e_{52}^{cH})}{m_{21}\cdot(e_{51}^{cH}-e_{52}^{cH})}, \\ \frac{m_{44}\cdot(e_{44}^{cH}-e_{52}^{cH}-e_{52}^{cH})}{m_{44}\cdot(e_{44}^{cH}-e_{52}^{cH})} = \frac{m_{21}\cdot(e_{21}^{c}-e_{21}^{c}-e_{52}^{c}-e_{52}^{c})}{m_{21}\cdot(e_{21}^{c}-e_{52}^{c}-e_{52}^{c})}$
LPC	$c_{53}^{\text{CH}} = c_{37}^{\text{CH}}, c_{53}^{\text{T}} = c_{37}^{\text{T}}, c_{53}^{\text{T}} = c_{34}^{\text{T}}$	$=\frac{m_{48}\cdot(e_{48}^{CH}\cdot c_{48}^{CH}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{CH}-e_{53}^{CH})}=\frac{m_{34}\cdot(e_{43}^{CH}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{34}\cdot(e_{44}^{CH}-e_{53}^{CH})},\\ \frac{m_{48}\cdot(e_{48}^{CH}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{CH}-e_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}\cdot e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}\cdot e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}\cdot e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}-e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}-e_{48}^{CH}\cdot c_{53}^{CH}+e_{53}^{CH}\cdot c_{53}^{CH})}{m_{48}\cdot(e_{48}^{M}-e_{53}^{CH}\cdot c_{53}^{CH}+e_{53}^{CH}\cdot c_{53}^{CH})}=\frac{m_{48}\cdot(e_{48}^{M}-e_{48}^{CH}\cdot c_{53}^{CH}+e_{53}^{CH}\cdot c_{53}^{CH}+e_{53}^{CH}+e_{53}^{CH}\cdot c_{53}^{CH}+e_{53}^{CH}+e_{53}^{CH}\cdot c_{53}^{CH}+e_{53}^{$
		$\frac{m_{48}\cdot(e_{48}^{CH}\cdot e_{48}^{CH}-e_{53}^{CH}\cdot e_{53}^{CH})}{\dot{m}_{48}\cdot(e_{48}^{M}-e_{53}^{M})} = \frac{\dot{m}_{37}\cdot(e_{37}^{M}\cdot e_{37}^{M}-e_{33}^{M}\cdot e_{53}^{M})}{\dot{m}_{37}\cdot(e_{37}^{M}-e_{33}^{M})}, \\ \frac{\dot{m}_{48}\cdot(e_{48}^{CH}\cdot e_{48}^{CH}-e_{53}^{CH}\cdot e_{53}^{CH})}{\dot{m}_{48}\cdot(e_{48}^{M}-e_{53}^{M}-e_{53}^{M})} = \frac{\dot{m}_{34}\cdot(e_{34}^{M}-e_{34}^{M}-e_{35}^{M}\cdot e_{53}^{M})}{\dot{m}_{44}\cdot(e_{44}^{M}-e_{53}^{M})},$
		$\frac{\dot{m}_{48}\cdot(e_{48}^{\rm CH}-e_{53}^{\rm CH}-e_{53}^{\rm CH})}{\dot{m}_{48}\cdot(e_{48}^{\rm A}-e_{53}^{\rm CH})} = \frac{\dot{m}_{48}\cdot(e_{48}^{\rm A}-e_{43}^{\rm T}-e_{53}^{\rm T}-e_{53}^{\rm T})}{\dot{m}_{48}\cdot(e_{48}^{\rm A}-e_{53}^{\rm T})}$
OP	$c_{31}^{\text{CH}} = c_{30}^{\text{CH}}, c_{31}^{\text{T}} = c_{30}^{\text{T}}$	-
EXP1	$c_{15}^{\rm CH} = c_{16}^{\rm CH}, c_{15}^{\rm M} = c_{16}^{\rm M}$	$\frac{\dot{C}_{16}^{-} - \dot{C}_{15}^{T}}{\dot{E}_{16}^{+} - \dot{E}_{15}^{T}} = \frac{W_{\text{EXP1}}}{W_{\text{EXP1}}}$
ICN1	$c_{55}^{\rm CH} = c_{56}^{\rm CH}, c_{36}^{\rm CH} = c_{39}^{\rm CH}, c_{55}^{\rm M} = c_{56}^{\rm M}, c_{36}^{\rm M} = c_{39}^{\rm M}, c_{55}^{\rm T} = c_{56}^{\rm T}$	-
NC5	$c_{39}^{ m CH}=c_{40}^{ m CH}$	$rac{\dot{C}_{40}^{-}}{E_{40}^{-}} = rac{C_{40}^{-} - C_{39}^{M}}{E_{40}^{M} - \hat{E}_{39}^{M}}$

Table B.13: Definition of the auxiliary equations (F and P rule). Case BD2S

component	$\dot{E}_{\mathrm{F},k}$	$\dot{E}_{\mathbf{P},k}$	
ICN2	dissipative component: $c_{56}^{\text{CH}} = c_{57}^{\text{CH}}$, $c_{56}^{\text{M}} = c_{57}^{\text{M}}$, $c_{56}^{\text{T}} = c_{57}^{\text{T}}$, $c_{40}^{\text{CH}} = c_{41}^{\text{CH}}$, $c_{40}^{\text{M}} = c_{41}^{\text{CH}}$, $c_{40}^{\text{M}} = c_{41}^{\text{CH}}$,	-	
CDREB	$c^{\rm CH}_{49} = c^{\rm CH}_{50}, c^{\rm CH}_{45} = c^{\rm CH}_{46}, c^{\rm M}_{49} = c^{\rm M}_{50}, c^{\rm M}_{45} = c^{\rm M}_{46}, c^{\rm T}_{49} = c^{\rm T}_{50}$	-	
TV1	$c_{19}^{\rm CH} = c_{20}^{\rm CH}, c_{19}^{\rm M} = c_{20}^{\rm M}$	-	
SUB	$c_{25}^{\rm CH} = c_{26}^{\rm CH}, c_{34}^{\rm CH} = c_{35}^{\rm CH}, c_{25}^{\rm M} = c_{26}^{\rm M}, c_{34}^{\rm M} = c_{35}^{\rm M}, c_{34}^{\rm T} = c_{35}^{\rm T}$	-	
TV2	$c_{26}^{\rm CH} = c_{27}^{\rm CH}, c_{26}^{\rm M} = c_{27}^{\rm M}$	-	
TV3	$c_{21}^{\text{CH}} = c_{22}^{\text{CH}}, c_{21}^{\text{M}} = c_{22}^{\text{M}}$	-	
LNGP	$c_{54}^{\rm CH} = c_{55}^{\rm CH}, c_{54}^{\rm T} = c_{55}^{\rm T}$	-	
WP	$c_{59}^{ m CH}=0,c_{59}^{ m T}=c_{63}^{ m T}$	-	
HE5	$c_{57}^{\rm CH} = c_{58}^{\rm CH}, c_{60}^{\rm CH} = 0, c_{57}^{\rm M} = c_{58}^{\rm M}, c_{59}^{\rm M} = c_{60}^{\rm M}, c_{60}^{\rm T} = c_{58}^{\rm T}$	-	
PMHPC	$c_{52}^{\mathrm{T}} = \frac{\dot{c}_{20}^{\mathrm{T}} + \dot{c}_{13}^{\mathrm{T}} + \dot{c}_{47}^{\mathrm{T}}}{E_{7}^{\mathrm{T}}}, c_{52}^{\mathrm{M}} = \frac{\dot{c}_{20}^{\mathrm{M}} + \dot{c}_{33}^{\mathrm{M}} + \dot{c}_{47}^{\mathrm{M}}}{E_{7}^{\mathrm{M}}}$	-	
PMLPC	$c_{53}^{\mathrm{T}} = \frac{\dot{c}_{16}^{\mathrm{T}} + \dot{c}_{51}^{\mathrm{T}} + \dot{c}_{22}^{\mathrm{T}} + \dot{c}_{27}^{\mathrm{T}}}{E_{53}^{\mathrm{T}}}, c_{53}^{\mathrm{M}} = \frac{\dot{c}_{16}^{\mathrm{M}} + \dot{c}_{51}^{\mathrm{M}} + \dot{c}_{22}^{\mathrm{M}} + \dot{c}_{27}^{\mathrm{M}}}{E_{53}^{\mathrm{M}}}$	_	

Appendix B Exergy-based methods

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Appendix C Economic analysis

In the following paragraph, a detailed explanation for the estimation of the component costs is given. The estimation of the component cost was previously published in [18, 133, 135].

C.1 Estimation of the component costs

As already mentioned in Section 3.4, the component costs are estimated using costs graphs and costs correlations. The temperature, pressure, and material factors are selected according to the used literature. In general, all components where the temperature of the working fluid is higher than -29 °C are made of carbon steel. Components with a temperature lower than -29 °C are produced of stainless steel [202], because at low temperatures the deformability of carbon steel decreases and it will get rough.

The available cost data and graphs correspond to different years hence the Chemical Engineering Plant Index (CEPCI) is necessary. Table C.1 contains all used CEPCIs.

year	CEPCI
2000	394.1
2002	395.6
2004	444.2
2015	556.8

Table C.1: Chemical Engineering Plant Index for selected years [215]

Distillation column

The costs for the high- and low-pressure column are estimated in two steps. First, the costs for the empty shells are calculated which depends on the height and the diameter of the column followed by the cost of the trays which depends on the number of trays as well as on the column diameter.

Figure C.1 shows a general schematic of a distillation column with reboiler and condenser. In this figure three different heights are shown: the tray spacing (h_{tray}), the height of the sump of the column (h_{SC}), and the height of the top of the column (h_{TC}). In order to determine the height of the column, the distance between the sieve trays has to be determined. Table C.2 shows the ranges for the tray spacing according to literature. In [77] and [216], the value is explicitly given for cryogenic air separations units or cryogenic systems, respectively, thus a tray spacing of 350 mm is assumed. The height of the sump of the column (h_{SC}) and the height of the top of the column (h_{TC}) are assumed to be 1.8 m and 1.2 m, according to [171], respectively. For the calculations of the real stages within each column the tray efficiency is required. Table C.3 gives an overview of values used in literature. The values obtained from [80] and [77] are particularly for air separation units, thus an average tray efficiency of 80 % is used.

As given in Chapter 5, 54 and 96, theoretical stages are assumed for the high- and low-pressure column, respectively. The diameter of both columns is obtained from Apsen Plus [161]. In [126] a similar diameter of the column is assumed. Table C.4 gives an overview of all important assumptions and shows the results for the real number of stages and the height of the columns for all cases.



Figure C.1: General schematic of a distillation column

Table C.2: Tray spacings		Table C.3	Trav efficiencies
literature	$h_{ m tray}$ mm	literature	η_{tray}
 [77] [144] [161] [171] [216] [216] [217] 	80 - 300 305 - 915 609.6 600 200 - 900 ¹⁹ 200 - 300 ²⁰ 300 - 600	[77] [80] [170] [171] [144] [217] [219]	$ \begin{array}{r} 70 \\ 60 - 90 \\ 60 - 65 \\ 70 \\ 60 \\ 60 - 85 \\ 30 - 80 \\ 60 - 90^{21} \end{array} $
[218] [219]	610 600	[219]	10 - 20 ²²

Table C.4: Characteristics of the high- and low-pressure column

specification	unit	HPC	LPC
kind of column		sieve tray column	sieve tray column
diameter	m	Case A 1.7	Case A 1.5
ulameter	m	Case B 1.9	Case B 2.7
theoretical stages	-	54	96
tray efficiency	-	0.8	0.8
tray spacing	mm	350	350
real stages	-	68	120
height of the column	m	24	42

The values obtained for the height of the columns correspond to values available in literature. In [77], the height of high- and low-pressure column amounts to 14 to 25 m and 25 to 40 m, respectively. The height for the HPC fits to this range. The height of the LPC is slightly higher compared with data available in literature, because the LPC is simulated as a sieve tray column, while the values in literature are valid for packed columns. The sum of the heights of the HPC and LPC amounts to 69 m, which also correspond to the data available in literature. The height of the cold box varies between 15 to 60 m according to [218], or can even reach a height of 70 m [77, 220].

¹⁹in general

²⁰for cryogenic systems

²¹ for aqueous solutions

²² for absorption and stripping

Finally, the costs are estimated using cost graphs for the empty shell and the trays available in [144]. The pressure and material factor for stainless steel are also given in [144]. The bar module factor is taken from [143]. A value of 4.3 is assumed which corresponds to the bare module factor of chemical vessels. The bare module costs of the columns for the Cases A, AD1, AD2, and AD2S as well as the Cases B and BD2S are given in Tables C.5 and C.6, respectively.

LPC Unit HPC height 24 42 m diameter 1.7 1.5 m 106 \$ 4.6 3.8 column shell C_{BM} 10⁶ \$ sieve trays C_{BM} 2.3 1.7 10⁶ \$ total column CBM 6.9 5.5

Table C.5: Estimation of the C_{BM} for distillation columns, Cases A, AD1, AD2, and AD2S

Table C.6: Estimation of the C_{BM} for distillation columns, Cases B and BD2S

	Unit	HPC	LPC
height	m m	24	42
column shell C _{PM}	10 ⁶ \$	5.2	5.5
sieve trays $C_{\rm BM}$	10 ⁶ \$	2.5	4.5
total column C_{BM}	106\$	7.8	10.0

Heat exchanger

The cost estimation of the heat exchangers is based on the heat transfer area. The relation of the heat duty obtained from Aspen Plus [161] and the heat transfer area is shown in Equation 3.1 [221]. The overall heat transfer coefficient depends on the phase of the streams inside the particular heat exchanger and is assumed based on data available in literature [222].

$$\dot{Q} = U \cdot A \cdot \Delta T_{\rm in} \tag{3.1}$$

For a two stream heat exchanger, the logarithmic mean temperature is calculated using Equation 3.2, where ΔT_{max} and ΔT_{min} are also obtained from the simulations.

$$\Delta T_{\rm ln} = \frac{\Delta T_{\rm max} - \Delta T_{\rm min}}{\ln\left(\frac{\Delta T_{\rm max}}{\Delta T_{\rm min}}\right)} \tag{3.2}$$

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Figure C.2: Cost functions for the cost estimation of the heat exchangers (adopted from [223])

The calculation of ΔT_{ln} has to be adjusted for the multi-stream heat exchangers. First, the highest and lowest ΔT has to be determined in order to calculate the logarithmic mean temperature difference. For the cost estimation of the condenser/reboiler, the temperature difference between condensation and evaporation temperature ($\Delta T_{\text{CD/REB}}$) is used as ΔT_{ln} (Table C.10).

For the estimation of the costs of the heat exchanger, the kind of each heat exchanger has to be initially determined. In this thesis, the heat exchangers are distinguished between shell and tube and plate heat exchanger. The purchased equipment costs of both kinds of heat exchangers are obtained from cost graphs published in [223]. These graphs are shown in Figure C.2. The graphs were plotted using Microsoft Excel in order to determine the respective mathematical function for the cost estimation of the shell and tube as well as plate heat exchanger shown in Equations 3.3a and 3.3b, respectively.

The material, pressure, and bare module factors are also selected according to [223]. The shell and tube heat exchangers are made of carbon steel and the plate heat exchangers are made of stainless steel.

for shell and tube heat exchangers

$$PEC_{0,2004} = -0.0025 \cdot A^2 + 59.484 \cdot A + 3104.8 \tag{3.3a}$$

for plate heat exchangers

$$PEC_{0,2004} = 6 \cdot 10^{-6} \cdot A^3 - 0.0285 \cdot A^2 + 100.48 \cdot A + 2323.6$$
(3.3b)

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Important parameters for cost estimation of the shell and tube as well as plate heat exchangers for Case A are given in Tables C.9 and C.9, respectively. The costs of the shell and tube heat exchangers for Cases AD1, AD2, and AD2S are shown in Tables C.13, C.18, and C.22, respectively. The costs of the plate heat exchanger for Cases AD1, AD2, and AD2S are shown in Tables C.13, C.18, and C.22, respectively. The costs of the plate heat exchanger for Cases AD1, AD2, and AD2S are shown in Tables C.14, C.19, and C.23, respectively. Tables C.26 and C.31 show the costs for the shell and tube heat exchangers is Case B and BD2S, respectively. The costs for the plate heat exchangers are given in Tables C.27 and C.32, respectively.

Compressor

The estimation of the costs of the compressors depends on the power consumption. The costs are estimated using equation Equation 3.4 [142]. The base value of the costs ($PEC_{BS,2000}$), the base size of the electricity consumption (\dot{W}_{BS}), and the cost exponent (*m*) are taken from [142].

$$PEC_{0,2000} = PEC_{\text{BS},2000} \cdot \left(\frac{\dot{W}}{\dot{W}_{\text{BS}}}\right)^m \tag{3.4}$$

The temperature, pressure, and material factors are also given in [142]. However, there are no temperature factors for a temperature below 0 °C, thus these factors were assumed. Figure C.3 shows the linearizion of the pressure and temperature factor. The mathematical functions of the temperature and pressure factor are given in Equations 3.5 and 3.6, respectively. The temperature factor is assumed to be one for a temperature range between 0 °C and 100 °C. The pressure factor is assumed to be one for a range between 0.5 bar and 7 bar. Typical average material factors are given in Table C.7.

$$f_{\rm T} = 0.0028 \cdot T + 0.7417$$
 for $T < 0 \,^{\circ}{\rm C}$ (3.5a)

$$f_{\rm T} = -0.0055 \cdot T + 1.0167$$
 for $T < 0 \,^{\circ}{\rm C}$ (3.5b)

$$f_{\rm p} = -1.6487 \cdot p + 1.7686$$
 for $p < 0.5$ bar (3.6a)

$$f_{\rm p} = 0.0096 \cdot p + 0.9626$$
 for $p > 7$ bar (3.6b)

The costs obtained from Equation 3.4 already include the cost for the motor. In Case A, the NC3 and NC4 are driven by EXP1 and EXP2, thus the costs for the motors are subtracted. All important parameters for the cost estimation are given in Table C.11. The results of the compressor costs for Cases AD1, AD2, and AD2S are shown in Tables C.15, C.20, and C.24, respectively. Tables C.28 and C.33 show the results for the costs of compressors for Case B and Case BD2S, respectively.



Figure C.3: Pressure and temperature factors (adopted from [142])

material	fм
carbon steel	1
aluminum	1.3
stainless steel (low grades)	2.4
stainless steel (high grades)	3.4
hastelloy C	3.6
monel	4.1
nickel and inconel	4.4
titanium	5.8

 Table C.7: Typical average material factors (taken from [142])

Expander

The cost estimation of the expanders is based on the electricity generation. The cost data are obtained from [144] and are shown graphically in Figure C.4. The mathematical function which fits to this graph is given in Equation 3.7. All important parameters for the cost estimation for Cases A, AD1, B, and BD2S are given in Tables C.12, C.16, C.29, and C.34, respectively.

$$PEC_{2002} = 3220.9 \cdot \dot{W}^{0.5963} \tag{3.7}$$



Figure C.4: Cost function for the cost estimation of the expanders (data adopted from [144])

component group	literature [224] %	Case A %	Case B %
column block	13	17.9	25.0
heat exchanger	9	15.3	11.5
compressor	32	24.8	29.4
expander	9	5.0	2.0
oxygen pump	5.0	-	0.08
prepurification unit	13	8	8

Table C.8: Estimation of the costs for the prepurification unit

Prepurification unit

The costs for the prepurifcation unit are estimated on a given percentage share of the costs of the remaining components. In [224], the contribution of the purchased component costs on the total component costs is given for the different components for an air separation unit. Table C.8 shows the given and the calculated shares for Cases A and B.

For Case A, the given and calculated shares for the column block and the expander are close to each other. The shares for the heat exchanger and compressor group diverge significantly from the given values. In Case B, the calculated share for the column block is even higher than in Case A, while the shares for the heat exchanger and compressor are close to the data given in literature. The reason for the partially huge differences of the calculated value and the value obtained from literature is that the percentage values obtained from literature are already more than 50 years old and new technologies and new materials influence the costs. Therefore, it is assumed that the cost for the prepurification block amounts to 8% of the overall costs instead of 13%. For all integrated systems the costs for the prepurification unit are calculated based on a share of 8% of Case A or Case B.

Pump

In the simulations of Cases AD21, AD2, and AD2S and Cases B and BD2S one or even two pumps are used. The estimation of the costs of the pump is also based on the power consumption and data available in [223] are used. All pumps are assumed to be centrifugal pumps. Figure C.5 shows the obtained function for the estimation of the costs of the pumps. The related mathematical function is given in Equation 3.8.



Figure C.5: Cost function for the cost estimation of pumps (data adopted from [223])

Pressure, material, and bare module factor are also obtained from [223]. All important parameters for the cost estimation for Cases AD1, AD2, AD2S, B, and BD2S are given in Tables C.17, C.21, C.25, C.30, and C.35, respectively.

$$PEC_{2004} = 4147.8 \cdot \dot{W}^{0.3447}$$

(3.8)

	unit	IC1	IC2	IC3	IC4	ICO	ICN	HE3
heat duty	MW	1.30	1.93	6.94	4.41	1.00	2.47	0.46
$T_{\rm hot,i}$	°C	113.1	147.5	176.2	117.1	366.8	357.9	419.4
$T_{\rm hot,o}$	°C	35.0	35.0	20.0	20.0	20.0	20.0	357.9
T _{cold,i}	°C	15.0	15.0	15.0	15.0	15.0	15.0	33
T _{cold,o}	°C	25.4	30.4	42.7	32.6	19.0	24.8	170
U	W/m ² K	42.5	42.5	42.5	42.5	42.5	42.5	50
ΔT_{\log}	Κ	45.8	54.9	39.1	28.1	80.8	78.1	236.9
A	m ²	668	828	4.174	3.693	291	743	97
$C_{\rm BM}$	10 ⁶ \$	0.157	0.190	0.782	0.709	0.076	0.173	0.033

Table C.9: Estimation of the C_{BM} for shell and tube heat exchangers, Case A

	unit	MHE	HE1	HE2	CD/REB
heat duty	MW	3.61	9.59	0.67	2.01
ΔT_{\min}	°C	2	4.2	28.3	-
$\Delta T_{\rm max}$	°C	32.4	36.9	39.4	-
$\Delta T_{\rm CD/REB}$	°C	-	-	-	0.47
U	W/m ² K	70	50	50	2,000
ΔT_{\log}	Κ	10.9	15.1	33.6	0.47
A	m ²	4,723	12,724	398	2,137
C _{BM}	10 ⁶ \$	1.246	2.935	0.110	0.383

Table C.10: Estimation of the C_{BM} for plate heat exchangers, Case A

Table C.11: Estimation of the C_{BM} for compressors, Case A

	unit	AC1	AC2	NC1	NC2	NC3	NC4	NC5	OC
$\eta_{ m is} \ \dot{W}$	% MW	84 1.64	84 1.89	84 5.74	84 4.26	84 0.82	84 0.48	84 2.96	84 1.00
C _{BM}	10 ⁶ \$	0.578	0.660	1.275	1.148	0.298	0.166	1.427	0.811

Table C.12: Estimation of the C_{BM} for expanders, Case A

	unit	EXP1	EXP2
$\eta_{ m is} \ \dot{W}$	% MW	84 0.82	84 0.48
C _{BM}	10 ⁶ \$	0.845	0.615

Table C.13: Estimation of the C_{BM} for shell and tube heat exchangers, Case AD1

	unit	IC1	IC2	ICO	ICN	HE3
heat duty	MW	1.30	1.93	0.71	1.63	0.46
T _{hot,i}	°C	113.1	147.5	269.0	244.7	333.3
T _{hot,o}	°C	35.0	35.0	20.0	20.0	312.0
T _{cold,i}	°C	15.0	15.0	15.0	15.0	33.0
T _{cold,o}	°C	25.4	30.4	20.7	28.0	170.0
U	W/m ² K	42.5	42.5	42.5	42.5	50
ΔT_{\log}	Κ	45.8	54.9	62.3	56.2	216.0
A	m ²	668	828	267.7	684.8	42.6
C _{BM}	10 ⁶ \$	0.157	0.190	0.071	0.160	0.021

					-	
	unit	MHE	HE1	HE2	HE4	CD/REB
heat duty	MW	3.61	5.78	1.12	7.49	2.01
ΔT_{\min}	°C	2	10.9	11.9	168.5	-
$\Delta T_{\rm max}$	°C	47.2	32.2	32.2	404.4	-
$\Delta T_{\rm CD/REB}$	°C	-	-	-	-	0.47
U	W/m ² K	70	50	50	50	2,000
ΔT_{\log}	Κ	14.3	19.7	20.4	269.5	0.47
A	m ²	3,607	5,876	1,099	556	2,137
C _{BM}	10 ⁶ \$	0.725	1.355	0.249	0.133	0.383

Table C.14: Estimation of the C_{BM} for plate heat exchangers, Case AD1

Table C.15: Estimation of the C_{BM} for compressors, Case AD1

	unit	AC1	AC2	NC1	NC2	NC3	NC5	OC
$\eta_{ m is} \ W$	% MW	84 1.64	84 1.89	84 3.88	84 2.21	84 0.79	84 2.96	84 0.74
C _{BM}	10^{6} \$	0.578	0.660	1.379	0.844	0.640	1.427	0.601

Table C.16: Estimation of the C_{BM} for expanders, Case AD1

	unit	EXP1
$\eta_{ m is}$	%	84
W	MW	0.80
$C_{\rm BM}$	10 ⁶ \$	0.843

Table C.17: Estimation of the C_{BM} for the pump, Case AD1

	unit	LNGP
$\eta_{ m is}$ W	% MW	70 0.058
C _{BM}	10 ⁶ \$	0.108

Table C.18: Estimation of the C_{BM} for shell and tube heat exchangers, Case AD2

	unit	ICO	ICN	HE3
heat duty	MW	0.22	0.59	0.43
T _{hot,i}	°C	97.1	97.1	419.4
T _{hot,o}	°C	20.0	20	365.2
T _{cold,i}	°C	15.0	15	24.8
T _{cold,o}	°C	25.3	35.3	170
U	W/m ² K	42.5	42.5	50
ΔT_{\log}	Κ	25.1	22.6	292.5
A	m ²	203	619	29
C _{BM}	10 ⁶ \$	0.057	0.147	0.018

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	unit	IC1	IC2	IC5	MHE	HE2	HE4	CD/REB
heat duty	MW	0.89	0.90	1.09	3.46	2.52	2.86	2.01
$\Delta T_{\rm max}$	°C	189.9	131.1	136.1	2.0	7.4	15.8	-
ΔT_{\min}	°C	138.5	81.6	86.1	37.3	187.2	351.7	-
$\Delta T_{\rm CD/REB}$	°C	-	-	-	-	-	-	0.47
U	W/m ² K	42.5	42.5	42.5	70	50	50	2,000
$\Delta T_{\rm log}$	Κ	162.9	104.4	109.2	12.1	55.7	108.2	-
A	m ²	128	203	235	4078	906	528	2152
C _{BM}	10 ⁶ \$	0.039	0.057	0.064	0.908	0.214	0.127	0.385

Table C.19: Estimation of the C_{BM} for plate heat exchangers, Case AD2

Table C.20: Estimation of the C_{BM} for compressors, Case AD2

	unit	AC1	AC2	AC3	NC1	NC2	NC5	OC
$\eta_{ m is} \ \dot{W}$	% MW	84 1.23	84 1.26	84 0.61	84 0.50	84 0.74	84 3.12	84 1.01
C _{BM}	10 ⁶ \$	0.480	0.493	0.336	1.208	0.541	1.465	0.811

Table C.21: Estimation of the C_{BM} for the pump, Case AD2

	unit	LNGP
$\eta_{ m is}$ W	% MW	84 0.058
C _{BM}	10 ⁶ \$	0.108

Table C.22: Estimation of the C_{BM} for shell and tube heat exchangers, Case AD2S

	unit	ICO	ICN	HE3
heat duty	MW	0.27	0.73	0.43
T _{hot,i}	°C	114.7	114.7	419.4
T _{hot,o}	°C	20.0	20.0	365.2
$T_{\rm cold,i}$	°C	15.0	15.0	24.8
T _{cold,o}	°C	21.3	32.4	170.0
U	W/m ² K	42.5	42.5	50
$\Delta T_{\rm log}$	Κ	30.2	27.6	292.5
A	m ²	207	622	29
C _{BM}	10 ⁶ \$	0.057	0.147	0.018

	unit	IC1	IC2	IC5	MHE	HE2	HE4	HE5	CD/REB
heat duty	MW	0.89	0.9	1.09	3.46	2.78	2.67	5.55	2.01
$\Delta T_{\rm max}$	°C	96.8	64.6	74.1	29.90	226.2	346.7	73.2	-
ΔT_{\min}	°C	52.9	19.2	19.6	2.0	7.6	123.1	73.2	-
$\Delta T_{\rm CD/REB}$	°C	-	-	-	-	-	-	-	0.47
U	W/m ² K	42.5	42.5	42.5	70	50	50	50	2,000
$\Delta T_{\rm log}$	Κ	72.7	37.4	41.0	10.4	64.5	215.9	25.4	-
A	m ²	287	568	626	4771	861	247	4,367	2,152
C _{BM}	10 ⁶ \$	0.054	0.135	0.146	1.0	0.206	0.067	0.920	0.385

Table C.23: Estimation of the C_{BM} for plate heat exchangers, Case AD2S

Table C.24: Estimation of the C_{BM} for compressors, Case AD2S

	unit	AC1	AC2	AC3	NC1	NC2	NC5	OC
$\eta_{ m is} \ \dot{W}$	% MW	84 1.23	84 1.25	84 0.61	84 0.60	84 0.82	84 3.13	84 1.01
C _{BM}	10 ⁶ \$	0.480	0.493	0.336	1.738	2.519	1.465	0.811

Table C.25: Estimation of the C_{BM} for pumps, Case AD2S

	unit	LNGP	WP
$\eta_{ m is} \ \dot{W}$	% MW	70 0.058	70 0.0006
$C_{\rm BM}$	10 ⁶ \$	0.108	0.023

Table C.26: Estimation of the C_{BM} for shell and tube heat exchangers, Case B

	unit	IC1	IC2	ICN
heat duty	MW	2.66	4.10	6.77
T _{hot,i}	°C	113.0	151.7	496.9
$T_{\rm hot,o}$	°C	35.0	35.0	20.0
$T_{\rm cold,i}$	°C	15.0	15.0	15.0
T _{cold,o}	°C	36.2	47.7	42.0
U	W/m ² K	42.5	42.5	42.5
ΔT_{\log}	Κ	42.2	50.9	99.6
A	m ²	1,481	1,896	1,605
C _{BM}	10 ⁶ \$	0.322	0.402	0.346

	unit	MHE	SUB	CD/REB
heat duty	MW	10.44	0.02	3.54
$\Delta T_{\rm max}$	°C	37.8	24.5	-
ΔT_{\min}	°C	2.7	13.7	-
$\Delta T_{\rm CD/REB}$	°C	-	-	0.56
U	W/m ² K	70	50	2,000
ΔT_{\log}	Κ	13.4	18.6	-
A	m ²	11,158	20	3,170
$C_{\rm BM}$	10 ⁶ \$	2.349	0.011	0.667

Table C.27: Estimation of the C_{BM} for plate heat exchangers, Case B

Table C.28: Estimation of the C_{BM} for compressors, Case B

	unit	AC1	AC2	AC3	NC5
$\eta_{ m is}$ W	% MW	84 3.36	84 4.00	84 2.46	84 6.40
$C_{\rm BM}$	10 ⁶ \$	0.803	0.940	1.314	2.222

Table C.29: Estimation of the C_{BM} for expanders, Case B

	unit	EXP1
$\eta_{ m is}$	%	84
W	MW	0.271
$C_{\rm BM}$	10^{6} \$	0.435

Table C.30: Estimation of the C_{BM} for the pump, Case B

	unit	OP
$\eta_{ m is} \ \dot{W}$	% MW	70 0.007
$C_{\rm BM}$	10 ⁶ \$	0.054

Table C.31: Estimation of the C_{BM} for shell and tube heat exchangers, Case BD2S

	unit	IC1
heat duty	MW	2.66
Thot,i	°C	113.0
$T_{\rm hot,o}$	°C	35.0
$T_{\rm cold,i}$	°C	2.4
T _{cold,o}	°C	20.0
U	W/m ² K	42.5
ΔT_{\log}	Κ	57.6
A	m ²	1,086
C _{BM}	10 ⁶ \$	0.243

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	unit	IC2	IC5	ICN1	ICN2	MHE	HE5	SUB	CD/REB
heat duty	MW	1.01	3.01	2.4	0.05	10.06	6.66	0.02	3.54
$\Delta T_{\rm max}$	°C	54.3	113.1	124.9	129.0	21.9	87.8	24.5	-
ΔT_{\min}	°C	31.3	45.1	7.9	124.6	2.7	5.0	13.7	-
$\Delta T_{\rm CD/REB}$	°C	-	-	-	-	-	-	-	0.56
U	W/m ² K	42.5	42.5	42.5	42.5	70	50	50	2,000
$\Delta T_{\rm log}$	Κ	41.7	74.0	42.4	126.8	9.2	28.9	18.6	-
A	m^2	567	957	1,329	9	15,683	4.612	29	3,166
C _{BM}	10 ⁶ \$	0.096	0.146	0.262	0.009	3.303	0.971	0.011	0.667

Table C.32: Estimation of the C_{BM} for plate heat exchangers, Case B

Table C.33: Estimation of the C_{BM} for compressors, Case BD2S

	unit	AC1	AC2	AC3	NC5
$\eta_{ m is} \ \dot{W}$	% MW	84 3.36	84 3.71	84 2.38	84 2.40
C _{BM}	10 ⁶ \$	0.803	0.844	1.264	3.040

Table C.34: Estimation of the C_{BM} for expanders, Case BD2S

	unit	EXP1
$\eta_{ m is}$ W	% MW	84 0.271
C _{BM}	10 ⁶ \$	0.435

Table C.35: Estimation of the C_{BM} for pumps, Case BD2S

	unit	OP	WP	LNGP
$\eta_{ m is}$ W	% MW	70 0.007	70 0.0009	70 63.1
C _{BM}	10^{6} \$	0.054	0.027	0.111

C.2 Calculation of the fixed and total capital investment

A detailed calculation of the fixed capital investment for Cases A, AD1, AD2, and AD2S and for Cases B and BD2S are shown in Tables C.36 and C.37, respectively.

Table C.38 shows the calculation of the total capital investment for Cases A, AD1, AD2, and AD2S. The total capital investment of Cases B and BD2S is shown in Table C.39.

Case AD2S Case A Case AD1 Case AD2 10^{6} \$ 10^{6} \$ 10^{6} \$ 10^{6} \$ 24.9 total bare module costs (C_{BM}) 28.4 24.3 21.3 service facilities/architectural work (25% of C_{BM}) 5.3 6.2 7.1 6.1 contingency (10% of C_{BM}) 2.4 2.5 2.8 2.1 fixed capital investment 38.4 32.9 28.7 33.7

Table C.36: Estimation of the fixed capital investment, Cases A, AD1, AD2, and AD2S

Table C.37: Estimation of the fixed capital investment, Cases B and BD2S

	Case B 10 ⁶ \$	Case BD2S 10 ⁶ \$
total bare module costs (C_{BM}) service facilities/architectural work (25% of C_{PM})	28.9 7.2	31.4 7.8
contingency (10% of C_{BM})	2.9	3.1
fixed capital investment	39.1	42.3

Table C.38: Estimation of the total capital investment, Cases A, AD1, AD2, and AD2S

	Case A 10 ⁶ \$	Case AD1 10 ⁶ \$	Case AD2 10 ⁶ \$	Case AD2S 10 ⁶ \$
date of commercial operation: January 1st, 2017				
plant facility investment 1	23.0	19.7	17.2	20.2
(January 1 st , 2015) (60 % of FCI)				
plant facility investment 2	15.4	13.1	11.5	13.5
(January 1 st , 2016) (40 % of FCI)				
interest for PFI1	4.8	4.1	3.6	4.2
interest for PFI2	1.5	1.3	1.1	1.3
Total capital investment	44.7	38.3	33.5	39.3

	Case B 10 ⁶ \$	Case CBD2S 10 ⁶ \$
date of commercial operation: January 1st, 2017		
plant facility investment 1 (January 1st, 2015) (60 % of FCI)	23.4	25.4
plant facility investment 2 (January 1st, 2016) (40% of FCI)	15.6	16.9
interest for PFI1	4.9	5.3
interest for PFI2	1.6	1.7
total capital investment	45.6	49.4

Table C.39: Estimation of the total capital investment, Cases B and BD2S