Pipeline System Hydraulic & Optimization Study Report

01	05/03/2021	Final Issue	L.Maggiore	E.Bonato	A.Terenzi
00	18/12/2020	Final Issue	L.Maggiore	E.Bonato	A.Terenzi
A	26/11/2020	Issue for review	L.Maggiore	E.Bonato	A.Terenzi
Rev.	**Date**	**Description**	**Prepared**	**Checked**	**Approved**

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1. INTRODUCTION

1.1 FOREWORD

In the context of negative emissions and decarbonizing industry, carbon capture and storage (CCS) is being discussed as an option for Switzerland. The search for domestic storage sites is ongoing, in the meantime, there could be a possibility of collecting Swiss CO2 and sending it to storage sites under the North Sea, that are planned to open by end of 2024 (Northern Lights project by Equinor, Shell, Total).

In Switzerland, KVA Linth is currently performing a feasibility study for a capture plant with a potential provider, other emitters are also exploring cost and feasibility.

Saipem has been awarded for the feasibility and cost estimate of building a “collection network” (similar to a distribution grid for gas) to connect to Switzerland’s largest CO2 emitters on the one hand and to transmission pipelines on the other hand by 2030.

The study should give a first indication of cost, according to a Class 5 estimate (see Ref. [1]).

Switzerland has currently 32 large emitters, defined as point sources that emit over 100,000 tons/y of CO2 (see Figure 1.1.1). Together, these 32 large emitters emit about 7 million tons of CO2 per year.

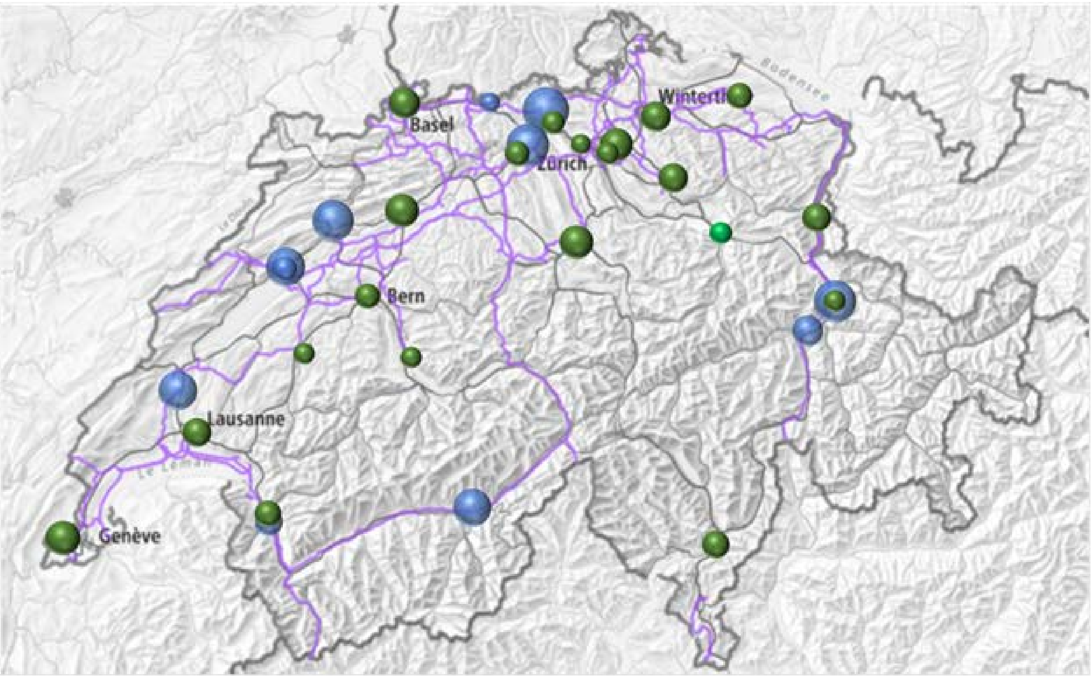


Figure 1.1.1: Large emitters and current natural gas pipeline network in Switzerland

Currently, none of these plants has a capture facility – it is expected that the current study should provide an indication of optimal conditioning parameters (water content and purity) for the CO2.

The CO2 collecting network subject of the present study will transport the captured CO2 stream up to a delivery point, from where a long transmission pipeline will deliver the CO2 to a selected location, for final sequestration.

Two options are possible:

- Transmission towards the North could start in Basel
- Transmission towards South should be assumed to be in Collombey, where an existing oil pipeline leads to Genoa

The transmission pipeline is not part of the current SoW.

It is requested that the new pipeline network to follow the existing natural gas pipelines corridors as much as possible. A specific effort shall be made to clarify possible configurations for the Kanton of Zurich, where different scenarios are possible to connect additional smaller point sources.

1.2 Scope

Scope of the present study is to identify the optimized transport configuration of the subject CO2 network collection system. In general, the long distance transmission of CO2 could be operated both in gas and dense phase conditions, and both options are considered in this study. Due consideration is given to the applicability of the relevant maximum operating pressure in different environmental conditions (installations within urban areas require a limitation).

For each identified system configuration, the number and size of compressor stations at emitters and system nodes will be identified together with pipeline sizes and characteristics. The different system configurations are compared based on the minimization of investment transportation cost-index (ATCI, actualized transport cost index) for the unit volume of gas.

In order to properly predict pressure levels and compression requirements in the network, a steady-state hydraulic analysis will be carried out for each identified system configuration.

1.3 Definitions

The abbreviations when used in this document will have the meanings described here in the following list:

COMPANY/OWNER	VBSA
CONTRACTOR	Saipem S.p.A.
PROJECT	CO2 COLLECTION NETWORK CONCEPTUAL STUDY

1.4 Abbreviations

API	American Petroleum Institute
ATCI	Actualized Transport Cost Index
CAPEX	Capital Investment Cost
CCS	Carbon Capture and Storage
CS	Compression Station
DF	Design Factor
DP	Design Pressure
d/s	Downstream
HDPE	High Density Polyethylene
ESDV	Emergency Shut Down Valve

HP	High Pressure
KM	Kilometre
KP	Kilometre Post
LP	Low Pressure
MOP	Maximum Operating Pressure
MOT	Maximum Operating Temperature
MM	Million
NPS	Nominal Pipe Size
OD	Outside Diameter
OPEX	Operating Cost
PE	Polyethylene
PL	Pipeline
SCADA	Supervisory Control and Data Acquisition
SMYS	Specified Minimum Yield Strength
WT	Wall Thickness

1.5 Applicable Codes & Standards

- ISO 27913-2016, "Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems (2016)
- ISO 13623-2017, "Petroleum and natural gas industries — Pipeline transportation systems" (2017)
- DNVGL-RP-F104, "Design and operation of carbon dioxide pipelines" (2019)
- API SPECIFICATION 5L-2018, 46th Edition, "Line Pipe" (2018)
- ASME B36.10, Welded and Seamless Wrought Steel Pipe
- BS EN 13480, Metallic industrial piping — Part 4: Fabrication and installation

1.6 References

[1] Doc. No. 000-ZA-09000 Pipeline System Basis of Design
[2] Knoope et al. "Economic optimization of CO2 pipeline configurations" - Energy Procedia (2013)
[3] Perry R.H., Green D., *Perry's Chemical Engineers' Handbook, 6th Edition*, McGraw-Hill, New York (1984)
[4] T.Baba et al., "Experimental evaluation of performance and mechanical reliability for high pressure CO2 integrally geared compressor", Journal of the Global Power and Propulsion Society, 4, pp. 128–144 (2020)
[5] Blevins R.D, Applied Fluid Dynamics Handbook, Van Nostrand Reinhold Company, New York (1984)
[6] Marchi E., Rubatta A., Meccanica dei Fluidi, UTET, Torino (1981)
[7] Bird R.B., Steward W.E., Lightfoot E.N., Transport Phenomena, John Wiley & Sons, New York (1960)
[8] Doc. No. 000-LC-B-80000 Overall Map of Pipeline Routes
[9] Doc. No. 000-LA-E-80001 Pipeline System Routing Study
[10] Doc. No. RE-PM673-00001 - Northern Lights Project Concept report

2. EXECUTIVE SUMMARY

A hydraulic and optimization study has been carried out for the Swiss CO2 collection network. The CO2 is captured at the 32 big emitters[1] of Switzerland and collected into 2 main trunklines (East and West Trunkline) that will transport the CO2 up to the delivery locations. The emitters are connected to the trunkline by means of dedicated flowlines. The overall emission rate is equal to 7.5 million tons of CO2 per year.

Two delivery options are considered: Basel and Collombey. The East Trunkline is connected to Basel and it can operate in one direction only, whereas the West Trunkline connects Collombey to Basel and it can operate in both directions (refer to the below Figure 2.1). A bypass line shall be provided in Basel area to allow the connection of the 2 trunklines.

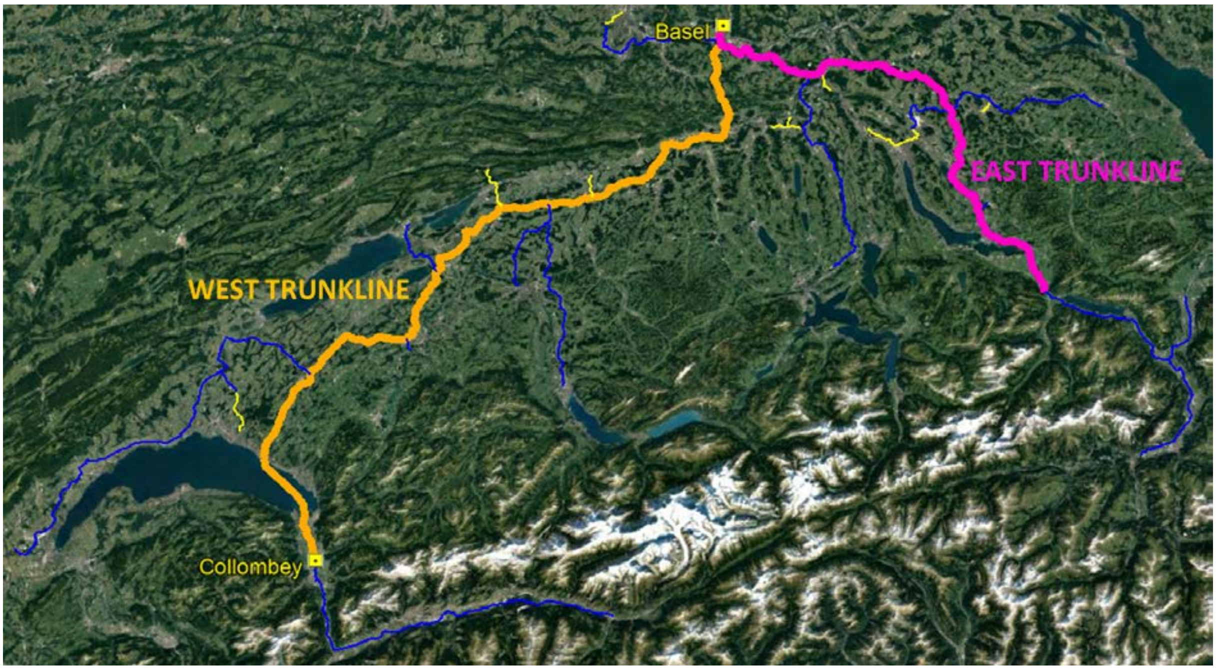


Figure 2.1: CO2 Collection Network - Trunklines Routing.

The total assumed lifetime of the system is 30 years, with the system ready for CO2 transportation in 2023.

The considered material for line pipe is ISO3183 L450MB (equivalent to API5L X65), since it is of a relatively high strength therefore minimizing wall thickness, it is relatively straightforward to weld in field and it is readily available. No significant savings are expected if using lower steel grades, typically used in low pressure gas lines.

The proposed CO2 compressor type is called “integrally geared compressor”, that is characterized by the presence of multiple stages of compression, having each one a proper independent regulation of rotational speed of its own shafts and impellers. Furthermore, it is characterized by a simpler intercooler implementation with respect to

1 Refer to Table 3.2.1 for the list of the considered emitters. One of the 32 big emitters (ERZ KHKW Josefstrasse) has been disregarded since it will be out of service in 2021. One additional emitter (ARA Werdholzli) is considered in Zurich area, having an emission rate lower than 100 ktons/year.

traditional inline compressors. The above mentioned characteristics allow for a better compression efficiency and reduced power consumption, especially for CO2 applications.

Two different options are considered for the transport of the CO2 from the emitter up to the delivery points:

- **Gaseous Phase Transport**: maximum operating pressure = 35 barg. This is the maximum pressure level ensuring no liquid formation associated to phase change in the pipeline thus allowing single phase stable transport (i.e. purely gas). This solution has the advantage to keep quite low pressures in the system, however large diameters could be required in case of high flowrates.
- **Dense Phase Transport**: maximum operating pressure = 145 barg. Dense phase transport for CO2 is particularly efficient, as the CO2 in dense phase conditions shows the density of a liquid and the viscosity similar to a gas, however this solution involves higher compression requirements. A maximum design pressure of 150 barg is considered being the limit for rating #900: higher operating pressures are technically feasible, however they will have higher compression cost and probably permission issues. In order to keep the CO2 in dense phase, a minimum pressure of 85 barg is to be maintained along the lines.

Several possible collection system configurations are considered. For each configuration CAPEX and OPEX are estimated for the pipeline and for the compressor stations. The comparison between the different configurations is carried out considering a parameter called ATCI (Actualized Transport Cost Index). Here below is a list of the different analyzed configurations:

- **Gaseous Phase Transport - Base Case.** The CO2 is transported in gaseous phase, with a MOP of 35 barg. Due to safety reasons, some flowlines crossing urban areas are considered with a MOP = 10 barg (i.e. low pressure flowlines).
- **Gaseous Phase Transport - “Collombey Split”.** This configuration is analyzed to evaluate the savings expected without the installation of the first 54 km of the West Trunkline, including the Geneva Lake offshore section. In this scenario both Basel and Collombey deliveries are operating simultaneously. The emitters south of Collombey (Lonza, Cimo and Satom Monthey) are routed to Collombey, whereas the rest of the emitters feed Basel outlet.
- **Gaseous Phase Transport - Low Pressure Flowlines MOP = 5 barg.** This configuration is as per base case, with the difference that the maximum operating pressure for the low pressure flowlines is 5 barg instead of 10 barg.
- **Gaseous Phase Transport - No low pressure flowlines.** This configuration considers the possibility to install high pressure flowlines (i.e. MOP = 35 barg) also in urban areas.
- **Dense Phase Transport.** The CO2 is transported in dense phase, with a MOP of 145 barg. Gaseous phase transport is foreseen in low pressure flowlines (MOP=10 barg) and in some pipeline sections where dense phase transport is deemed not feasible due to safety reasons (in these sections the MOP is fixed to 35 barg).

In the below Table 2.1, a list of the expected advantages and disadvantages relevant to the 2 considered transport options (i.e. gaseous/dense phase) is reported.

Table 2.1: Pro and Cons for Gaseous and Dense Phase Transport Options.

	Gas Phase Transport		Dense Phase Transport	
	Pro	**Cons**	**Pro**	**Cons**
Hydraulic Transport Efficiency	Low Operating Pressure, marginal impact of elevation profile.	Low density and relatively high friction impact, need consideration of Joule-Thompson cooling consequences.	High density and low friction, no Joule-Thompson cooling.	High Operating Pressure, impact of elevation profile for hydrostatic pressure.
Compression Requirements	Low Compression Energy.	Compressors (more expensive than pumps) are needed in the whole pipeline systems	Pumps may be used in intermediate booster stations.	High Compression Energy.
Design Pressure, Sizing & Construction Requirements	Low Design Pressure, Low Pipeline System Rating & Wall Thickness, no ductile fracture propagation issues, installation in urban areas in possible.	Large Pipeline Diameter Required, largest line pipe involve increase of trench and ROW dimension and line pipe weight handling.	Small Pipeline Diameter Required.	High Design Pressure, High Pipeline System Rating & Wall Thickness, need consideration of steel toughness requirements for ductile fracture propagation. More stringent requirement could derive from stress analysis, installation of high pressure lines is not allowed in urban areas.
CAPEX & OPEX	Convenient in a system with large number of compressor stations (i.e. emitters), or a single short distance pipeline.	Not convenient for a single long distance pipeline	Convenient for a single long distance pipeline.	Not convenient in a system with large number of compressor stations due to multiple plant cost impact, or a single short distance pipeline.
Safety	Consequences of pipe rupture and relevant fluid release are limited, due to lower operating pressure.	-	-	High pressure is more critical, higher impact of pressure burst and fluid accumulation from leaks.
Risk Mitigation Measures in Pipeline Design	No special mitigation is needed.	-	-	• Lower design factor in critical areas • Installation of additional automatic block valves • Increased pipeline cover • Mechanical protection such as slab, culvert, casing, separation wall • Increased clearance from settlement and single houses could be required as QRA result.

The following main results can be highlighted from the study, with reference to the internal gathering network:

1. The trunkline size selected for the gaseous phase trunklines (both East and West) is 30”. For the dense phase option, a 14” trunkline is selected for the East System and a 16” trunkline is selected for the West System. The West Trunkline is 229 km long and includes 16 km of offshore section relevant to the crossing of Geneva Lake, the 30” East Trunkline is 142 km.

2. The West trunkline can operate in both directions (i.e. to Basel and to Collombey). When operating towards Collombey, with Basel delivery shutdown, it can collect part of the East Trunkline rate in addition to the West emitters rate. It is estimated that the West Trunkline can transport an additional flowrate coming from the East Trunkline of around 2000 ktons/year in gaseous phase and 1000 ktons/year in dense phase, corresponding respectively to around 50% and 25% of the East emitters total rate. In case of East trunkline operation to Collombey, only the East emitters closer to the west system can be in operation (i.e. up to the Zurich area). This is because an increasing distance of the emitter from the delivery point (Collombey) results in increased pressure drops that could exceed the pipeline system MOP.
   It is possible to deliver the full flow of both trunklines to Collombey, but this has a significant impact on their size requirements. In the current configuration, developed according to Basis of Design, the flow to Collombey is considered as the sum of the normal flow in the West trunkline (simply reversed), and a fraction of the East trunkline flow. Furthermore, this is considered as a short term operation related to Basel terminal out of service. Considering full flow to Collombey instead, as a long term operation, involves the following trunkline size increase (without intermediate pressure boosting station):

   - Gaseous Phase Transport: 42” for the west trunkline, 36” for the east trunkline if considering the current overdesign margin on the flow rate; 36” for both trunklines would be sufficient without flow capacity overdesign margin.
   - Dense Phase Transport: 24” for the west trunkline, 20” for the east trunkline if considering the current overdesign margin on the flow rate; 20” for both trunklines would be sufficient without flow capacity overdesign margin.

   Given the significant trunkline size increase, another feasible option could be to install an additional pressure boosting station at Basel. In this way, east trunkline size can be kept as current, and the updated west trunkline size would be, considering the flow rate overdesign:

   - 36” for the gaseous transport
   - 22” for the dense phase transport

   To be considered that when increasing the flow capacity, increased frictional pressure losses are not the only parameter to be taken into account; both velocity limits and Joule-Thompson fluid cooling need to be considered also (these factors have been considered in the evaluation of upgraded sizes above).

3. Centralized dehydration solution is not recommended. The CO2 supplied at the emitters from capture units is wet at atmospheric conditions. Dehydration units can be installed either at the emitter (decentralized dehydration) or at the system manifolds (centralized dehydration). In case of centralized dehydration, plastic pipes could be used to transport the wet CO2 up to the manifold avoiding the corrosion issues that would arise using carbon steel pipes. However, due to the significant length of the flowlines (i.e. frequently more than 10 km), if the CO2 enters the pipeline at saturated conditions, water

drop out can be experienced in the line due to fluid cooling and the consequent water accumulation in the lines could cause system instability (i.e. compressors malfunctioning, slug flow, etc...). Due to this the dehydration should be decentralized and located at the emitters.

4. The adoption of plastic pipes for the low pressure flowlines is not recommended and carbon steel is considered for the whole pipeline system. With the decentralized dehydration, no water is present in the lines and carbon steel can be used in flowlines as well. This conclusion is also strengthened by the fact that no significant savings are expected by using plastic instead of carbon steel. In fact, in order to operate at the required pressure and temperature ranges, large wall thicknesses are required for the HDPE pipes (in the order of centimeters). This leads to HPDE pipe material costs comparable with the carbon steel pipes and on the other hand involves criticalities relevant to the construction, in particular for the welding process; for all the above reasons, the use carbon steel is suggested instead of plastic.

5. The connection of the Giubiasco emitter to the collection network system has a significant impact on the overall pipeline CAPEX. Giubiasco is isolated and located around 100 km far from the nearest emitter (Axpo Tegra). The routing development for this flowline is extremely challenging, crossing both mountain regions and a narrow densely populated valley. Moreover Giubiasco emitter contributes to only 2% of the total emissions (4% of the East Trunkline flowrate) and it is estimated that due to the length and the complications peculiar of this flowline, its cost has an impact on the East trunkline system pipeline CAPEX for more than 20% (10% of the overall system pipeline CAPEX).

6. In Zurich area, the 7km existing tunnel crossing the city center is considered available for CO2 transportation purposes (refer to Figure 3.6.2). The CO2 coming from the 3 Zurich emitters (KVA Limmattal, ARA Wedholzli and KVA Hagenholz) is collected in a flowline that will be routed inside the tunnel. The flowline size within the tunnel is 10” with a MOP = 10 barg, for the gaseous base case option.

7. Gaseous Phase Transport is the optimal transport option, since providing the lowest ATCI (see below Table 2.2). Due to the presence of several emitters spread around the Swiss territory and not close one to each other, many compression stations are required to collect the CO2 (46 compression units in base case). Therefore, the gaseous phase transport, with lower compression requirements, is more convenient if compared to dense phase. With gaseous transport the higher pipeline CAPEX (i.e. larger diameters) is balanced by the lower compression CAPEX and the resulting total investment cost is similar for gas and dense options. Furthermore, the OPEX requirements for the dense phase transport are much higher, leading to a substantial convenience of the gaseous phase transport wrt. the dense phase (around 20% cheaper in terms of ATCI).

8. The ATCI relevant to the Collombey Split solution is 6% lower than base case. This is mainly due to the savings related to the shorter west trunkline (not crossing Geneva Lake). However, this solution is less flexible than base case, having imposed delivery points: Collombey for Lonza, Cimo and Satom emitters; Basel for all the other emitters. Should Basel be not available as a delivery point, most of the Swiss CO2 could not be collected.

9. The configuration with low pressure flowlines MOP fixed to 5 barg presents a slightly higher pipeline CAPEX since some low pressure flowlines are larger. In this case the boosting stations d/s low pressure flowlines require higher compression energy demand and higher energy consumption. In this case the ATCI is 2% higher than in base case.

10. The configuration without low pressure flowlines presents slightly lower pipeline CAPEX if compared to the base case since some flowlines are smaller due to the higher operating pressure. On the other hand, the avoidance of low pressure flowlines allows to save several boosting stations along the network with significant savings in CS CAPEX/OPEX. In this case the ATCI is 9% lower than in base case.

11. Footprint for compressor areas. The minimum estimated space for a single compressor + dehydration unit is: 50 x 50 m (provided that control and HVAC buildings, and the electrical substation can be allocated within a general plant area shared with the capture plant). This area has been estimated on the basis of the compressor unit size - the proposed integrally geared compressor type is very compact, 15x5 m, no model exists more compact than this. The additional space requirements have been estimated for the associated piping, the dehydration equipment and the safety distances. Actually, this is an estimate fit for the current project stage accuracy level, this does not exclude spaces can be further reduced by a dedicated more advanced engineering evaluation. The 50x50 m space requirements estimate is valid for emitters for which a single compressor unit is needed, that are all the emitters except the following:

    - Juracime + Varo Refining (considered as a unique CS)
    - Holcim Schweiz AG (1)
    - Holcim Schweiz AG (2)

    For these 3 emitters, 3 compressor units are needed given the larger flow capacity required, hence the above space can be roughly multiplied by 3 in length (150 x 50 m).

12. The following unit cost are provided, to roughly estimate the economic impact of including an additional emitter + flowline system to the current transport system :

    a. Gas Transport Option: Total Cost Index ATCI = 0.030 €/ton/km.
    CAPEX contribution = 0.011 €/ton/km, OPEX contribution = 0.019 €/ton/km
    PL contribution = 0.007 €/ton/km, CS contribution = 0.023 €/ton/km (equivalent to 15 €/ton)

    b. Dense Phase Transport Option: Total Cost Index ATCI = 0.041 €/ton/km
    CAPEX contribution = 0.014 €/ton/km, OPEX contribution = 0.027 €/ton/km
    PL contribution = 0.006 €/ton/km, CS contribution = 0.035 €/ton/km (equivalent to 23 €/ton)

    The above costs are referred to the flowline systems only, trunkline cost is excluded. The assumed flow capacity overdesign for trunkline sizing is +30% with respect to the currently foreseen total emitters capacity. This means that to a certain extent, the trunkline size can be kept unchanged when adding additional emitters, i.e. if the additional flow rate contribution is within the above mentioned margin. In case of large transport capacity variation the trunkline size should be revised.

13. The following CAPEX and initial investment cost/length are estimated for the trunkline:

    - For gaseous phase: 30” Trunkline CAPEX = 1036 MM€, investment cost/length = 2.79 MM€/km
    - For dense phase: 16” West Trunkline CAPEX = 415 MM€, investment cost/length =1.79 MM€/km
    14” East Trunkline CAPEX = 193 MM€, investment cost/length =1.36 MM€/km

The above numbers are valid for the 30”(gas) and 14”/16” (dense) trunklines. The compressors cost is not included in the unit cost per length of the trunkline. However, it is pointed out that a variation of the system flowrate can result in a different trunkline size, with different investment costs.

Table 2.2: CAPEX, OPEX and ATCI Summary for all Analysed Configurations.

	PL CAPEX		CS CAPEX		OVERALL CAPEX		PL OPEX	CS OPEX - O&M	CS OPEX - Energy	OVERALL OPEX		ATCI	
	MM€	Δ wrt. base case	MM€	Δ wrt. base case	MM€	Δ wrt. base case	MM€	MM€	MM€	MM€	Δ wrt. base case	€/ton	Δ wrt. base case
Gaseous - Base Case	1769		941		2711		26.5	37.7	73.6	137.8		25.9	
Gaseous - Collombey Split	1523	-13.9%	931	-1.1%	2454	-9.5%	22.8	37.2	72.9	133.0	-3.5%	24.3	-6.1%
Gaseous - LP flowlines MOP=5bar	1790	1.2%	941	0.0%	2732	0.8%	26.9	37.7	77.3	141.8	2.9%	26.4	2.0%
Gaseous No LP flowlines	1758	-0.6%	763	-18.9%	2522	-7.0%	26.4	30.5	65.1	122.0	-11.5%	23.5	-9.3%
Dense Phase Transport	1231	-30.4%	1462	55.3%	2693	-0.7%	18.5	58.5	116.5	193.4	40.3%	31.5	21.6%

The above results are relevant to the technical-economic analysis of the gathering system only. However, to provide a complete comparison of the different transport options, an additional analysis has been carried out considering the investment and operational costs of the export compression stations to be installed at the delivery points (Basel and Collombey) to export the CO2 abroad, in order to reach the storage site.
It is assumed that the CO2 will be exported by means of a CO2 export pipeline that, being a point-to-point long transmission pipeline, will operate in dense phase conditions, which is by far the most economical option.
The main results are presented in the below Table 2.3 in terms of CAPEX, OPEX and ATCI.
Table 2.4 reports a comparison for the installed compression power and consumption requirements for the gathering network and for the export stations, in case of gaseous phase (base case) and dense phase scenarios.

Table 2.3: CAPEX, OPEX and ATCI Summary for gathering network, export compression stations and overall system.

CO2 GATHERING NETWORK						COMPRESSION TO EXPORT PIPELINE			OVERALL SYSTEM		
	PIPELINE CAPEX	GATHERING CS CAPEX	GATHERING CAPEX	GATHERING OPEX	GATHERING ATCI	export CS CAPEX	export CS OPEX	export CS ATCI	CAPEX	OPEX	ATCI
	MM€	MM€	MM€	MM€/y	€/ton	MM€	MM€/y	€/ton	MM€	MM€/y	€/ton
Base Case Gas Transport	1769	941	2711	137.8	25.9	435.0	59.2	7.9	**3146**	**197.0**	**33.8**
Gaseous Collombey Split (west)	1523	931	2454	133.0	24.3	435.0	59.2	7.9	**2889**	**192.2**	**32.3**
Gaseous lowP MOP=5bar	1790	941	2732	141.8	26.4	435.0	59.2	7.9	**3167**	**201.0**	**34.4**
Gaseous MOP=35 bar (all)	1758	763	2522	122.0	23.5	435.0	59.2	7.9	**2956**	**181.2**	**31.4**
Dense Phase Transport	1231	1462	2693	193.4	31.5	80.8	5.2	0.9	**2773**	**198.6**	**32.4**

Table 2.4: Installed Compression Power and Consumptions Summary for gathering system and export stations.

			Base Case Gas Transport	Dense Phase Transport
Gathering System	compression unit number	#	**46**	**55**
	installed power	MW	155.0	228.6
	consumption	MW	93.4	147.7
Export Compression Stations	compression unit number	#	8	8
	installed power	MW	170.4	10.0
	consumption	MW	58.5	2.5
OVERALL SYSTEM	**compression unit number**	**#**	**54**	**63**
	installed power	**MW**	**325.4**	**238.6**
	consumption	**MW**	**151.9**	**150.2**

The following conclusions can be highlighted from the analysis, for the whole system inclusive of the export stations:

1. In case of a gaseous phase transport in the gathering network, the installed power required for the export compressor station is around 100 MW in Basel (4 units, 24.8 MW each) and 70 MW in Collombey (4 units, 17.8 MW each). In case of dense phase transport in the gathering network, the export pump stations are much smaller, with an installed power of 5 MW each.
   If the overall system (gathering network + export stations) is considered, similar overall consumptions are predicted for collecting and exporting CO_2 (151.9 MW in case of gaseous gathering network – base case, 150.2 MW in case of dense phase gathering network).

2. If the gathering network is operated in gaseous phase the investment and operating costs of the export compression stations are much higher than in case of a dense phase gathering network. This is due to the higher compression requirements: from 10 bar to 145 bar with a gaseous phase gathering network, from 100 to 145 bar with a dense phase gathering network. When considering the overall system (i.e. gathering system and export compression stations) the savings provided by gas phase transport in the gathering system are compensated by the increasing requirement of the export compression station, especially in terms of operating costs, and the differences among gas and dense phase solutions flatten out.

3. The configuration with no low-pressure flowlines is confirmed as the most convenient solution in terms of overall ATCI, followed by “Collombey split” and Dense Phase Transport. Minor differences are predicted in terms of ATCI among the different solutions: the most convenient case is less than 10% cheaper than the most expensive one.

4. Footprint for export compressor areas: the estimated space for the gas compression station in Basel and Collombey is within 170x170m. Refer to Appendix 5 (Section 17) for a preliminary layout of the station.

3. BASIC DATA

The following Sections report the basic data of the CO2 Collection network, as mainly drawn from Ref.[1].

3.1 DESIGN OPERATING PARAMETERS

The following Table 3.1.1 reports the design data and the operating parameters for the CO2 Collection Network.

Table 3.1.1: CO2 Collection Network – Main Design Parameters

Parameter		Gaseous Phase Transport	Dense Phase Transport
Fluid	-	CO2	
Design Pressure	[barg]	40(1)	150
Maximum Design Temperature	[°C]	50	50
Design Flowrate (2)	[ktons/year]	5095 (East Trunkline) 3909 (West Trunkline)	5095 (East Trunkline) 3909 (West Trunkline)
Design Life	[years]	30	30
Hydraulic Roughness	[µm]	20	46

Notes:

1) A design pressures of 8/13 barg is selected for the low pressure flowlines located in densely populated areas such as Zurich Kanton.
2) Trunkline flowrates are reported. For detailed information on single emitter rates, refer to Section 0. The flowrate used for sizing includes a 30% margin on the total CO2 captured by emitters, in such a way to take into account possible re-routing and additional future emitter contribution.

3.2 CO2 EMITTERS DATA AND TRANSPORTATION RATES

Following Table 3.2.1 reports a list of the considered CO2 emitters together with the respective location and emission rates, as per Ref.[1]. Each CO2 emitter is connected to the main trunkline by means of a dedicated flowline. Depending on the emitter geographical location, the emitter can be connected either to the East or West Trunkline, as indicated in the below table.

Table 3.2.1: CO2 Collection Network – List of CO2 emitters

Emitter	Longitude	Latitude	CO2 Emission Rate	Routed to	Notes
			ktons/year	-	-
Giubiasco	8.9887	46.1722	188.5	East Trunkline System	*Disregarded as per Section 7.3*
Axpo Tegra AG	9.4246	46.8263	240.8	East Trunkline System	
Holcim (Schweiz) AG (2)	9.5529	46.9155	454.5	East Trunkline System	*Considered as a unique emitter*
GEVAG Trimmis	9.557	46.9161	122.0	East Trunkline System	
VfA Buchs	9.4836	47.1756	206.5	East Trunkline System	
KVA Linth	9.04	47.135	123.3	East Trunkline System	
KEZO Hinwil	8.8206	47.3083	218.4	East Trunkline System	
KVA Thurgau	9.1383	47.5575	166.1	East Trunkline System	

KVA Winterthur	8.7526	47.4981	225.1	East Trunkline System	
KVA Limmattal	8.403	47.4166	103.6	East Trunkline System	*Zurich Urban Area*
ARA Werdholzli	8.4814	47.4009	40.0	East Trunkline System	*Zurich Urban Area*
ERZ KHKW Hagenholz	8.5653	47.4142	400.0	East Trunkline System	*Zurich Urban Area*
Renergia Zentralschweiz AG	8.376	47.1135	286.6	East Trunkline System	
Jura Cement Fabriken	8.1568	47.4147	470.4	East Trunkline System	
GEKAL Buchs	8.1035	47.389	156.9	East Trunkline System	
KVA Turgi	8.2678	47.4844	133.8	East Trunkline System	
Holcim (Schweiz) AG (1)	8.2391	47.5217	554.5	East Trunkline System	
DSM Nutritional Products AG - Werk Sisseln	7.9786	47.5476	100.9	East Trunkline System	
IWB Basel	7.5833	47.5467	242.5	East Trunkline System	
Les Cheneviers	6.0322	46.1942	302.1	West Trunkline System	
TRIDEL Lausanne	6.6392	46.5277	211.2	West Trunkline System	
Holcim (Suisse) SA	6.5464	46.6557	378.7	West Trunkline System	
LONZA AG	7.8882	46.2967	366.0	West Trunkline System	
SATOM Monthey	6.96	46.2781	175.9	West Trunkline System	
Cimo SA	6.9653	46.2529	196.4	West Trunkline System	
SAIDEF Fribourg	7.1218	46.7725	112.8	West Trunkline System	
Juracime SA	7.0296	47.034	158.8	West Trunkline System	*Considered as a unique emitter*
Varo Refining Cressier SA	7.0358	47.04	383.4	West Trunkline System	
Vigier Cement AG	7.2493	47.1848	436.9	West Trunkline System	
Energiezentrale Forsthaus (KVA)	7.4139	46.9515	160.1	West Trunkline System	
AVAG KVA AG	7.6062	46.7621	113.3	West Trunkline System	
KEBAG AG	7.5706	47.2153	284.2	West Trunkline System	

Some of the above emitters are located very close to each other, therefore it is assumed that the following emitters can be considered as a unique emission source (i.e. it is assumed that a centralized local compression system could be installed for the CO2 captured from the following plants, in order to save one compression station):

- Holcim (Schweiz) AG (1) and GEVAG Trimmis (total CO2 emission = 576.6 ktons/year): according to the above coordinates, the distance between the 2 emitters is below 300 meters and they are in the same industrial area.
- Juracime SA and Vigier Cement AG for the WT (total CO2 emission = 542.2 ktons/year): according to the above coordinates, the distance between the 2 emitters is below 800 meters and they are in the same industrial area.

The total CO2 rate for the East Trunkline is 4246 ktons/year, while the total CO2 rate for the West Trunkline is 3280 ktons/year.

A margin of 20% is considered on the above flowrates for the hydraulic analysis of the system, allowing to take into account for pipeline routing uncertainties, emission uncertainties and future expansion of the system. It is pointed out that the above rates are relevant to the produced CO2 and typically the capture process has an efficiency of around 90%, therefore in this study an embedded additional margin of around 10% is also considered.

3.3 Fluid Delivery Points

The list and location of the 2 proposed delivery points are reported in the below Table 3.3.1.

The proposed network configuration shall be capable to deliver the CO2 to both the delivery points.

It is foreseen to operate the western trunkline in both directions, i.e. to Basel and to Collombey, while the Eastern Trunkline will be designed considering all the Eastern emitters being routed only to Basel delivery point. In case this delivery point is not available, it will be evaluated the possibility not to capture the CO2 at some Eastern emitter in order to reduce the relevant trunkline flowrate thus sending the residual to Collombey area.

Table 3.3.1: CO2 Delivery Points

CO2 Delivery Point	Longitude	Latitude
Basel area	7.8973	47.5827
Collombey area	6.9562	46.2967

3.4 Fluid Composition

The considered CO2 stream composition is reported in Table 3.4.1 (Ref.[1]). This is a typical composition from post-combustion capture process. The same composition is considered for all the emitters.

Table 3.4.1: CO2 Stream Molar Composition

Component	Molar fraction
	%
CO2	99.793
CH4	0.010
N2	0.170
C2+	0.010
CO	0.001
O2	0.010
NOx	0.005
SOx	0.001

The recommended maximum water content to be achieved as a consequence of the dehydration process, for the fluid entering the pipeline system, is 30 ppmv. This limit is as defined by the Northern Light Project (Ref.[10]), allowing to avoid any issue of corrosion, water drop out or hydrate formation within the whole chain of the CO2 transport system to the sequestration site (involving also CO2 refrigeration to subzero temperatures and liquefaction for ship transport). The required dehydration performance can be achieved by using a molecular sieve based technology. For what concern the maximum allowable content of other impurities, reference is made to Table A.1 of ISO 27913.

3.5 OPERATIONAL AND BATTERY LIMIT CONDITIONS

Operational and battery limit conditions to be considered for the CO2 Transport Network are reported in the following Table 3.5.1.

Table 3.5.1: Operational and Battery Limit Conditions

Parameter		Gaseous Phase Transport	Dense Phase Transport
CO2 Temperature u/s compression (Ref.[1])	[°C]	30	
CO2 Pressure u/s compression (Ref.[1])	[barg]	0	
CO2 Max Temperature d/s compression (Ref.[1])	[°C]	45	
Max Operating Pressure	[barg]	35 (1)	145 (2)
Delivery Pressure at Basel (3)	[barg]	10	100 (East Trunkline) / 122 (West Trunkline)
Delivery Pressure at Collombey (3)	[°C]	10	110 (West Trunkline)

Notes:

1) A MOP=5/10 barg is considered for low pressure flowlines, located in urban areas;
2) A MOP =170 barg is considered for the West Trunkline offshore section crossing Geneva Lake;
3) In case of dense phase transport, the delivery pressures are determined in order to keep the pressure above 80/85 along the network in order to avoid vapor formation at peak points of the elevation profile.

3.6 PIPELINE

The following criteria are used to size the pipeline when performing the hydraulic calculations:

1) The calculated operating pressure in normal operating conditions shall not exceed the value reported in Table 3.5.1.
2) In case of or gaseous transport, the fluid velocity in the pipeline should not exceed 20 m/s (optimal value in the range 5-10 m/s)
3) In case of or dense phase transport, the fluid velocity in the pipeline should not exceed 4 m/s (optimal value in the range 1-2 m/s)
4) The pipeline must be operated free of water in normal operating conditions
5) The pipeline must be operated free of solids in normal operating conditions

Long distance pipelines shall be designed with the installation of permanent pig traps to allow free passage of gauge, scraper and intelligent inspection pigs. Inspection intelligent pig runs will be required every five years.

Table 3.6.1 reports the characteristics of the line pipes assumed for this study. The steel grade and type of welding have been selected on the basis of standard manufacturing capabilities and economic optimization criteria.

Table 3.6.1: Line pipe characteristics considered for this study

Design Code	ISO 13623
Design Pressure	as per Table 3.1.1
Steel Grade	ISO L450MB (equivalent to API 5L X65)
Welding	SAW H
Internal Coating	n/a
External Coating	3 mm PE
Corrosion Allowance	1 mm
Design Factor	by Design Standard, as per applicable Location Factor
Burial Depth	1 m

The line pipe wall thickness evaluation for hoop stress considerations is based upon the methodology outlined in Clause 6.4.1.1 of ISO 13623:2017.

The minimum required line pipe wall thickness for hoop stress considerations is then determined by the addition of any required corrosion allowance.

According to the reference ISO standard, the maximum hoop stress on the pipe, σ_{hp}, due to internal fluid pressure shall be determined in accordance with following equation:

$$\sigma_{hp} = (p_{id} - p_{od}) \cdot \frac{(D_o - t_{\min})}{2 \cdot t_{\min}}$$

where:

p_{id} is the design pressure
p_{od} is the minimum external hydrostatic pressure
D_o is the nominal outside diameter
t_{min} is the specified minimum wall thickness

The minimum wall thickness for hoop stress can be calculated by replacing the following correlation in the previous equation:

$$\sigma_{hp} = f_h \cdot \sigma_y$$

where:

f_h is the hoop-stress design factor (based on class location)
σ_y is the minimum yield strength of the pipe material (SMYS) at maximum design temperature.

The specified minimum wall thickness is the nominal wall thickness less the allowance for manufacturing as per applicable pipe specification and corrosion.

In the below Figure 3.6.1 and Figure 3.6.3, the preliminary pipeline routings are reported for the East and West Trunkline Systems respectively. Figure 3.6.2 reports a detail of the Zurich Area. Basel is the delivery point for the East trunkline, whereas the West trunkline is bidirectional, with Basel and Collombey as possible delivery points.

A list with the length of all the flowlines and trunkline sections is reported in Table 3.6.2. The detailed elevation profile for each pipeline segment is reported in Appendix 4 (Section 15).

Table 3.6.2: Flowline and Trunkline sections lengths.

Name	Length
-	[m]
Les Cheneviers	82,748
LONZA AG	92,905
Cimo SA	908
SATOM Monthey	158
Holcim (Suisse) SA	249
TRIDEL Lausanne_LP	10,960
TRIDEL Lausanne_HP	6,835
W32	35,805
W31	4,964
EnergieZentrale Forsthaus (KVA)	22,815
AVAG KVA AG	46,650
SAIDEF Fribourg	3,318
Varo Refining Cressier SA	764
Juracime SA	453
Vigier Cement AG	11,730
KEBAG AG	5,998
W6	17,752
W9	5,057
Renergia Zentralschweitz AG	46,459
E12	15,988
KVA Turgi	5,380
Holcim (Schweiz) AG	246
Jura Cement Fabriken	2,676
GEKAL Buchs	4,934
E13	3,455
E14	592
KVA Winterthur	3,881
KVA Limmattal	6,691
KVA Thurgau	32,523
KEZO Hinwil	2,998
ARA Werdholzli	150
ERZ KHKW Hagenholz	609
E7_HP	18,803
E7_LP	2,806
E6	13,636
E9	1,377
E10	6,374
E11	*32*

Axpo Tegra AG	15,471
Holcim (Schweiz) AG - Trimmis GR ?	139
GEVAG Trimmis	163
VfA Buchs	18,280
KVA Linth	247
TRUNKLINE EAST (Rhine Valley)	56,980
DSM Nutritional Products AG - Werk Sisseln	917
IWB Basel_HP	42,954
IWB Basel_LP	6,077
TRUNKLINE EAST (Linth to Basel)	141,679
TRUNKLINE WEST	229,340

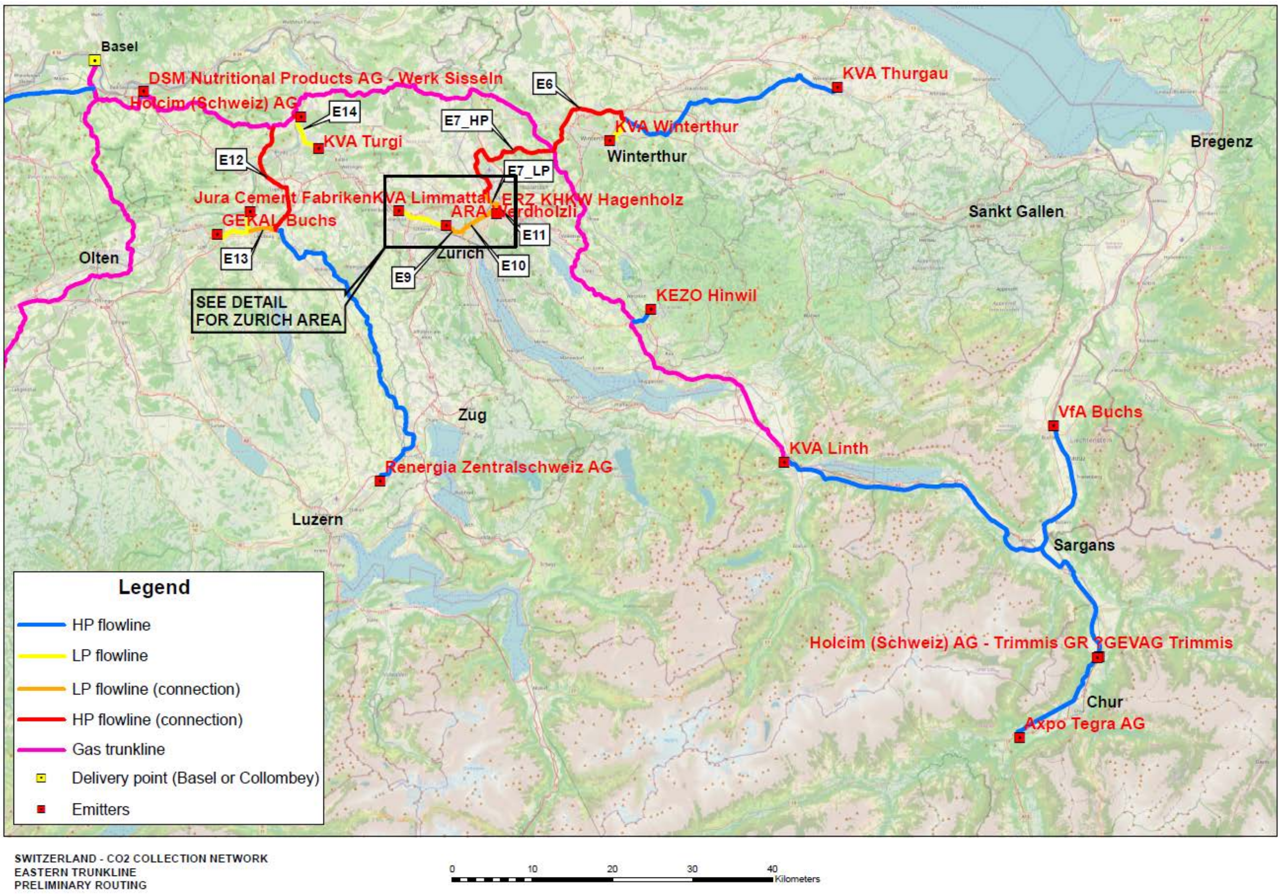


Figure 3.6.1: East Trunkline to Basel – Proposed Routing

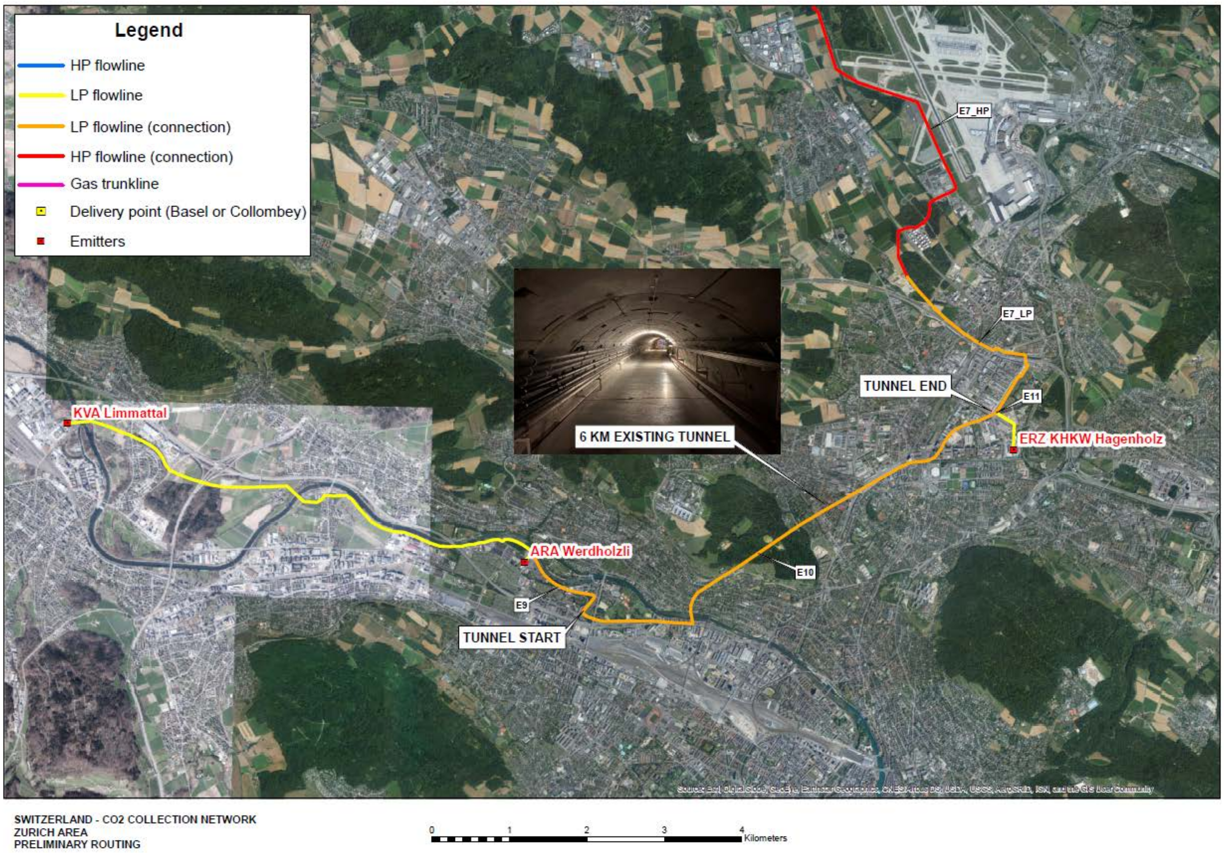


Figure 3.6.2: East Trunkline to Basel – Zurich Area Detail

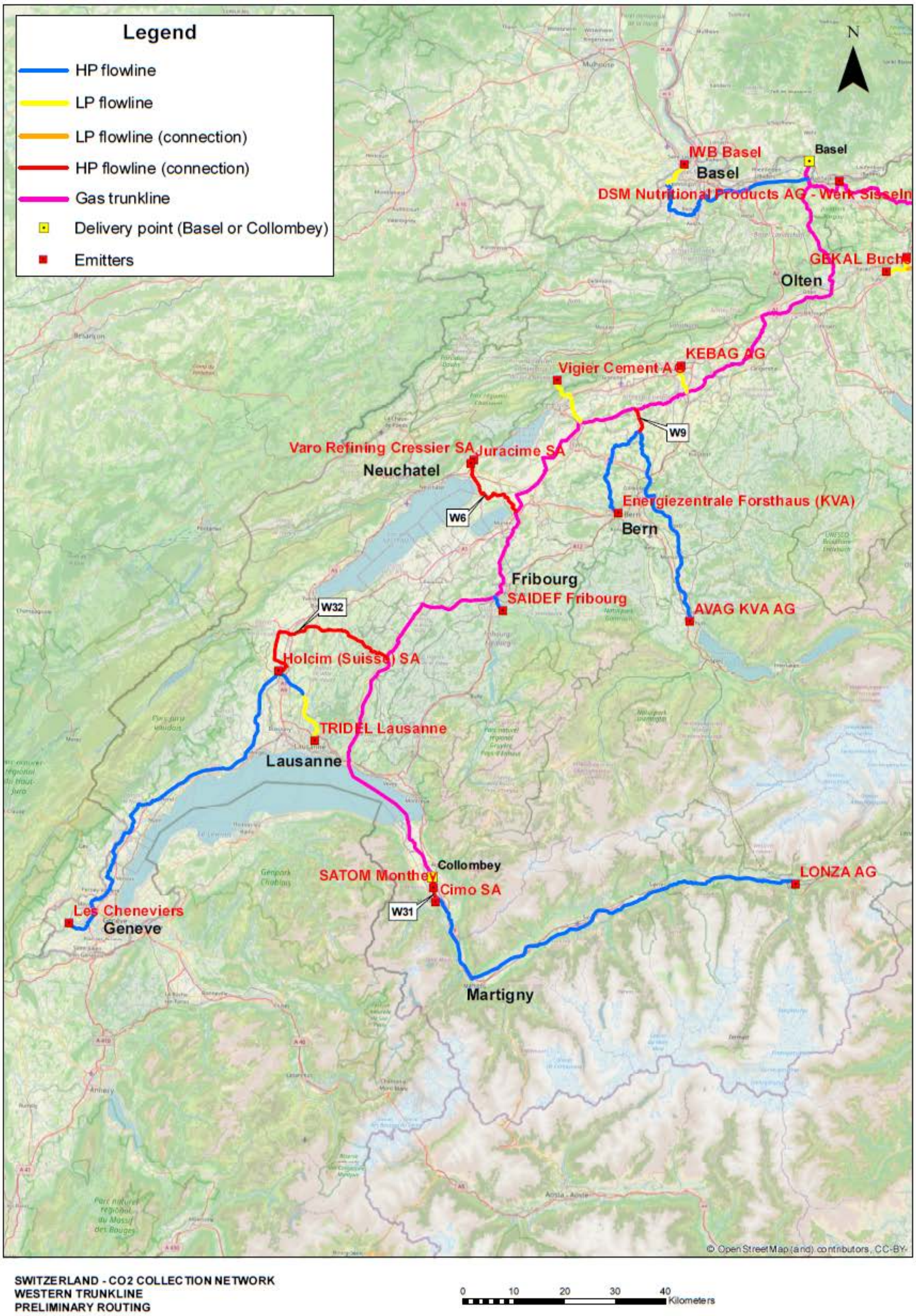


Figure 3.6.3: West Trunkline to Basel – Proposed Routing

In the following Figure 3.6.4 and Figure 3.6.5, the pipeline elevation profiles are reported for East Trunkline and West Trunkline respectively, assuming Basel as delivery point in both cases.

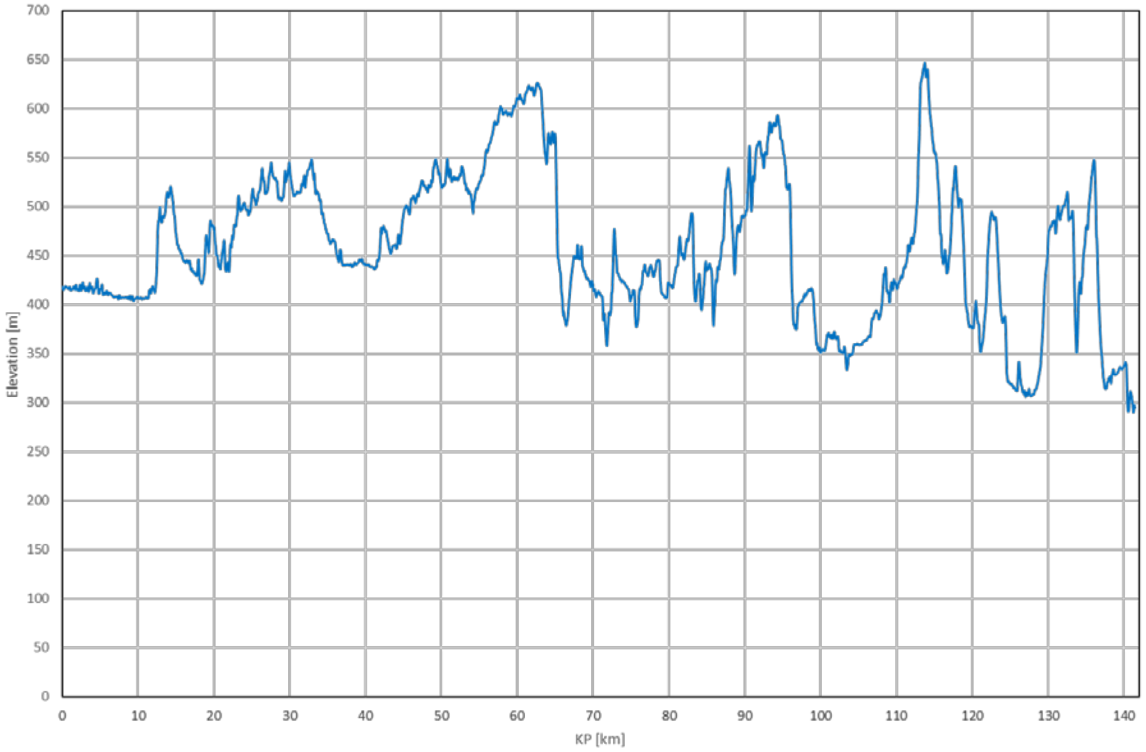


Figure 3.6.4: Eastern Trunkline to Basel – Elevation Profile

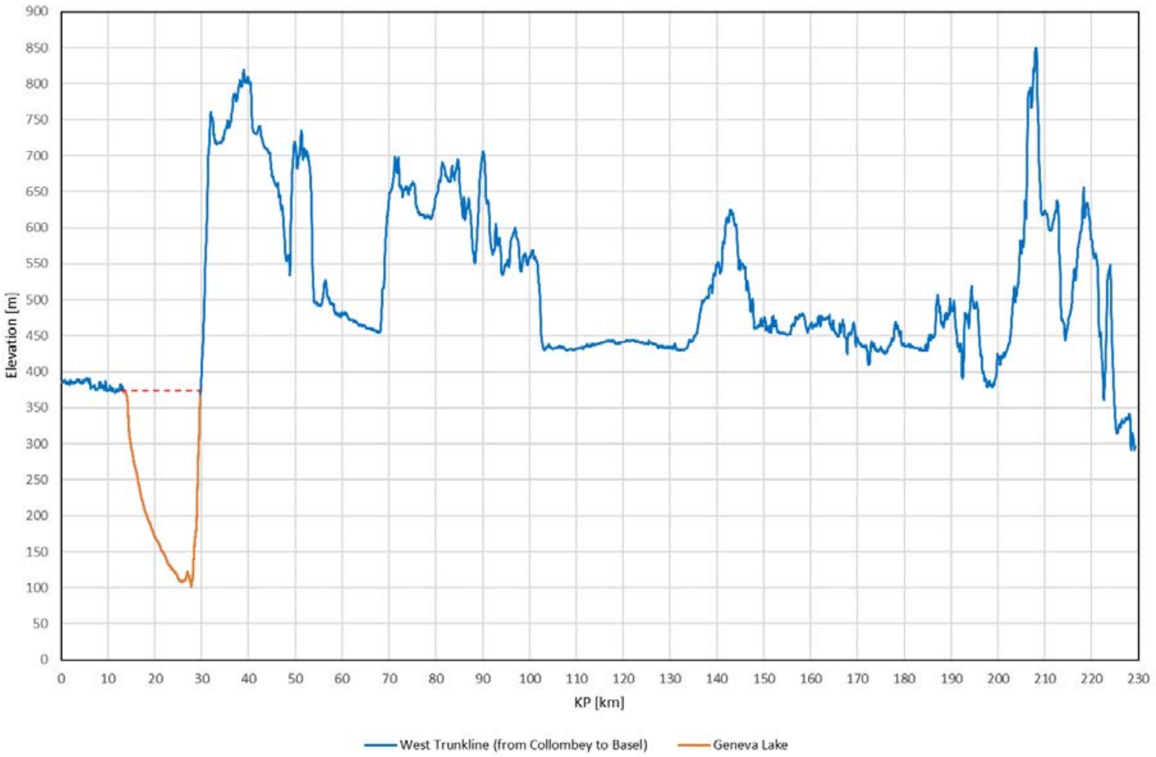


Figure 3.6.5: Western Trunkline to Basel – Elevation Profile

3.7 Environmental Conditions

As per Ref.[1], the following minimum and maximum temperatures can be considered as representative of winter and summer conditions:

- Minimum soil temperature at 1 m burial depth = 3°C
- Maximum soil temperature at 1 m burial depth = 16°C

Based on Saipem internal database, the soil type along the route is expected to be a clay/rock type, with an estimated thermal conductivity of 1.5 W/mK.

3.8 Compression Stations

Following a recent experience concerning a feasibility study of a CO2 transport system in Italy, a similar compression system has been proposed for the current project. The proposed compressor type is called “integrally geared compressor”, that is characterized by the presence of multiple stages of compression, having each one a proper independent regulation of rotational speed of its own shafts and impellers. Furthermore, it is characterized by a simpler intercooler implementation with respect to traditional inline compressors.

The above mentioned characteristics allow for a better compression efficiency and reduced power consumption, especially for CO2 applications, as reported by both compressor manufacturer and published papers (see for instance Ref.[4]). According to manufacturer information, these systems can also handle wet CO2 streams.

The compression system proposed for the current project is integrated with the dehydration equipment (considered as using the molecular sieve technology); for the gas phase transport option, the wet CO2 stream from the last stage compressor outlet will be routed to the dehydration system; for the dense phase option, the dehydration occurs as an intermediate stage between the last gas discharge output and the inlet of the last stage compressor, where the final compression up to dense phase conditions is carried out.

A typical scheme of the whole integrated system (compression + dehydration) is shown in Figure 3.8.1 for the gas phase transport option, and in Figure 3.8.2 for the dense phase option. The gas phase configuration includes 3 compression stages, with the last one bringing the fluid up to 40 barg maximum. The dense phase configuration includes a fourth stage d/s the dehydration stage, bringing the fluid up to 140 barg maximum.

In the current project transport system, variations of the above configurations can be present in the urban areas, where the maximum allowable operating pressure in gas phase (20 barg) is achieved by two compression stages only. Furthermore, the pressure boosting stations d/s the low pressure flowlines from the urban areas may have one or more compression stages depending on the considered transport option.

The following efficiencies are assumed for the calculation of the CS electric power consumption:

- Compressor Adiabatic Efficiency 0.75
- Compressor Mechanical Efficiency 0.99

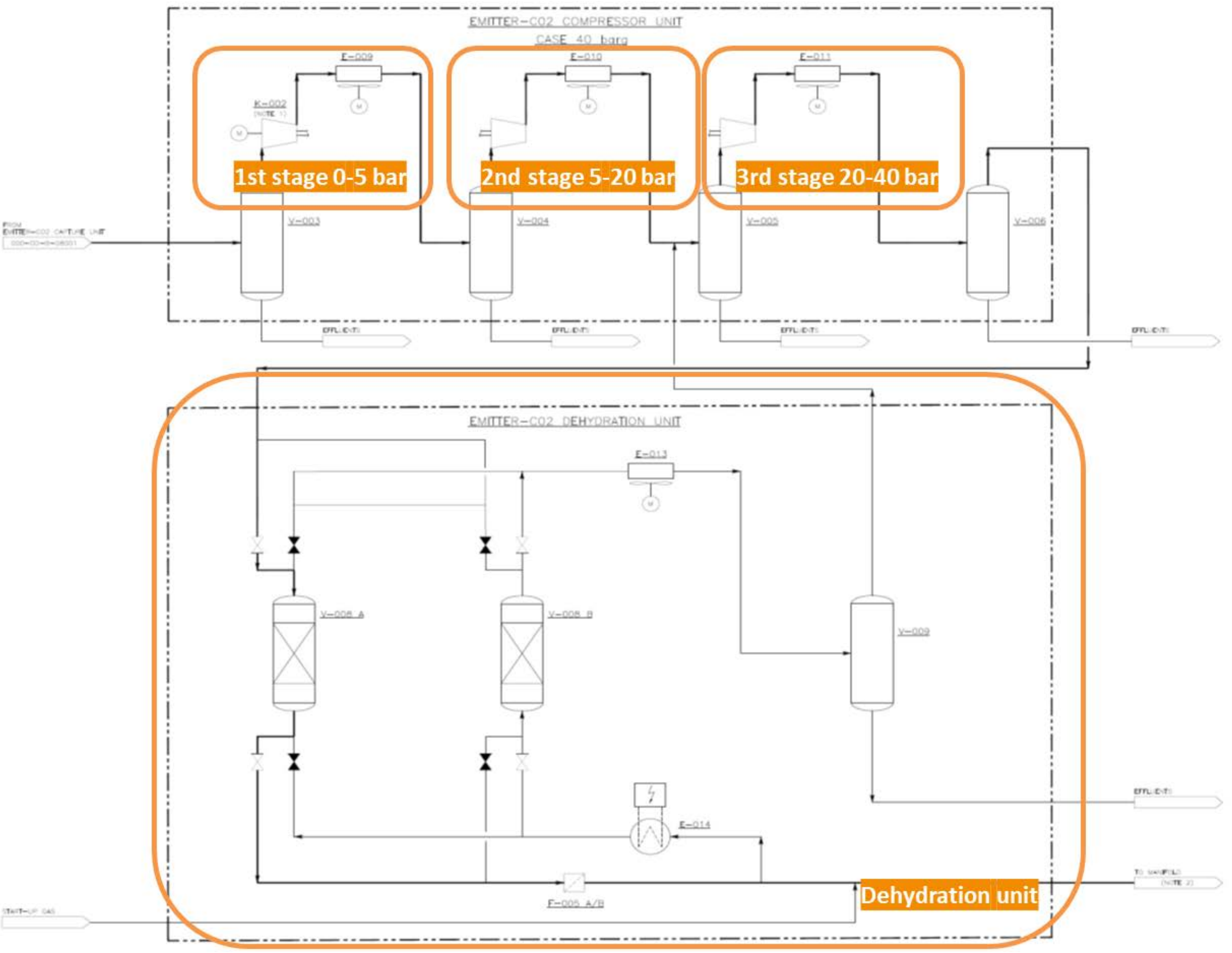


Figure 3.8.1: Compression Unit System from 0 barg to 40 barg

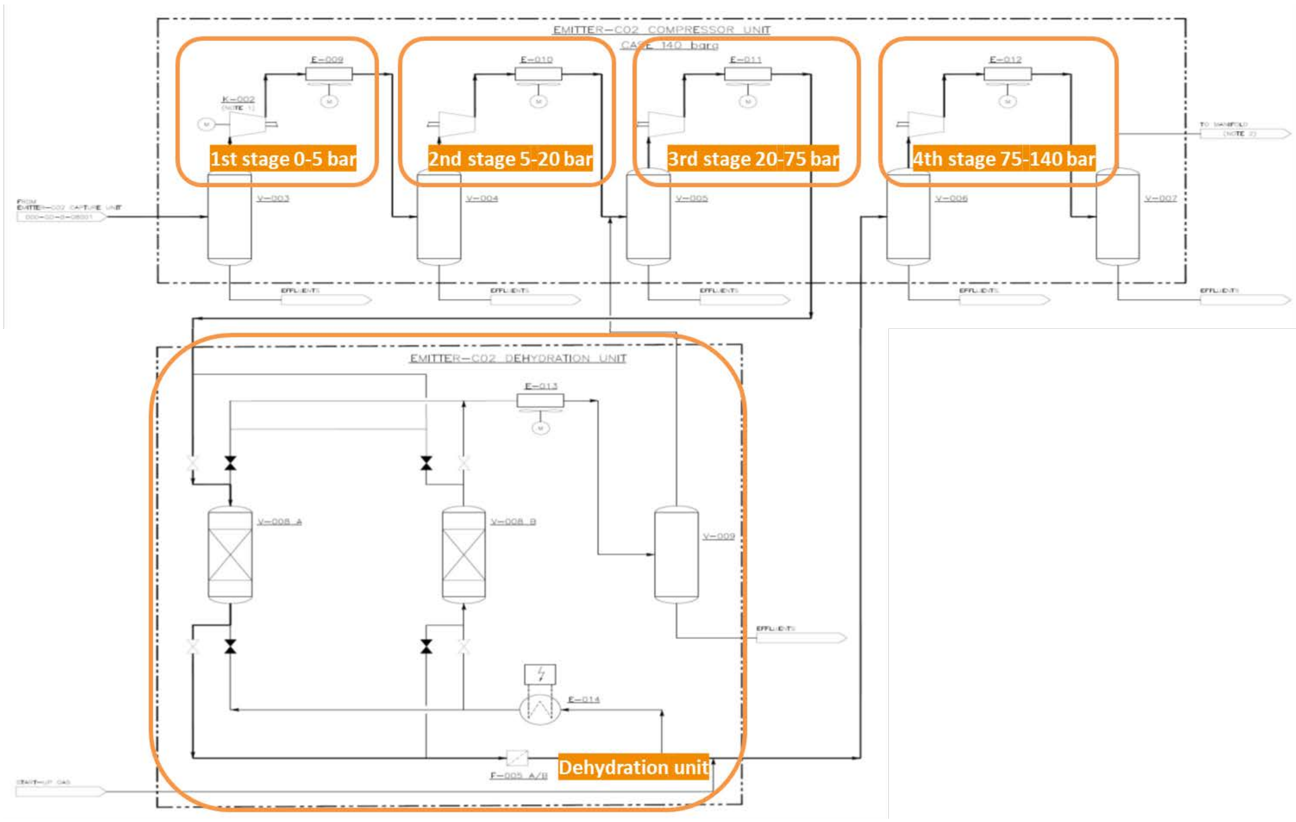


Figure 3.8.2: Compression Unit System from 0 barg to 140 barg

4. METHODOLOGY

4.1 THERMODYNAMIC ANALYSIS

A thermodynamic analysis of the reference gas compositions as per Section 3.4 has been carried out to calculate their thermodynamic and transport properties, to be used in the pipeline hydraulic analysis, and to verify they are compliant with the design specifications.

Thermodynamic characterization is performed by Multiflash v6.2.

Multiflash is a versatile PVT simulation program developed for reservoir engineers, flow assurance specialists, PVT lab engineers and process engineers. Multiflash is a powerful and versatile system for modelling physical properties and phase equilibria. It can be used as a stand-alone program or in conjunction with other software. Multiflash allows reservoir engineers, flow assurance specialists and process engineers to combine reliable fluid characterization procedures. The flow assurance package allows the user to input and characterize fluid compositions in Multiflash or access fluid compositions in Multiflash fluid databases provided by clients or colleagues. Flash and unit operation calculations can be performed on the fluids, and the package also allows the user to generate property tables for the fluids. The risk of formation of hydrates, wax, asphaltenes, and scale can be assessed. The effects of inhibitors and formation water are taken into account.

4.2 OPTIMIZATION BASED ON ATCI MINIMIZATION

The optimization analysis of the CO2 collection network, to define the pipeline diameter, the number/size of compressor stations is based on the minimization of investment (CAPEX) and operating (OPEX) costs, by evaluating all the possible alternative transport configurations.

The optimization technique used in Saipem is based on the criteria to calculate a transportation cost-index (ATCI, actualized transport cost index) for the unit volume of transported gas, and to compare it for all the investigated alternatives. The alternative having the lowest transportation cost-index will be the “optimum configuration” to be selected.

The transportation cost-index ATCI is calculated on the basis to amortize the investment and operating costs at the end of the project lifetime, by considering money interest and inflation.

To calculate the Actualized Transport Cost Index (ATCI), the investment cost and the operating cost are adjusted to each year of operation by means respectively of amortization and the inflation rates, starting from the start-up year.

While the costs are all evaluated at the initial construction time and then actualized at the effective investment time, on the basis of the investment costs inflation rate, the ATCI is calculated by actualizing the sum of all the costs and the flow rates at the initial operating time when the amortization process begins.

The adopted optimization procedure makes reference to the methodology described in Ref.[2], based on the following iterations and equations:

1. Calculation of the investment cost referred to year k_inv

$IC_{k\_inv} = (IC_0)\ (CAF)$ (4.2.1)

$CAF = (1 + i)^{k\_inv - 1}$ (4.2.2)

where:

IC_{k_inv}	Investment Cost referred to year k_inv
IC_0	Investment Cost referred to the initial construction time (beginning of year No.1)
CAF	Compound-Amount Factor
i	Investment Cost Inflation Rate
k_inv	Time (year) at the end of which the investment cost occurs, starting from the initial construction year. This calculation refers to the new investment cost occurring at the beginning of the year *k_inv*.

2. Calculation of the annual constant instalment to amortize the investment during lifetime

$$APSD_k = \sum_{j=1}^{N_{inv}} F(j)CRF(j) \quad (4.2.3)$$

$$F(j) = \begin{cases} IC_{k\_inv}(j) & \text{if } n(j) \geq k \geq k\_inv(j) \\ 0 & \text{if } k < k\_inv(j) \text{ and } k > n(j) \end{cases} \quad (4.2.4)$$

$$CRF(j) = \frac{i'(1+i')^{n(j)}}{(1+i')^{n(j)} - 1} \quad (4.2.5)$$

Fixed part investment life:

$$n(j) = N - k\_inv(j) + 1 \quad (4.2.6)$$

Rotating part investment life:

$$n(j) = \begin{cases} LRP & \text{if } N \geq LRP + k\_inv + 1 \\ N - k\_inv(j) + 1 & \text{otherwise} \end{cases} \quad (4.2.7)$$

where:

$APSD_K$	Annual Pipeline System Depreciation (relevant to the end of year *k*)
K	Year of System Depreciation evaluation (referred to the initial construction time)
N_{inv}	Total number of investments
j = j-th	investment index
CRF(j)	Capital Recovery Factor relevant to the *j-th* investment
$IC_{k\_inv}(j)$	Investment Cost of *j-th* investment referred to year *k_inv*
i'	interest rate
n(j)	Lifetime of the *j-th* investment (referred to the initial construction time)
N	Lifetime of the system (referred to the initial construction time)
LRP	Life rotating part

3. Calculation of the annual operating costs, inclusive of their inflation rate

The operating costs are composed by energy, maintenance and overhead costs.

$AOC_K = (AOC_0)\ (CAF)$ (4.2.8)

$CAF = (1+i'')^k$ (4.2.9)

where:

AOC_k	Annual Operating Cost (relevant to the end of year k)
AOC_0	Annual Operating Cost referred to the initial time
CAF	Compound-Amount Factor
i''	Operating Costs Inflation Rate
k	Operating year (referred to the initial construction time)

4. Calculation of the Total Annual Instalment (relevant to the end of year k)

$TAI_k = APSD_k + AOC_k$ (4.2.10)

5. Calculation of the Total Annual Instalment Actualized at the initial time of system operation

$ATAI_k = (TAI_k)\ (PWF)$ (4.2.11)

$PWF = (1 + i')^{-k_O}$ (4.2.12)

where:

PWF	Present-Worth Factor referred to the initial operating time
k_O	Operating year (referred to the initial operating time)

6. Calculation of the Sum of the Actualized Total Annual Instalments for the entire lifetime

$$\mathrm{SATAI} = \sum_{k=1}^{N} ATAI_k \qquad (4.2.13)$$

7. Calculation of the Sum of the Actualized Annual Transport Capacities for the entire lifetime

$$\mathrm{SAAC} = \sum_{k_O=1}^{N_C} AC_{k_O} \qquad (4.2.14)$$

where:

AC_{k0}= Annual transport Capacity (relevant to year k_O)

8. Calculation of the Actualized Transport Cost Index

$$\mathrm{ATCI} = \frac{SATAI}{SAAC} \qquad (4.2.15)$$

4.3 PIPELINE HYDRAULICS

Schlumberger Olga v2017 has been used for the network steady state analysis. A representation of the hydraulic model used for simulation purposes is shown in the below Figure 4.3.1 (relevant to the West Trunkline System).

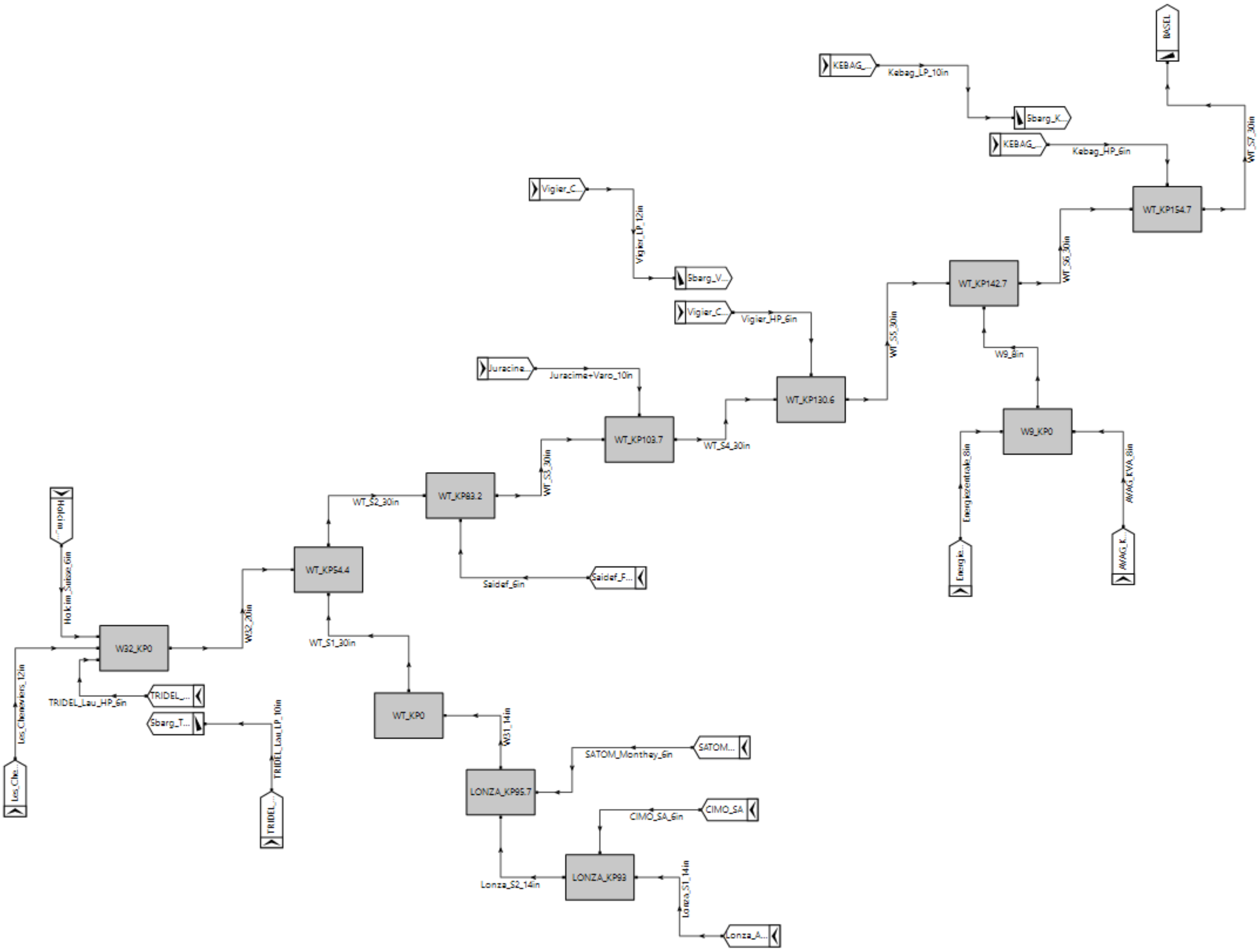


Figure 4.3.1: OLGA Hydraulic Model for West Trunkline System.

Olga is a dynamic one-dimensional model for three-phase hydrocarbon flow in pipelines and pipelines networks, also capable to simulate process equipment as compressors, heat exchangers, separators, check-valves, controllers and mass sources/sinks. Olga model consists of separate continuity equations for the gas, liquid bulk and liquid droplets that can be coupled through interfacial mass transfer. Only two momentum equations are used: one for the continuous liquid phase and one for the combination of gas and possible liquid droplets. One mixture energy equation is applied; both phases are at the same temperature. This yields 6 conservation equations. Boundary conditions define the interface between the pipeline system and its surroundings. Basically, either flow rate or pressure must be specified at each pipeline boundary. Necessary fluid properties (gas/liquid mass fraction, density, viscosity, etc.) are assumed to be function of temperature and pressure and have to be supplied by the user as tables in a special input file. Two basic flow regime classes are applied: distributed and separated flow. OLGA can also be applied for simulation of one phase flows, both steady state and transient for gas and steady state and slow transient for liquid. In particular, it can be applied to simulate emergency or maintenance depressurizations of gas piping and pipeline systems.

The hydraulic modelling used in the optimization methodology as per previous Section 4.2 is based on the full consideration of fluid thermodynamics and heat exchange between pipe and soil. The adopted pressure drop model describes the steady flow of gas along a pipe section with constant cross section. The relevant friction factor is calculated according to Darcy method.

Both winter and summer transport conditions are analysed.

Pipeline hydraulic calculations are carried out by solving the whole set of conservation equations, that in their transient 1D formulation are given below (see Ref. [5]):

Continuity: $$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0 \quad (4.3.1)$$

Momentum: $$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u^2}{\partial x} = -\frac{\partial p}{\partial x} - \frac{\lambda}{D_i}\frac{\rho u^2}{2} + \rho g \cos\alpha \quad (4.3.2)$$

Energy: $$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho u H}{\partial x} = \frac{4}{D_i} h_0 (T - T_w) \quad (4.3.3)$$

where:

ρ = fluid density
u = fluid velocity
t = time
x = longitudinal coordinate
λ = Darcy friction coefficient
D_i= Pipe inner diameter
α = elevation angle
g = gravity constant
E= specific internal energy
H = specific enthalpy
h_0= internal heat transfer coefficient
T = fluid temperature
T_w= inner pipe wall temperature

Clearly steady state conditions are simulated by dropping the time dependent terms in the above equations. The inner pipe wall temperature T_w is related to the environment temperature T_e and can be calculated on the basis of the heat flux through the pipe wall and to the environment.

In steady state conditions, the right side of Equation (4.3.3) can be expressed through the overall heat transfer coefficient U_0:

$$\frac{4}{D_i}U_0(T-T_e) \quad (4.3.4)$$

$$U_0 = r_0^{-1}\left(\frac{1}{r_0h_0}+\frac{1}{k_s}\ln\left(\frac{r_e}{r_0}\right)+\frac{1}{r_eh_e}\right)^{-1} \quad (4.3.5)$$

where:
r_0 = pipeline inner radius
r_e = pipeline outer radius
k_s = conductive pipe wall material thermal conductivity
h_e = external heat transfer coefficient

Equation (4.3.5) shows that the heat transfer process between the pipeline internal fluid and the environment is due to different contributions:

- Internal forced convection between fluid and pipe wall (natural convection will occur only if static conditions are considered)
- Conduction through pipe wall layers
- External conduction through soil for pipeline buried sections.

The temperature trend along the pipeline length is obtained, starting from specified inlet conditions, by considering both the fluid cooling by expansion (Joule-Thompson effect) and the heat exchange between fluid inside the pipeline and the external environment through the pipe wall.

The friction factor coefficient λ is obtained by the Colebrook-White correlation for rough pipes (see Ref. [6]):

$$\frac{1}{\sqrt{\lambda}} = -2Log\left(\frac{\varepsilon}{3.7Di}+\frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \quad (4.3.6)$$

where:
ε = pipe roughness
Re = fluid Reynolds number

The internal heat transfer coefficient is given by Sieder-Tate correlation (see Ref. [23]):

$$h_0 = 0.026\frac{k}{Di}\left(\mathrm{Pr}^{1/3}\right)\mathrm{Re}^{0.8} \quad (4.3.7)$$

where k is the internal fluid thermal conductivity and Pr is the internal fluid Prandtl number.
The external heat transfer coefficient h_e from the outer surface of a buried pipeline to the soil, in steady state conditions, is given by (see Ref. [7]):

$$h_e = \frac{k_{soil}}{r_e\cosh^{-1}\left(H/r_e\right)} \quad (4.3.8)$$

Where:
k_{soil} = Soil thermal conductivity
H = Centre pipe depth (m)

The soil-pipe heat transfer modelling based on the application of Equation (4.3.8) reduces the complex 2D thermal problem of the buried pipe in the soil to a 1D formulation applicable to the cylindrical geometry modelling.

5. PIPELINE WALL THICKNESS CALCULATION

5.1 PIPELINE WALL THICKNESS AS PER ISO-13623

In Table 5.1.1 and Table 5.1.2 the wall thickness calculations for gaseous transport pipelines are reported. Table 5.1.3 reports the calculation for the dense phase transport pipelines. Commercial wall thicknesses have been selected based on ASME B36.10M. The minimum construction wall thicknesses reported in BS EN 13480 are also taken into consideration for the wall thickness selection.

For hydraulic simulation purposes, the wall thickness relevant to a design factor of 0.67 is considered. A detailed class location analysis is to be performed in the next phase of the project.

Table 5.1.1: Wall Thickness Calculation Summary (ISO-13623) – Low Pressure Flowlines (DP = 13 barg)

ND	OD	CA	Steel Grade	DP	DF	SMYS	Longit. Joint Factor	Calc WT ISO 13623	Calc WT + CA	Negative Mill Tolerance	Nominal WT	Commercial Selected WT
[in]	[mm]	[mm]	-	[barg]	-	[barg]	-	[mm]	[mm]	[mm]	[mm]	[mm]
6"	168.3	1.00	X-65	13.0	0.55	4480	1	0.44	1.44	0.50	1.94	4.78
6"	168.3	1.00	X-65	13.0	0.67	4480	1	0.36	1.36	0.50	1.86	4.78
6"	168.3	1.00	X-65	13.0	0.77	4480	1	0.32	1.32	0.50	1.82	4.78
8"	219.1	1.00	X-65	13.0	0.55	4480	1	0.58	1.58	0.50	2.08	6.35
8"	219.1	1.00	X-65	13.0	0.67	4480	1	0.47	1.47	0.50	1.97	6.35
8"	219.1	1.00	X-65	13.0	0.77	4480	1	0.41	1.41	0.50	1.91	6.35
10"	273.0	1.00	X-65	13.0	0.55	4480	1	0.72	1.72	0.50	2.22	6.35
10"	273.0	1.00	X-65	13.0	0.67	4480	1	0.59	1.59	0.50	2.09	6.35
10"	273.0	1.00	X-65	13.0	0.77	4480	1	0.51	1.51	0.50	2.01	6.35
12"	323.8	1.00	X-65	13.0	0.55	4480	1	0.85	1.85	0.50	2.35	6.35
12"	323.8	1.00	X-65	13.0	0.67	4480	1	0.70	1.70	0.50	2.20	6.35
12"	323.8	1.00	X-65	13.0	0.77	4480	1	0.61	1.61	0.50	2.11	6.35
14"	355.6	1.00	X-65	13.0	0.55	4480	1	0.94	1.94	0.50	2.44	6.35
14"	355.6	1.00	X-65	13.0	0.67	4480	1	0.77	1.77	0.50	2.27	6.35
14"	355.6	1.00	X-65	13.0	0.77	4480	1	0.67	1.67	0.50	2.17	6.35
16"	406.4	1.00	X-65	13.0	0.55	4480	1	1.07	2.07	0.50	2.57	6.35
16"	406.4	1.00	X-65	13.0	0.67	4480	1	0.88	1.88	0.50	2.38	6.35
16"	406.4	1.00	X-65	13.0	0.77	4480	1	0.76	1.76	0.50	2.26	6.35
18"	457.0	1.00	X-65	13.0	0.55	4480	1	1.20	2.20	0.50	2.70	6.35
18"	457.0	1.00	X-65	13.0	0.67	4480	1	0.99	1.99	0.50	2.49	6.35
18"	457.0	1.00	X-65	13.0	0.77	4480	1	0.86	1.86	0.50	2.36	6.35
24"	610.0	1.00	X-65	13.0	0.55	4480	1	1.60	2.60	0.50	3.10	7.92
24"	610.0	1.00	X-65	13.0	0.67	4480	1	1.32	2.32	0.50	2.82	7.92
24"	610.0	1.00	X-65	13.0	0.77	4480	1	1.15	2.15	0.50	2.65	7.92

Table 5.1.2: Wall Thickness Calculation Summary (ISO-13623) – High Pressure Gaseous Phase Pipelines (DP = 40 barg)

ND	OD	CA	Steel Grade	DP	DF	SMYS	Longit. Joint Factor	Calc WT ISO 13623	Calc WT + CA	Negative Mill Tolerance	Nominal WT	Commercial Selected WT
[in]	[mm]	[mm]	-	[barg]	-	[barg]	-	[mm]	[mm]	[mm]	[mm]	[mm]
6"	168.3	1.00	X-65	40.0	0.55	4480	1	1.36	2.36	0.50	2.86	4.78
6"	168.3	1.00	X-65	40.0	0.67	4480	1	1.11	2.11	0.50	2.61	4.78
6"	168.3	1.00	X-65	40.0	0.77	4480	1	0.97	1.97	0.50	2.47	4.78
8"	219.1	1.00	X-65	40.0	0.55	4480	1	1.76	2.76	0.50	3.26	6.35
8"	219.1	1.00	X-65	40.0	0.67	4480	1	1.45	2.45	0.50	2.95	6.35
8"	219.1	1.00	X-65	40.0	0.77	4480	1	1.26	2.26	0.50	2.76	6.35
10"	273.0	1.00	X-65	40.0	0.55	4480	1	2.20	3.20	0.50	3.70	6.35
10"	273.0	1.00	X-65	40.0	0.67	4480	1	1.81	2.81	0.50	3.31	6.35
10"	273.0	1.00	X-65	40.0	0.77	4480	1	1.57	2.57	0.50	3.07	6.35
12"	323.8	1.00	X-65	40.0	0.55	4480	1	2.61	3.61	0.50	4.11	6.35
12"	323.8	1.00	X-65	40.0	0.67	4480	1	2.14	3.14	0.50	3.64	6.35
12"	323.8	1.00	X-65	40.0	0.77	4480	1	1.87	2.87	0.50	3.37	6.35
14"	355.6	1.00	X-65	40.0	0.55	4480	1	2.86	3.86	0.50	4.36	6.35
14"	355.6	1.00	X-65	40.0	0.67	4480	1	2.35	3.35	0.50	3.85	6.35
14"	355.6	1.00	X-65	40.0	0.77	4480	1	2.05	3.05	0.50	3.55	6.35
16"	406.4	1.00	X-65	40.0	0.55	4480	1	3.27	4.27	0.61	4.88	6.35
16"	406.4	1.00	X-65	40.0	0.67	4480	1	2.69	3.69	0.50	4.19	6.35
16"	406.4	1.00	X-65	40.0	0.77	4480	1	2.34	3.34	0.50	3.84	6.35
20"	508.0	1.00	X-65	40.0	0.55	4480	1	4.09	5.09	0.73	5.82	7.92
20"	508.0	1.00	X-65	40.0	0.67	4480	1	3.36	4.36	0.62	4.99	7.92
20"	508.0	1.00	X-65	40.0	0.77	4480	1	2.93	3.93	0.50	4.43	7.92
22"	559.0	1.00	X-65	40.0	0.55	4480	1	4.50	5.50	0.79	6.29	7.92
22"	559.0	1.00	X-65	40.0	0.67	4480	1	3.70	4.70	0.67	5.37	7.92
22"	559.0	1.00	X-65	40.0	0.77	4480	1	3.22	4.22	0.60	4.83	7.92
24"	610.0	1.00	X-65	40.0	0.55	4480	1	4.91	5.91	0.84	6.76	7.92
24"	610.0	1.00	X-65	40.0	0.67	4480	1	4.04	5.04	0.72	5.76	7.92
24"	610.0	1.00	X-65	40.0	0.77	4480	1	3.52	4.52	0.65	5.16	7.92
30"	762.0	1.00	X-65	40.0	0.55	4480	1	6.14	7.14	1.02	8.15	9.53
30"	762.0	1.00	X-65	40.0	0.67	4480	1	5.04	6.04	0.86	6.91	9.53
30"	762.0	1.00	X-65	40.0	0.77	4480	1	4.39	5.39	0.77	6.16	9.53

Table 5.1.3: Wall Thickness Calculation Summary (ISO-13623) – Dense Phase Pipelines (DP = 150 barg)

ND	OD	CA	Steel Grade	DP	DF	SMYS	Longit. Joint Factor	Calc WT ISO 13623	Calc WT + CA	Negative Mill Tolerance	Nominal WT	Commercial Selected WT
[in]	[mm]	[mm]	-	[barg]	-	[barg]	-	[mm]	[mm]	[mm]	[mm]	[mm]
6"	168.3	1.00	X-65	150.0	0.55	4480	1.000	4.97	5.97	0.85	6.82	7.11
6"	168.3	1.00	X-65	150.0	0.67	4480	1.000	4.10	5.10	0.73	5.83	7.11
6"	168.3	1.00	X-65	150.0	0.77	4480	1.000	3.58	4.58	0.65	5.24	7.11
8"	219.1	1.00	X-65	150.0	0.55	4480	1.000	6.47	7.47	1.07	8.54	8.74
8"	219.1	1.00	X-65	150.0	0.67	4480	1.000	5.34	6.34	0.91	7.25	8.74
8"	219.1	1.00	X-65	150.0	0.77	4480	1.000	4.66	5.66	0.81	6.47	8.74
10"	273.0	1.00	X-65	150.0	0.55	4480	1.000	8.06	9.06	1.29	10.36	11.13
10"	273.0	1.00	X-65	150.0	0.67	4480	1.000	6.66	7.66	1.09	8.75	11.13
10"	273.0	1.00	X-65	150.0	0.77	4480	1.000	5.81	6.81	0.97	7.78	11.13
14"	355.6	1.00	X-65	150.0	0.55	4480	1.000	10.50	11.50	1.64	13.15	14.27
14"	355.6	1.00	X-65	150.0	0.67	4480	1.000	8.67	9.67	1.38	11.05	14.27
14"	355.6	1.00	X-65	150.0	0.77	4480	1.000	7.57	8.57	1.22	9.79	14.27
16"	406.4	1.00	X-65	150.0	0.55	4480	1.000	12.00	13.00	1.86	14.86	15.88
16"	406.4	1.00	X-65	150.0	0.67	4480	1.000	9.91	10.91	1.56	12.47	15.88
16"	406.4	1.00	X-65	150.0	0.77	4480	1.000	8.65	9.65	1.38	11.03	15.88

After wall thickness definition, a suitable value of Charpy Energy to avoid ductile fracture propagation has to be determined. This issue is mainly relevant to the transport in dense phase conditions, occurring at high operating pressure, that could involve significant toughness requirements to avoid fracture propagation; in fact, as a consequence of the rupture induced depressurization the internal fluid persists in two-phase conditions for a significant time and length, with pressure kept high at the relevant saturation value thus promoting fracture propagation.

The methodology followed to determined steel toughness requirements is reported in described in ISO 27913-2016. This methodology is based on the fact that the decompression curve for CO_2-based mixtures typically exhibits a very long, constant pressure plateau. Thus, by referring to the BTCM approach, the procedure for determining arrest toughness can be set by ensuring that the arrest pressure (the intercept of the fracture velocity curve on the pressure axis) is higher than the saturation pressure (corresponding to the pressure plateau) for all conditions within the operating envelope. Following ISO 27913-2016, by putting the fracture velocity to zero and the arrest pressure set equal to the highest pressure at which the decompression path intersects the phase boundary P_d, the Battelle fracture arrest equation becomes:

$$C_V = \frac{-24\sigma_f^2\sqrt{\frac{Dt}{2}}}{12.5\pi E} ln\left[1.2cos\left(\frac{3.33\pi\sigma_d}{2\sigma_f}\right)\right] \qquad \text{(Eq.5.1.1)}$$

where:

$$\sigma_d = \frac{P_d D}{2t}$$

$\sigma_f = SMYS + 69MPa$

C_V = Charpy Energy (J)
σ_f = flow stress (MPa)
σ_d = arrest stress (MPa)
E = steel Young's modulus (MPa)
D = outside pipe diameter (mm)
t = pipe wall thickness (mm)

In this study, a conservative estimation of Charpy Energy has been made by considering the possibility to transport off-spec fluid composition, even if the design composition is an almost pure CO_2.
Hence, the resulting selected cricondenbar for arrest toughness calculations is 8.5 MPa.

For the dense phase pipeline system, the governing factor to determine the pipeline wall thickness minimum requirements is the resistance to ductile fracture propagation described above. The thickness values reported in Table 5.1.3 satisfy this requirement.

6. FLUID THERMODYNAMIC CALCULATIONS

Fluid thermodynamic analysis has been carried out by Multiflash v6.2 on the basis of the composition reported in Section 3.4, using the following correlations:

- Equation of State GERG-2008
- Viscosity Correlation SuperTRAPP
- Thermal Conductivity Correlation SuperTRAPP

Following Figure 5.1.1 reports phase envelope for the reference compositions of Table 3.4.1.

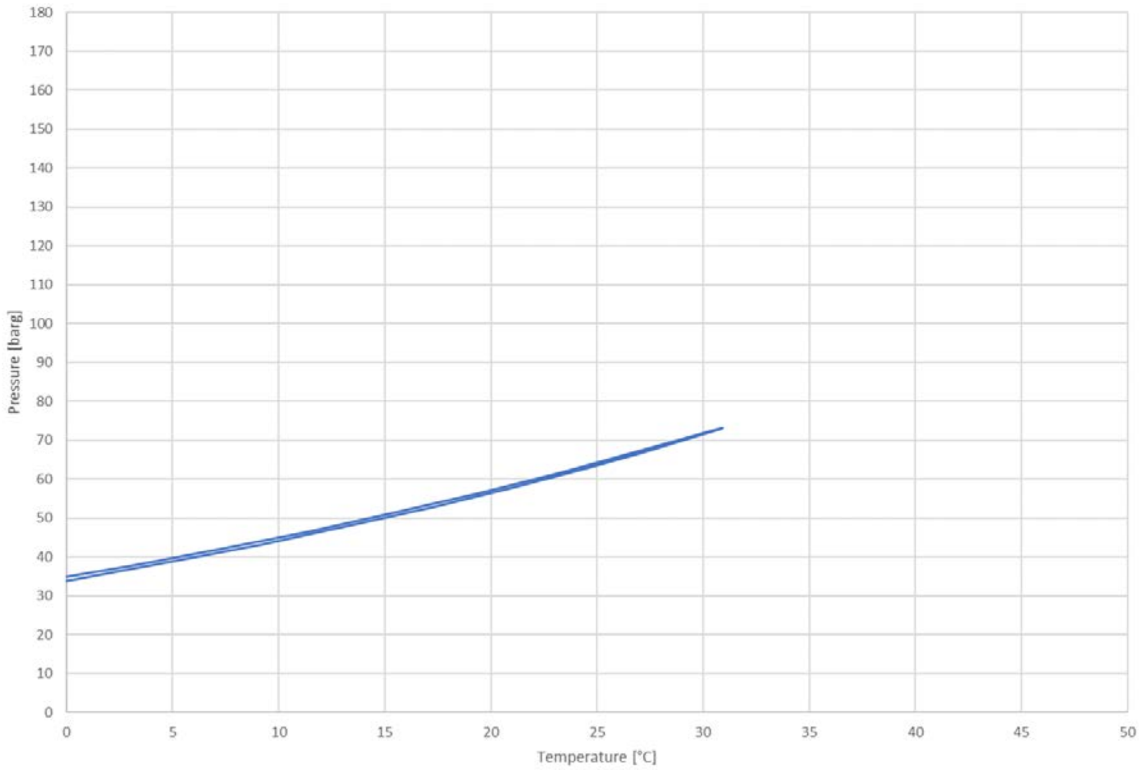


Figure 5.1.1: CO_2 Phase Envelope

In order to confirm the properties predicted by Multiflash, a comparison with reference NIST database data has been performed and it is reported in the following Figure 5.1.2 and Figure 5.1.3 for density and viscosity respectively, in terms of variations with pressure. The fluid properties are evaluated at three different temperatures: 16°C, 30°C and 45°C.

In all cases, a good matching of the Multiflash properties with the NIST database can be observed and the accuracy of the thermodynamic model is confirmed.

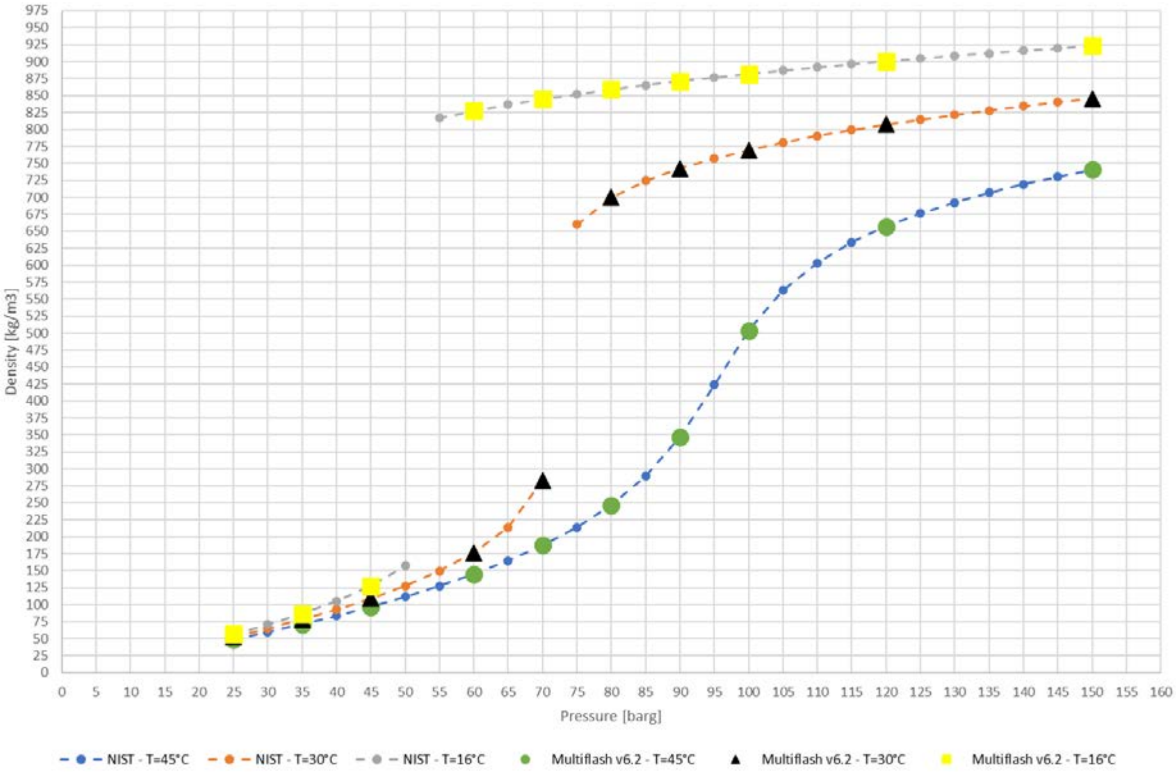


Figure 5.1.2: NIST vs Multiflash v6.2 – Density Comparison

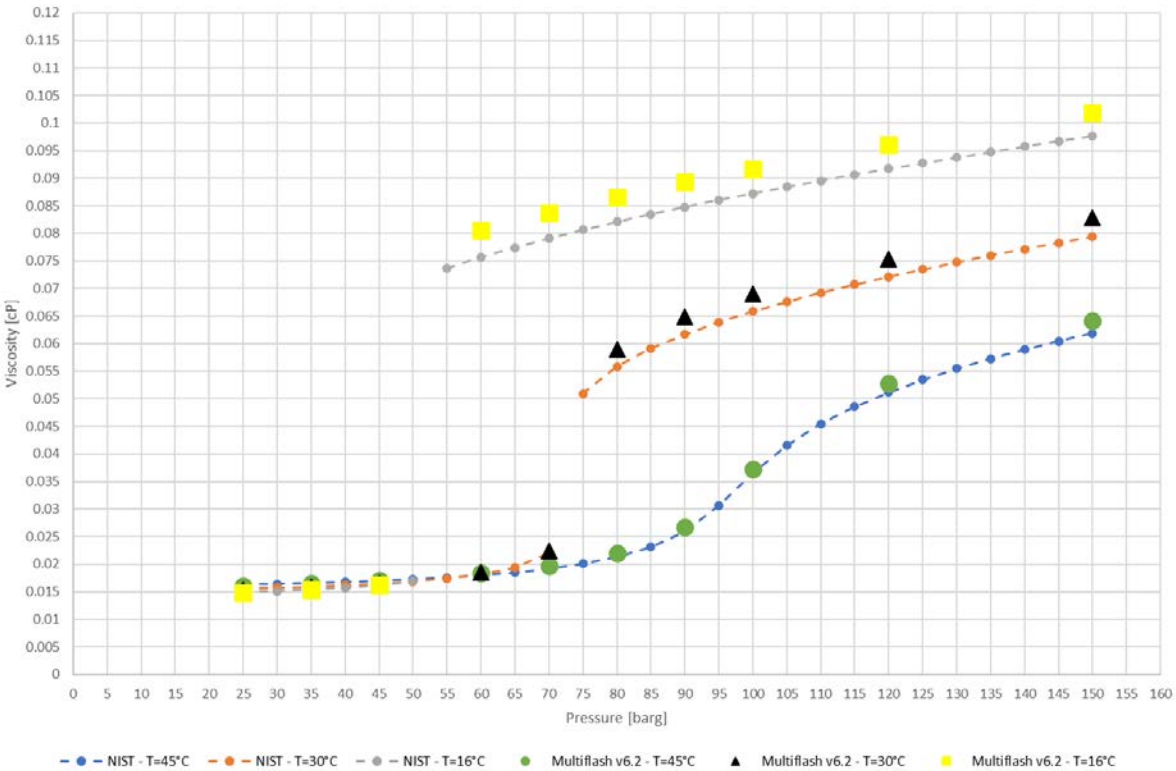


Figure 5.1.3: NIST vs Multiflash v6.2 – Viscosity Comparison

7. PIPELINE SYSTEM POSSIBLE CONFIGURATIONS

7.1 POSSIBLE REFERENCE PIPELINE CONFIGURATIONS

Two different options have been considered for the transport of the CO2 from the emitter up to the delivery points:

- Gaseous Phase Transport: maximum operating pressure = 35 barg, design pressure = 40 barg. This is the maximum pressure level that guarantees no liquid formation in the line and assures single phase transport (i.e. purely gas). This solution has the advantage to keep quite low pressures in the system, however large diameters could be required in case of high flowrates.

- Dense Phase Transport: maximum operating pressure = 145 barg, design pressure = 150 barg. Dense phase transport for CO2 is particularly efficient, as the CO2 in dense phase conditions shows the density of a liquid and the viscosity of a gas. A maximum design pressure of 150 barg is considered being the limit for rating #900: higher pressures are possible but more expensive with no substantial advantages. In order to keep the CO2 in dense phase, a minimum pressure of 85 barg is to be maintained along the lines.

Each emitter is connected to the main trunkline by means of a dedicated flowline. Two different options are identified to connect the flowlines to the trunkline (refer to Figure 7.1.1):

- Manifold Type Configuration: a group of flowlines (usually close to each other) are collected in a manifold and then connected to the trunkline with a single line.
- Finger Type Configuration: each emitter is directly connected to the trunkline with a dedicated flowline.

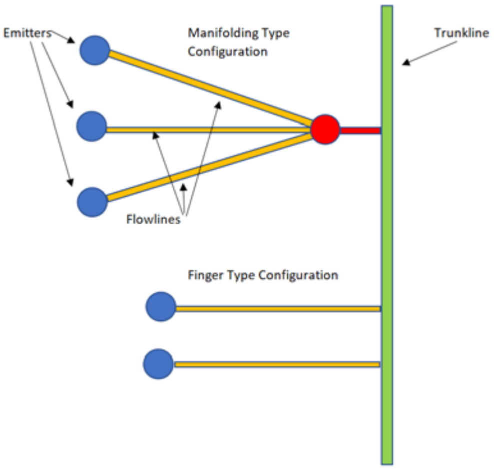


Figure 7.1.1: Possible configurations for the network flowlines.

The finger type configuration is particularly efficient in case of gaseous phase transport, as the compression station located at the emitter can provide the pressure required to enter the trunkline without the need for any additional compression.
On the other hand, the manifold type configuration could be the best choice in case of dense phase transport: the flowlines operate in gaseous phase and the boosting station at the manifold provides the pressure to enter the dense phase trunkline.

Due to safety restrictions, in some areas it will probably not be possible to install a high pressure flowline (either gaseous or dense phase). This condition is typical of urban areas, with high density population. For these areas low pressure flowlines shall be installed, with a maximum operating pressure of 10 barg. In principle, plastic pipes could be adopted for low pressure flowlines as well as carbon steel.
According to the above, 4 configurations are identified for the connection of the flowlines to the trunkline, as shown in Figure 7.1.2:

- Configuration 1: gaseous phase transport, no low pressure flowlines. Only the compression at emitters is required.
- Configuration 2: dense phase transport, no low pressure flowlines. Dense phase boosting compression is foreseen at the manifold. Some areas could present safety limitations for dense pressure transport: in this case a full compression is required downstream the constrained area.
- Configuration 3: gaseous phase transport with possibility of low pressure flowlines. Additional compression is required outside urban areas. Plastic pipes could be used for low pressure flowlines.
- Configuration 4: dense phase transport with possibility of low pressure flowlines. Dense phase boosting compression is foreseen at the manifold. Additional compression is required outside urban areas. Plastic pipes could be used for low pressure flowlines.

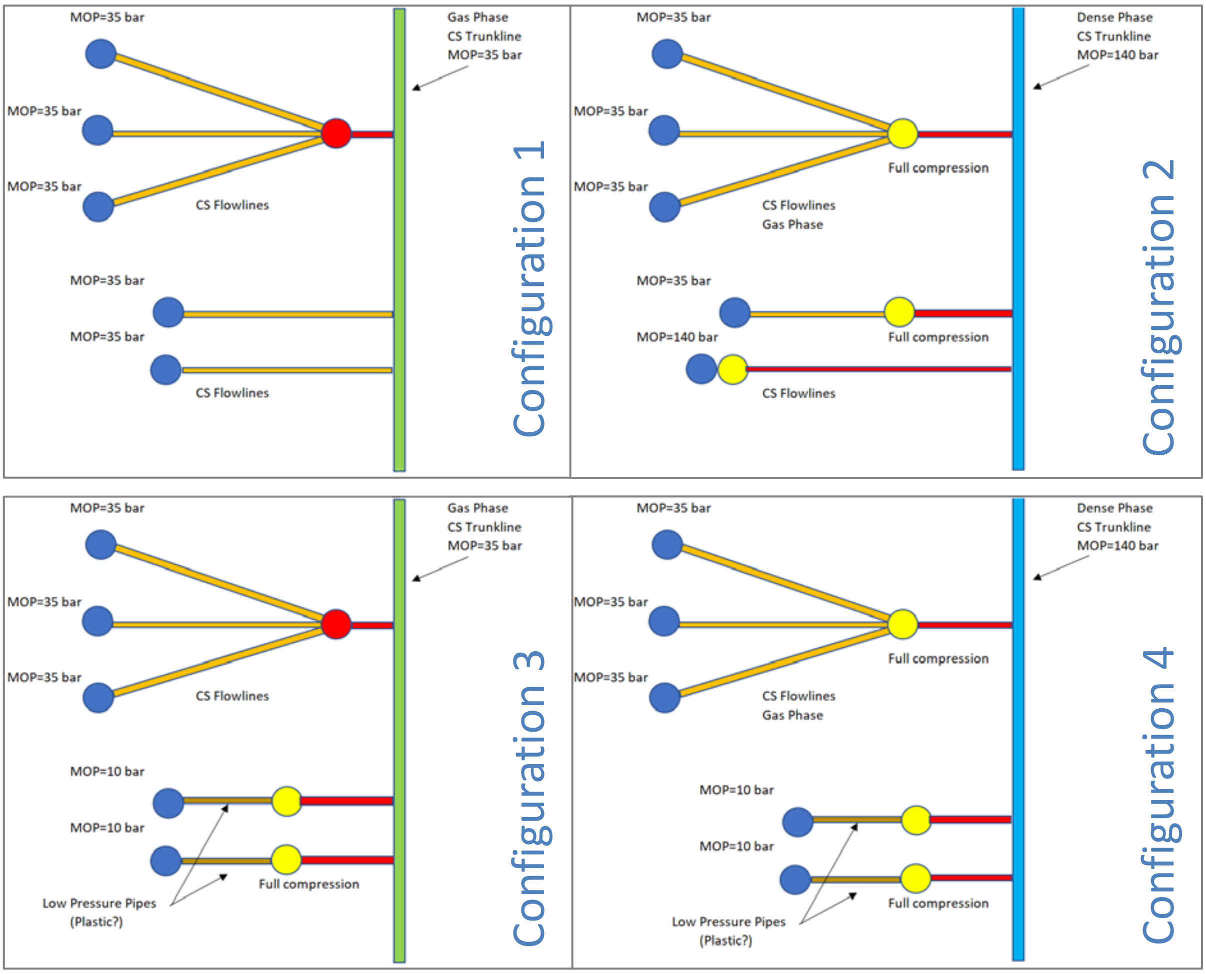


Figure 7.1.2: Possible System Configurations

7.2 DEHYDRATION ARRANGEMENT

The CO2 supplied at the emitters from capture units is wet at atmospheric conditions.

Dehydration units could be installed either at the emitter (decentralized dehydration) or at the system manifolds (centralized dehydration). In case of centralized dehydration, plastic pipes could be considered to transport the wet CO2 up to the manifold avoiding the corrosion issues that would arise using carbon steel pipes.

However, as shown in the below Figure 7.2.1, if the CO2 enters the pipeline at saturated conditions, either at atmospheric pressure or after the compression required to enter the line, the pipeline operating curve enters the water formation region, leading to water condensation in the line.
In a reference flowline of 10" size and 20 km long, with CO2 captured from flue gases and saturated at atmospheric conditions, a water content of around 5 m^3 is predicted in steady state conditions in the line, which can increase during transient operations (i.e. shutdown).
If the CO2 is saturated at pipeline inlet conditions (i.e. compressor discharge), a liquid content of 1.5 m^3 is predicted in the line due to fluid cooling and consequent condensation.
A similar behavior is expected in the other flowlines, which can be even larger than 10” or longer than 20 km, worsening the liquid accumulation in the line. Significant water accumulation volumes in the lines can cause system instability (i.e. compressors malfunctioning, slug flow, etc...).
Due to this it is recommended to dehydrate the CO2 stream coming from flue gases at atmospheric conditions before entering the lines (i.e. the centralized dehydration solution is disregarded).

According to the above, carbon steel pipes can be used for low pressure flowlines, being the CO2 already dehydrated, with no corrosion issues. This conclusion is also strengthened by the fact that no significant savings are expected by using plastic instead of carbon steel. In fact, in order to operate at the required pressure and temperature ranges (MOP = 10 barg, MOT = 45°C), large wall thicknesses are required for the HDPE pipes (in the order of centimeters). This leads to material costs similar to the carbon steel option and on the other hand implies a series of criticalities relevant to the construction, in particular for the welding process.
Due to the above reasons the adoption of plastic pipes for the low pressure flowlines is discouraged and carbon steel is considered for the whole pipeline system.

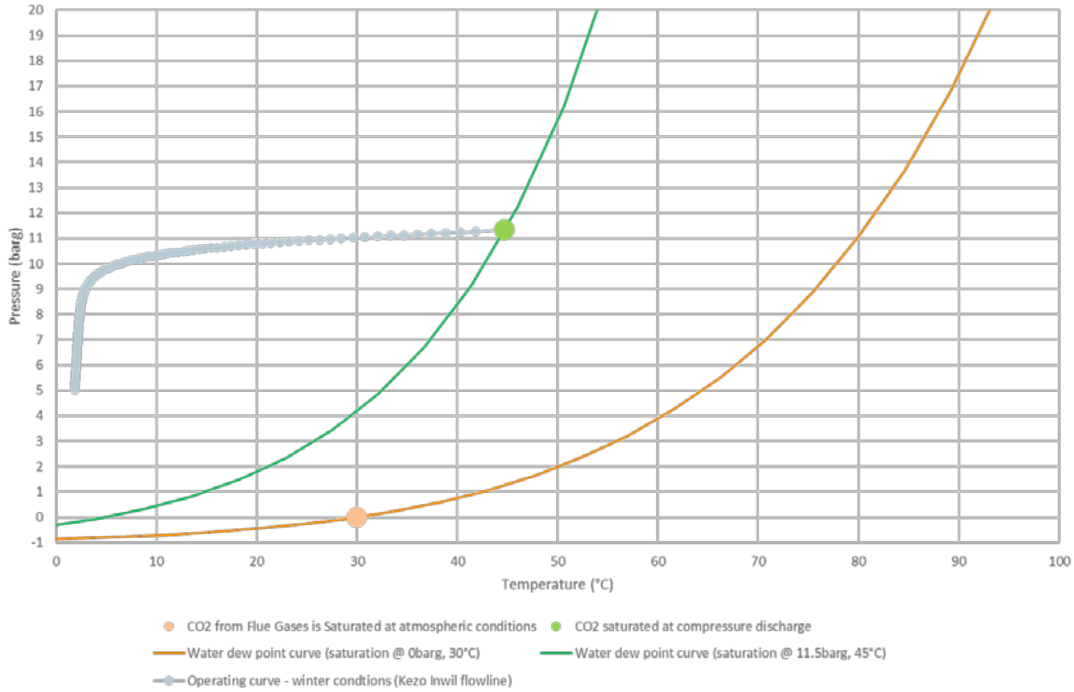


Figure 7.2.1: Water dew point curve at atmospheric conditions and pipeline inlet condition vs operating curve

As reported in Section 3.8, acceptable efficiencies for the dehydration process are achieved at operating pressure above 20 bar. Since the dehydration is decentralized and located at each emitter, if it is located outside urban areas it can be concluded that:

- In case of gaseous phase transport, it is always convenient to compress the CO2 up to the MOP of 35 barg in order to save compression stations along the network.
- In case of dense phase transport, the compression at the emitter will be either up to 35 barg or 145 barg depending on the type of flowlines configuration (i.e. manifold type or finger type)

If the emitter is located inside an urban area instead, a first compression is required at the emitter up to 20 barg in order to efficiently carry out the dehydration process. After the dehydration process, the pressure shall be reduced down to the MOP of the low pressure flowline by means of a lamination valve, with consequent energy dissipation. Once outside the urban area, an additional compression station shall be installed to boost the CO2 stream up to the required trunkline pressure (see the below Figure 7.2.2 relevant to low pressure flowlines in manifold type configuration, gaseous phase transport scenario).

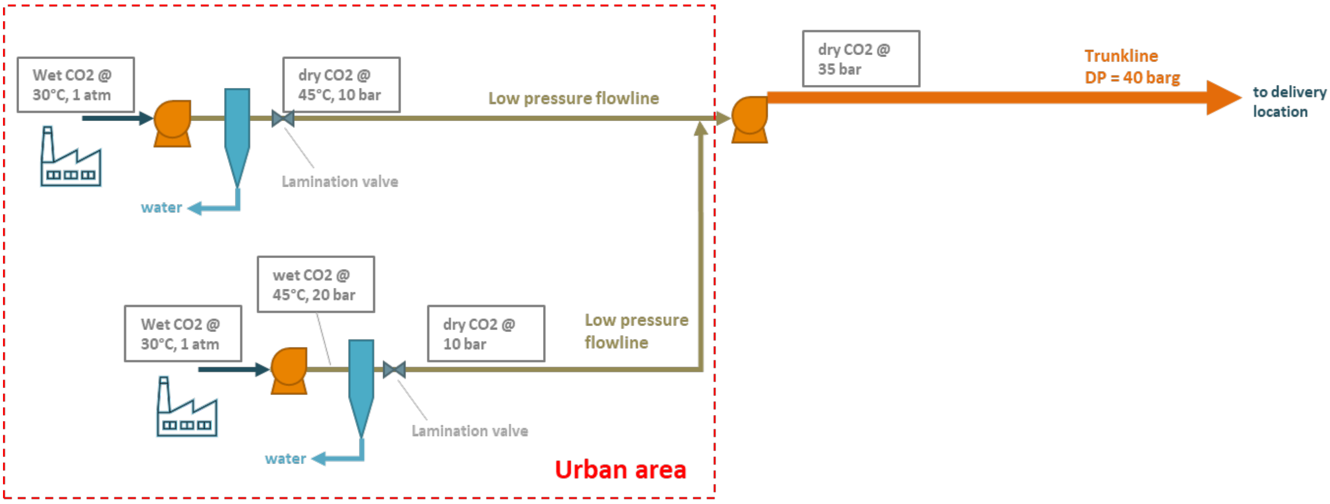


Figure 7.2.2: Compression units required in case of low pressure flowlines – Manifold type configuration.

7.3 RECOMMENDED EXCLUSION OF GIUBIASCO CO2 SOURCE

According to the coordinates provided in Table 3.2.1, the emitter of Giubiasco is isolated and located about 100 km far from the nearest emitter (Axpo Tegra). The routing development for this flowline is extremely challenging, crossing both mountain regions and a narrow densely populated valley (see Figure 7.3.1).

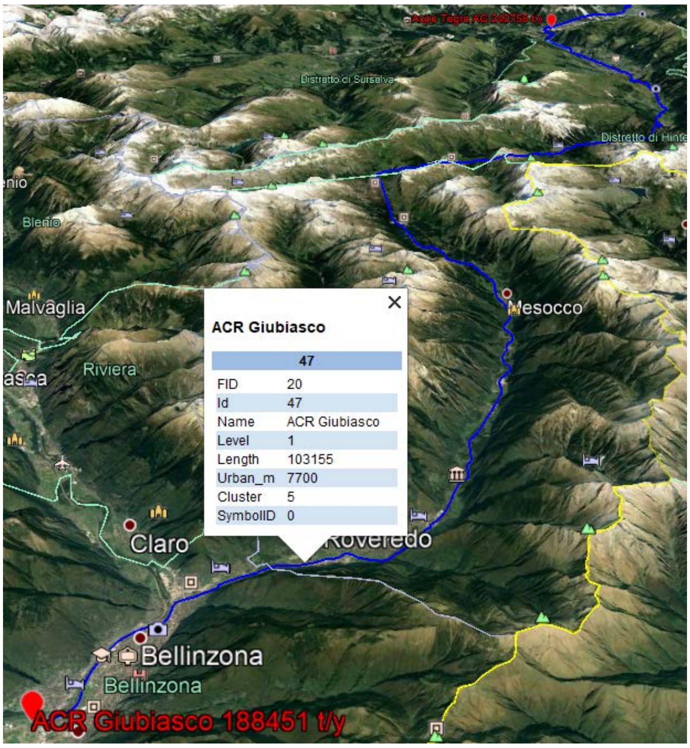


Figure 7.3.1: Giubiasco Flowline routing.

Giubiasco emitter contributes for only 2% of the total emissions (4% of the East Trunkline flowrate).
It is estimated that due to the length and the complications peculiar to this flowline, its cost has an impact on the East trunkline system CAPEX in excess of 20% (10% of the overall system pipeline CAPEX).

Due to the above it is recommended to exclude Giubiasco from the emitters to be connected to the CO2 collection network.

In all the system configurations analysed in this document this emitter and the relevant flowline have been disregarded.

8. PIPELINE TRANSPORT SYSTEM IN GAS PHASE

8.1 PIPELINE NETWORK OPERATING IN GAS PHASE

In the below Figure 8.1.1 and Figure 8.1.2 the network configuration for the CO2 transport in gaseous phase is shown for the West and East Trunkline Systems respectively.
This configuration represents the base case configuration for gaseous phase transport and it has been developed based on the routing of each flowline and of the 2 trunklines (Ref.[8],[9]).
The following is to be considered:

- A compression station with dehydration unit is present at each emitter. If the relevant flowline does not cross any urban area no additional CS is required, otherwise one additional flowline is required once outside the urban area. The low pressure flowlines are considered with a MOP = 10 barg.
- Due to the above, the finger type configuration has been preferred for both East and West Systems, with few exceptions (Zurich area flowlines and Gekal Buchs / Jura Cement lines)
- In the East System (Figure 8.1.2), Turgi LP flowline is assumed to be routed into Holcim 1 plant. At this location the Turgi HP compression will be foreseen together with Holcim 1 compression. This allows to save 1 compression station.
- The 30” West Trunkline is 229 km long and includes 16 km of offshore section relevant to the crossing of Geneva Lake. This trunkline can operate in both directions (i.e. to Basel and to Collombey). When operating towards Collombey, with Basel delivery shutdown, it is capable of collecting part of the East Trunkline rate.
- The 30” East Trunkline is 142 km long and it is assumed to transport CO2 up to Basel delivery point as base transport configuration. An additional 20” trunkline of 57 km is foreseen to collect the CO2 coming from the Rhine Valley emitters.

Together with the above described base case configuration, the following sensitivity cases are considered to provide comparative values of ATCI:

1. **“Collombey Split”.** This configuration is analyzed to evaluate the savings expected without the installation of the first 54 km of the West Trunkline, including the offshore section of the Geneva Lake. In this scenario both Basel and Collombey deliveries are operating simultaneously. Only the emitters south of Collombey (Lonza, Cimo and Satom Monthey) are routed to Collombey, whereas the rest of the emitters deliver the CO2 to Basel (no modification for the East Trunkline, the West Trunkline starts at KP54 – refer to Figure 8.1.1).

2. **Low Pressure Flowlines MOP = 5 barg.** This configuration is as per base case, with the difference that the maximum operating pressure for the low pressure flowlines is 5 barg instead of 10 barg. This scenario is considered to evaluate cost impact of larger low pressure flowlines, in case the MOP has to be decreased due to safety/regulation constraints.

3. **No low pressure flowlines.** This configuration considers the possibility to install high pressure flowlines (i.e. MOP = 35 barg) in urban areas also. This scenario allows to evaluate the cost impact of the low pressure flowlines, and to quantify the potential savings in case urban area restrictions are relaxed.

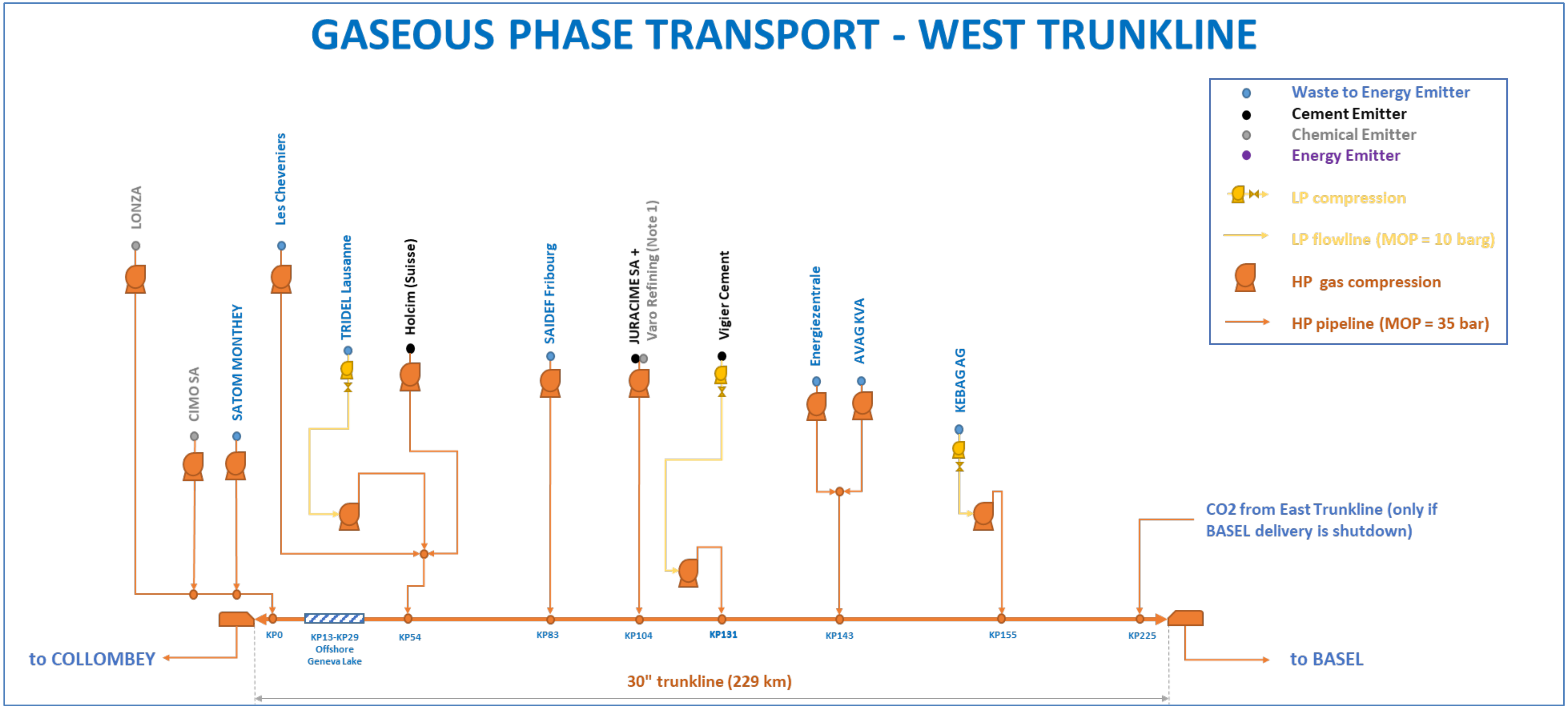


Figure 8.1.1: West Trunkline System for Gaseous Phase Transport (Base Case).

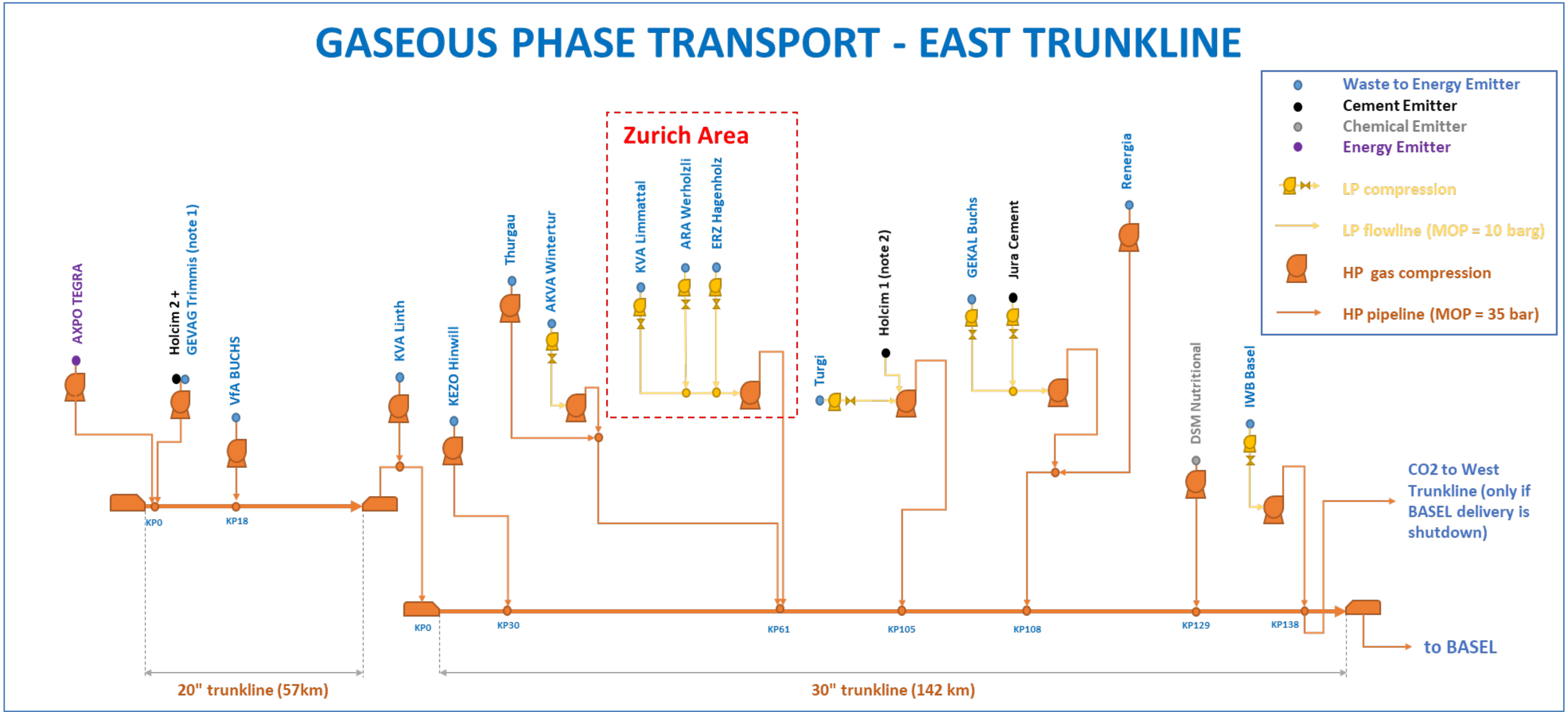


Figure 8.1.2: East Trunkline System for Gaseous Phase Transport (Base Case).

8.2 Pressure And Temperature Profiles At Design Conditions In Gas Phase

In the following Table 8.2.1 and Table 8.2.2 the pipe sizes for all network segments are reported together with the calculated pressure and flowrates at system nodes, for west and east trunklines respectively.

Table 8.2.1: Gaseous Phase Transport – West System. Summary of pipe sizes, rates and pressures at system nodes.

from	to	length	ND	CO2 Flowrate	CS Suction Pressure	CS discharge Pressure
-	-	m	in	ktons/y	barg	barg
LONZA AG	LONZA_KP_92.8	92980	14	366.0	0.1	32.0
Cimo SA	LONZA_KP_92.8	100	6	196.4	0.1	29.5
LONZA_KP_92.8	LONZA_KP_95.7	2700	14	562.4	-	-
SATOM Monthey	LONZA_KP_95.7	100	6	175.9	0.1	28.2
LONZA_KP_95.7	WT_KP0	2200	14	738.3	-	-
WT_KP0	WT_KP13.5	13380	30	738.3	-	-
WT_KP13.5	WT_KP29.7	16320	30	738.3	-	-
WT_KP29.7	WT_KP54.4	24700	30	738.3	-	-
Les Cheneviers	W32_KP0	82750	12	302.1	0.1	34.4
TRIDEL Lausanne	TRIDEL LP-HP	11000	10	211.2	0.1	9.0
TRIDEL LP-HP	W32_KP0	6850	6	211.2	5.0	34.7
Holcim (Suisse) SA	W32_KP0	100	6	378.7	0.1	29.2
W32_KP0	WT_KP54.4	35800	20	892.0	-	-
WT_KP54.4	WT_KP83.2	28800	30	1630.4	-	-
SAIDEF Fribourg	WT_KP83.2	3400	6	112.8	0.1	26.4
WT_KP83.2	WT_KP103.7	20500	30	1743.2	-	-
Juracime + Varo	WT_KP103.7	17755	10	542.2	0.1	34.6
WT_KP103.7	WT_KP130.6	26900	30	2285.4	-	-
Vigier Cement AG	VIGIER LP-HP	11800	12	436.9	0.1	11.1
VIGIER LP-HP	WT_KP130.6	100	6	436.9	5.0	24.6
WT_KP130.6	WT_KP142.7	12100	30	2722.4	-	-
Energiezentrale	W9_KP0	22900	8	160.1	0.1	29.1
AVAG KVA AG	W9_KP0	46700	8	113.3	0.1	29.3
W9_KP0	WT_KP142.7	5100	8	273.4	-	-
WT_KP142.7	WT_KP154.7	12000	30	2995.8	-	-
KEBAG AG	KEBAG LP-HP	6000	10	284.2	0.1	8.9
KEBAG LP-HP	WT_KP154.7	500	6	284.2	5.0	23.2
WT_KP154.7	BASEL	74900	30	3279.9	-	-

Table 8.2.2 Gaseous Phase Transport – East System. Summary of pipe sizes, rates and pressures at system nodes.

Flowline						
from	to	length	ND	CO2 Flowrate	CS Suction Pressure	CS discharge Pressure
-	-	m	in	ktons/y	barg	barg
Axpo Tegra AG	ET_E KP0	538	8	240.8	0.1	32.1
ET_E KP0	ET_E KP15	15000	8	240.8	-	-
Holcim (Schweiz) AG	ET_E KP15	150	8	576.6	0.1	27.2
ET_E KP15	ET_E KP33.5	18400	20	817.3	-	-
VfA Buchs	ET_E KP33.5	18280	8	206.5	0.1	30.8
ET 20'' KP33.5	ET KP0	38500	20	1023.8	-	-
KVA Linth	ET KP0	434	6	123.3	0.1	23.3
ET KP0	ET KP29.7	29700	30	1147.1	-	-
KEZO Hinwil	ET KP29.7	3000	6	218.4	0.1	26.6
ET KP29.7	ET KP61.2	31400	30	1365.5	-	-
KVA Thurgau	E6 KP0	32524	10	166.1	0.1	28.6
KVA Winterthur	Winterthur LP-HP	3780	10	225.1	0.1	6.8
Winterthur LP-HP	E6 KP0	100	6	225.1	5.0	26.7
E6 KP0	ET 30'' KP61.2	13650	10	391.2	-	-
KVA Limmattal	E9 KP0	6700	8	103.6	0.1	9.5
ARA Werdholzli	E9 KP0	150	6	40.0	0.1	7.9
E9 KP0	E10 KP0	1380	8	143.6	-	-
E10 KP0	Zurich Cluster	6400	10	143.6	-	-
ERZ KHKW Hagenholz	Zurich Cluster	610	12	400.0	0.1	6.4
Zurich Cluster	Zurich LP-HP	2805	16	543.6	-	-
Zurich LP-HP	ET KP61.2	18810	10	543.6	5.0	32.8
ET KP612	ET KP104.7	43300	30	2300.3	-	-
KVA Turgi	Holcim (Schweiz) AG	5410	8	133.8	0.1	7.8
Holcim (E14)	ET KP104.7	300	8	688.3	0.1	20.8
ET KP104.7	ET KP108.3	3600	30	2988.6	-	-
Jura Cement Fabriken	E13 K0	2556	12	470.4	0.1	8.3
GEKAL Buchs	E13 K0	5000	8	156.9	0.1	9.5
E13 K0	E13 LP-HP	3400	16	627.3	-	-
E13 LP-HP	E12 K0	100	8	627.3	5.0	26.6
Renergia Zentral.	E12 K0	46500	10	286.6	0.1	33.2
E12 K0	ET KP108.3	16000	14	913.9	-	-
ET KP108.3	ET KP129.1	20800	30	3902.5	-	-
DSM Nutritional	ET KP138.1	800	6	100.9	0.1	14.9
ET KP129.1	ET KP138.1	8900	30	4003.4	-	-
IWB Basel	IWB Basel LP-HP	6100	10	242.5	0.1	8.1
IWB Basel LP-HP	ET KP138.1	42954.0	8	242.5	5.0	31.9
ET KP138.1	Basel	4200	30	4245.9	-	-

Pressure and Temperature Profiles are shown for the West and East Trunkline respectively in the below Figure 8.2.1 and Figure 8.2.2. Summer conditions are considered, being the most conservative in terms of pressure drops in the lines.
The arrival temperature is around 12°C for both the trunklines, which is below the ambient temperature of 16°C. This is related to the gas expansion in the lines and associated cooling due to Joule-Thomson effect. Pressure profiles are well below the MOP of 35 barg.

Figure 8.2.3 and Figure 8.2.4 show the velocity and elevation profiles for both the trunklines. The maximum gas velocity experienced in the lines is around 14 m/s in the West Trunkline and 17 m/s in the East Trunkline. In both cases the velocities are well below the limit of 20 m/s for gas lines.

Figure 8.2.5 shows the pressure and temperature profiles of the west trunkline in case of operation to Collombey. Also in this case the maximum pressure is below the MOP of 35 barg with a fixed pressure at Collombey of 10 barg. The arrival temperature is 7°C. In this case it is estimated that the West Trunkline can transport a flowrate of around 2000 ktons/year coming from the East Trunkline, in addition to the West emitters rate. The flowrate coming from the East trunklines represents around 50% of the global East emitters rate. In case of East trunkline operation to Collombey, only the East emitters closer to the west system can be in operation (i.e. up to the Zurich area). This is because an increasing distance of the emitter from the delivery point (Collombey) results in increased pressure drops that could lead to the violation of the maximum operating pressure of 35 barg.

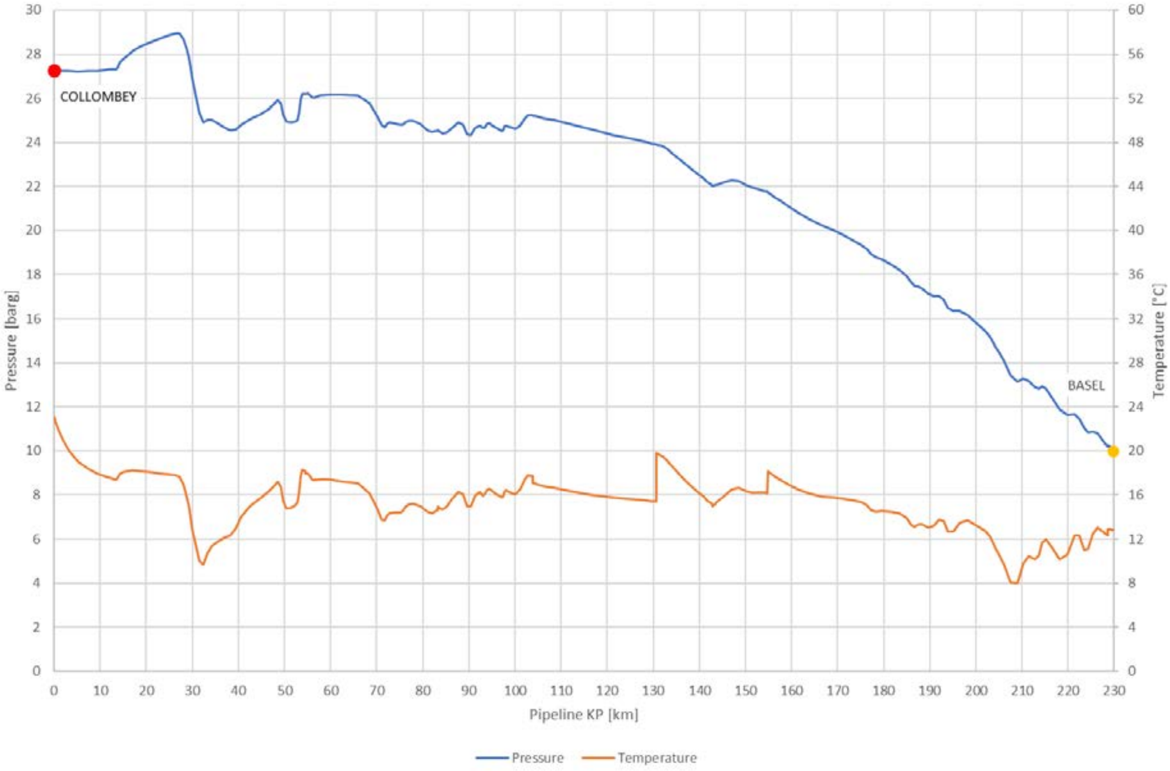


Figure 8.2.1: Gaseous Phase Transport. West Trunkline Pressure and Temperature Profiles.

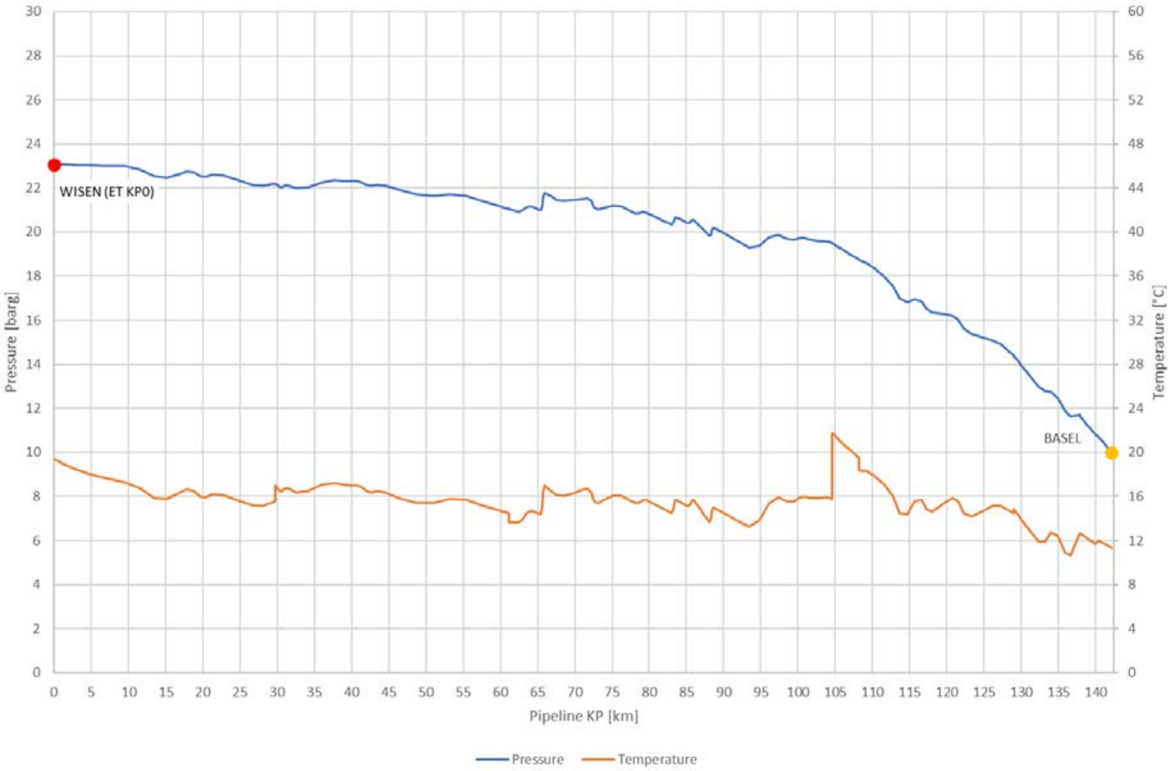


Figure 8.2.2: Gaseous Phase Transport. East Trunkline Pressure and Temperature Profiles.

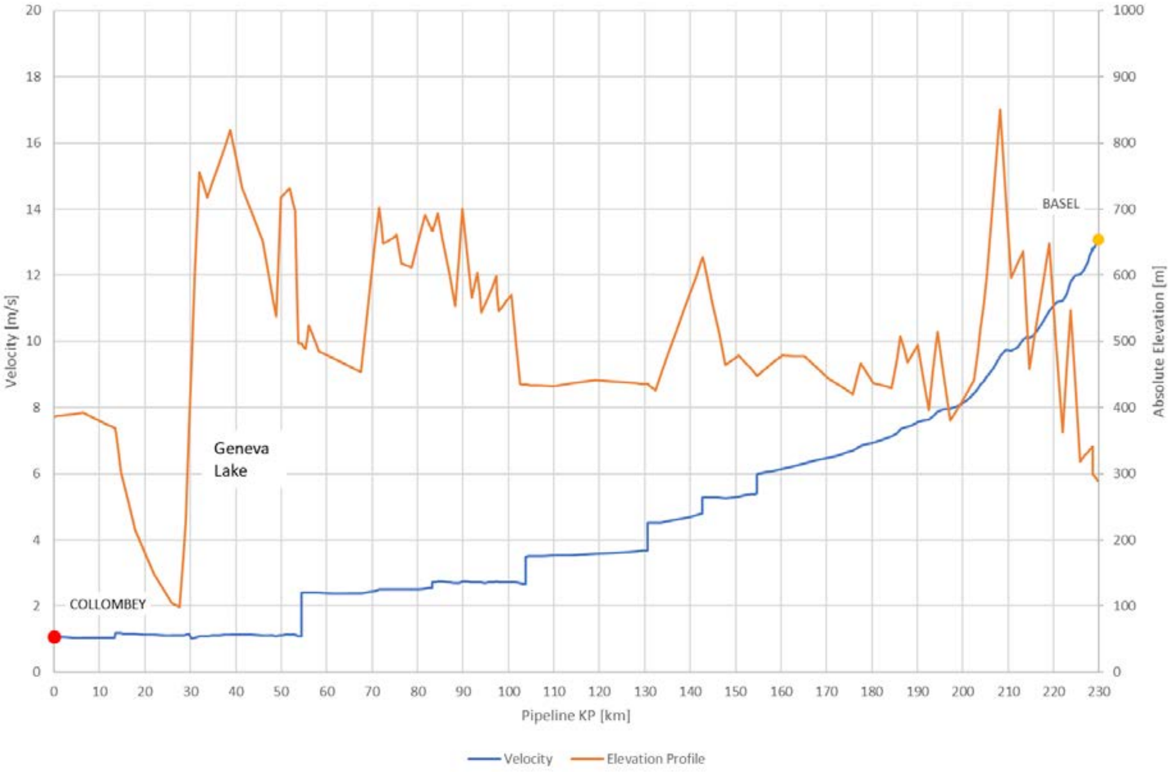


Figure 8.2.3: Gaseous Phase Transport. West Trunkline Velocity and Elevation Profiles.

Figure 8.2.4: Gaseous Phase Transport. East Trunkline Velocity and Elevation Profiles.

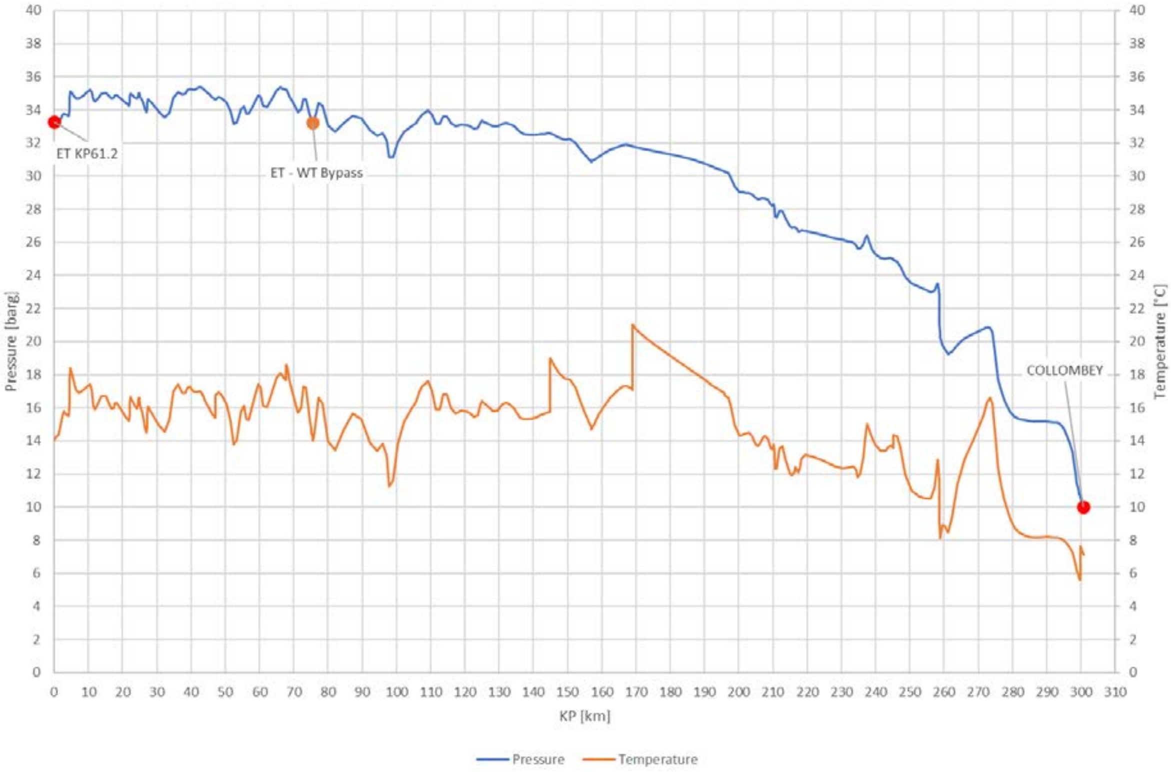


Figure 8.2.5: Gaseous Phase Transport to Collombey. Trunklines Pressure and Temperature Profiles.

8.3 Compression Stations

8.3.1 Compressor Station at Emitters

In the below Table 8.3.1, a list of the compression stations located at the emitters is reported. For each compression station the flowrate, the CS class, the suction and discharge pressure, the compressor units number (operating and spare), the installed power and the consumption are reported.

Most of the compressor stations have no spare units, with the exception of Holcim 1, Holcim 2 and Juracime/Varo for which a 2+1 philosophy has been adopted, being the CO2 flowrate above the reference limit of 500 ktons/y.
It can be noted that a total of 35 compression units are required at the emitters, the overall installed power is 109 MW, with a consumption of 79.5 MW.
The calculation of energy consumption costs (reported in Table 12.3.1) are carried out considering a utilization factor of 90%.

Table 8.3.1: Compressor Stations at the emitters. Gaseous phase transport.

Location	CO2 Flowrate	CS class	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	-	barg	barg	-	-	-	MW	MW
TOTALS						**35.0**		**109.0**	**79.5**
EAST TRUNKLINE									
Axpo Tegra AG	240.8	class2	0	32.1	3	1	0	3.5	2.4
Holcim (2) + Trimmis	576.6	class2	0	27.2	3	2	1	10.6	8.2
VfA Buchs	206.5	class2	0	30.8	3	1	0	3.5	2.0
KVA Linth	123.3	class1	0	23.3	3	1	0	2.1	1.1
KEZO Hinwil	218.4	class2	0	26.6	3	1	0	3.5	2.1
KVA Thurgau	166.1	class1	0	28.6	3	1	0	2.1	1.6
KVA Winterthur	225.1	class2	0	6.8	2	1	0	2.4	1.9
KVA Limmattal	103.6	class1	0	9.5	2	1	0	1.4	0.9
ARA Werdholzli	40.0	class1	0	7.9	2	1	0	1.4	0.3
ERZ KHKW Hagenholz	400.0	class4	0	6.4	2	1	0	4.2	3.5
KVA Turgi	133.8	class1	0	7.8	2	1	0	1.4	1.2
Holcim (1) + Turgi	688.3	class3	0	20.8	3	2	1	14.8	9.1
Jura Cement Fabriken	470.4	class4	0	8.3	2	1	0	4.2	4.1
GEKAL Buchs	156.9	class1	0	9.5	2	1	0	1.4	1.4
Renergia Zentral.	286.6	class2	0	33.2	3	1	0	3.5	2.9
DSM Nutritional	100.9	class1	0	14.9	2	1	0	1.4	0.9
IWB Basel	242.5	class2	0	8.1	2	1	0	2.4	2.1
WEST TRUNKLINE									
LONZA AG	366.0	class3	0	32.0	3	1	0	4.9	3.6
Cimo SA	196.4	class1	0	29.5	3	1	0	2.1	1.9
SATOM Monthey	175.9	class1	0	28.2	3	1	0	2.1	1.7
Les Cheneviers	302.1	class3	0	34.4	3	1	0	4.9	3.0
TRIDEL Lausanne	211.2	class2	0	9.0	2	1	0	2.4	1.8
Holcim (Suisse) SA	378.7	class3	0	29.2	3	1	0	4.9	3.7
SAIDEF Fribourg	112.8	class1	0	26.4	3	1	0	2.1	1.1
Juracime + Varo	542.2	class2	0	34.6	3	2	1	10.6	8.2
Vigier Cement AG	436.9	class4	0	11.1	2	1	0	4.2	3.8
Energiezentrale	160.1	class1	0	29.1	3	1	0	2.1	1.5
AVAG KVA AG	113.3	class1	0	29.3	3	1	0	2.1	1.1
KEBAG AG	284.2	class2	0	8.9	2	1	0	2.4	2.4

8.3.2 Boosting Station d/s Emitters

In the below Table 8.3.2, a list of the compression stations located at the emitters is reported. For each compression station the flowrate, the CS class, suction and discharge pressure, compressor units number (operating and spare), the installed power and the consumption are reported.

A 2+1 compression philosophy is adopted for the boosting station at Zurich and d/s Gekal/Jura Cement emitters. It can be noted that 11 additional compression units are required d/s the emitters, the overall installed power is 45.9 MW, with a consumption of 13.9 MW.

Table 8.3.2: Boosting Stations d/s emitters. Gaseous phase transport.

Location	CO2 Flowrate	CS class	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	-	barg	barg	-	-	-	MW	MW
TOTALS						**11.0**		**45.9**	**13.9**
EAST TRUNKLINE									
Winterthur LP-HP	225.1	class2	5	26.7	2	1	0	3.5	1.0
Zurich LP-HP	543.6	class2	5	32.8	2	2	1	10.6	3.9
E13 LP-HP	627.3	class3	5	26.6	2	2	1	14.8	4.0
IWB Basel LP-HP	242.5	class2	5	31.9	2	1	0	3.5	1.1
WEST TRUNKLINE									
TRIDEL LP-HP	211.2	class2	5	34.7	2	1	0	3.5	1.0
VIGIER LP-HP	436.9	class4	5	24.6	2	1	0	6.4	1.8
KEBAG LP-HP	284.2	class2	5	23.2	2	1	0	3.5	1.1

9. PIPELINE TRANSPORT SYSTEM IN DENSE PHASE

9.1 Pipeline Network Operating In Dense Phase

In the below Figure 9.1.1 and Figure 9.1.2 the network configuration for the CO2 transport in dense phase is shown for the West and East Trunkline Systems respectively.

The following is to be considered:

- A compression station with dehydration unit is present at each emitter. If the relevant flowline does not cross any urban area, no additional CS is required. If urban areas are present along the flowline, low pressure operation (MOP = 10 barg) is considered (gaseous phase). Due to safety reasons relevant to the high operating pressures, for some flowlines it is deemed not possible to operate in dense phase conditions even if they do not cross urban areas: for this lines a high pressure gas flowline is considered, with MOP = 35 barg (refer for example to Les Cheveniers or IWB Basel flowlines).
- Gaseous Phase transport is considered for the 57km trunkline across Rhine Valley (MOP = 35 barg). This is due to the fact that it is not possible to operate in dense phase conditions in this area, presenting a challenging elevation profile with peak points above 1000 m, leading to significant pressure head in the lines (i.e. the maximum CO2 density in dense conditions is in the order of 950 kg/m^3). Due to this it is not possible to keep the MOP below the fixed value of 145 barg without allowing for gas formation in the peak points of the elevation profile. Since the difficulties associated to pipeline construction in this section constraints the routing close to populated areas, the operation at quite high pressures above 150 barg appears not advisable and gaseous phase transport has been considered for this pipeline section in this study. However, a reduction in trunkline size is feasible wrt. the gaseous phase base case, from 20” to 16”, being the delivery point much closer (i.e. in this case the delivery point of the gas sub-system is the compressor suction at Linth whereas in base case the overall system delivery point is Basel).
- In the West System (Figure 9.1.1), the flowrate from Lonza and Cimo SA is routed to Satom Montey Plant and enters the compressor downstream the dehydration unit (2° stage compression discharge). In this way it is possible to save 1 compression station, with a larger CS at Satom Monthey Plant.
- In the East System (Figure 9.1.2) Turgi LP flowline is assumed to be routed into Holcim 1 plant. At this location the Turgi HP compression will be foreseen together with Holcim 1 compression. This allows to save 1 compression station.
- The 16” West Trunkline is 229 km long and includes 16 km of offshore section relevant to the crossing of Geneva Lake. This trunkline can operate in both directions (i.e. to Basel and to Collombey). When operating towards Collombey, with Basel delivery shutdown, its spare transport capacity allows to collect part of the East Trunkline flowrate. In the offshore section across the Geneva Lake the maximum operating pressure (internal) is 170 barg, due to the increased pressure head at the bottom of the lake (maximum depth around 300 meters).
- The 14” East Trunkline is 142 km long and it can operate towards Basel only.

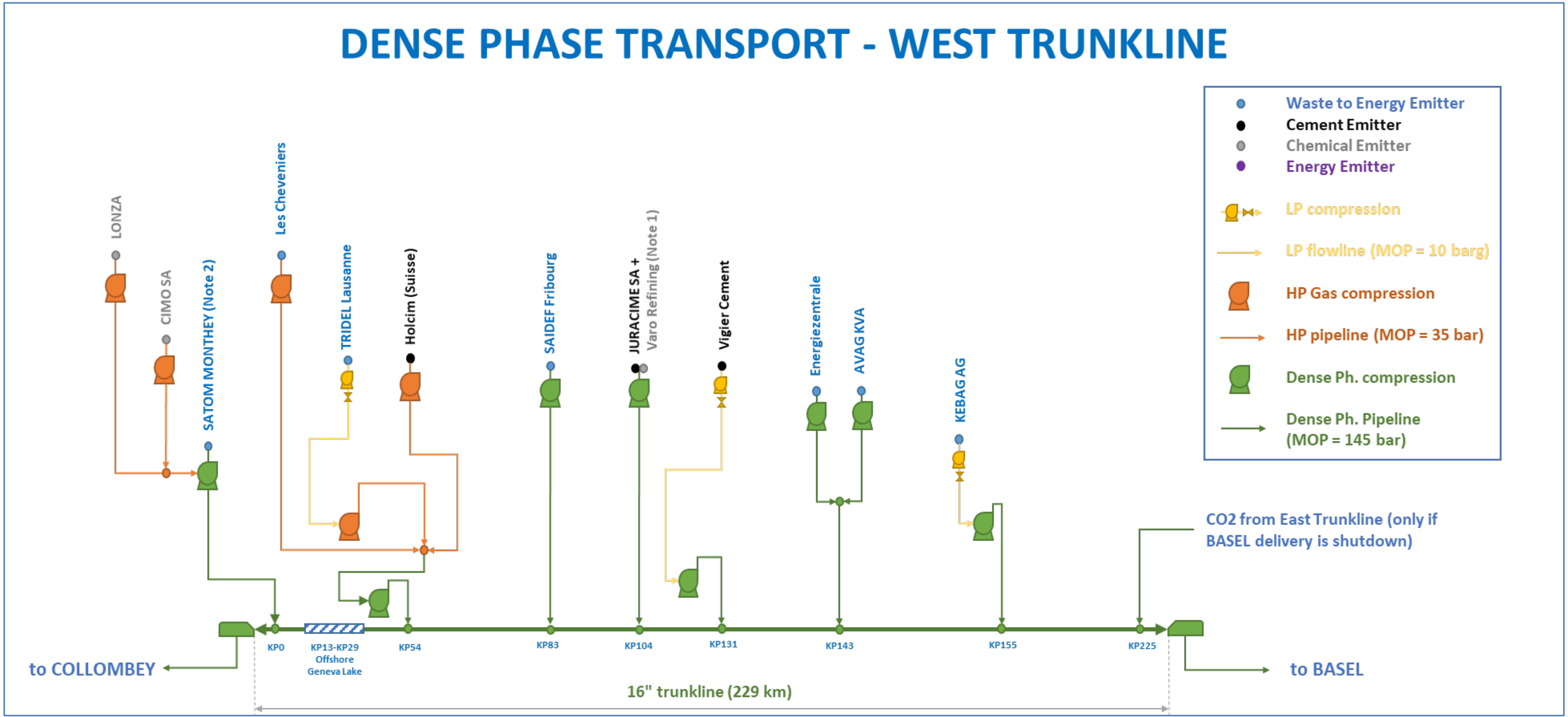


Figure 9.1.1: West Trunkline System for Dense Phase Transport.

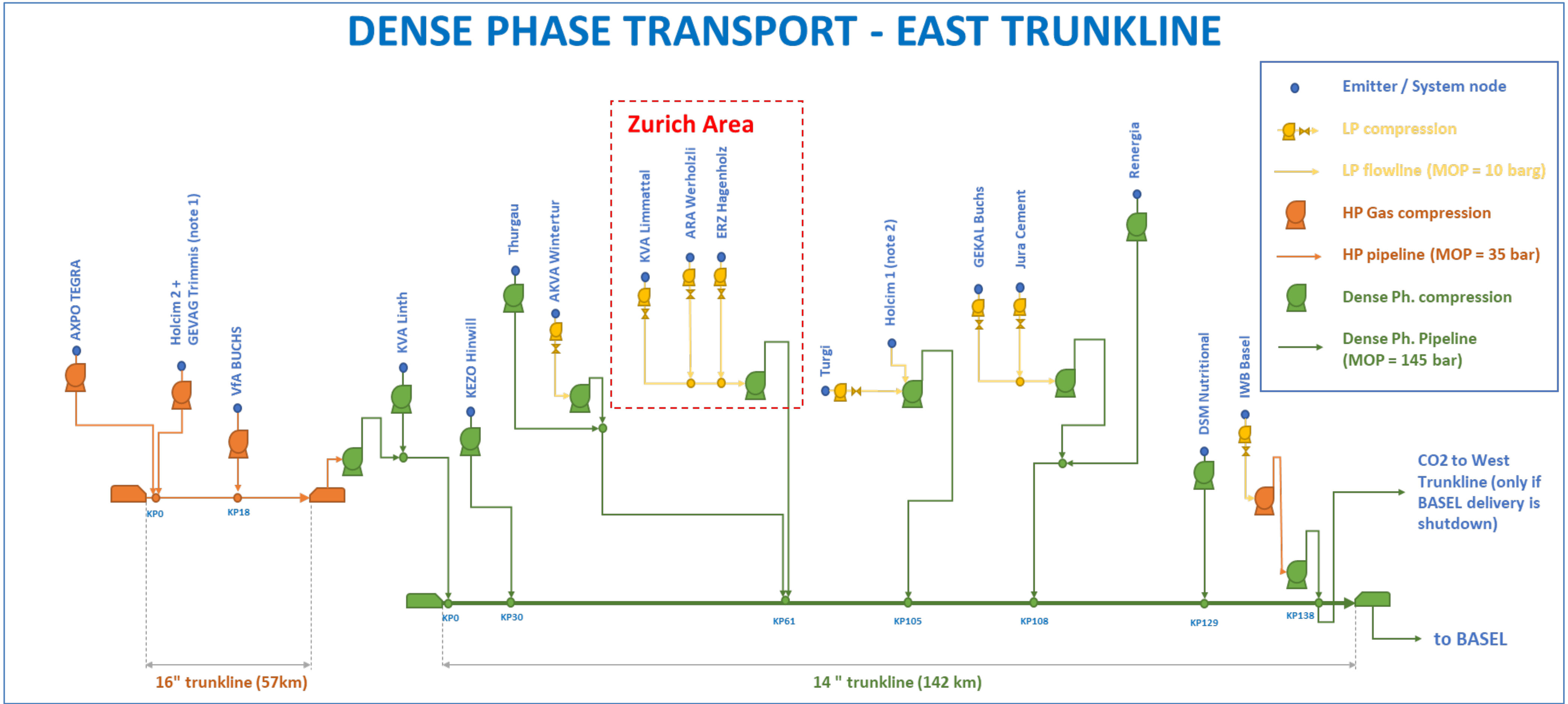


Figure 9.1.2: East Trunkline System for Dense Phase Transport.

9.2 Pressure And Temperature Profiles At Design Conditions In Dense Phase

In the following Table 9.2.1 and Table 9.2.2 the pipe sizes for all network segments are reported together with the calculated pressure and flowrates at system nodes, for west and east trunklines respectively.

Table 9.2.1: Dense Phase Transport – West System. Summary of pipe sizes, rates and pressures at system nodes.

from	to	length	ND	CO2 Flowrate	CS Suction Pressure	CS discharge Pressure	PHASE
-	-	m	in	ktons/y	barg	barg	-
LONZA AG	LONZA_KP_92.8	92980	14	366.0	0.1	26.3	GAS
Cimo SA	LONZA_KP_92.8	100	6	196.4	0.1	22.0	GAS
LONZA_KP_92.8	SATOM PLANT	2700	14	175.9	-	-	GAS
W31_KP0 (SATOM PLANT)	WT_KP0	2200	16	738.3	0.1	143.8	DENSE
WT_KP0	WT_KP13.5	13380	16	738.3	-	-	DENSE
WT_KP13.5 (OFFSHORE)	WT_KP29.7 (OFFSHORE)	16320	16	738.3	-	-	DENSE
WT_KP29.7	WT_KP54.4	24700	16	738.3	-	-	DENSE
Les Cheneviers	W32_KP0	82750	12	302.1	0.1	21.4	GAS
TRIDEL Lausanne	TRIDEL LP-HP	11000	10	211.2	0.1	9.0	GAS
TRIDEL LP-HP	W32_KP0	6850	6	211.2	5.0	23.0	GAS
Holcim (Suisse) SA	West_Cluster	100	6	378.7	0.1	11.2	GAS
West_Cluster	W32_KP0	100	12	892.0	-	-	GAS
W32_KP0	WT_KP54.4	35800	10	892.0	10.0	141.8	DENSE
WT_KP54.4	WT_KP83.2	28800	16	1630.4	-	-	DENSE
SAIDEF Fribourg	WT_KP83.2	3400	6	112.8	0.1	121.3	DENSE
WT_KP83.2	WT_KP103.7	20500	16	1743.2	-	-	DENSE
Juracime + Varo	WT_KP103.7	17755	8	542.2	0.1	138.2	DENSE
WT_KP103.7	WT_KP130.6	26900	16	2285.4	-	-	DENSE
Vigier Cement AG	VIGIER LP-HP	11800	12	436.9	0.1	11.1	GAS
VIGIER LP-HP	WT_KP130.6	100	6	436.9	5.0	131.5	DENSE
WT_KP130.6	WT_KP142.7	12100	16	2722.4	-	-	DENSE
Energiezentrale	W9_KP0	22900	6	160.1	0.1	118.7	DENSE
AVAG KVA AG	W9_KP0	46700	6	113.3	0.1	119.8	DENSE
W9_KP0	WT_KP142.7	5100	6	273.4	-	-	DENSE
WT_KP142.7	WT_KP154.7	12000	16	2995.8	-	-	DENSE
KEBAG AG	KEBAG LP-HP	6000	10	284.2	0.1	8.9	GAS
KEBAG LP-HP	WT_KP154.7	500	6	284.2	5.0	125.9	DENSE
WT_KP154.7	BASEL	74900	16	3279.9	-	-	DENSE

Table 9.2.2: Dense Phase Transport – East System. Summary of pipe sizes, rates and pressures at system nodes.

from	to	length	ND	CO2 Flowrate	CS Suction Pressure	CS discharge Pressure	PHASE
-	-	m	in	ktons/y	barg	barg	-
Axpo Tegra AG	ET_E KP0	538	8	240.8	0.1	32.8	GAS
ET_E KP0	ET_E KP15	15000	8	240.8	-	-	GAS
Holcim (Schweiz) AG	ET_E KP15	150	8	576.6	0.1	28.1	GAS
ET_E KP15	ET_E KP33.5	18400	16	817.3	-	-	GAS
VfA Buchs	ET_E KP33.5	18300	8	206.5	0.1	29.9	GAS
ET 20'' KP33.5	ET KP0 compressor	38800	16	1023.8	-	-	GAS
ET KP0 compressor	ET KP0	100	8	1023.8	10.0	133.6	DENSE
KVA Linth	ET KP0	434	6	123.3	0.1	133.6	DENSE
ET KP0	ET KP29.7	29700	14	1147.1	-	-	DENSE
KEZO Hinwil	ET KP29.7	3000	6	218.4	0.1	124.8	DENSE
ET KP29.7	ET KP61.2	31500	14	1365.5	-	-	DENSE
KVA Thurgau	E6 KP0	32500	6	166.1	0.1	135.3	DENSE
KVA Winterthur	Winterthur LP-HP	3780	10	225.1	0.1	6.8	GAS
Winterthur LP-HP	E6 KP0	100	6	225.1	5.0	130.7	DENSE
E6 KP0	ET 30'' KP61.2	13700	6	391.2	-	-	DENSE
KVA Limmattal	E9 KP0	6700	8	103.6	0.1	9.5	GAS
ARA Werdholzli	E9 KP0	150	6	40.0	0.1	7.9	GAS
E9 KP0	E10 KP0	1380	8	143.6	-	-	GAS
E10 KP0	Zurich Cluster	6400	10	143.6	-	-	GAS
ERZ KHKW Hagenholz	Zurich Cluster	610	12	400.0	0.1	6.4	GAS
Zurich Cluster	Zurich LP-HP	2805	16	543.6	-	-	GAS
Zurich LP-HP	ET KP61.2	18810	6	543.6	5.0	140.6	DENSE
ET KP612	ET KP104.7	43300	14	2300.3	-	-	DENSE
KVA Turgi	Holcim (Schweiz) AG	5410	8	133.8	0.1	7.8	GAS
Holcim (E14)	ET KP104.7	300	6	688.3	0.1	123.8	DENSE
ET KP104.7	ET KP108.3	3600	14	2988.6	-	-	DENSE
Jura Cement Fabriken	E13 K0	2556	12	470.4	0.1	8.3	GAS
GEKAL Buchs	E13 K0	5000	8	156.9	0.1	9.5	GAS
E13 K0	E13 LP-HP	3400	16	627.3	-	-	GAS
E13 LP-HP	E12 K0	100	6	627.3	5.0	121.1	DENSE
Renergia Zentral.	E12 K0	46500	6	286.6	0.1	131.8	DENSE
E12 K0	ET KP108.3	16000	8	913.9	-	-	DENSE
ET KP108.3	ET KP129.1	20800	14	3902.5	-	-	DENSE
DSM Nutritional	ET KP138.1	800	6	100.9	0.1	108.2	DENSE
ET KP129.1	ET KP138.1	8900	14	4003.4	-	-	DENSE
IWB Basel	IWB Basel LP-HP	6100	10	242.5	0.1	8.1	GAS
IWB Basel LP-HP	IWB Basel GAS-DENSE	42854.0	8	242.5	5.0	31.3	GAS
IWB Basel GAS-DENSE	ET KP138.1	100.0	6	242.5	10.0	102.2	DENSE
ET KP138.1	Basel	4200	14	4245.9	-	-	DENSE

Pressure and Temperature Profiles are shown for the West and East Trunkline respectively in the below Figure 9.2.1 and Figure 9.2.2. Summer conditions are considered, being the most conservative in terms of pressure drops in the lines.

The arrival temperature is around 12°C for both the trunklines, which is below the ambient temperature of 16°C. This is related to the gas expansion in the lines and consequent cooling due to Joule-Thomson effect. Pressure profiles are below the MOP of 145 barg. It is pointed out that in order to keep the trunkline in dense phase conditions a minimum pressure of 85 barg has to be maintained along the line, including the peak points of the elevation profiles. This can be done by fixing the Basel delivery point pressure at 120 barg and 100 barg for the West and East trunklines respectively.

Figure 9.2.3 and Figure 9.2.4 show the velocity and elevation profiles for both the trunklines. The maximum gas velocity experienced in the lines is around 14 m/s in the West Trunkline and 17 m/s in the East Trunkline. In both cases the velocities are well below the limit of 20 m/s for gas lines.

Figure 9.2.5 shows the pressure and temperature profiles of the west trunkline in case of operation to Collombey. Also in this case the maximum pressure is below the MOP of 145 barg with a fixed pressure at Collombey of 110 barg and the fluid velocities are below the limit of 4 m/s. The arrival temperature is 24°C. In this case it is estimated that the West Trunkline can transport a flowrate of around 1000 ktons/year coming from the East Trunkline, in addition to the West emitters rate. The flowrate coming from the East trunklines represents around 25% of the global East emitters rate. In case of East trunkline operation to Collombey, only the East emitters closer to the west system can be in operation (i.e. up to the Zurich area). This is because an increasing distance of the emitter from the delivery point (Collombey) results in increased pressure drops that could lead to the violation of the maximum operating pressure of 145 barg.

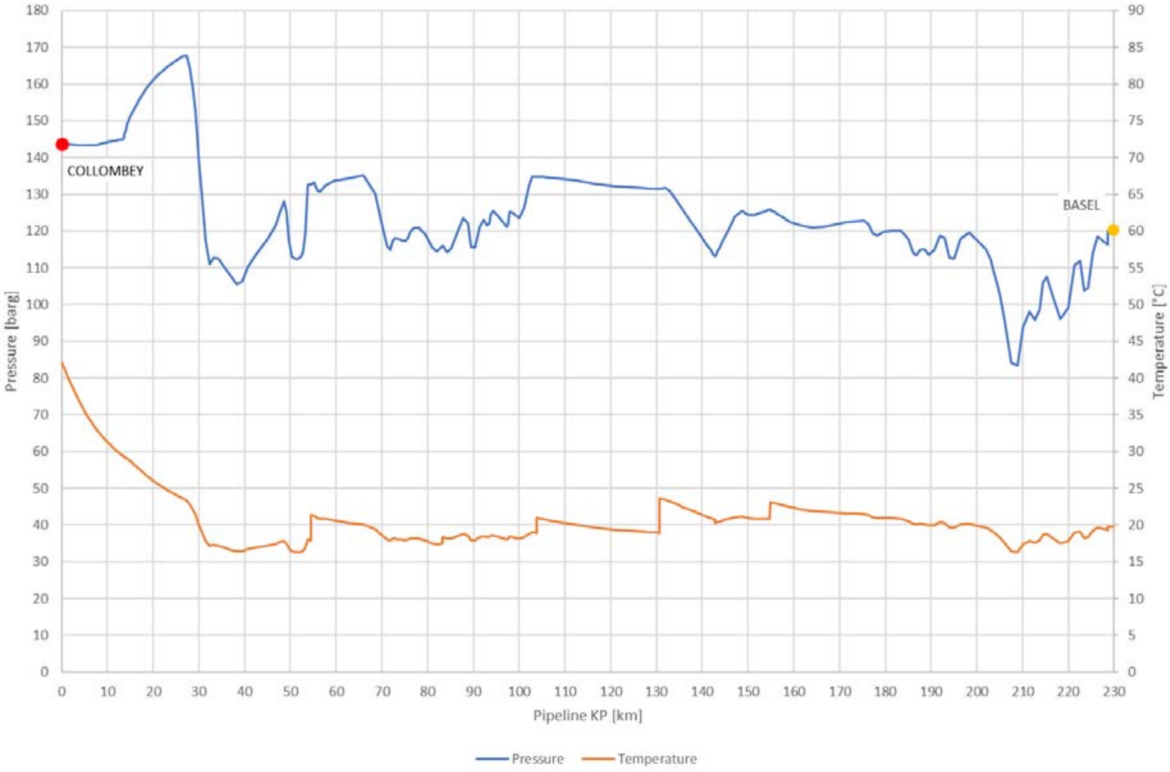


Figure 9.2.1: Dense Phase Transport. West Trunkline Pressure and Temperature Profiles.

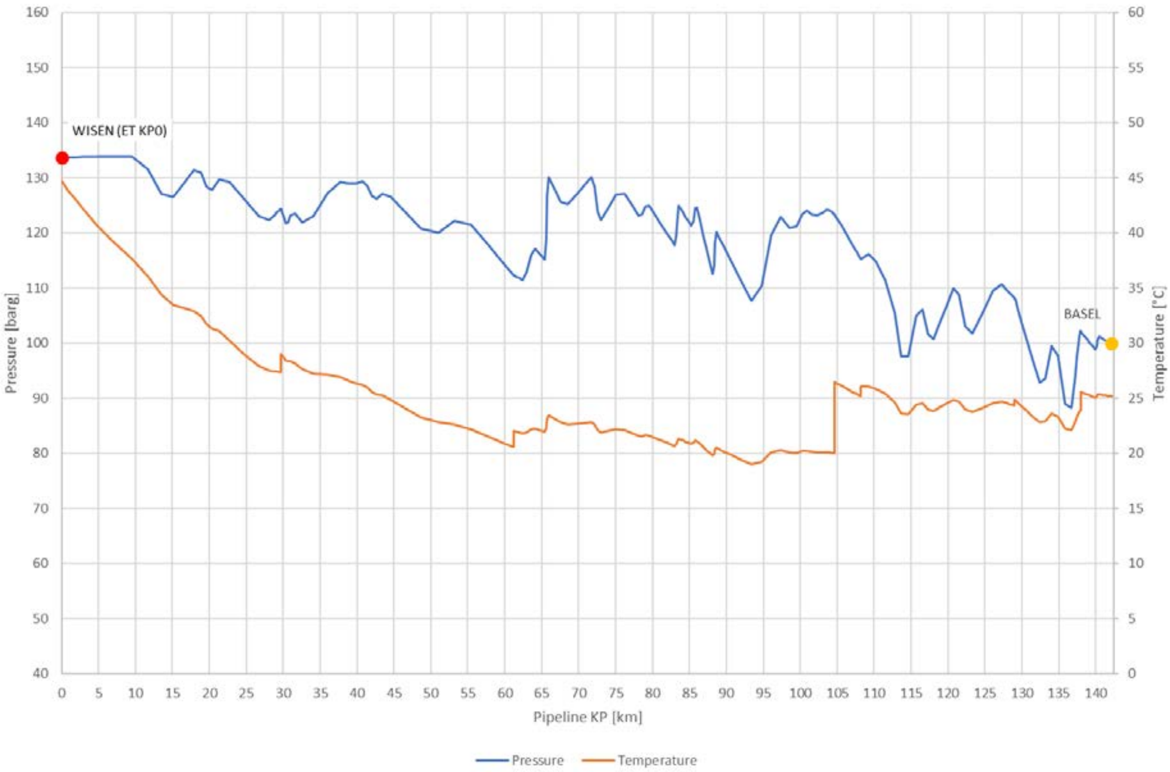


Figure 9.2.2: Dense Phase Transport. East Trunkline Pressure and Temperature Profiles.

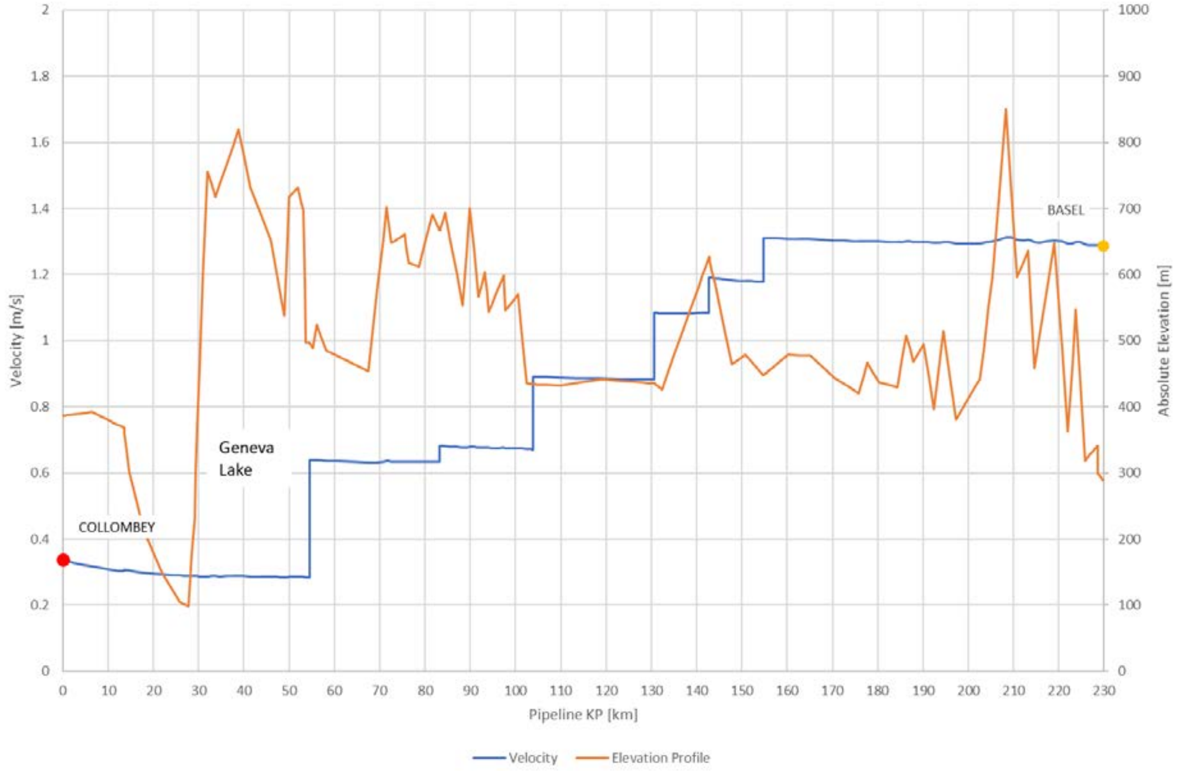


Figure 9.2.3: Dense Phase Transport. West Trunkline Velocity and Elevation Profiles.

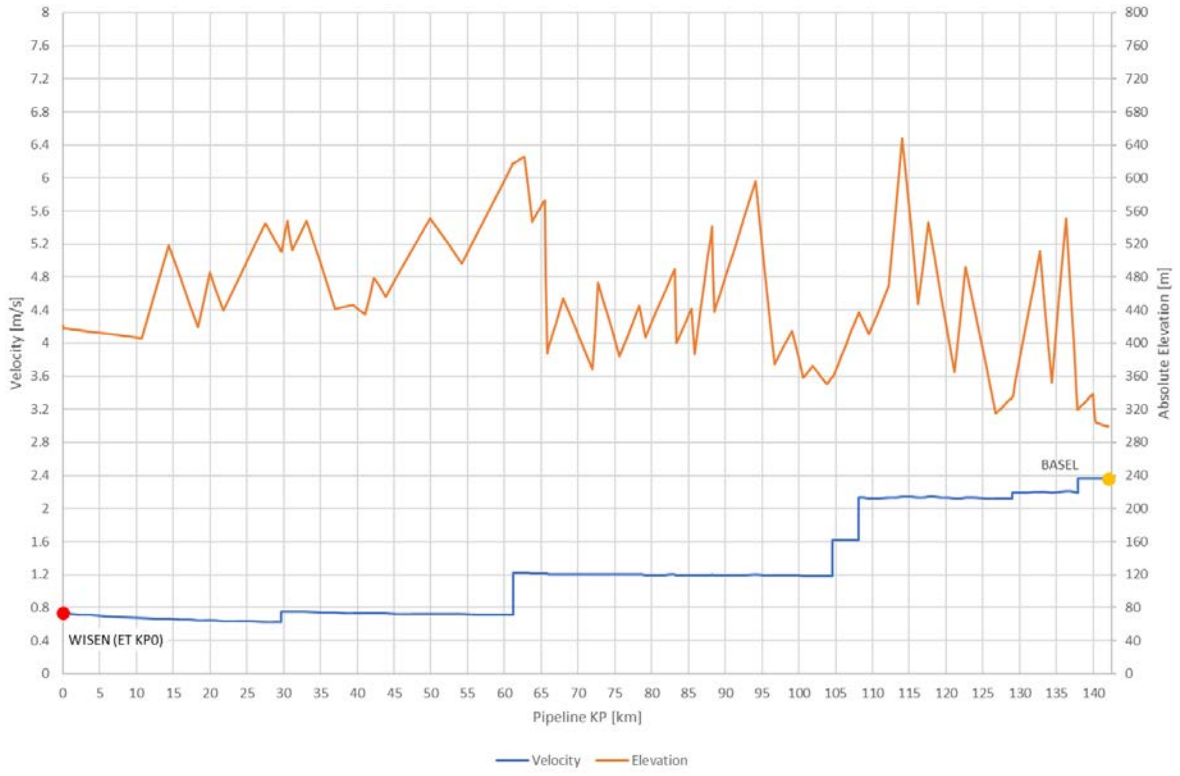


Figure 9.2.4: Dense Phase Transport. East Trunkline Velocity and Elevation Profiles.

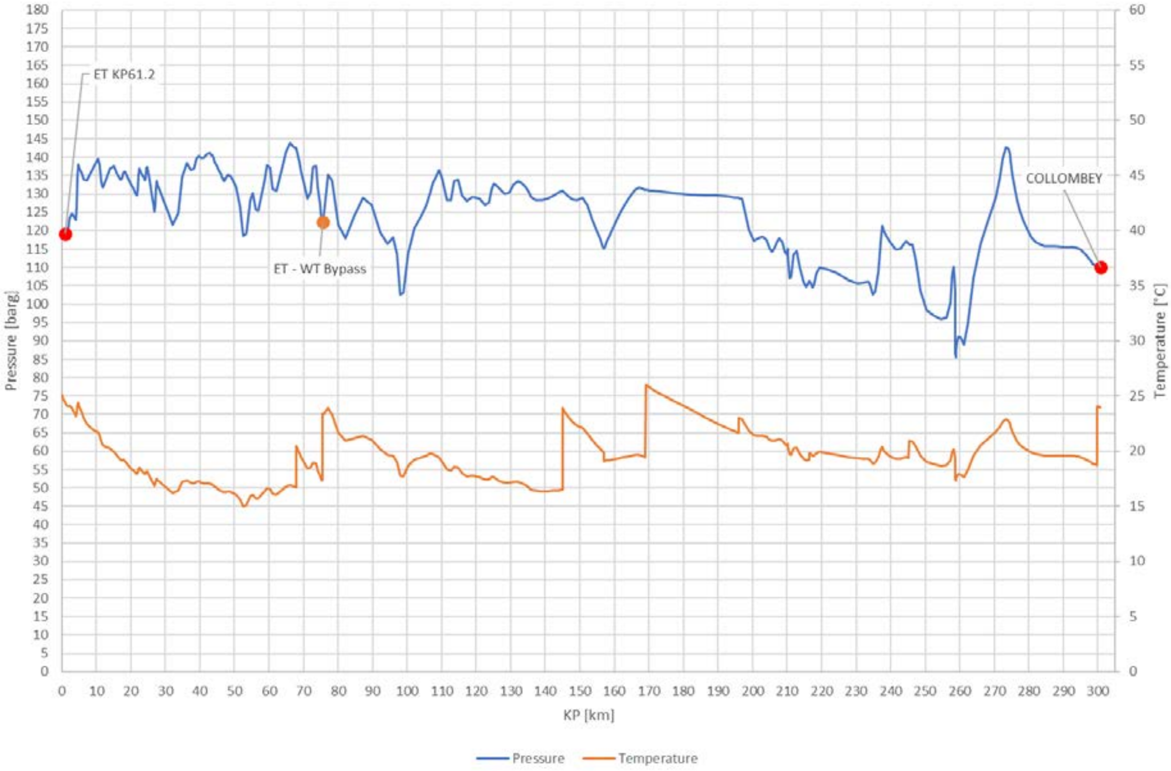


Figure 9.2.5: Dense Phase Transport to Collombey. Trunklines Pressure and Temperature Profiles.

9.3 Boosting Stations

9.3.1 Compression Station at Emitters

In the below Table 9.3.1, a list of the compression stations located at the emitters is reported. For each compression station the flowrate, the CS class, the suction and discharge pressure, the compressor units number (operating and spare), the installed power and the consumption are reported.

Most of the compressor stations have no spare units, except for Holcim (1), Holcim(2)/Trimmis and Juracime/Varo arranged according to a 2+1 philosophy, being the CO2 flowrate above the reference limit of 500 ktons/y.

It can be noted that a total of 37 compression units are required at the emitters (2 more than in gaseous base case, due to the increased flowrate at Satom Plant), the overall installed power is 138.2 MW, with a consumption of 100.6 MW.

The calculation of energy consumption costs (reported in Table 12.3.1) are carried out considering a utilization factor of 90%.

Table 9.3.1: Compressor Stations at the emitters. Dense phase transport.

Location	CO2 Flowrate	CS class	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	-	barg	barg	-	-	-	MW	MW
TOTALS						**37.0**		**138.2**	**100.6**
EAST TRUNKLINE									
Axpo Tegra AG	240.8	class2	0	32.8	3	1	0	3.5	2.4
Holcim (2) + Trimmis	576.6	class2	0	28.1	3	2	1	10.6	8.3
VfA Buchs	206.5	class2	0	29.9	3	1	0	3.5	2.0
KVA Linth	123.3	class1	0	133.6	4	1	0	2.7	1.6
KEZO Hinwil	218.4	class2	0	124.8	4	1	0	4.6	2.7
KVA Thurgau	166.1	class1	0	135.3	4	1	0	2.7	2.1
KVA Winterthur	225.1	class2	0	6.8	2	1	0	2.4	1.9
KVA Limmattal	103.6	class1	0	9.5	2	1	0	1.4	0.9
ARA Werdholzli	40.0	class1	0	7.9	2	1	0	1.4	0.3
ERZ KHKW Hagenholz	400.0	class4	0	6.4	2	1	0	4.2	3.5
KVA Turgi	133.8	class1	0	7.8	2	1	0	1.4	1.2
Holcim (1) + Turgi	688.3	class3	0	123.8	4	2	1	19.1	13.0
Jura Cement Fabriken	470.4	class4	0	8.3	2	1	0	4.2	4.1
GEKAL Buchs	156.9	class1	0	9.5	2	1	0	1.4	1.4
Renergia Zentral.	286.6	class2	0	131.8	4	1	0	4.6	3.6
DSM Nutritional	100.9	class1	0	108.2	4	1	0	2.7	1.3
IWB Basel	242.5	class2	0	8.1	2	1	0	2.4	2.1
WEST TRUNKLINE									
LONZA AG	366.0	class3	0	26.3	3	1	0	4.9	3.4
Cimo SA	196.4	class1	0	22.0	3	1	0	2.1	1.8
W31_KP0 (SatomPlant)	738.3	class3	0	143.8	4	2	1	19.1	14.0
Les Cheneviers	302.1	class3	0	21.4	3	1	0	4.9	2.7
TRIDEL Lausanne	211.2	class2	0	9.0	2	1	0	2.4	1.8
Holcim (Suisse) SA	378.7	class3	0	11.2	2	1	0	3.3	3.3
SAIDEF Fribourg	112.8	class1	0	121.3	4	1	0	2.7	1.4
Juracime + Varo	542.2	class2	0	138.2	4	2	1	13.7	10.3
Vigier Cement AG	436.9	class4	0	11.1	2	1	0	4.2	3.8
Energiezentrale	160.1	class1	0	118.7	4	1	0	2.7	2.0
AVAG KVA AG	113.3	class1	0	119.8	4	1	0	2.7	1.4
KEBAG AG	284.2	class2	0	8.9	2	1	0	2.4	2.5

9.3.2 Boosting Station d/s Emitters

In the below Table 9.3.2, a list of the compression stations located at the emitters is reported. For each compression station the flowrate, the CS class, suction and discharge pressure, compressor units number (operating and spare), the installed power and the consumption are reported.

It can be noted that 18 additional compression units are required d/s the emitters (7 more than in gaseous base case), the overall installed power is 86.4 MW, with a consumption of 47.2 MW.

Table 9.3.2: Boosting Stations d/s emitters. Dense phase transport.

Location	CO2 Flowrate	CS class	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	-	barg	barg	-	-	-	MW	MW
TOTALS						**18.0**		**86.4**	**47.1**
EAST TRUNKLINE									
ET KP0 compressor	1023.8	class4	10.0	133.6	3	2	1	13.4	9.8
Winterthur LP-DENSE	225.1	class2	5.0	130.7	3	1	0	4.6	1.9
Zurich LP- DENSE	543.6	class2	5.0	140.6	3	2	1	13.7	6.8
E13 LP- DENSE	627.3	class3	5.0	121.1	3	2	1	19.1	7.6
IWB Basel LP-HP	242.5	class2	5.0	31.3	2	1	0	3.5	1.1
IWB Basel GAS-DENSE	242.5	class2	10.0	102.2	3	1	0	2.5	1.4
WEST TRUNKLINE									
TRIDEL LP- DENSE	211.2	class2	5.0	23.0	2	1	0	3.5	0.8
W32_KP0	892.0	class4	10.0	141.8	3	2	1	13.4	10.8
VIGIER LP- DENSE	436.9	class4	5.0	131.5	3	1	0	8.2	4.2
KEBAG LP- DENSE	284.2	class2	5.0	125.9	3	1	0	4.6	2.7

10. EXPORT COMPRESSION STATIONS AT DELIVERY POINTS

In this Section, the characteristics relevant to the export compression stations to be installed at the delivery points in Basel and Collombey are reported.

It is assumed that the CO2 will be exported abroad by means of a CO2 export pipeline. It is also assumed that this export pipeline, being a point-to-point long transmission pipeline, will operate in dense phase conditions since it is by far the most economical option.

For the definition of the export compression stations parameters, a discharge pressure of 145 barg is considered, allowing the export pipeline to operate in dense phase region.

In Basel, a flowrate of 7500 tons/year is arriving from the gathering network. A CS design margin of 10% is considered, resulting in a design flowrate for the compressor station of 8300 ktons/year.
In Collombey, the maximum flowrate that can be exported is equal the West trunkline rate (3400 tons/year) plus a maximum of 2000 tons/year (refer to section 2) coming from the East trunkline, resulting in a design flowrate for the compressor station of 5400 ktons/year.

It is pointed out that the compression station in Collombey will be in operation only if Basel is shutdown, according to the current project operational philosophy. When calculating the consumptions of the export compression stations, it is assumed to always have Basel station in operation, being the most conservative scenario in terms of energy demand.

10.1 EXPORT STATIONS FOR GASEOUS PHASE GATHERING NETWORK

If the gathering network is operated in gaseous phase, the arrival pressure at Basel and Collombey is equal to 10 barg. This value represents the suction pressure for the export compression station to be installed at the delivery points.
In the below Table 10.1.1, a list of the compression stations located at the delivery points is reported. For each compression station the flowrate, the suction and discharge pressure, the compressor units number (operating and spare), the installed power and the consumption are reported.
It can be noted that a total of 8 compression units are required at the 2 delivery points emitters, the overall installed power is 170.4 MW, with a maximum consumption at Basel of 58.5 MW.

Table 10.1.1: Export Compression Stations at Delivery Points - Gaseous Phase Gathering Network.

Location	CO2 Flowrate	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	barg	barg	-	-	-	MW	MW
TOTALS					8.0		170.4	58.5
EXPORT COMPRESSION STATIONS - GASEOUS PHASE GATHERING SYSTEM								
Basel Export CS	8300	10.0	145.0	3	3	1	99.2	58.5
Collombey Export CS	5400	10.0	145.0	3	3	1	71.2	38.1

10.2 EXPORT STATIONS FOR DENSE PHASE GATHERING NETWORK

If the gathering network is operated in dense phase, the minimum arrival pressure at Basel and Collombey is equal to 100 barg. This value represents the suction pressure for the pressure boosting station to be installed at the delivery point.

In the below Table 10.2.1, a list of the pressure boosting stations located at the delivery points is reported. For each pump station the flowrate, the suction and discharge pressure, the pump units number (operating and spare), the installed power and the consumption are reported.

It can be noted that a total of 8 pump units are required at the 2 delivery points emitters, the overall installed power is 10 MW, with a maximum consumption at Basel of 2.5 MW.

Table 10.2.1: Export Boosting Stations at Delivery Points - Dense Phase Gathering Network.

Location	CO2 Flowrate	Suction pressure	Discharge pressure	Compression Stages	Operating Units	Spare Units	Installed power	Consumption
	ktons/year	barg	barg	-	-	-	MW	MW
TOTALS					**8.0**		**10.0**	**2.5**
EXPORT COMPRESSION STATIONS - DENSE PHASE GATHERING SYSTEM								
Basel Export CS	8300	100.0	145.0	1	3	1	5.0	2.5
Collombey Export CS	5400	100.0	145.0	1	3	1	5.0	1.8

11. OTHER TRANSPORT SYSTEM COMPONENTS

11.1 Metering and Pigging Stations

Metering stations can be installed at compression facilities, including filters and metering lines, in a suitable arrangement to measure the flow as per actual state of-the-art.

Station piping will be rated against ASME B31.3 design code, with a design pressure not exceeding the rating class 900# at the specified design temperature.

Each stand-alone metering station will include utility systems, electrical and instrumentation appurtenances as required for local monitoring and control, DCS based and linked to the SCADA including accommodation and operating buildings. For metering stations integrated with compressor stations, station appurtenances and filtration systems will be those necessary for the compressor station.

Trunklines and flowlines longer than 10 km will be provided with pig trap facilities for both intelligent and cleaning pigging operations; the pipelines length in the optimized pipeline system is well within the current pigging technology covering distance capability.

11.2 Telecommunication and SCADA System

A traditional telecommunication system for voice communication and process data transfer based on optical cable buried in parallel to the pipeline has been considered as main carrier, with the relevant estimated cost impact (see Section 12).
The project locations will normally be unmanned. Control and monitoring will normally be carried out from remote location, i.e. the Dispatching System Center, by means of a SCADA System connected to all locations via the telecommunication system and remote terminal units (RTUs).
Local and manual control of the equipment and stations will also be possible by operating through local instrumentation and control room, provided at each location.
The SCADA System will also include in-line and off-line tasks such as leak detection, pipeline efficiency monitoring, operator training and operation simulation, to offer the most complete and effective support to the operations.

11.3 Pressure and Overpressure Control Systems

In order to exploit the full pipeline flow capacity, it is foreseen that the normal operating pressure of the CO2 Pipeline is close to MAOP.

It is foreseen that a pressure control system will be installed to limit the operating pressure below the specified Maximum Operating Pressure, as well as to ensure the minimum operating pressure is above the specified limit, for dense phase transport conditions. A feasible system can be based on master control of flow rate at emitters (with pressure in override), and on pressure control valves at each trunkline outlet.

An overpressure control system shall be installed to prevent excessive pipeline pressurization during transient events. For such a pipeline system, a typical method is to monitor the pipeline pressure and trigger pipeline inlet ESDV closure once the safety pressure limits are exceeded.

11.4 Block Valves

Due to the vast pipeline inventory for a CO2 pipeline, pipeline sectioning through intermediate block valve shall be carried out.

The location and performance requirements of intermediate block valves should be based on local legislative requirements (if any) and the risk management strategy, the following is relevant:

- Block valves, when closed, reduce the volume of released product in case of pipeline containment failure.
- Block valves increase maintainability by limiting section of pipe that requires depressurization.
- The effectiveness of block valves to limit the scale of a leak will be dependent on effective leak detection.
- The block valve closes based on a signal typically from the control system, either manually or automatic.

The reference standard for this project, i.e. ISO-27913, does not provide a specific guidance for block valve spacing requirements. DNVGL-RP-F104 makes reference to the Canadian pipeline design standard, CSA-Z-662. This last one specifies the following for CO2 pipelines:

Valve spacing in Class1 Location : Not Specified

Valve spacing in Class2, 3 & 4 Location : 15 km

Class1 Location is defined as a zone with less than 10 dwelling units, the others have a great number of dwelling units.

The number and spacing of block valves for the current project will be defined at a later project stage based on the above general criteria.

12. PIPELINE OPTIMIZATION CALCULATION RESULTS

12.1 Cost Estimate Model Validation

In order to validate the present document cost estimations, a preliminary comparison with reference literature data has been carried out for the calculated ATCI values.

In Ref.[2], ATCI calculations are carried out for a reference gaseous phase transport CO2 onshore pipeline of 100 km, crossing agricultural regions, having only one source point. The calculation is carried out for different CO2 flowrates.

The reference configuration is typical of some flowlines of the Swiss network, such as Renergia (46 km), AVAG KVA (47 km) and Les Cheveniers (83 km) flowlines, which are selected for the model validation.

In order to provide a reliable comparison, ATCI values for the Swiss network have been calculated considering a typical pipeline construction cost in agricultural regions of 15 USD/in/m, which is much lower of the expected construction cost in Switzerland (i.e. 60 USD/in/m, as per Section 12).

In the below Figure 11.1.1, a comparison wrt. the available reference points (yellow triangles) is shown in terms of ATCI values at different transport capacities. The Swiss flowlines appear to be in the same trend line of the reference points. Higher costs are expected due to the shorter length and the smaller flowrate of the lines.

The ATCI values calculated for the overall East and West systems are close to the ATCI values calculated for the flowlines and these points are above the reference data. This is because a collection network can be considered as a group of several flowlines, with an increasing number of sources and compression stations that leads to higher costs wrt. a single line. In the same Figure the ATCI values for East and West Systems are also reported with the expected construction costs in Switzerland, increasing the cost difference wrt. the reference points, valid for agricultural regions.

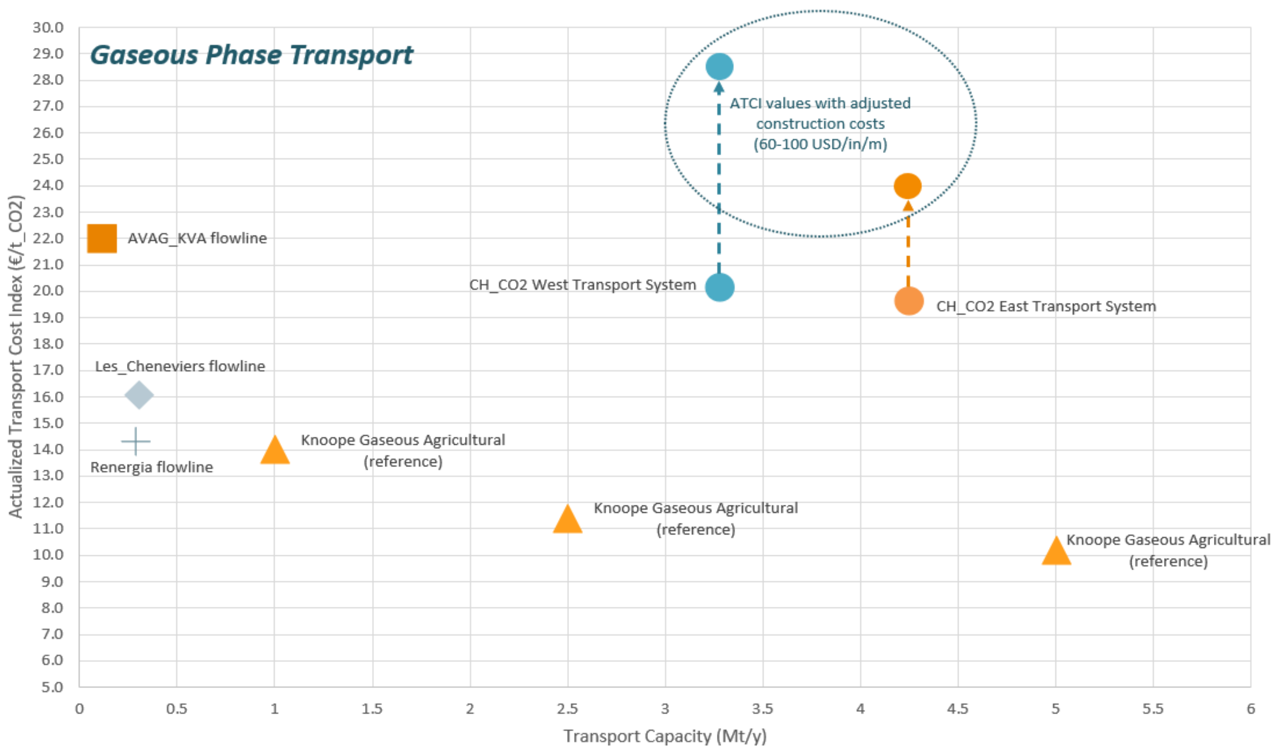


Figure 11.1.1: ATCI comparison with Ref.[2] for Swiss Flowlines and East and West Transport Systems.

12.2 CAPEX AND OPEX CALCULATIONS

The detailed calculations for CAPEX, OPEX and O&M costs are reported in Appendix 3 – Section 14, according to the methodology described in Section 12.

12.3 ATCI CALCULATION SUMMARY

A summary of the analyzed scenarios is reported in the below Table 11.3.1, in terms of CAPEX, OPEX and ATCI. For each analyzed solution relevant to the gathering network, the relevant ATCI index is calculated according to the methodology described in Section 4.2.

Table 12.3.1: CAPEX, OPEX and ATCI Summary for all Analysed Configurations of the Gathering Network.

	PL CAPEX		CS CAPEX		OVERALL CAPEX		PL OPEX	CS OPEX - O&M	CS OPEX - Energy	OVERALL OPEX		ATCI	
	MM€	Δ wrt. base case	MM€	Δ wrt. base case	MM€	Δ wrt. base case	MM€ /y	MM€/y	MM€/ y	MM€ /y	Δ wrt. base case	€/ton	Δ wrt. base case
Gaseous Base Case	1769		941		2711		26.5	37.7	73.6	137.8		25.9	
Gaseous Collombey Split	1523	-13.9%	931	-1.1%	2454	-9.5%	22.8	37.2	72.9	133.0	-3.5%	24.3	-6.1%
Gaseous LP flowlines MOP=5bar	1790	1.2%	941	0.0%	2732	0.8%	26.9	37.7	77.3	141.8	2.9%	26.4	2.0%
Gaseous No LP flowlines (MOP= 35bar)	1758	-0.6%	763	-18.9%	2522	-7.0%	26.4	30.5	65.1	122.0	-11.5%	23.5	-9.3%
Dense Phase Transport	1231	-30.4%	1462	55.3%	2693	-0.7%	18.5	58.5	116.5	193.4	40.3%	31.5	21.6%

The above table shows that:

- An ATCI value of 25.9 €/ton is expected for the base case in gaseous transport (MOP=35 barg), with the low pressure flowlines MOP fixed at 10 barg. A 30” trunkline is selected for this configuration (both for East and West systems) and a total of 46 compression units are required in this case.

- Significant savings in pipeline CAPEX are expected with the Collombey Split configuration, that allows to avoid the installation of the trunkline offshore section. In this case smaller CSs are required at Cimo and Satom, with associated lower OPEX (compared to the base case).

- The configuration with low pressure flowlines MOP fixed at 5 barg presents a slightly higher pipeline CAPEX since some low pressure flowlines are larger. In this case the boosting stations d/s low pressure flowlines require higher compression energy demand and higher energy consumption.

- The configuration without low pressure flowlines (i.e. MOP=35 barg for all the emitters) presents slightly lower pipeline CAPEX if compared to the base case since some flowlines are smaller due to the higher operating pressure. On the other hand, the avoidance of low pressure flowlines allows to save several boosting stations along the network with significant savings in CS CAPEX/OPEX. A total of 35 compression units are required in this case.

- In case of dense phase transport, the savings due to the smaller trunklines (14”/16”) are balanced by the additional compression costs and the overall CAPEX is close to the gaseous base case value. However, OPEX is certainly higher wrt. base case, due to the higher compression unit number (55) and the higher operating pressure requirements.

In the below Table 12.3.2 the results relevant to the gathering network are summarized together with the calculated costs for the export compression stations to be installed at the delivery points. The overall system cost indexes are also reported.

Table 12.3.2: CAPEX, OPEX and ATCI Summary for gathering network, export compression and overall system.

	CO2 GATHERING NETWORK					COMPRESSION TO EXPORT PIPELINE			OVERALL SYSTEM		
	PIPELINE CAPEX	GATHERING CS CAPEX	GATHERING CAPEX	GATHERING OPEX	GATHERING ATCI	export CS CAPEX	export CS OPEX	export CS ATCI	CAPEX	OPEX	ATCI
	MM€	MM€	MM€	MM€/y	€/ton	MM€	MM€/y	€/ton	MM€	MM€/y	€/ton
Base Case Gas Transport	1769	941	2711	137.8	25.9	435.0	59.2	7.9	**3146**	**197.0**	**33.8**
Gaseous Collombey Split (west)	1523	931	2454	133.0	24.3	435.0	59.2	7.9	**2889**	**192.2**	**32.3**
Gaseous lowP MOP=5bar	1790	941	2732	141.8	26.4	435.0	59.2	7.9	**3167**	**201.0**	**34.4**
Gaseous MOP=35 bar (all)	1758	763	2522	122.0	23.5	435.0	59.2	7.9	**2956**	**181.2**	**31.4**
Dense Phase Transport	1231	1462	2693	193.4	31.5	80.8	5.2	0.9	**2773**	**198.6**	**32.4**

The above table shows that:

- The costs relevant to the installation and operation of export compression stations at delivery points are significantly impacting the overall costs in case the gathering network is operated in gaseous phase.
- When considering the overall system (i.e. gathering system and compression station to the export pipeline) the savings provided by gas phase transport in the gathering system are compensated by the increasing requirement of the export compression stations, especially in terms of operating costs, and the differences among gas and dense phase solutions flatten out (the most convenient case is less than 10% cheaper than the most expensive one).
- The configuration without low pressure flowlines (i.e. MOP=35 barg for all the emitters) is confirmed as the solution with the lowest overall ATCI = 31.4 €/ton. However, dense phase transport option is not the most expensive solution and with an overall ATCI of 32.4 €/ton is cheaper than the base case gaseous option (ATCI=33.8 €/ton).

13. APPENDIX 1 – COST ESTIMATION PARAMETERS - CONFIDENTIAL

14. APPENDIX 2 – COST ESTIMATION OF OFFSHORE PIPELINE SECTION - GENEVA LAKE - CONFIDENTIAL

15. APPENDIX 3 – CALCULATION TABLES FOR CAPEX, OPEX AND O&M COSTS - CONFIDENTIAL

16. APPENDIX 4 – PIPELINE ELEVATION PROFILES

16.1 EAST TRUNKLINE NETWORK

Figure 15.1.1, Figure 15.1.2, Figure 15.1.3, Figure 15.1.4, Figure 15.1.5, Figure 15.1.6, Figure 15.1.7 and Figure 15.1.8 show the elevation profiles relevant to East System pipelines. Only the lines showing substantial elevation changes are reported, for the other lines a flat profile is considered in the hydraulic model.

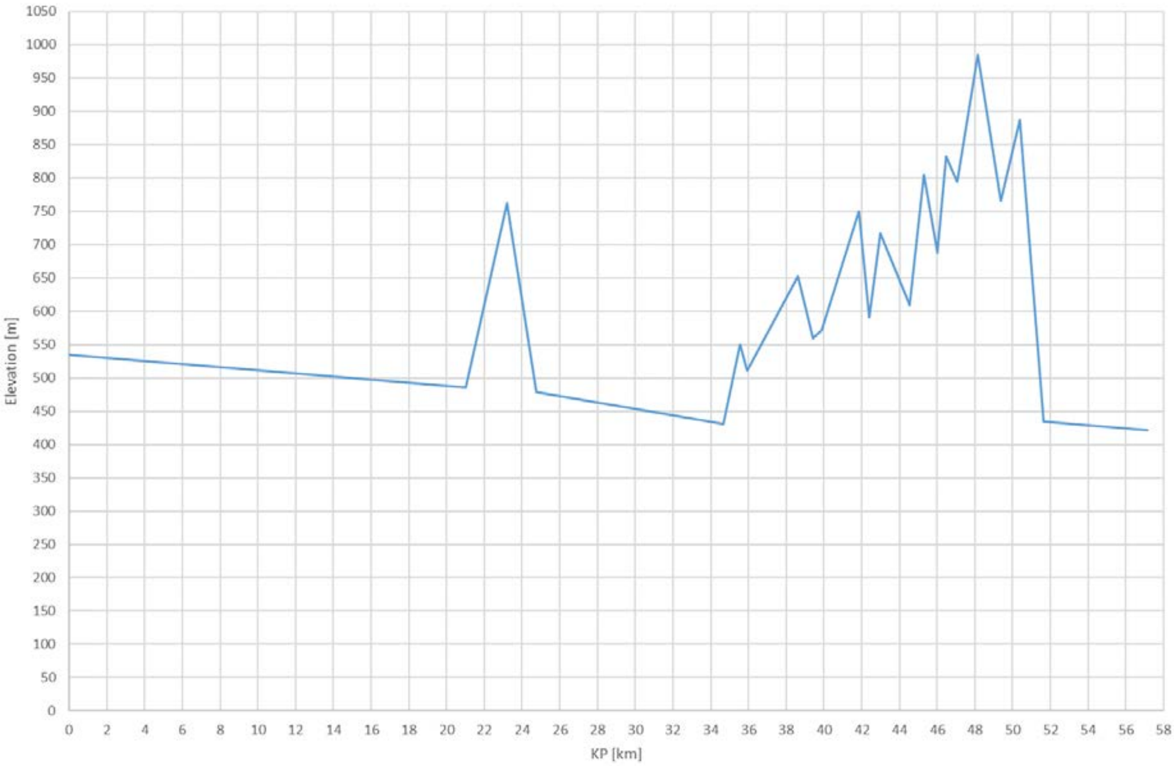


Figure 15.1.1: Elevation Profile – Rhine Valley Trunkline

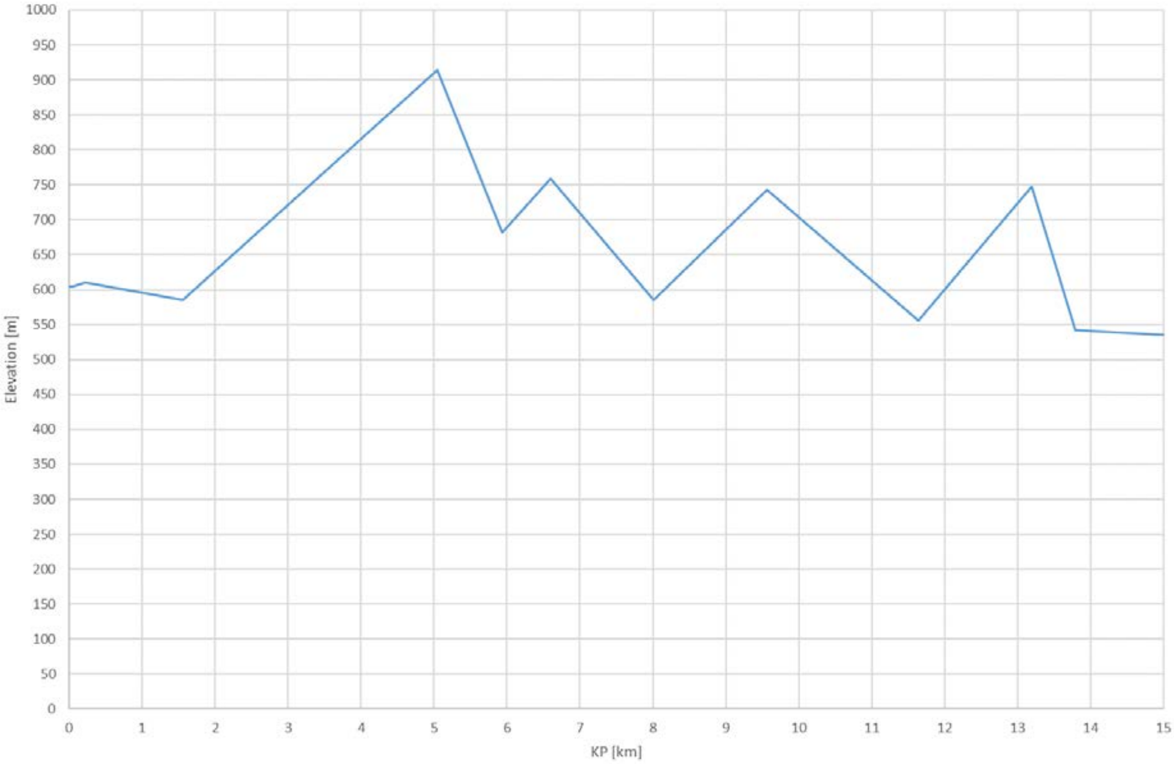


Figure 15.1.2: Elevation Profile – Axpo Tegra

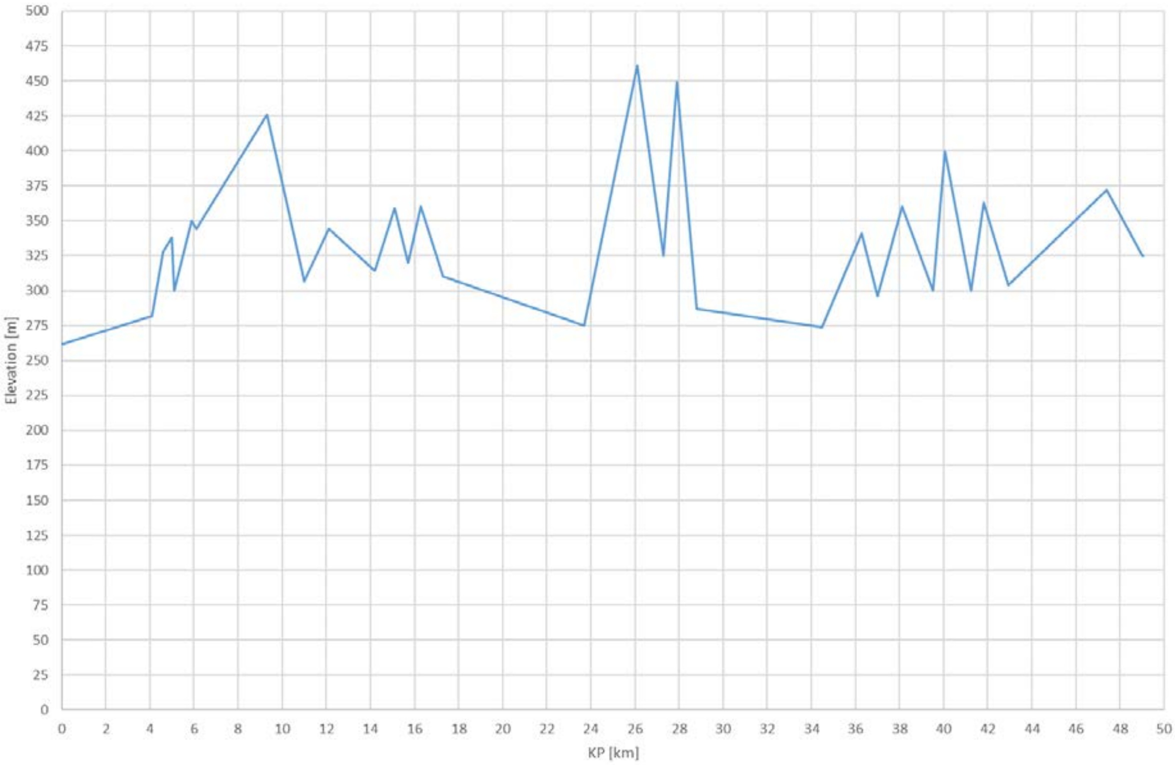


Figure 15.1.3: Elevation Profile – IWB Basel

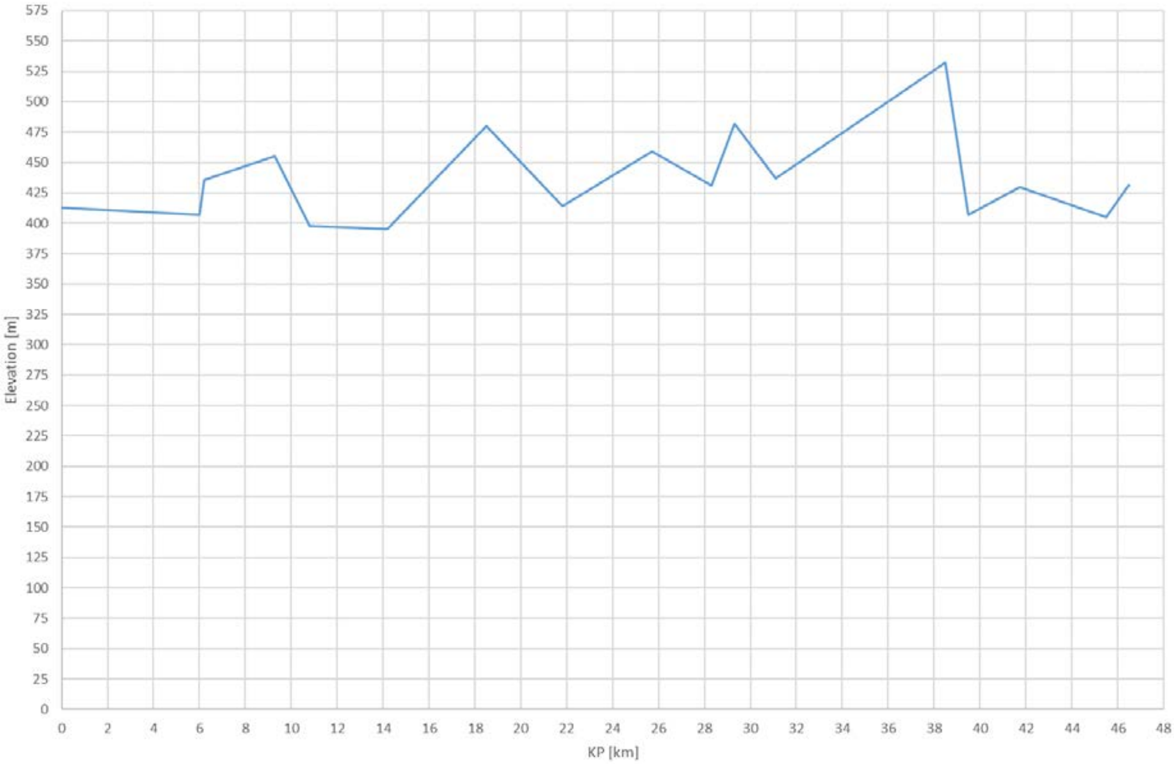


Figure 15.1.4: Elevation Profile – Renergia

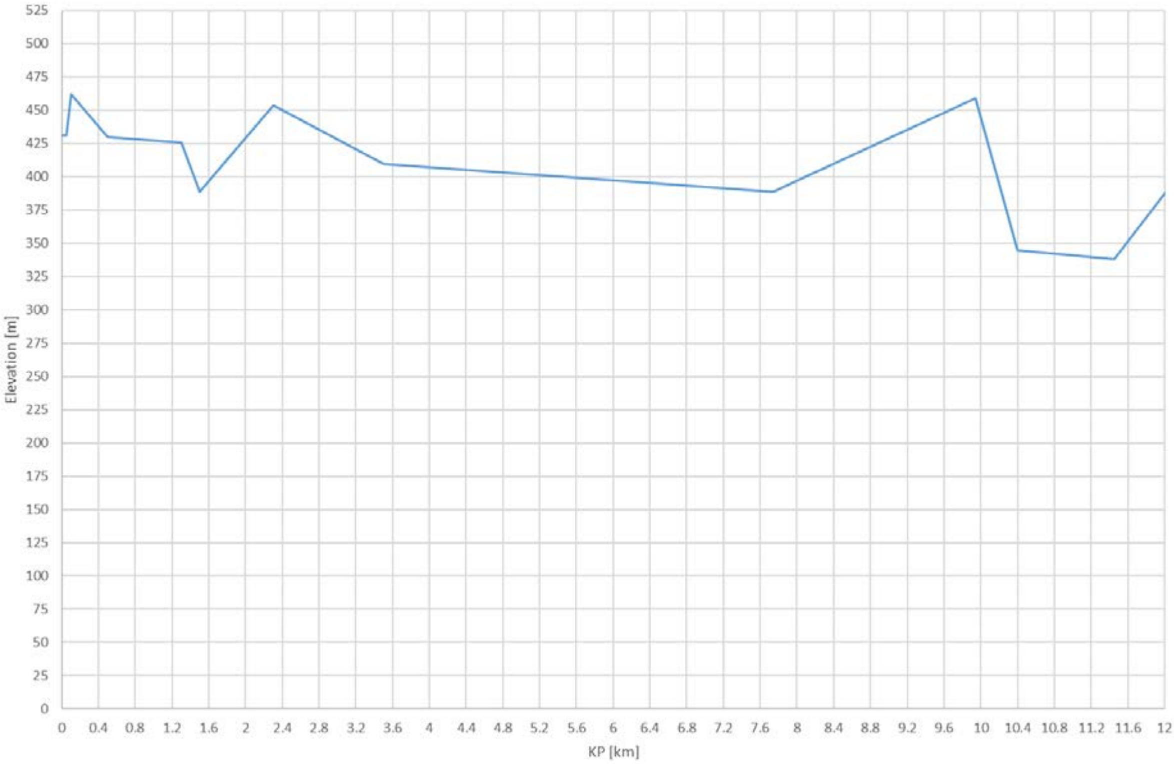


Figure 15.1.5: Elevation Profile – E12

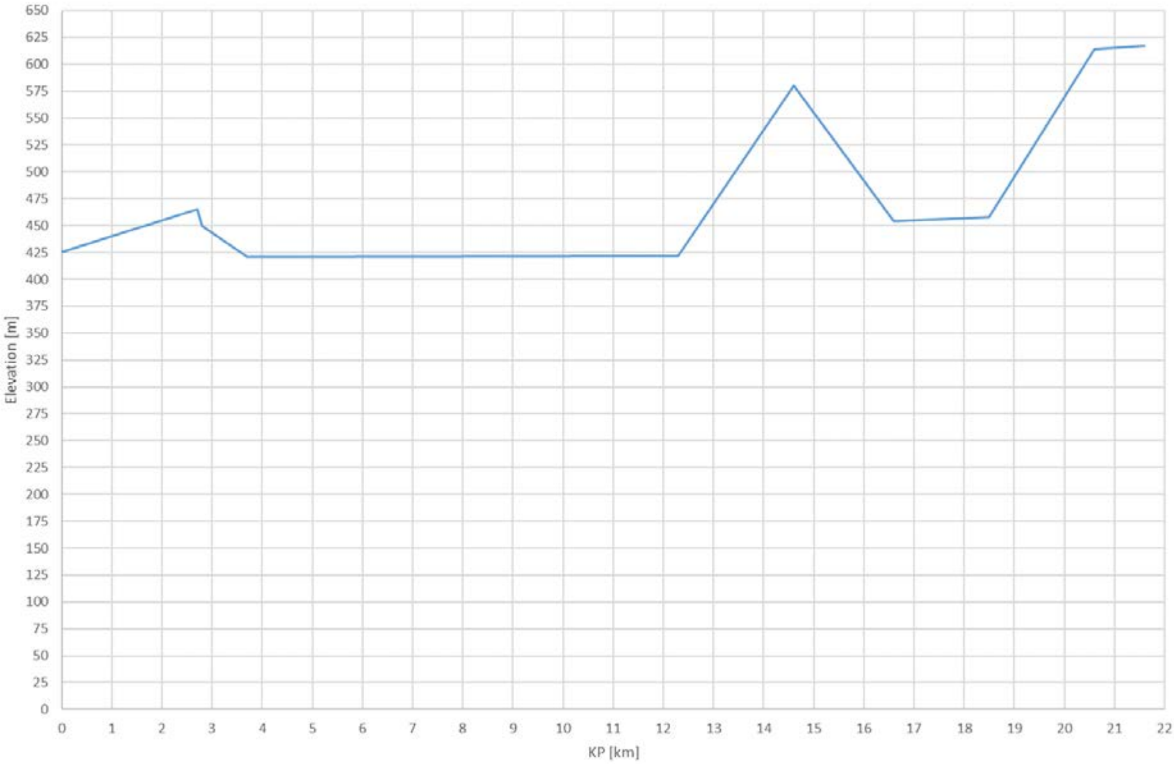


Figure 15.1.6: Elevation Profile – E7

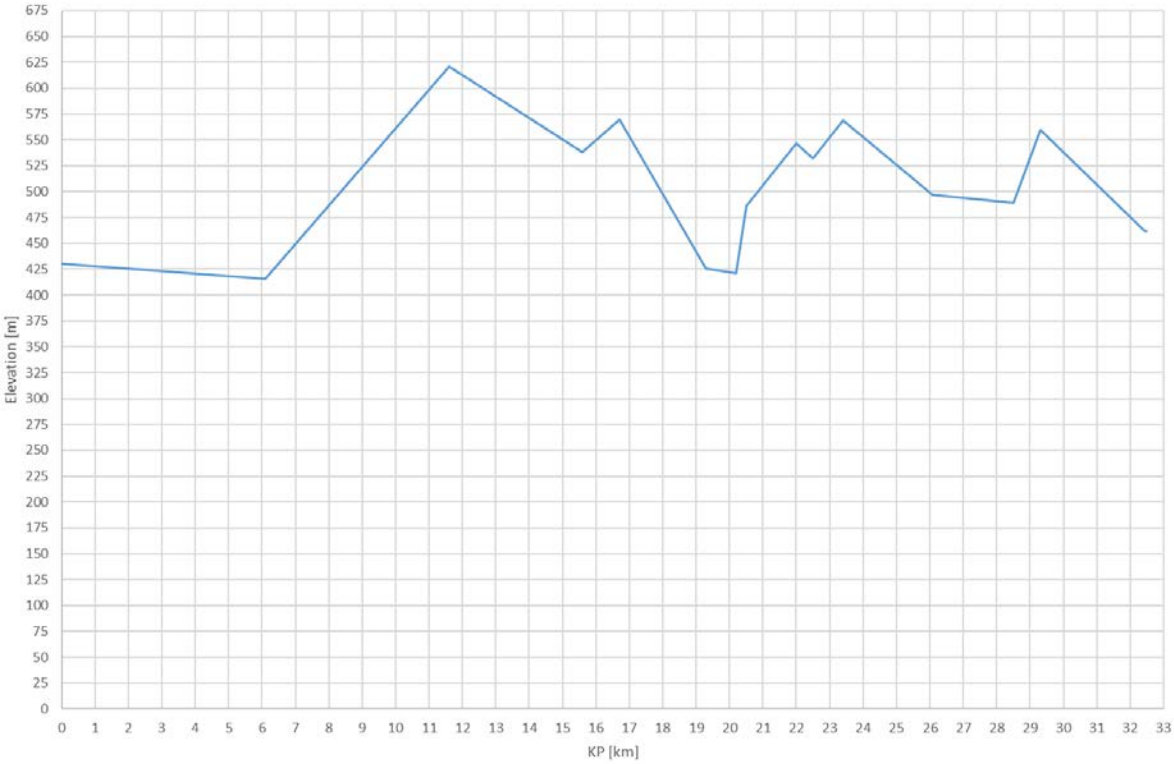


Figure 15.1.7: Elevation Profile – Thurgau

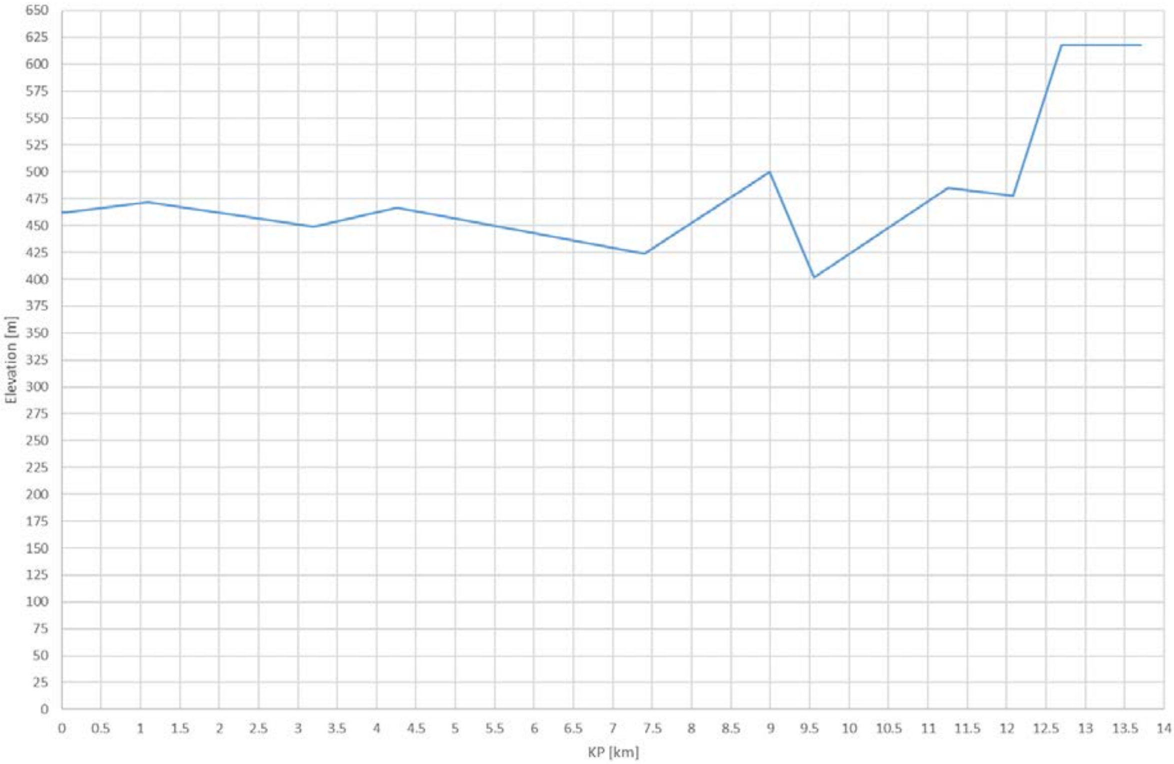


Figure 15.1.8: Elevation Profile – E6

16.2 WEST TRUNKLINE NETWORK

Figure 15.2.1, Figure 15.2.2, Figure 15.2.3, Figure 15.2.4, Figure 15.2.5, Figure 15.2.6, Figure 15.2.7, Figure 15.2.8 and Figure 15.2.9 show the elevation profiles relevant to West System pipelines. Only the lines showing substantial elevation changes are reported, for the other lines a flat profile is considered in the hydraulic model.

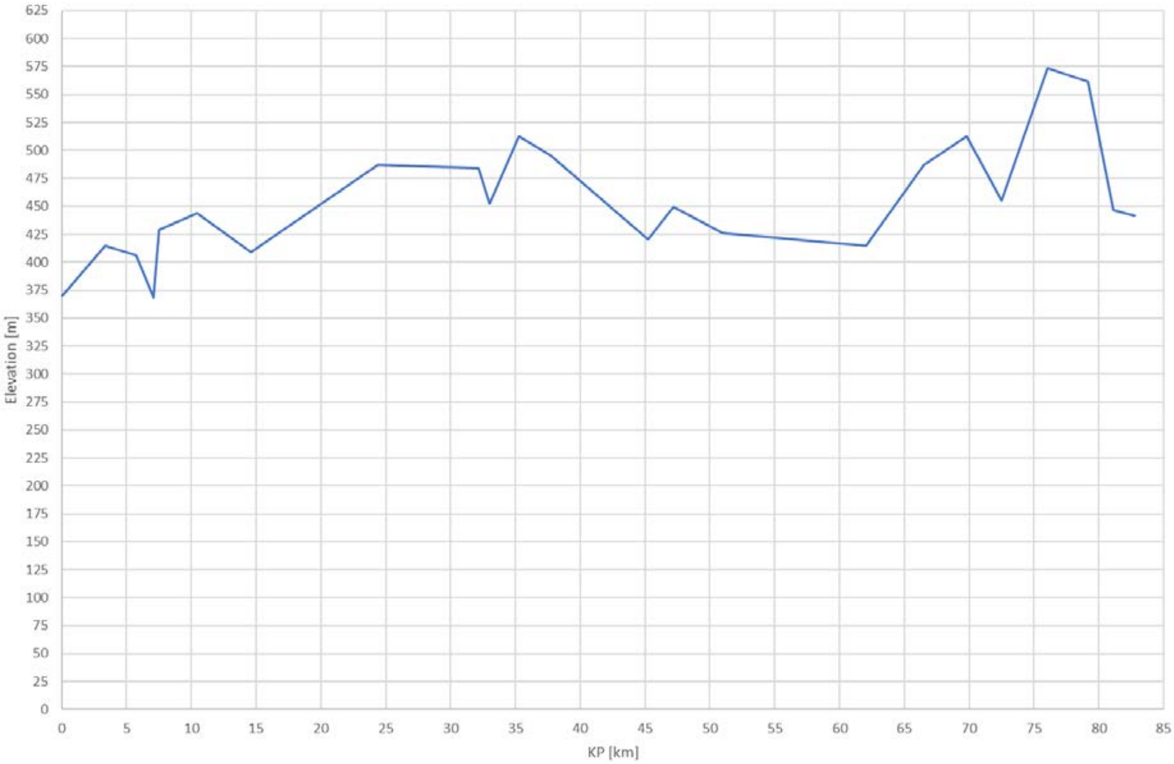


Figure 15.2.1: Elevation Profile – Les Cheneviers

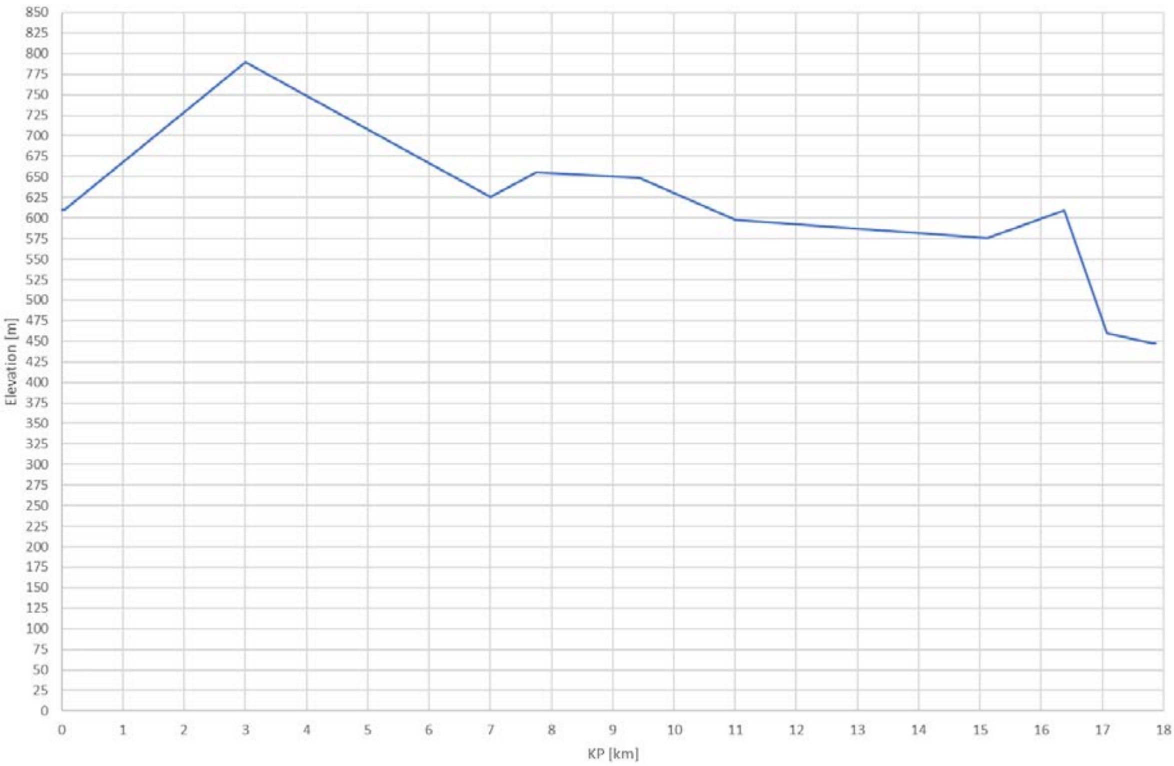


Figure 15.2.2: Elevation Profile – Tridel Lausanne

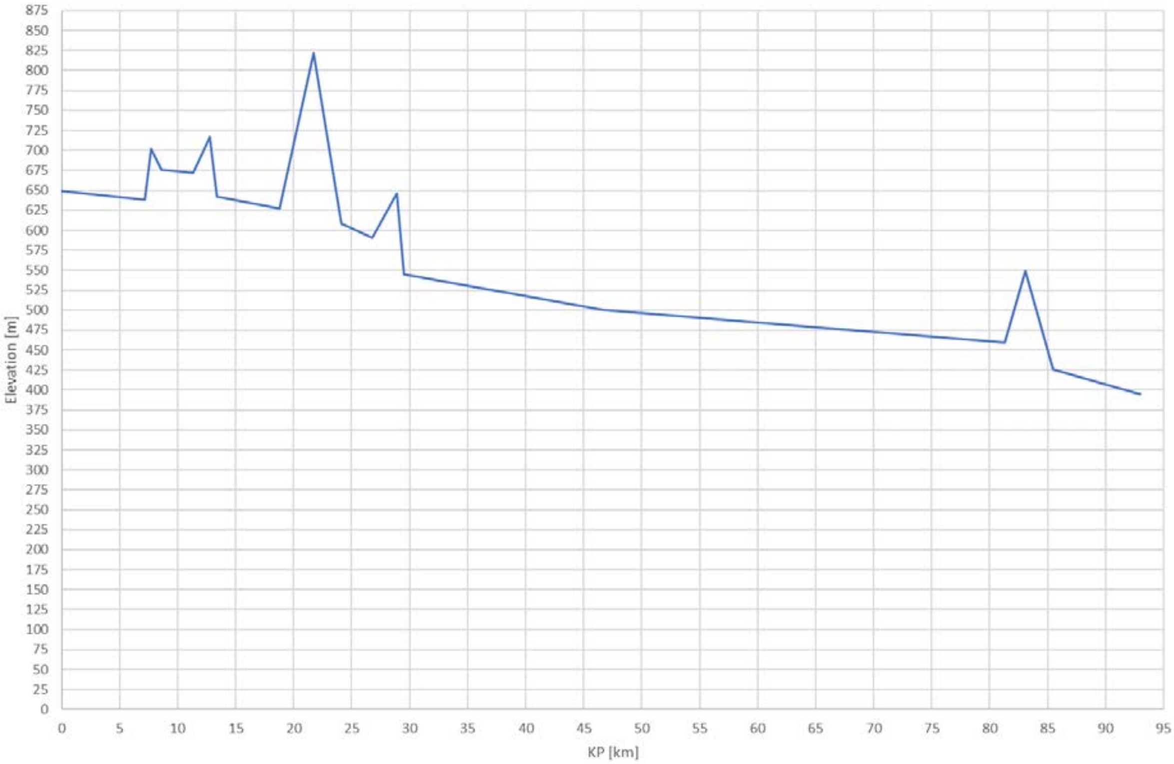


Figure 15.2.3: Elevation Profile – Lonza

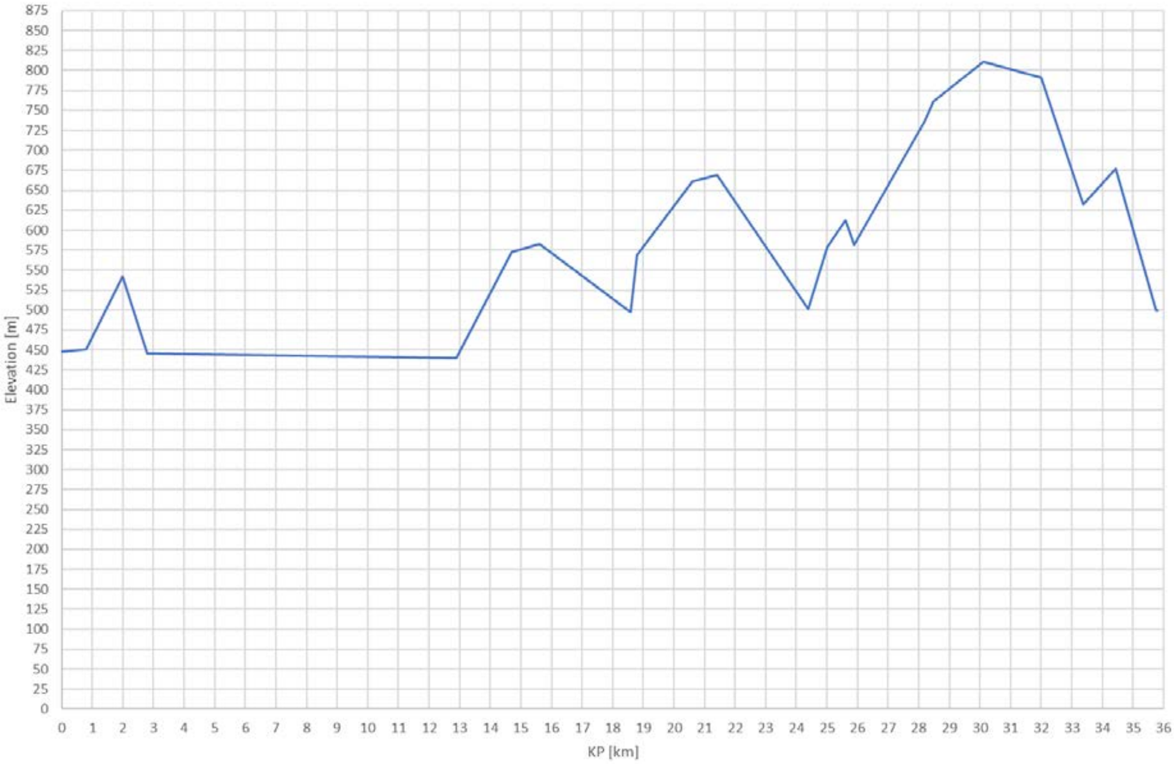


Figure 15.2.4: Elevation Profile – W32

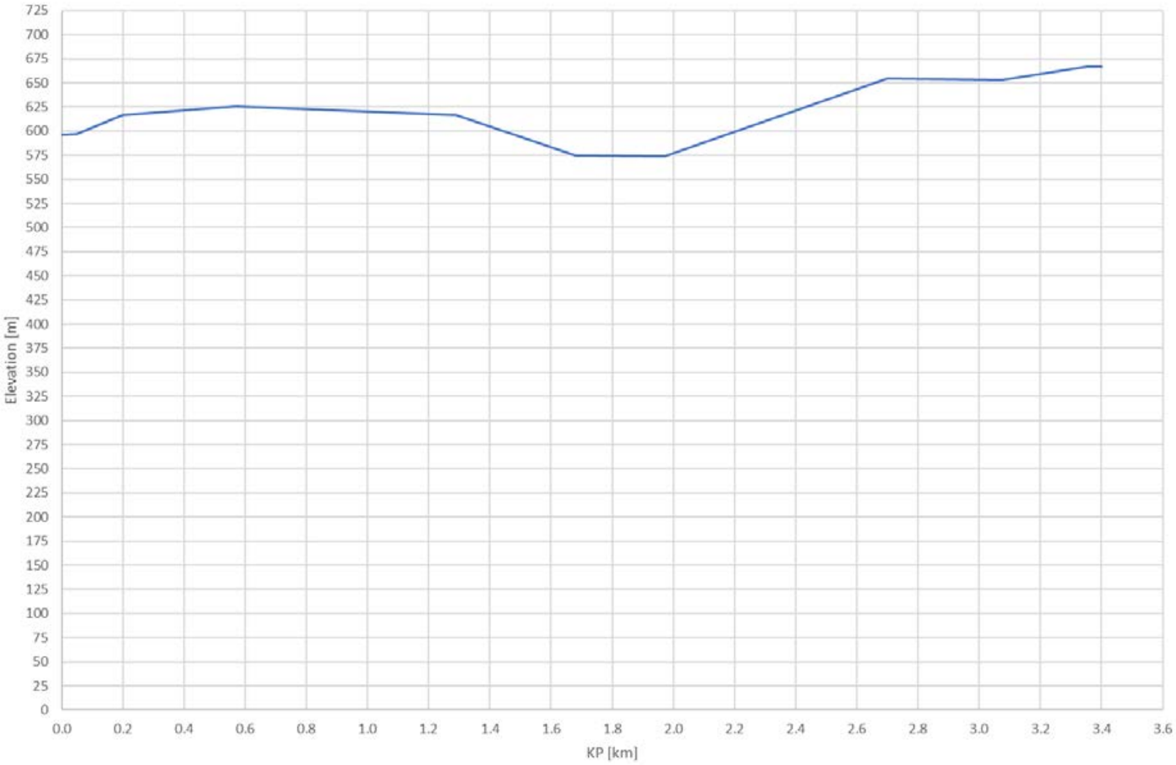


Figure 15.2.5: Elevation Profile – Saidef Fribourg

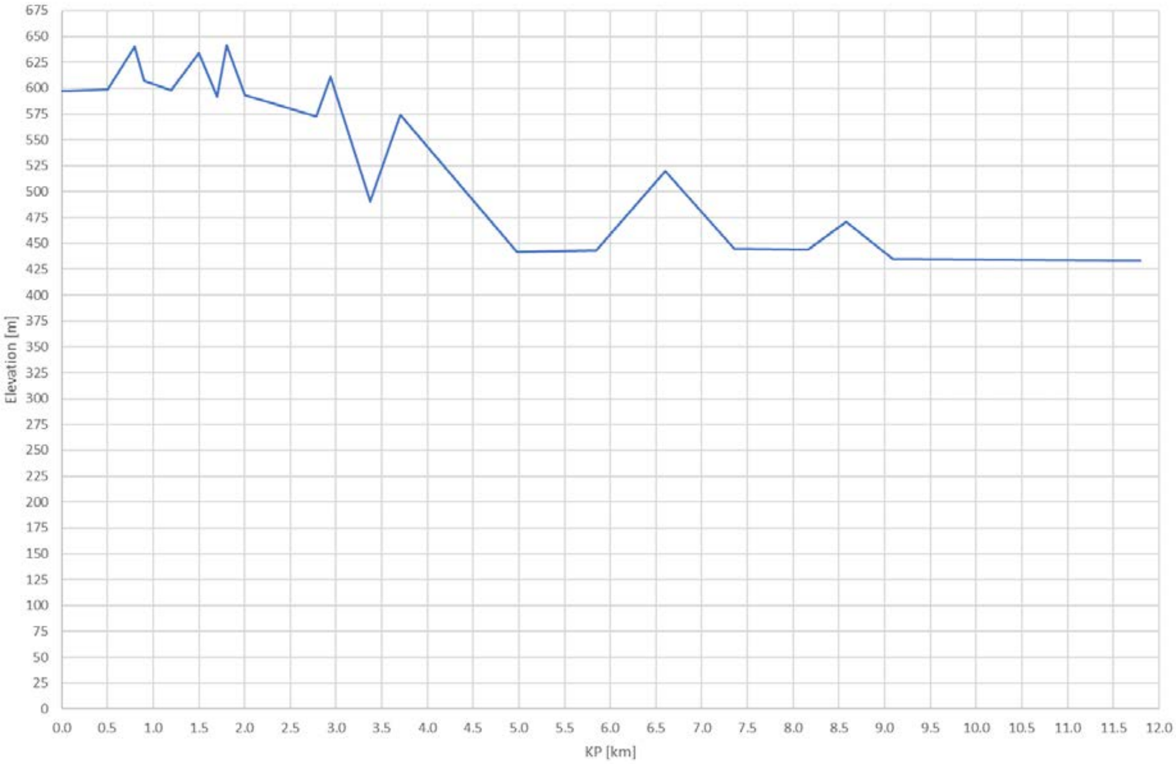


Figure 15.2.6: Elevation Profile – Vigier Cement

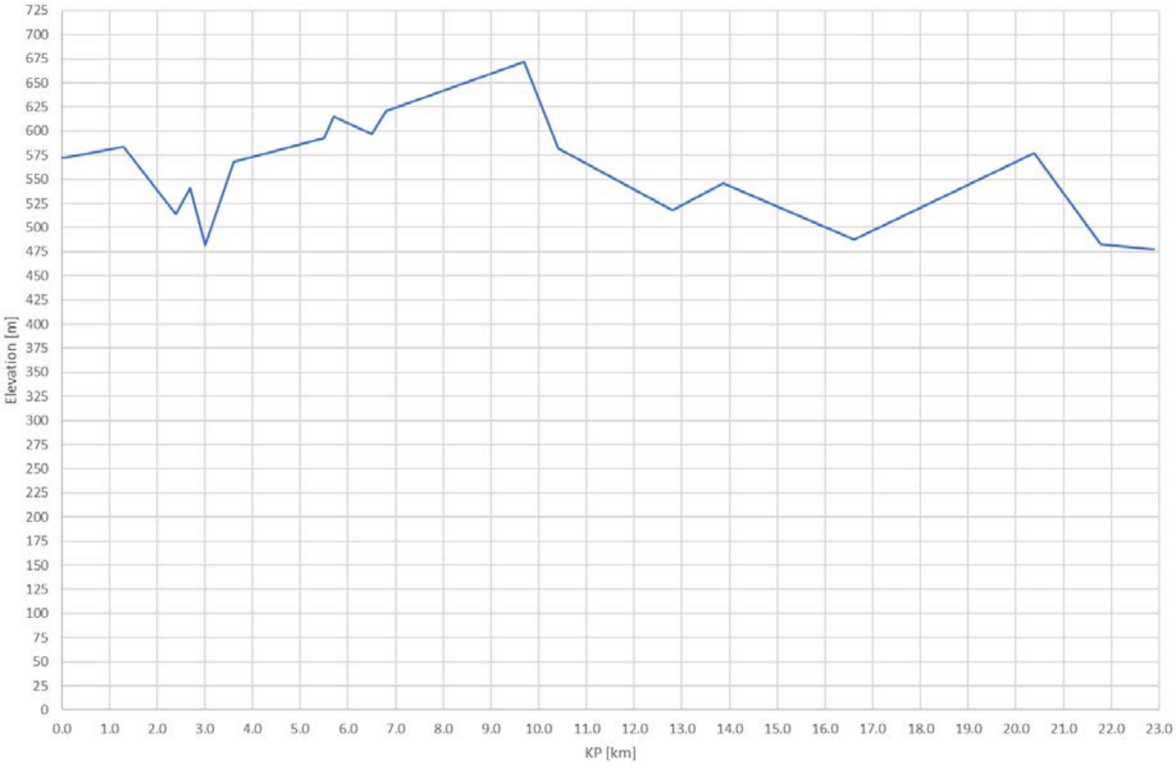


Figure 15.2.7: Elevation Profile – Energiazentrale

Figure 15.2.8: Elevation Profile – AVAG KVA

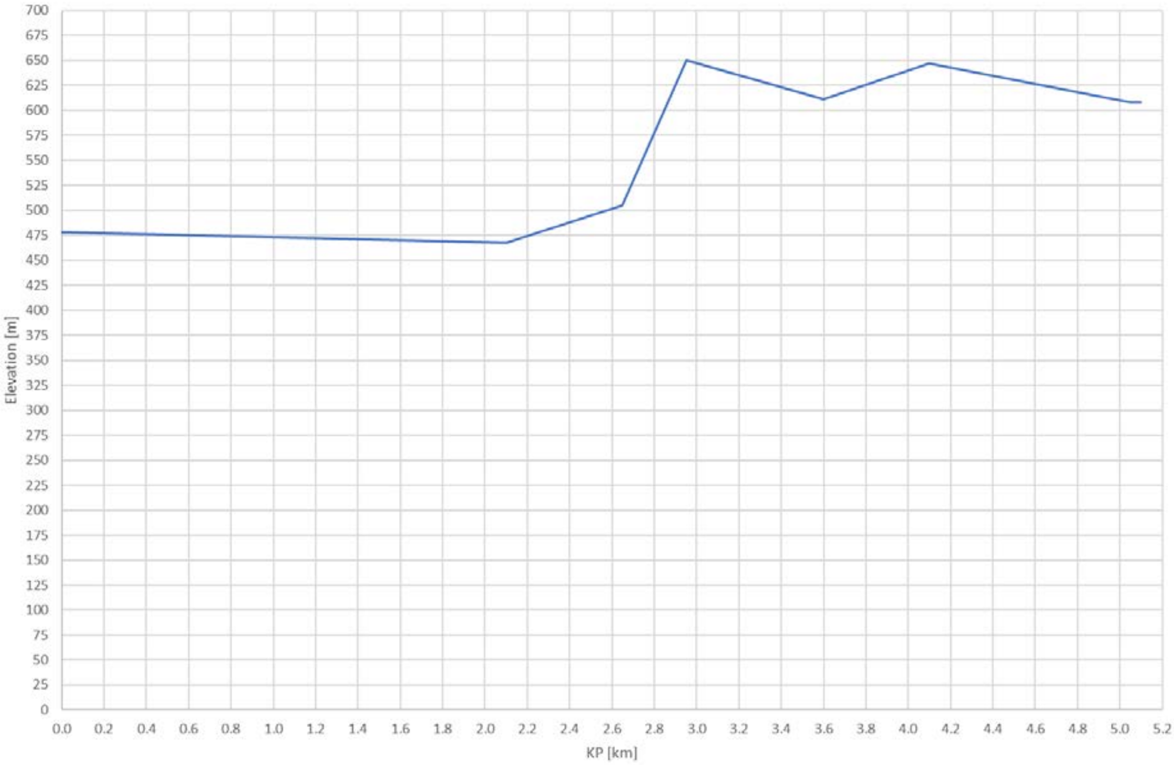
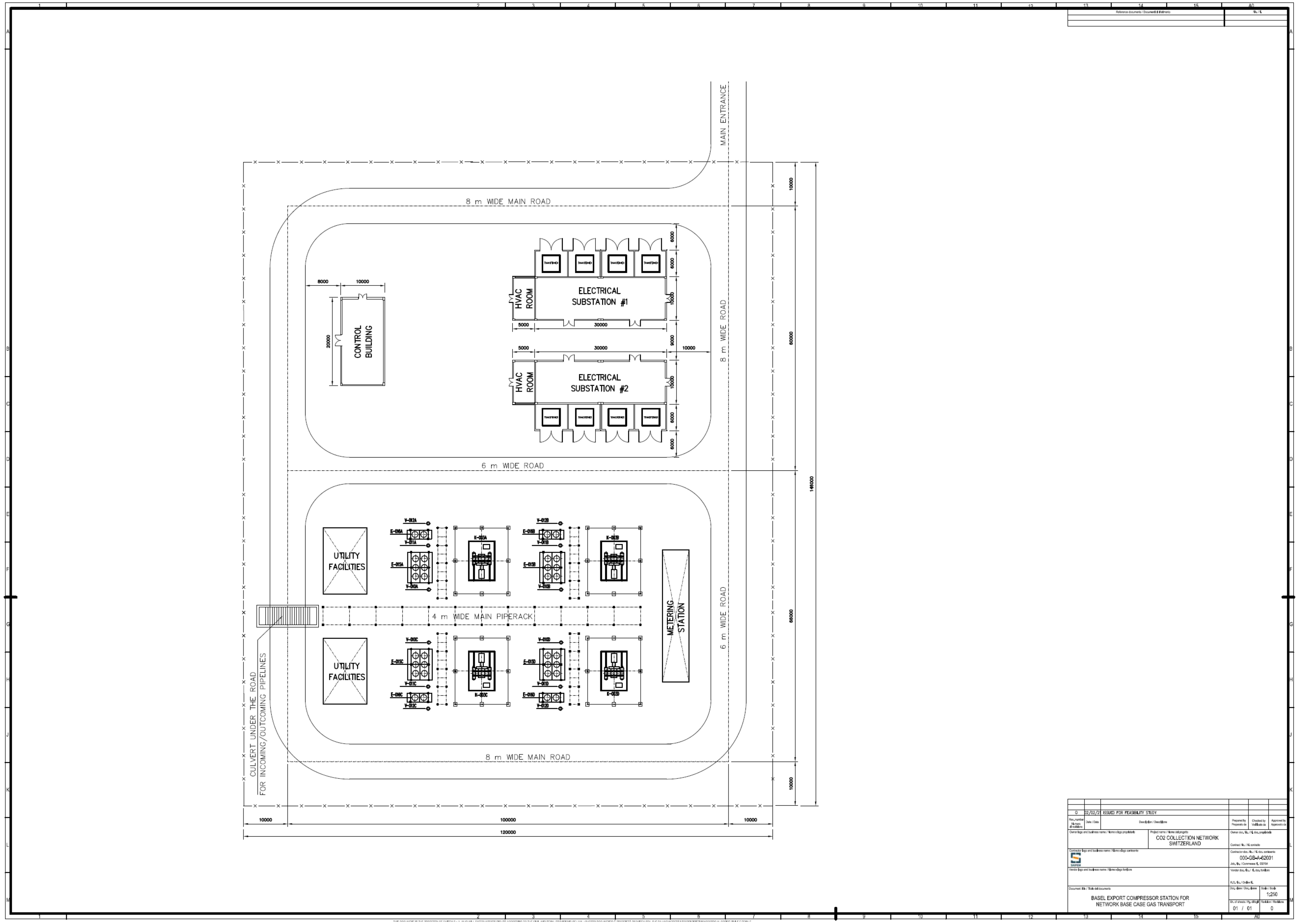


Figure 15.2.9: Elevation Profile – W9

17. APPENDIX 5 – BASEL EXPORT COMPRESSOR STATION PRELIMINARY LAYOUT



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