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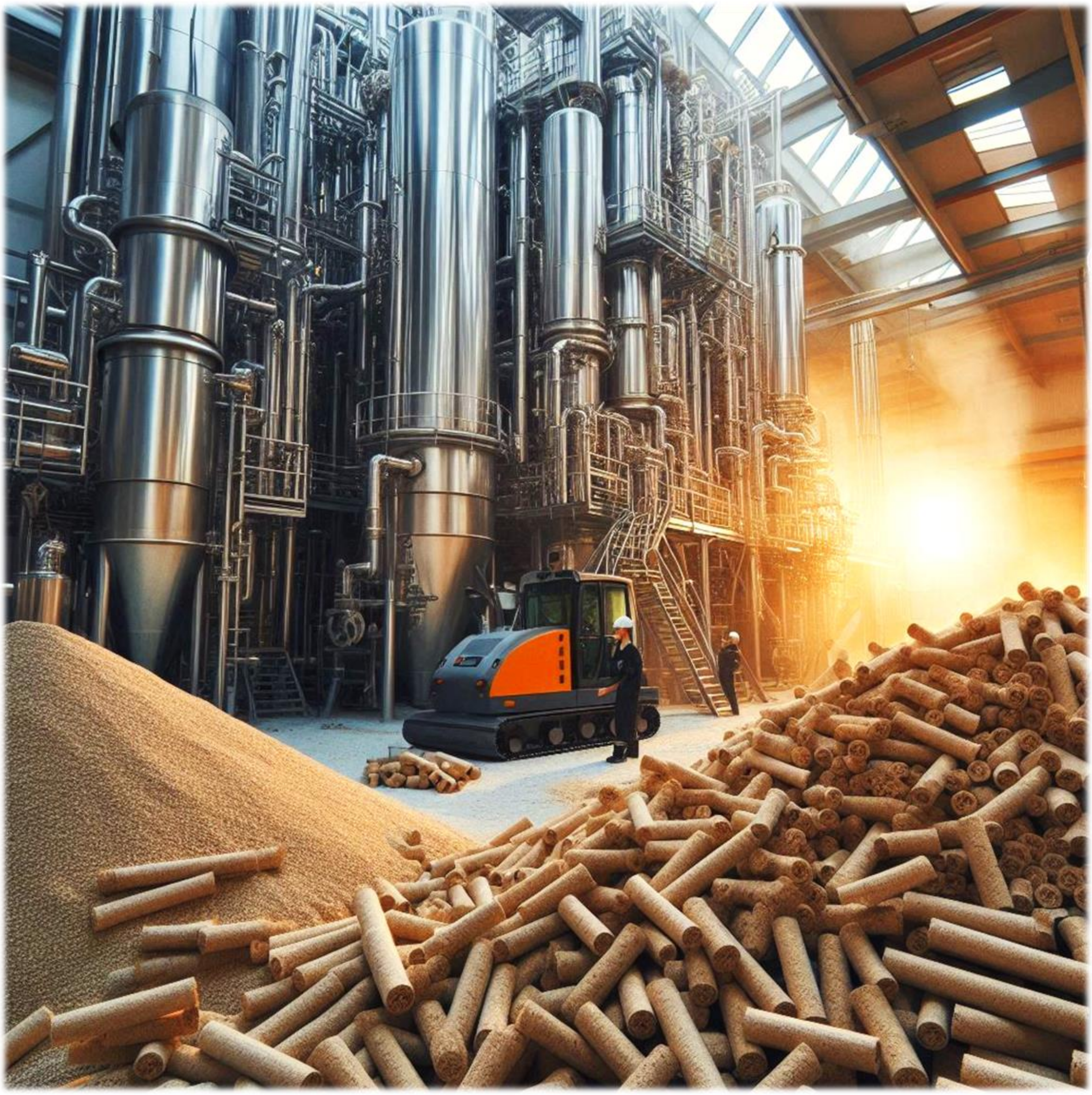
Report

Sustainable natural gas and aluminium production via biomass gasification and enhanced waste heat recovery in Novelis plant in Sierre City



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This study was prepared on behalf of SuisseEnergie. The authors are solely responsible for the content.

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CONTENT

SUMMARY

This detailed study aims to assess the sustainable utilization of renewable energy resources, especially biomass, in order to decarbonize heavy industries, such as secondary aluminium production. To this end, this study explores the feasibility of integrating biomass gasification to produce and supply fuel to high temperature furnaces in Novelis Sierre plant, whereas cascading the low-grade waste heat for district heating purposes and other cogeneration applications.

The analysis of the additional sustainable biomass potential indicates the availability of sufficient resources for a project of this kind in nearby cantons including Valais, Vaud, Fribourg, and Bern. Unlocking only 10% of the additional sustainable potential of biomass for energy use in these cantons is sufficient to supply the needs of Novelis aluminium plant and Sierre city during the winter season. Sourcing biomass from various regions in Switzerland remains economically viable; yet, procurement of biomass resources in farther locations may significantly increase wood energy prices. The energy consumption in biomass transportation slightly varies for different moisture content scenarios, with pelletized wood showing the most significant reduction. However, in this study wood chips supply is evaluated due to the local availability and fewer processing steps.

Different biomass energy conversion technologies for combined fuel, power and heat are analyzed to determine the most promising applications to use the limited valuable biomass resource. The biomass gasification system, which allows producing the synthetic natural gas (SNG) fed to Novelis aluminium plant, is compared to the conventional biomass boilers and cogeneration units. This analysis also encompasses the use of two different district heating networks, based either on the traditional water-based systems or new generation anergy distribution systems. Groundwater heat pumps (HP) are used to balance the space heating demand of the city. Eight biomass energy conversion scenarios are evaluated, namely:

1. SNG + water CAD: Biomass-to-SNG route with waste heat released to a water district heating network (CAD) without electricity generation.

2. SNG + cogeneration + water CAD: Similar to case 1, but with combined electricity and heat production in a Rankine cycle.

3. SNG + CO_2 CAD: Similar to case 1, but the CAD consists of a CO_2 district heating network, instead of a water-based CAD, without electricity generation.

4. SNG + cogeneration + CO_2 CAD: Similar to case 3, but with combined electricity and heat production in a Rankine cycle.

5. Syngas for CHP engine + water CAD: Biomass-derived syngas is used directly to run an internal combustion engine that produces combined power and heat. Fossil natural gas is imported from the grid to meet energy demand of the Novelis furnaces.

6. Boiler for SN + water CAD: A biomass boiler is used to produce high temperature steam in a steam network (SN) that generates power in a Rankine cycle. A water CAD supplies the city of Sierre. Novelis furnaces are fed with imported fossil natural gas.

7. Only heating boiler: Biomass is used only in a heating boiler to produce heat distributed through a conventional water CAD. Electricity and fossil natural gas are imported.

8. OxySNG + sCO_2 + CO_2 CAD: SNG is produced via biomass gasification and consumed in Novelis oxycombustion furnaces. The biogenic CO_2 separated is sequestrated to achieve negative emissions. The CAD consists of a CO_2 district heating network. A supercritical CO_2 power generation cycle is employed.

9. OxySNG + P2G + sCO_2 + CO_2 CAD: Similar to the case 8, but SNG production is boosted by reacting the biogenic CO_2 with hydrogen from water electrolysis in a methanation system. The so-called power-to-gas approach also enables the storage of renewable electricity in the form of SNG, in view of a limited availability of biomass resource. Waste heat is cascaded to a CO_2 CAD.

It is worth noticing that direct heat integration of the gasification unit with the aluminium plant remains challenging, in view of the harsh composition of the gasifier effluents, which may compromise the quality of the finished aluminium products. The technology footprint and the complexity of batch processing of solid aluminium also introduce other operational hurdles that must be carefully considered. On the other hand, indirect thermal integration between the aluminium and the gasification process has multiple benefits. As a source of local sustainable natural gas from renewable resources, the exploitation of the biomass enhances the sustainability and energy supply security of heavy industries, in view of the volatile natural gas and electricity market prices. In addition, the strategy of cascading waste heat from the biomass energy conversion and the aluminium production, starting from the highest temperature applications, through cogeneration, preheating of internal combustion air and gasifiers inputs, finalizing with the heat supply to a district heating system (CAD) at lower temperatures proved to be a suitable solution for meet the energy demands of the different industrial and societal actors, whereas producing net negative CO_2 emissions.

In effect, the biomass energy conversion routes for SNG production demand the largest biomass (>720 kWh/t_{Al}) and electricity (100-300 kWh/t_{Al}) imports, but just to the advantage of replacing fossil natural gas. Moreover, pre-combustion carbon capture units in the SNG plant and oxycombustion furnaces in Novelis aluminium plant facilitate the separation of biogenic CO_2 emissions, which can be captured and sequestered permanently, entailing net negative CO_2 emissions (up to -143 kg_{CO2}/tAl). In comparison, the traditional scenarios of biomass conversion are responsible for more than +120 kg_{CO2}/t_{Al} fossil CO_2 emitted. Also, thanks to a thorough waste heat recovery through the biomass conversion units and the aluminium furnace stacks using Rankine or transcritical CO_2 power systems, this approach increases the share of power self-generation to 30%. The case 4 presents the minimum energy consumption (i.e. SNG + cogeneration + CO_2 CAD), which can be explained by a more rational use of the biomass energy integrated to a waste heat steam network for combined heat and power production, linked to an anergy CO_2 network that capitalizes on the low-grade waste to deliver the space heating to the city. The total energy consumption of this configuration is 14% lower than the solution in which biomass is only used in a combustion boiler to supply heat. Direct biomass combustion (case7) holds the highest associated CO_2 emissions, due to the additional fossil natural gas consumption necessary to fuel the furnaces of Novelis Sierre plant.

A particular scenario in which biomass input is drastically reduced (89%) is the case in which power-to-gas technology and seasonal SNG/CO_2 storage is implemented (case 9). In fact, the so-called power-to-gas approach aims to capitalize on renewable electricity to boost the SNG production, thus the import of the woody biomass is limited to four colder months. The biogenic CO_2 is stored in liquid form, so that it can be upgraded to fuel by capitalizing on the renewable electricity available during the remaining months. The opex and indirect emissions associated to the large electricity import are the main challenges of this integrated route (P2G), as the indirect associated emissions may offset the positive impact of the avoided biogenic emissions. It was found that the maximum power capacity of the electrolyzer is 1220 kWh_{ee}/t_{Al}, which in turn produces 933 kWh_{H2}/t_{Al} (HHV). The maximum methanator capacity is 650 kWh_{SNG}/t_{Al}. The gasifier is consequently undersized, compared to the previous cases 1-4 and 8, only requiring a maximum biomass input of 250 kWh_{DB}/t_{Al} during the operative months (less than 7 MW for a typical 27.8 t/h aluminium remelting plant). Hence, the maximum gasifier size is sharply reduced to less than one third of the minimum capacity for the other SNG production routes. The integration of an anergy network for district heating purposes is competitive vis-à-vis a high temperature water-based network.

Finally, an extended analysis presented in Annex, considering the integration of aluminium plant in an industrial cluster together with methanol and sustainable aviation fuels plants shows opportunities of industrial symbiosis for the processes decarbonization. Waste heat cascading combined with heat pumping solutions show a high degree of compatibility with the future scenarios of decarbonization technologies and transition pathways. Overall, the project reveals that biomass gasification holds significant potential for decarbonizing heavy industry applications. Expectedly, biomass gasification setups are footprint intensive and costlier than simpler biomass boilers. Moreover, the developing technology readiness levels of some energy systems aggravates the risk perception, despite the efficiency and environmental benefits that more advanced energy technologies may have in the overall energy and industrial sector. However, an economic feasibility study based solely on present market conditions may be misleading, in view of the upcoming energy transition policies and anticipated cost-effective deployments of those advanced energy systems, which will help in displacing fossil resources and, thus, increase the industrial sustainability. In fact, new technological setups will be critical in scenarios of more stringent carbon taxations, as they can offset atmospheric emissions associated to the typical biomass energy use (e.g. direct biomass combustion), while helping to alleviate the environmental burden of the hard-to-abate heavy industries.

1. PROJECT OVERVIEW

The remelting and thermal treatment of aluminium scrap into new aluminium products is an energy intensive application reliant mostly on fossil fuels. It has associated an important environmental impact not only due to the atmospheric emissions, but also due to the waste heat rejected into fresh water bodies. Accordingly, more efforts towards the rational use of the energy resources consumed through the supply chain of the remelted aluminium are necessary. On the other hand, the simultaneous heat and biofuels production from biomass has proven to be the most impactful way of profiting from the biomass energy for heating applications, in comparison to conventional biomass combustion. Accordingly, this project investigates the use biomass to defossilize a secondary aluminium production plant in Novelis Sierre through the simultaneous production of fuels and heat. The relevance of this approach relies on the use of both residual heat and produced fuel to help diversifying the energy inputs of industries traditionally dependent on fossil natural gas. In this way, heavy industry sectors can reduce risk in face of imminent scenarios of fossil fuel or electricity shortage, while becoming pioneers in the utilization of agricultural and forestry residues for producing their own fuel and other value-added products. One of those firms is Novelis Sierre (VS), an innovative aluminium production firm with a vast experience in aluminium processing, seeking for increased aluminium recycling rates and a reduced use of fossil energy resources in its assets, strategically aligned with its energy transition objectives.

A schema of the energy integration approach for a biomass gasification unit in the Novelis site is presented in Figure 1. The scope encompasses the evaluation of the regional biomass availability (sustainable biomass potential), considering the competing options of biomass utilization, and its transportability and obtainability. In addition, the waste heat recovered from the biomass gasification unit and the synthetic natural gas production processes can be exploited directly or indirectly to meet specific energy demands of the aluminium plant and the urban agglomeration. Accordingly, the use of valuable biomass energy is prioritized at higher temperatures, and waste heat is cascaded to be used at middle (cogeneration and power generation cycles) and lower temperature applications (e.g. district heating network) [1].

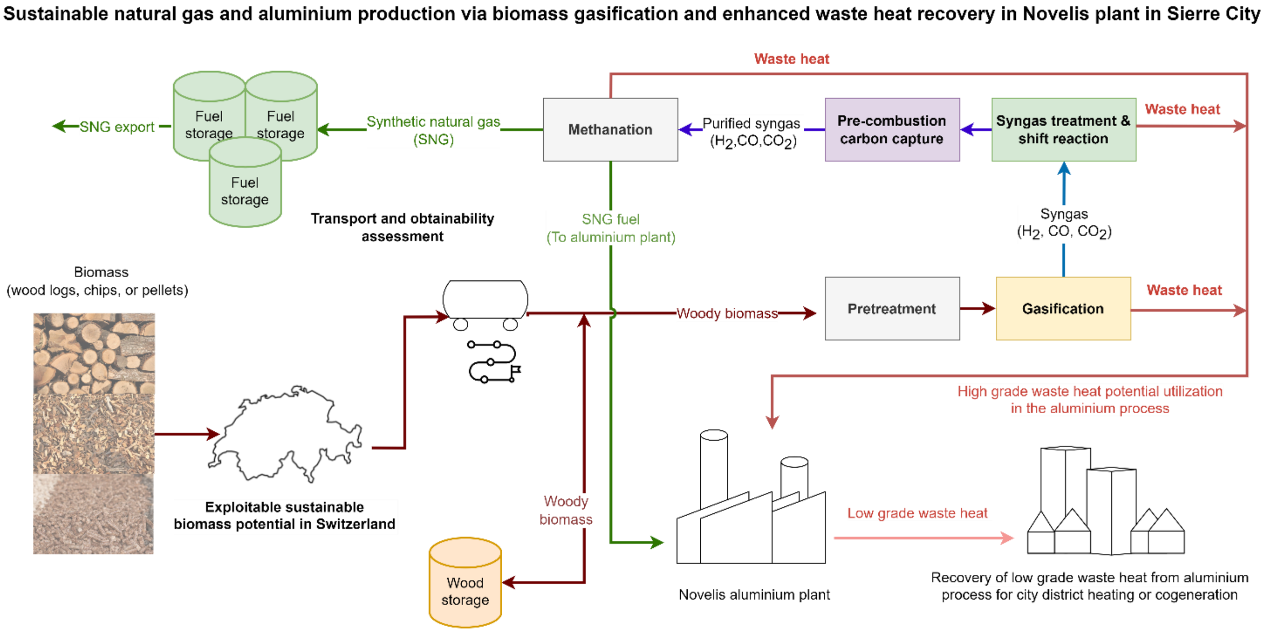


Figure 1. Schematic of the conceptual approach of an integrated biomass gasification unit for combined heat, power and fuel production [1].

2. REGIONAL BIOMASS INVENTORY

According to the International Energy Agency (IEA), biomass is defined as a biological material, which is directly or indirectly produced by photosynthesis. This includes wood and wood residues, crops residues, organic wastes from agriculture, landscape management, and households [2]. Biomass is considered an essential part of the energy transition and has the added value of being storable, either directly as wood or in the form of biogas or SNG. This energy storage capacity can help in future energy scenarios by compensating for the fluctuations of other renewable resources, such as wind and sun. Clearly, the actual added value will be only apparent when the whole energy system is considered.

In this report, the inventory data published by the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL) was used as the main reference for evaluating the available biomass potential in Switzerland [3]. This information is accessible in the form of metadata files published on envidat.ch website (last updated in September 2022), technical reports [2, 4, 5], and multiple scientific publications [6, 7]. Other references used for estimating the Swiss biomass potential in this study are:

- Online woody and non-woody biomass distribution maps, published by the Swiss federal authorities at (map.geo.admin.ch),
- Online map quantifying the existing and planned thermal networks using biomass resources, published by the Swiss federal authorities at (map.geo.admin.ch),
- Interviews with biomass sector specialists in Switzerland, like forestry entrepreneurs, experienced academics, and biomass treatment and distribution enterprises.

In Switzerland, WSL examined the relevant woody and non-woody biomass quantities and their respective primary energy potentials. Figure 2 shows the classification of the main biomass categories in Switzerland as established in [7].

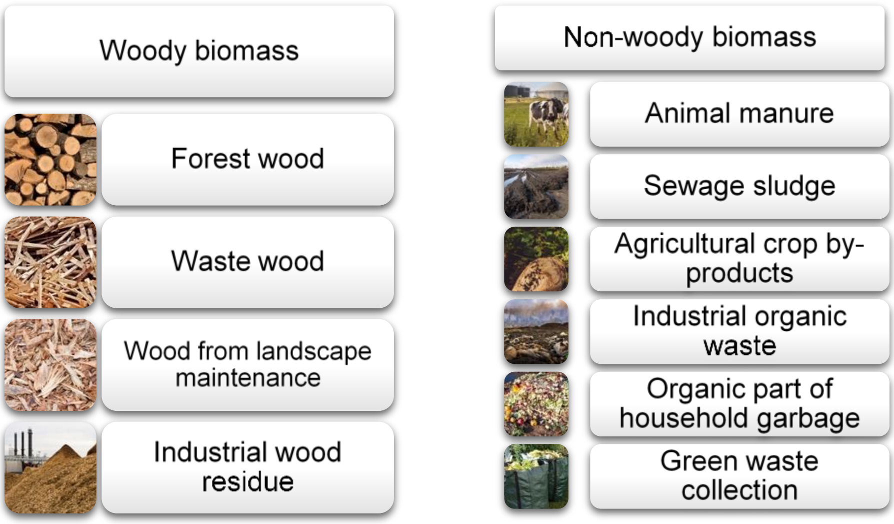


Figure 2. Classification of biomass categories in Switzerland based on WSL [7].

According to Figure 3, a uniform and consistent approach was adopted from WSL reports to estimate the current potentials for ten biomass categories for the whole of Switzerland. First, national scale data was collected for all the available types of biomass to estimate annual quantities that could be theoretically collected, defined as the theoretical potential. Thereafter, explicit and rational restrictions were applied for sustainable use of bioenergy production, according to the current state of the art, and subtracted from the *theoretical potential* to obtain a so-called *sustainable potential*. These restrictions include competing applications of biomass material utilization, environmental factors, supply costs currently governed by the forest protection subsidies, and scattered distributions of the small-scale facilities. Finally, the *additional sustainable potential* was estimated by subtracting the current bioenergy production and consumption from the sustainable potential. In order to determine the potential candidates to supply the biomass demand of the Novelis site, another parameter defined as the *exploitation percentage* was adopted to further discount the *additional sustainable biomass potential* available per Canton. This parameter aims to reflect the actual limitations to obtainability and transportability of the existing biomass in each Canton, as other costumers will be expectedly looking for the additional sustainable biomass potential, aside from Novelis.

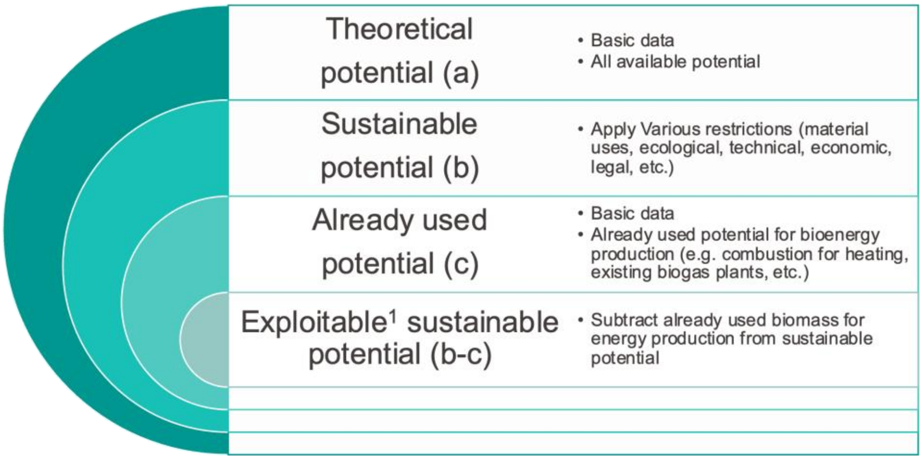


Figure 3. Definition of biomass potential levels by WSL [7].

According to these classifications, the *theoretical biomass potential* in Switzerland, based on the primary energy content, was estimated at an annual value of 209 PJ. The major contributions are attributed to the forest wood (108 PJ) and the animal manure (49 PJ). The *sustainable potential* energy content from these two resources is estimated at 26 PJ/y for forest wood and 27 PJ/y for animal manure [7]. A graphical summary of these values, as well as similar approximations for the other types of biomass, is shown in Figure 4.

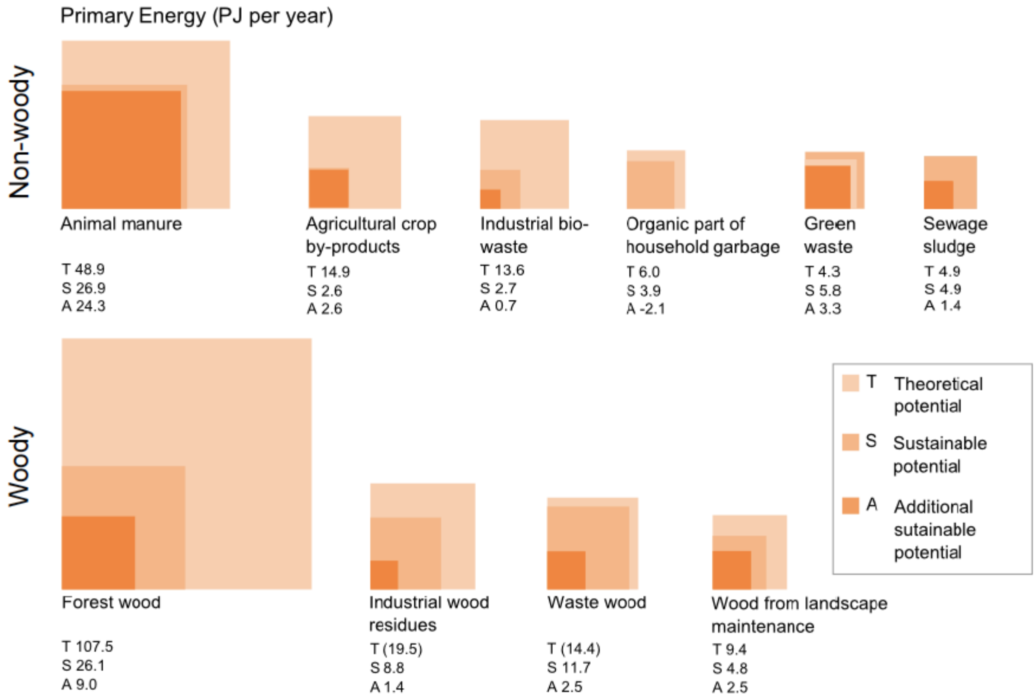


Figure 4. Primary energy potentials (PJ/y) for all types of biomass, adapted from [5, 7].

Although animal manure represents a major untapped energy resource in Switzerland, its large-scale utilization remains challenging, mainly due to the vast spatial distribution of cattle farms across the country, as well as the significant losses of biomethane potential it suffers during transportation and storage (up to 40%) [8]. This fact suggests a more modular approach by upgrading that resource via biodigestion facilities available at farms, which can exploit the produced biogas for their local needs. Another major challenge to the large-scale utilization of manure is high moisture content (~80%), incurring transportation costs and energy consumption.

For industrial applications, like high temperature heat supply, emphasis is given on utilizing woody biomass due to the large-scale potential, transportability, and the technological suitability of the gasification process [9–11]. For estimating the amount of woody biomass in Switzerland and the percentage available for exploitation by the current project, the four main woody biomass categories can be further classified and defined as shown in Figure 5. It is important to note that there is no energy cropping practice in Switzerland like in other regions, where crops such as sugar cane are grown for energy production purposes [12]. The priority in terms of organic resources is given first for food supply (i.e. non-woody biomass) and for material applications (e.g. timber wood). Important geological constraints also apply in cases of mountainous areas for avalanche protection. In the category of waste wood, some material applications result in left-over elements not suitable for gasification, such as glue, paint, PVC, or chemical preservatives. Therefore, an additional restriction is applied on the exploitable potential from this category for the purpose of this study to include only mechanically processed wood. This latter value is around 18% of the additional potential of waste wood based on national Swiss data.

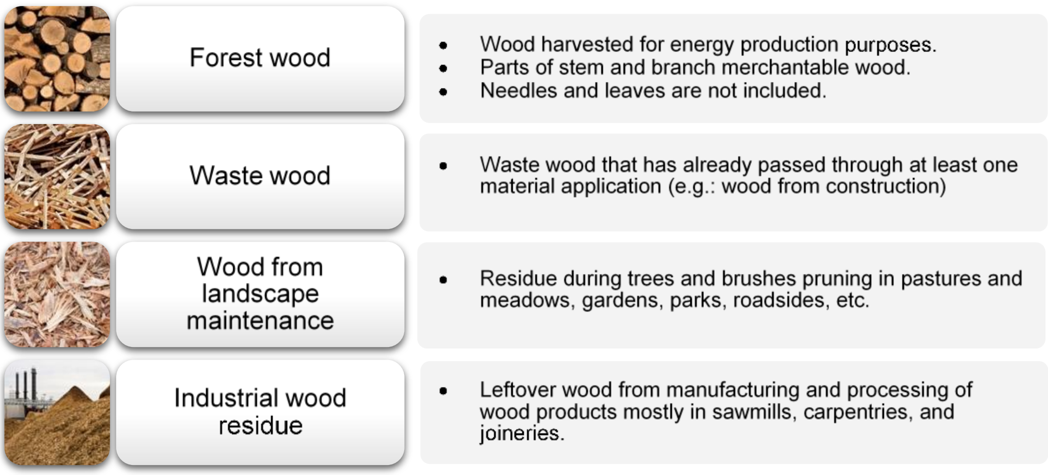


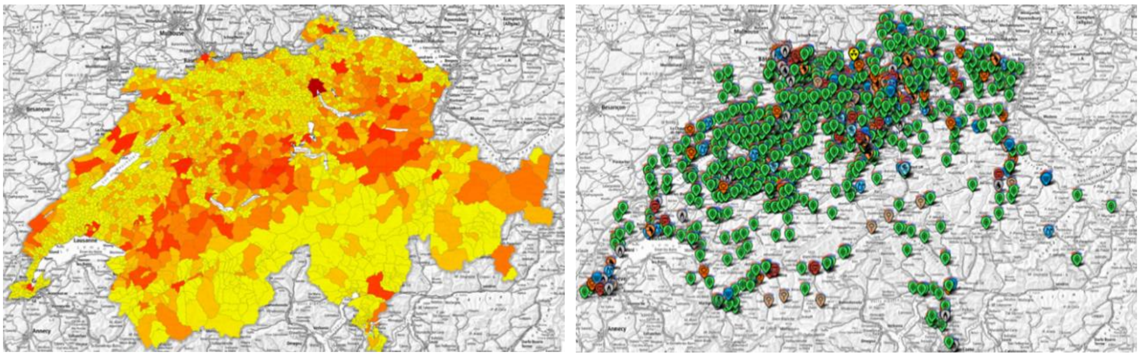
Figure 5. Classification and definitions of woody biomass resources in Switzerland [3].

In the case of forest wood harvested for energy purposes, different forest management scenarios may be taken into consideration. In the analysis published by WSL for national potentials in Switzerland, three scenarios were evaluated, including the business-as-usual continuous stock increase (CSI), the moderate stock reduction (MSR) – which assumes reduced forest wood stocks to 300 m^3/ha till 2046, after which the capacity remains constant – and the large stock reduction (LSR) – which assumes reduced stocks till 2046 with different targets of either 300 or 200 m^3/ha, depending on the region. For the *theoretical forest wood potential* of 108 PJ (see Figure 4) reported by WSL, a MSR scenario is assumed. In the next stage, restrictions related to mortality, protected areas, harvest losses, and material uses are applied to compute the sustainable potential. In this regard, two material usage alternatives are possible, including an energy friendly or less energy friendly scenario, such that the former scenario increases the potential biomass for energy uses by approximately 30%. It results in an estimation of about 26 PJ/y of sustainable forest wood potential in Switzerland for an energy friendly scenario. Finally, ecological, and financial restrictions are applied, subsidies in protection forests are considered, and currently used potential is subtracted from the remaining value to arrive at an *additional sustainable potential* of 9 PJ/y of forest wood in Switzerland. The largest potential is distributed over the Central Plateau and Jura and tabulated for the top 5 cantons in Switzerland and the Valais in Table 1. This table includes only the category of wood from forests and calculates the equivalent dry biomass weight based on a lower heating value of 17 GJ/t and a moisture content of 10%.

Table 1. Additional sustainable potential of forest wood in top 5 cantons plus Valais [3].

Canton	Energy Available [TJ/y]	Equivalent weight (Dry) [kt/y]
Bern	1,791	117
Vaud	1,077	70
Aargau	715	47
Zurich	713	47
St. Gallen	566	37
Valais	130	8.5

Figure 6 shows extracted images from online maps published by Swiss federal authorities highlighting the sustainable woody biomass potential across the country (a) and planned or existing biomass heating projects (b). Areas of darker shading indicate higher density of woody biomass potential. Figure 7 shows a summary of the woody biomass potential in Switzerland divided by the type of resource in terms of both sustainable and additional (actually available) sustainable potential.



(a) *(b)*

Figure 6. Geographical distributions from www.geo.admin.ch. (a) Woody biomass potential in Switzerland (areas of darker shading indicate higher density of woody biomass potential), (b) Planned and existing CAD systems using biomass in Switzerland.

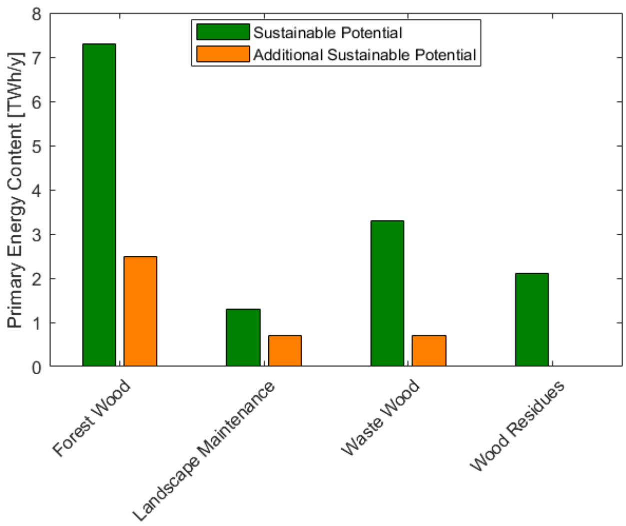


Figure 7. Woody biomass potential by category in Switzerland [3].

Actually, for a canton like Valais, the majority of woody biomass is attributed to wood from landscape maintenance and not forest wood, as it can be seen in Figure 8. This plot shows the additional sustainable potential of biomass in descending order for the 13 districts of Valais. Most of this additional potential is from landscape maintenance (~64%), followed by forest wood (~30%), and waste wood (~6%). It is worth noticing that there is no *additional sustainable potential* from wood residue of industrial processes in Valais. By realizing that other projects also plan to exploit the biomass potential available in the Valais and nearby Cantons, an additional parameter that adjusts the percentage of biomass from each Canton exploitable by Novelis is adopted and varied between 10%-50%. In this way, the sensitivity to the fraction of *additional sustainable potential* to which Novelis may eventually have access in multiple scenarios of biomass utilization can be evaluated in the light of the transportability and obtainability of the biomass resources. This further reduction accounts for newly existing or planned projects for biomass utilization in district heating applications, which is an increasing route for heating purposes in Switzerland.

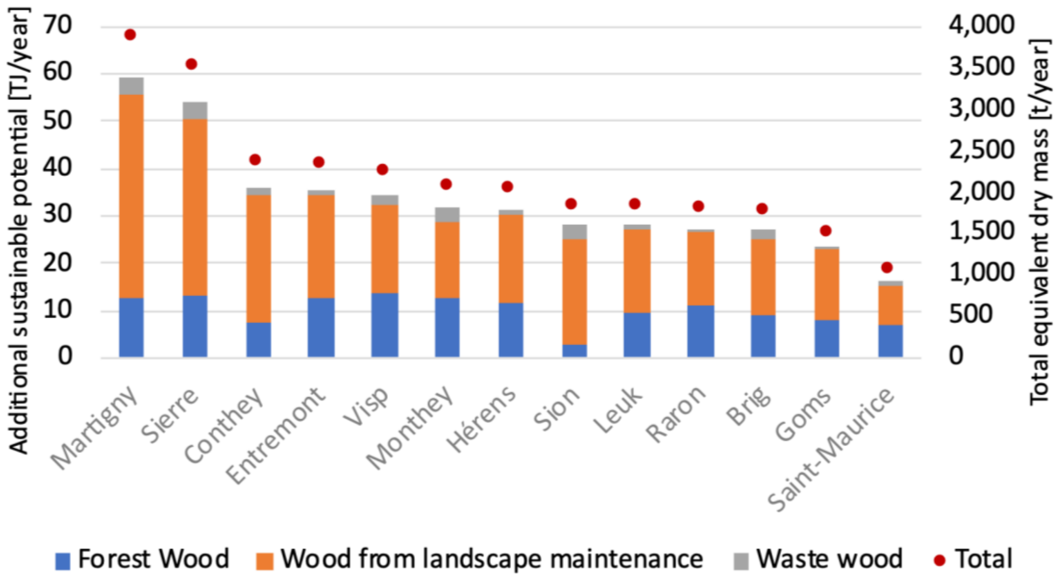


Figure 8. Additional biomass potential (TJ/y) and equivalent dry biomass (t/y) available in Valais [3].

Figure 9 lists the top 5 biomass heating projects under construction in Valais. The Canton encompasses a total of 17 existing district heating units (chauffage a distance - CAD) using wood chips or pellets and six more planned between 2024 – 2028 [13]. Overall, between existing and planned projects, it is expected an energy consumption of approximately 180 GWh/y from woody biomass resources (i.e. wood chips and pellets) in the next years. An important point to highlight is that, in comparison to the combustion of woody biomass, utilization pathways based on gasification of woody biomass combined with a power-to-gas approach could achieve about ten-fold reductions of CO_2 and particulate emissions, compared to direct combustion in domestic boilers [14]. This fact suggests a need for more efficient biomass conversion processes that enable the heat supply using biogenic, carbon-neutral solutions, at high temperatures to heavy industries, and simultaneously supply heat at low temperatures, typical of district heating applications, using the principle of heat cascade [1].

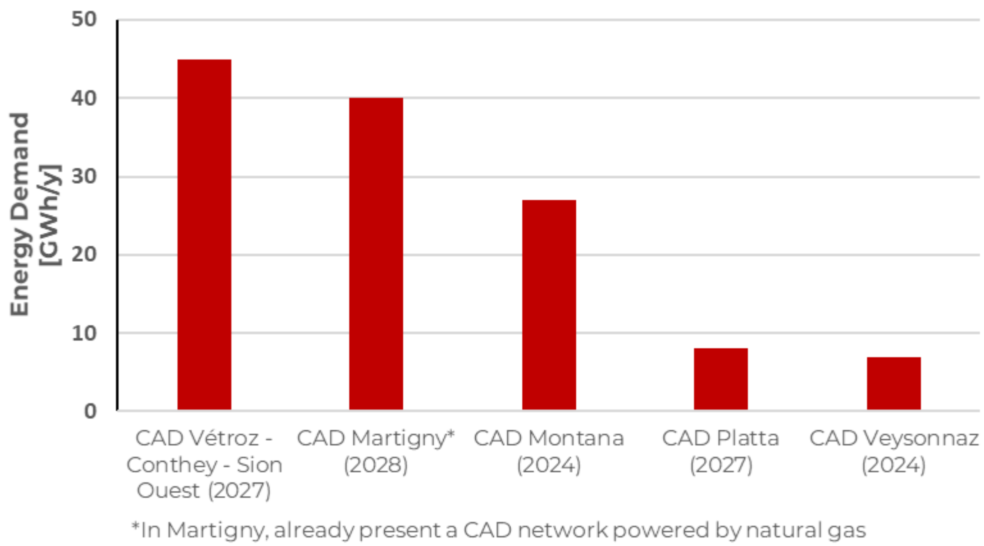


Figure 9. Expected energy consumption of the largest wood-based district heating systems under construction in Valais (in GWh/y) [13].

The Net Zero Lab team conducted some surveys in 2023 with practitioners and other actors involved with the biomass value chain in Valais in order to gather more information than that reported by WSL, including:

- Olivier Bourdin: Forest guard, Direction of the Triage Forestier du Cône de Thyon,
- Florian Rong: Independent engineer, Manager Ecovalbois
- Prof. Stéphane Genoud, Noemi Imboden, HES-SO Valais Energy Management Lab.

The main takeaways are summarized below, but the complete discussions are presented in Annex A4:

- Biomass is under-utilized in Valais and currently some wood just rots in the forest after being cut.
- WSL woody biomass potential is a conservative estimate, in fact the real potential is somewhere between the sustainable and the additional sustainable potential limits.
- There is an untapped potential of lower quality biomass (i.e. with higher moisture content and low grain size) that should be considered, such as needles (spikes) that are present in abundance at the truck port.
- In contrast to the Swiss plateau, wood can only be harvested between April and November in the Canton of Valais.
- High quality wood (e.g. plaquette) is almost fully exploited in Valais. Thus, some margins of improvement remain available only for lower quality biomass.
- Currently only 30% of wood utilization goes to energy applications in Valais.
- Logistics (i.e. transportation and drying) consume 5-6% of the energy content of the biomass (based on lower heating value).
- Industrial scale biomass utilization installations allow for higher efficiency of 90%, compared to small local applications (about 60% efficiency).
- Wood price fed to boiler is around 6 franc cents per kWh, but other factor can influence this price, at it has been seen during the energy contingency of 2022-2023.
- Costs of up to 8 ct/kWh are reported after previously stable values of 5.4 ct/kWh, which indicates increasing market prices. Increased price of biomass drives an increased financially exploitable potential in Valais and other parts of Switzerland.

3. MODELING APPROACH OF BIOMASS TRANSPORT AND OBTAINMENT

The biomass transport and obtainment was modeled in order to determine the impact of the upstream biomass supply chain on the energy consumption, cost and emissions of the woody resource fed to the gasification plant. The main assumption adopted are described, and preliminary results for different transportation scenarios are discussed.

3.1. Supply chain

The developed supply chain model for woody biomass is presented, covering all steps from the harvesting sites to the industrial site in Novelis Sierre. The model considers the previously discussed data on the quantity, type, and location of the biomass required to provide the desired amount of energy to the aluminium plant. The energy spent to process and transport the biomass, together with preliminary cost parameters were investigated. Starting from the biomass potential at the cantonal level, an algorithm was developed to calculate the geographical distribution of the harvested biomass. Despite the availability of biomass potential for each Swiss municipality, the choice of using a dataset with the 26 Swiss Cantons allows to deal with a reasonable amount of data for preliminary calculations. This fact also allows adopting the assumptions elaborated at the national level for the model statistics at cantonal level. Thus, the cantonal data were regarded as clusters of the woody biomass spatial distribution in Switzerland.

First, an effective amount of biomass available, per type and per canton has been evaluated. In the scope of this project, only *additional sustainable biomass potential* was considered. This fraction, as previously discussed, represents the share of resources still unexploited for which the harvest is considered economically and technically feasible. Ratios between the percentages of additional and used potentials calculated at national level were assumed as valid for each cantonal level. An additional penalizing parameter, defined as the *percentage of exploitable* biomass per canton, was also adopted to further limit the biomass availability to a realistic amount, bearing in mind competing applications and additional customers. All the scenarios were firstly run assuming that only 10% of *additional sustainable biomass potential* could be granted to the Novelis site. A less conservative scenario, in which the percentage of biomass exploitable was raised to 50% of the additional sustainable potential, has been also analysed. The more conservative scenario is due to the fact that WSL data, despite being officially accepted, may not include planned projects that are going to use part of this potential considered today as available. Only in Valais, at least 6 district heating projects using wood are currently in planning stage.

Once the geographical distribution of the resources was determined, the biomass supply chain has been investigated. The aim of this task is to estimate the grey energy demands and costs associated with biomass pre-treatment and transportation. The starting point of the supply chain is located at the harvest site, which can be a forest in case of forest wood, a recycling centre, or a lumber mill in case the biomass considered as sawdust or waste. Resources are initially transported by truck to an intermediate storage centre, wherein biomass is stored, dried in open air, and eventually further processed by artificial drying or pelletization. A storage centre per canton was assumed, located in the vicinity of its capital. Biomass in the form of chips is then shipped to the aluminium plant either by truck (in the case of Valais) or by train (for other cantons). The woody biomass can be further dried at the Novelis plant site in case it has not been completely dried at the processing centers (see Figure 10).

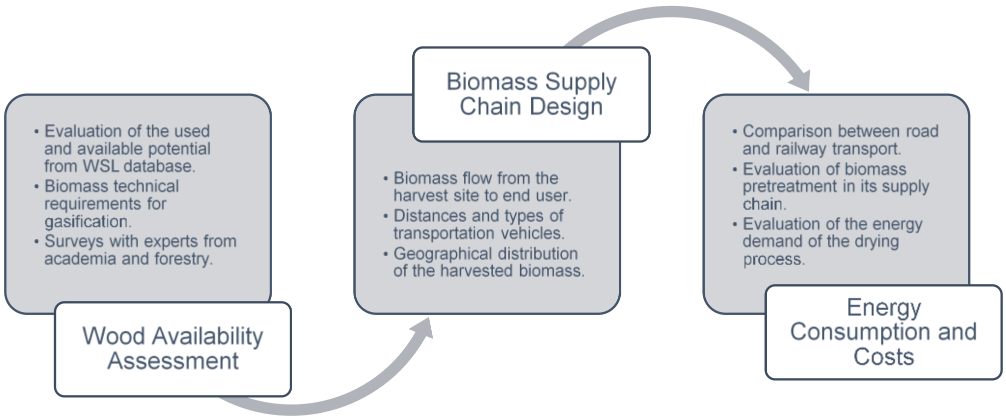


Figure 10. Steps implemented in the algorithmic approach to determine the location, availability and consumption of biomass energy resource used in Novelis site.

3.2. Harvesting

The aim of implementing enhanced biomass conversion technologies is making a more efficient use of dry biomass, whereas widening the range of wood resources that can be used for energy purposes. Thus, all the available wood from forests and maintenance of green areas, with an estimated water content of about 50%, was considered suitable for gasification. Residues from timber industry and wastes from demolitions or renovations were also included. Their usage allows to recover an important share of resources that would be otherwise lost. In fact, this kind of biomass is usually already dried up to an acceptable level and does not require further open-air drying. Residues such as sawdust and shavings, according to the national database, are already almost fully exploited, while a large share of waste wood is regarded as exploitable. According to the national database, waste wood is divided into four different categories: mechanically processed wood, glue, painted, laminated wood, wood containing halogen-organic compounds (e.g., PVC), and wood treated with wood preservatives. In order to estimate the effective amount of waste compatible with the gasification standards, a detailed analysis on the critical elements in wood was conducted. Contaminants include e.g. alkali compounds found in adhesives, chlorine from PVC or heavy metals contained in chromate arsenate timber [15–17]. In view of this, it was estimated that approximately 20% of the total waste wood is suitable for gasification and, consequently, this portion was included in the national biomass potential for biomass gasification purposes.

It is considered that wood is chipped directly at the harvest site, unless it is already in the form of chips, as it is the case of sawdust. The chipping process could be also performed after the first drying phase in open air. However, the choice of anticipating this process allows obtaining a uniform size of all the types of biomass considered at the very beginning of the supply chain. Grey energy consumption (i.e. coming from non-renewable resources) associated with the chipping process was estimated at approximately 1% of the energy content of the biomass [18, 19]. Additional amount of energy is needed to chip the wood before entering the gasifier, leading to a total grey energy consumption of around 3% [10]. Regarding its cost, wood is often sold at a market price which does not represent the real costs of the harvesting process [20]. For instance, in 2021, forestry authorities registered a financial loss during operations of 29 CHF/ha [21]. As a consequence, the real cost of harvesting wood is not investigated due to the fact that it is not strictly correlated to its market price. Moreover, market price of firewood should be reduced in case of wood residues and waste. Therefore, biomass price at the harvesting side was excluded from the costs analysis. The market price of wood chips in 2021 was approximately 85 CHF/m^3 [21].

3.3. Road transport

Since the biomass is assumed to be uniformly distributed over each canton, an average driving distance between harvest point and storage centre was introduced. Cantons were divided into three categories according to their surface extension. For the largest Cantons (e.g., Graubünden, Bern, Valais, Vaud, and Ticino), a typical driving distance of 50 km was adopted. Meanwhile, for medium and small Cantons, average distances of 35 km and 20 km, respectively, were considered. Following a similar approach to ref. [20], each typical path was divided into three different categories of routes (namely, forest routes, town roads and highways), each one characterized by a typical driving speed. This assumption allows to better estimate the total travel time, the fuel consumption and, eventually, the costs.

A chipping truck is used to directly process the biomass at the harvest site and then bring it to the intermediate storage. Several technical solutions are available, ranging from 4-axes or 5-axes trucks to self-unloading trailers [22]. The former one has a load volume of 36-46 bulk cubic meters, while the latter one can transport up to 80 m^3. Due to geographical conformation, as also confirmed by the experts consulted, massive heavy vehicles, which would enable maximizing the harvesting rate, cannot be in practice employed in forest areas. A standard diesel powered 4-axes lorry was chosen as transportation vector from the harvesting site to the intermediate storage plant. Meanwhile, a 5-axes lorry was introduced to ship the biomass resource from intermediate points to the loading platform at the closest train station, or directly to the plant in case of biomass within Valais. In this last case, the average distance between the two points was estimated as 10% of the total distance driven in the previous stage. Fuel consumption during transportation was estimated based on the data of previous Swiss studies on biomass supply chain [23].

3.4. Intermediate storage and drying

The biomass is allowed to dry in open air while being accumulated in the storage centre. At the end of this phase, the biomass reaches a water content level of approximately 30%. It was assumed that no losses in dry matter occur during this step. In the reference scenario, biomass is next shipped to the Novelis plant without any supplementary treatment and will be further dried directly on site. The energy demand of this stage was also computed, as it could be partially supplied by the waste heat of the integrated facilities of the gasification and aluminium production site. It is assumed that the drying process takes place at 120 °C and atmospheric pressure. The energy demand to pass from a certain moisture content (MC) to 10% MC is calculated. A simple model to evaluate energy consumption was deduced from previous studies on kiln drying [24].

3.5. Railway transportation

Railway transport is chosen in case of resources harvested outside Valais. Reference [25] claims 150 km as the break point distance after which shipping by train is more convenient than using trucks. Given the high efficiency of the electrified Swiss Railway network and already established partnership between Novelis and SBB, it is assumed that this distance can be even reduced in this specific case. Therefore, the option of receiving biomass by train on open-top container is investigated. From SBB catalogue, a railway car with a maximum payload of 60 t and volume capacity of 70 m^3 was chosen. A linear function to calculate operating costs was obtained by interpolation of prices given by SBB Cargo pricelist. Electrical energy consumption of train freight was estimated as 0.30 kWh/(t km) for woodchips with a MC of 30% and slightly increased in case of drier chips, following the experimental data of ref. [26].

3.6. Results of the biomass obtainment and transportation model

Three different yearly biomass energy demands from the Novelis plant were considered, namely 50 GWh/y, 90 GWh/y and 250 GWh/y. The second value is equivalent to the annual natural gas consumption of only two melting furnaces in the cast house at Novelis Sierre (90 GWh/y). The annual biomass energy demand of 50 GWh is representative of the scenario in which the gasification unit is operated only during the cold season, aiming to avoid an excessive demand of this limited renewable resource. On the other hand, the case of annual biomass energy demand of 250 GWh assumes that the total heating demand of the Novelis site is supplied using woody biomass resources. The estimated chemical energy content of the syngas at the gasifier outlet is approximately 70% of the energy content of the biomass originally fed to the gasifier. Moreover, an economic evaluation of the price of obtaining varying amounts of biomass from different cantons was evaluated and reported.

3.6.1. Geographical distribution

The objective of this analysis was to quantify the amount of biomass available according to the energy demand required by the site and evaluate its geographical distribution. Table 2 displays the results of the biomass requirement, the number of cantons involved, and the average distance travelled as a function of the energy demand of the Novelis site and the exploitation percentage adopted.

Table 2. Biomass requirement, number of cantons involved, and average distance travelled as a function of the energy demand and exploitation percentage adopted.

Energy Demand [GWh/y]	Exploitation [%]	Total Volume* [m^3]	Total Mass [t]	N° of cantons	Average distance [km]
50	10%	66,248	16,562	3	90
	50%	64,418	16,105	1	50
90	10%	118,250	29,562	4	120
	50%	116,554	29,139	2	66
250	10%	328,930	82,233	23	181
	50%	331,238	82,809	3	90

* 1 cubic meter of solid wood represents approximately 2.5 to 3 apparent cubic meters of wood chips; thus density is considered as 250 kg/m^3.

The graphical representation of the biomass distribution (Figure 11) highlights the great potential in terms of energy available of the geographical area nearby Valais.

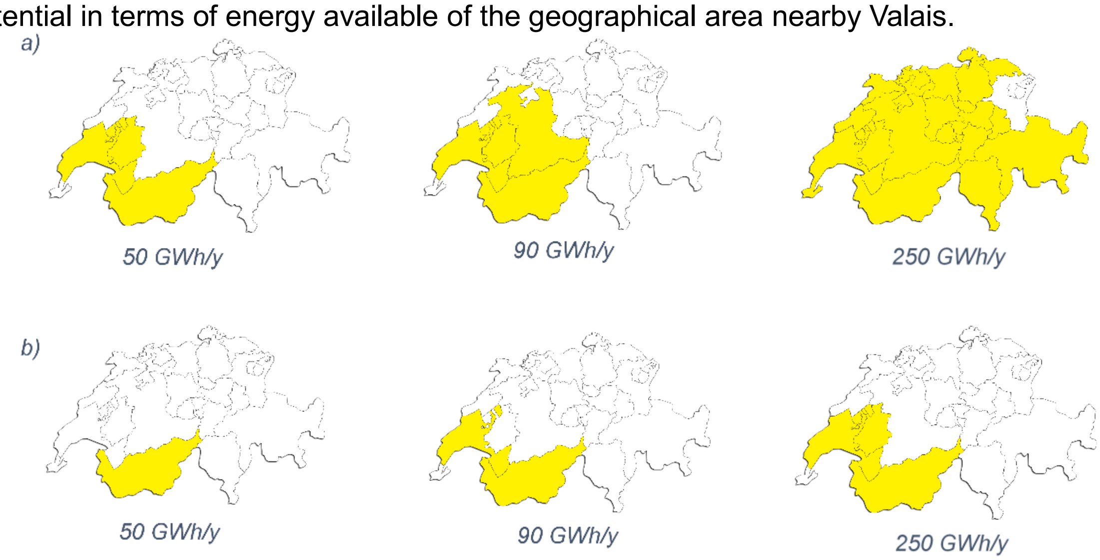


Figure 11. Geographical distribution of harvested biomass with an exploitation percentage of (a) 10% and (b) 50% of the biomass available in each Canton.

The limitation to a fraction of the biomass potential anticipates the future interest of other chemical, residential and energy sectors in this valuable resource. In case of a consumption of 50 GWh, it can be seen that with a percentage of exploitation of 50%, the sole Canton of Valais is capable of providing the required energy demand. Sufficient resources for a project of this kind could be available in nearby cantons including Valais, Vaud, and Fribourg, from where only a fraction of the additional sustainable biomass potential (50%) would be needed for supplying the aluminium plant in Novelis Sierre. Alternatively, only 10% of the additional sustainable biomass potential of Switzerland would suffice to supply the Novelis biomass energy demands. A smaller number of cantons required translates into shorter average distance travelled by the biomass, assuming that Cantons are ordered by distance. As a consequence, the energy spent in the transport stage and its cost can be reduced.

3.6.2. Effect of drying or pelletizing on the transportation performance

Variations in weight and density of transported freights can have a significant impact on the global energy and economic balance. Thus, grey energy and transportation costs of the biomass were investigated for three different supply chain alternatives. The grey energy associated with biomass transportation was computed as percentage of its embodied energy, corresponding to a lower heating value of 17 GJ/t and corrected according to its moisture content. The reference case consists of the transportation of chipped biomass with a moisture content of approximately 30% (i.e. only open air dried). In a second scenario, the impact of a further reduction in the transported weight is evaluated by drying the biomass up to 10% MC in a drying oven before shipping. In a third scenario, pelletization of the biomass is conducted following artificial drying. This further treatment increases the bulk density of the material up to 700 kg/m^3, thus, reducing the overall transported volume.

The results shown in Figure 12 highlight the importance of transporting a denser and drier biomass in the form of pellets. The benefits of the employed pre-treatments are more evident especially when transportation by train over long distances is considered. In this case, a sharp reduction in the grey energy and costs is observed, due to the lower weight transported and the reduced number of freight railway cars needed. In fact, the maximum mass payload of the wagon is still not reached, despite the increment in the bulk density of the biomass. It is worth noticing than, despite reduction in both transportation energy consumption and cost indicators are expected, this drop is less significant in the case of truck transportation than in the train-based case. It can be explained by the fact that freight transportation on road is largely influenced by the energy consumption and costs of the path between harvest site and storage centre, which are not affected by the pre-treatments studied. Moreover, trucks must comply with the maximum payload transportable on road. In the pelletization scenario, this limit is reached well before attaining the maximum volume capacity. Advantages of biomass pelletization are therefore fully exploited in case of long-distance transportation by train.

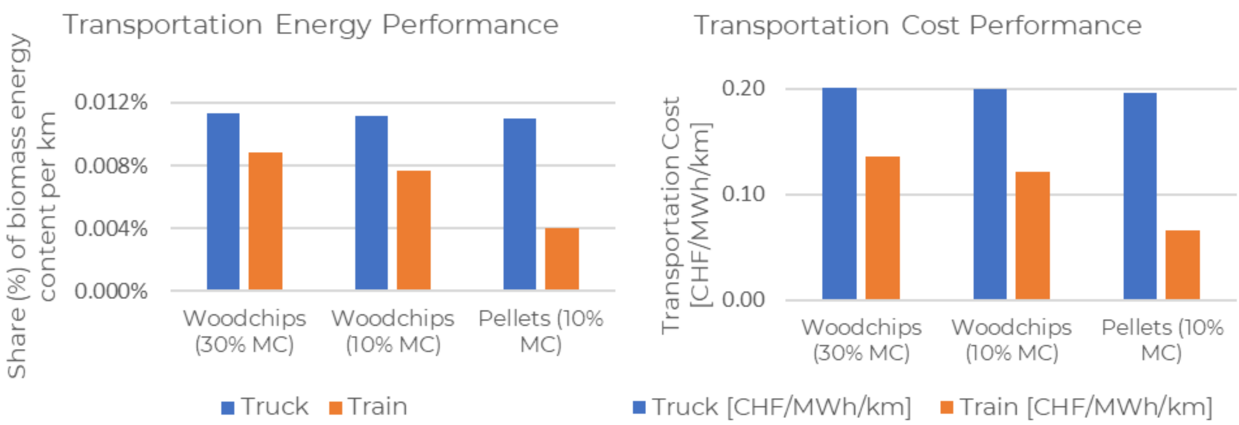


Figure 12. Energy consumption (left) and costs (right) in biomass transportation per km as a function of the moisture content (MC) and the use of pelletization.

Artificial drying before the arrival at the plant allows to reduce energy consumption and costs either for trucks or trains due to weight reduction. However, due to the proportional reduction in density, the amount of transportation unit required (i.e. trucks or railway cars) remains unchanged. Since these factors are the primal parameters to influence grey energy input and costs, biomass drying without being followed by a densification process has lower impact on these indicators compared to pelletization. In the worst case, there is a risk of biomass reabsorbing the released moisture.

3.6.3. Impact of the distance between harvesting site and storage center

The hypothesis of introducing only one intermediate storage centre per canton leads to the question whether this assumption is technically and economically feasible, even for large Cantons. Thus, for each of the three different canton categories (i.e., large, medium, small), a typical driving distance of respectively 50, 35, and 20 km was associated. In order to evaluate grey energy and costs of the transportation, it was assumed that the driving path is composed of forest routes, rural roads, and highways, similarly to the approach adopted in ref. [23]. Figure 13 summarizes the cost and energy implications of this evaluation based on the assumptions previously discussed. An average consumption equivalent to 0.55% of the energy content of the biomass was estimated to transport the biomass for 50 km. This corresponds to a cost of approximately 11.06 CHF/MWh. Meanwhile, in case of small cantons, for which a typical driving path of 20 km was assumed, fuel consumption of the truck and costs are drastically reduced to 0.23% and 6.91 CHF/MWh respectively. This result highlights the need of a distributed network of intermediate storage centres in Switzerland. Also, it confirms the higher efficiency of the railway network over road transportation in case of supply over long distances.

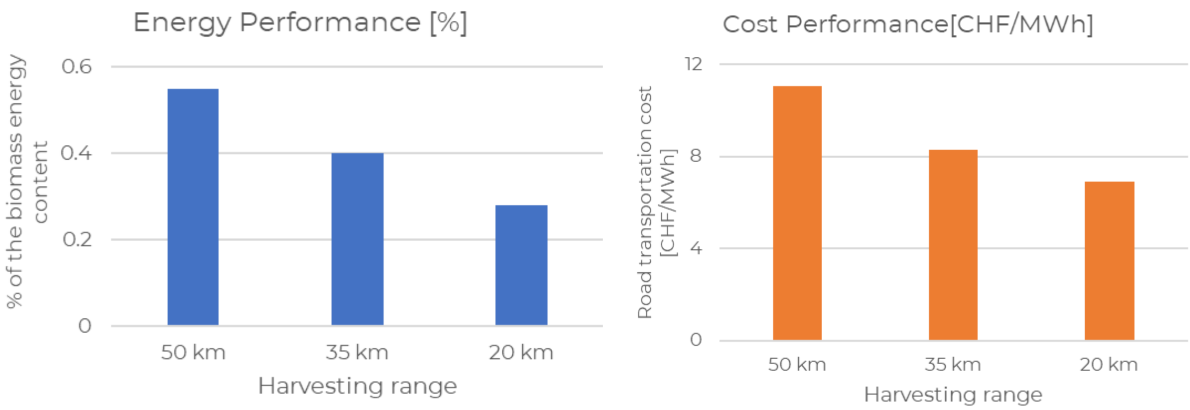


Figure 13. Energy consumption (left) and costs (right) of road transportation from the harvest area to the collection point for representative sizes of cantons. Note that transportation from the collection point to the Novelis Site is not included.

3.6.4. Indirect energy consumption of supply chain

The indirect energy consumption divided per category is reported in Figure 14. Harvesting and chipping operations are not considered for wood waste and residues, as it is assumed that these steps are already part of the previous utilization of these resources. Consequently, the curve for wood waste and residues exhibits a similar pattern to that of the wood price in Figure 15. A local minimum in the curve occurs at nearly 900 GWh. It indicates that for that heat demand, the amount of wood waste is high in comparison to the other feedstock. This fact effectively lowers the average indirect energy demands, since it allows to reduce pre-treatment processes needed. In contrast, energy demand for drying, in this specific case from 30% to 10% of moisture content, is represented by a constant heat load required for every type feedstock entering the plant. The result show that the grey energy spent in the entire supply chain fluctuates between 0.3 and 0.4 MWh/t_{dry} depending, respectively, on whether more wood residues or more forest wood is exploited. The only category increasing almost linearly with the energy demand is the indirect energy required for rail transportation. Yet, according to Figure 14, it is maximum 1% of the embodied energy content of the biomass. Therefore, it is reasonable to assume that excessive energy consumption in the wood supply chain may not be the primary obstacle preventing the implementation of a large-scale utilization of this resource.

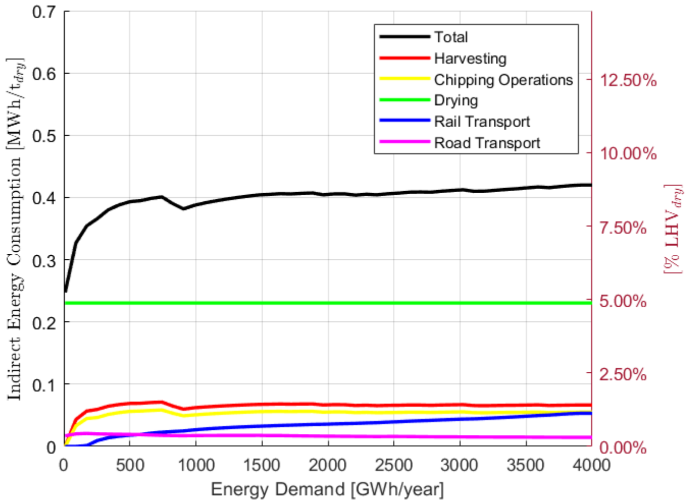


Figure 14. Indirect energy consumption of biomass supply chain.

3.6.5. Economic performance

The cost of wood was initially computed for two scenarios. In the first scenario, represented in Figure 15, it was assumed that only the wood from forest and landscape maintenance is accessible, due to the lack of waste wood. It also considered that only 50% of the additional potential of these resources is available (Figure 11b). Notably, this scenario poses additional constraints based on the insights from the interviewed experts. On the other hand, bearing in mind the additional sustainable potential of biomass in Switzerland (~4000 GWh/y), an unconstrained scenario allowed assessing the cost of biomass as if all the available resource were considered as available for industrial purposes (see Figure 16). According to Figure 15 and Figure 16, energy prices of wood tend to fluctuate due to the variable moisture content and the constant volumetric price set at 100 CHF/m^3. These costs are average costs of the biomass for a selected demand. Beyond 1000 GWh or wood energy, the procurement prices of wood stabilize and any influence of the type of feedstock on the price weakens. As for the transportation costs, the road transport, necessary for moving wood between forests and storage centres, remains almost unaffected by the progressive increase in the exploitation range (10 CHF/MWh). Only a slight reduction is observed due to the higher road transport costs for Valais, where the entire supply chain is conducted via road.

Rail transport costs are activated when exploiting resources outside Valais. This leads to an increase in total costs. The choice of railways also helps reducing the overall costs associated to transportation as long as no additional investments are required to adapt the existing railway infrastructure in the Novelis plant. The distance travelled on road by the biomass ranges from 30 to 50 km depending on the canton, while the railway distance varies between 90 and 350 km. Despite the significant disparity in distance covered by the two transportation methods, railway costs are only at most 10 CHF/MWh higher than road costs (Figure 16).Figure 16. Biomass cost breakdown and geographical distribution of transport costs with no restrictions on the additional biomass potential. Overall, for an energy demand ranging between 100 and 500 GWh/y, the total cost of biomass is expected to vary from 40 to 60 CHF/MWh. It is notable that for large-scale exploitations, costs may raise up to 70 CHF/MWh, with transportation costs alone reaching 30-40 CHF/MWh (North East of Switzerland). In the techno-economic evaluations outlined in the next sections, a conservative estimate of 60 CHF/MWh is used as the standard value for the biomass price.

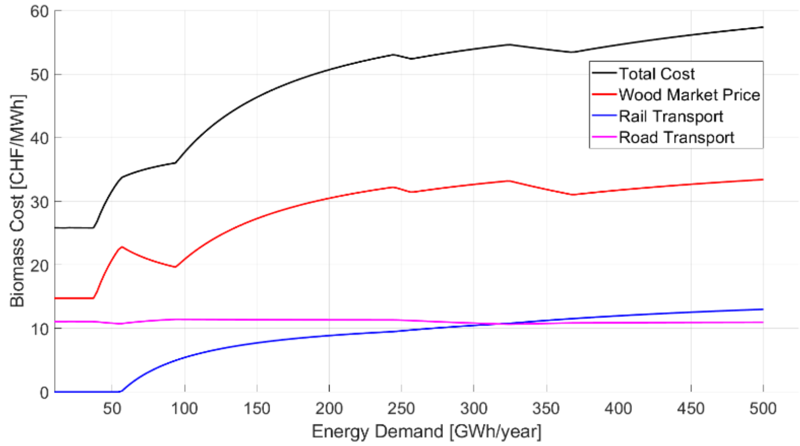


Figure 15. Cost breakdown of the biomass supply chain for increasing wood demand, assuming availability of 50% of the additional exploitable resources.

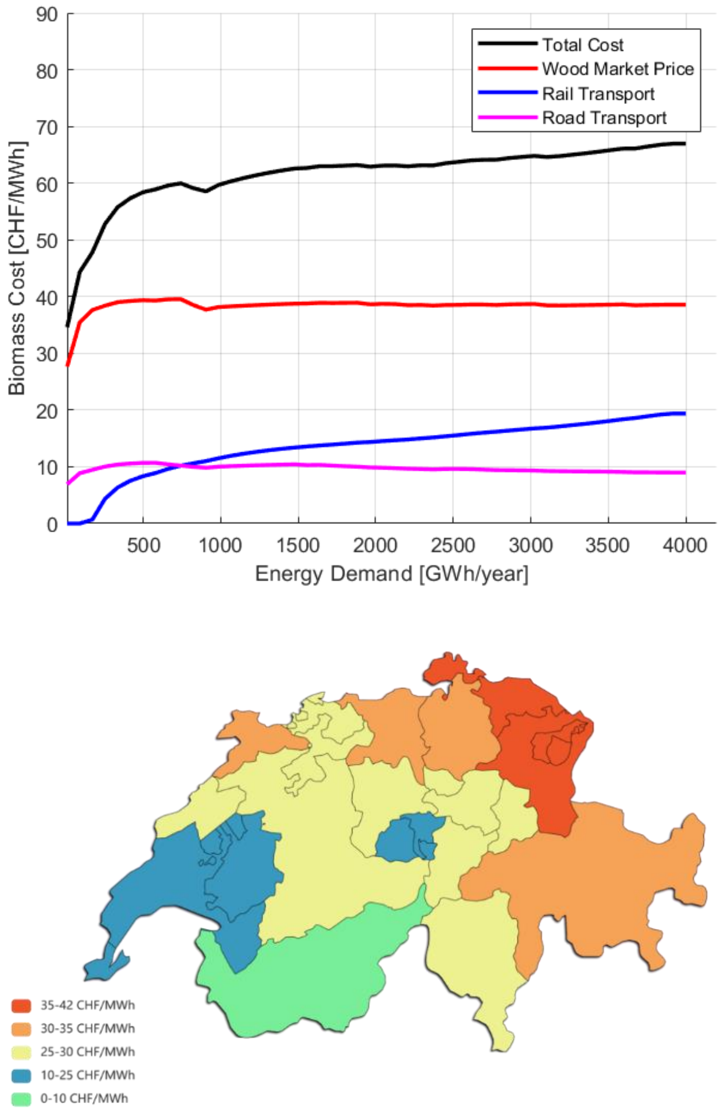


Figure 16. Biomass cost breakdown and geographical distribution of transport costs with no restrictions on the additional biomass potential.

4. BIOMASS ENERGY CONVERSION TECHNOLOGIES

Better technologies for thermal conversion of biomass have attracted a renewed interest with the aim of making a more efficient use of this resource. Gasification allows to convert biomass into syngas, which can be directly combusted or further processed to produce biofuels and chemicals. Syngas is a mixture of H_2, CO, CO_2, as well as methane, lower amount of heavier hydrocarbons, and other organic condensable compounds (e.g. tar). The exact composition of the mixture is influenced by several factors, such as type of feedstock, gasifier technology, temperature, pressure and gasifying agent (e.g. steam, air or oxygen) [27]. The main components of the biomass gasification route are discussed next.

Figure 17 shows the flowsheet of the gasification system modelled in Aspen Plus® software. The onsite biomass processing starts with two pre-treatment steps, i.e. the drying and chipping of biomass material. The biomass chipping is an energy intensive process that consumes up to 3% of the energy embodied (lower heating value) in the processed biomass [10]. Chipping is necessary to reduce the size of the material fed to the gasifier to less than 3 mm, in order to avoid the clogging of the feeding screw. External drying process (120°C) reduces the moisture content in the biomass from the inherent biomass moisture (30-50%) to 10%, in order to facilitate the feeding process and enhance the downstream operating conditions in the gasifier. Inside the gasification unit (Figure 18), heat is supplied so that the remaining amount of water is evaporated. As the temperature increases (> 300°C), biomass material starts suffering a process of devolatilization called pyrolysis, in which char, tar and volatiles are released in a series of multiple heterogeneous (char-gas) and homogeneous (gas-gas) reactions in the absence of oxygen. Next, the gaseous mixture reacts with the gasifying steam in a step known as reduction, which increases the amount of H_2, CO, CO_2, and CH_4 in the mixture.

A fraction of the produced char is burned with air in the combustion column of the dual fluidized bed reactor to supply the heat to the endothermic drying, pyrolysis and reduction steps [28]. Heat is indirectly transferred from the combustion to the gasification zone by recirculating sand with olivine, avoiding the dilution of the syngas with nitrogen. Flue gas from the combustion section and syngas leaving the reduction section of the gasifier can be cooled down to a suitable temperature to recover waste heat. This waste heat could be used to preheat the combustion air and generate steam, used in the aluminium plant or, lastly, in a district heating system. Syngas cooling temperature is limited by its tar content, as it can condense and impair the performance of downstream equipment. Tar formation is partially avoided by a proper choice of operating conditions and technologies, as well as use of catalyst materials in the bed of the gasifier. Tar in syngas can be removed by thermal cracking or mechanical treatments, such as cyclones, purifiers, and filters. Water scrubbing is also used to remove other impurities, such as ammonia and particulate matter [27].

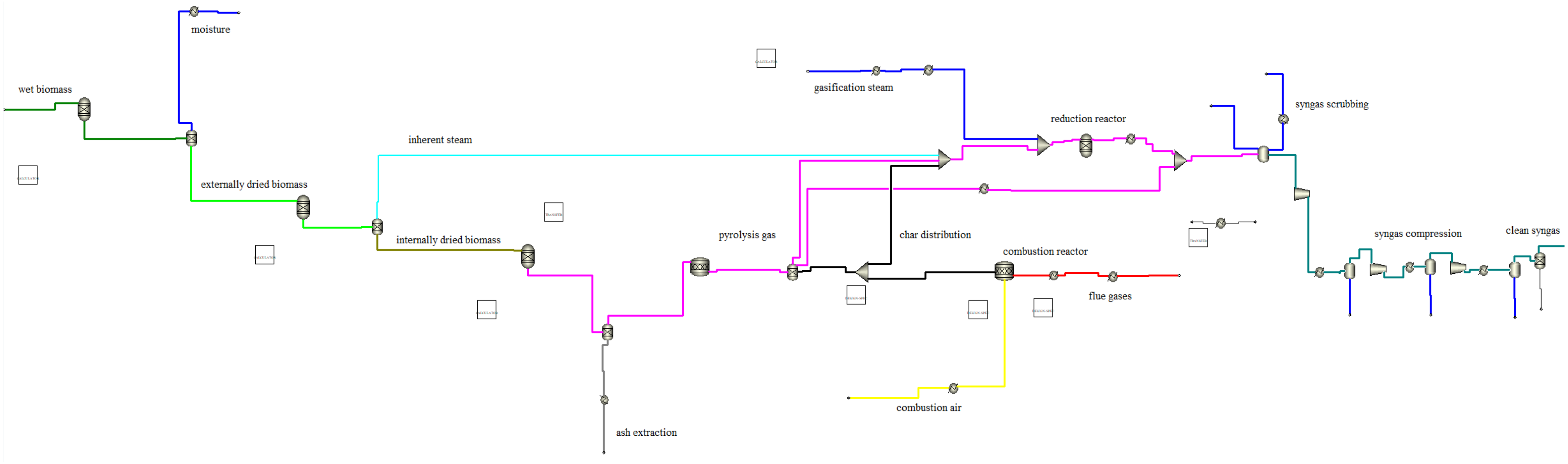


Figure 17. Aspen Plus® simulation flowsheet of the biomass gasification unit [27].

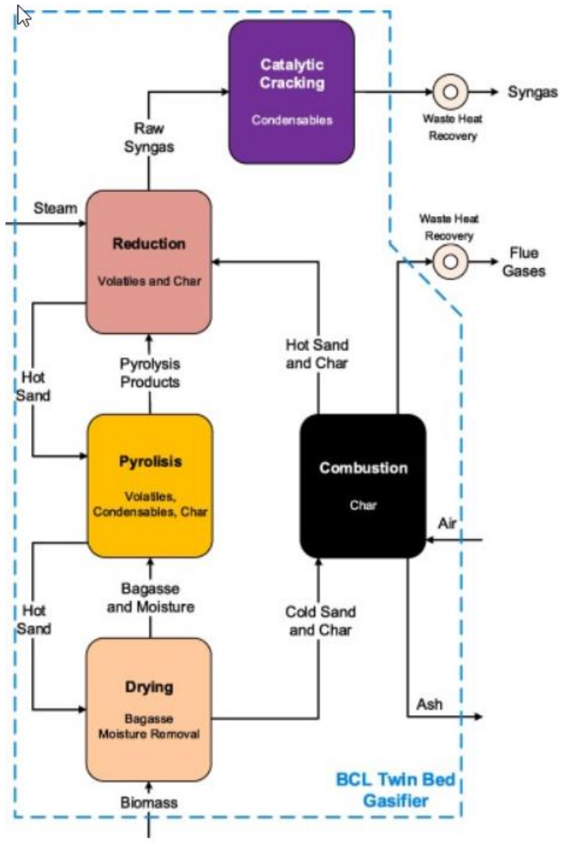


Figure 18. Schematic of the reactions inside the biomass gasification unit [10].

After the gasification section, the syngas can be used directly as fuel in the Novelis site, or further processed to obtain synthetic natural gas (SNG). In the latter case, the produced syngas is reacted with more steam in a series of autothermal reformer (900°C) and water gas shift reactor (~300°C) (Figure 19), in order to adjust the amount of hydrogen and carbon dioxide needed for the methanation reaction (also known as Sabatier reaction) (H2-CO2)/(CO+CO2) ~ 3. It is worth noticing that the syngas conditioning section releases a large amount of waste heat at temperatures above 300°C, thus, making it suitable to integrate the drying and streams preheating processes of the gasification unit to increase the overall system efficiency.

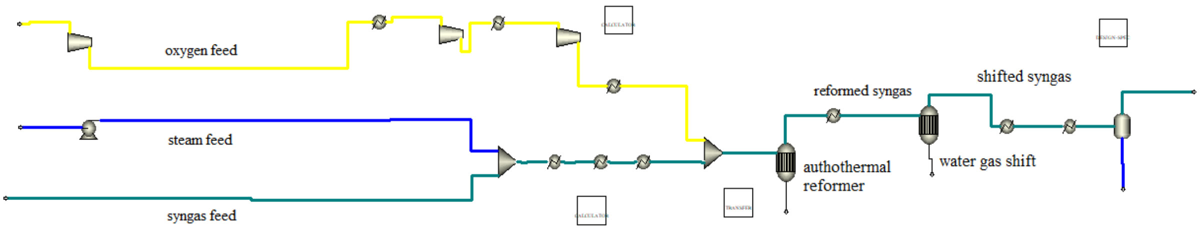


Figure 19. Aspen Plus® simulation flowsheet of the syngas conditioning unit [27].

Since the content of CO_2 in the syngas is much higher than that required to carry out the previously described reactions, a physical absorption unit based on the Selexol technology (DEPG solvent) is employed to remove part of the CO_2 at high concentration (Figure 20). This CO_2 has a high purity and can be commercialized, sequestrated (mineralized or injected) or even used to boost the syngas yield along with a co-electrolysis unit.

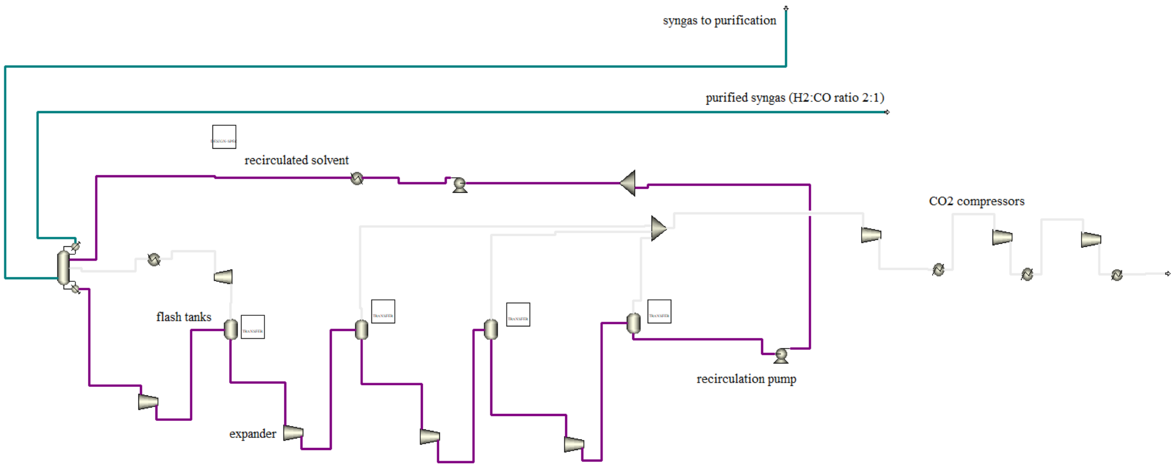


Figure 20. Aspen Plus® simulation flowsheet of pre-combustion carbon capture unit [27].

In the methanation process (Figure 21), the mixture rich in hydrogen and carbon monoxide reacts in three catalytic reactor beds with intercooling in order to increase the methane yield. The exothermic reaction also releases a large amount of waste heat at 300-500°C, that can be used at the Novelis site or for district heating purposes. The synthetic natural gas produced can be either consumed in the Novelis furnaces or stored to be used later. In the methanator, water is also produced. Table 3 summarizes the design parameters of the modelling and simulation of the biomass energy conversion technologies. These include parameters indicative of the process performance, such as the gasifier carbon efficiency, which is defined as the percentage of total carbon in the gasifier feedstock finally converted into product syngas. Specific details about the process streams and unit operations of a gasifier are reported in Table 4.

The process integration of a biomass-to-SNG unit to the Novelis aluminium plant will have an impact on the current plant energy balance. Thus, a systematic study, considering all the competing options, was performed to support the decision-making on the most suitable equipment sizes and the best biomass energy conversion routes. This energy integration approach is done using the OSMOSE Lua platform, developed by IPESE group in EPFL.

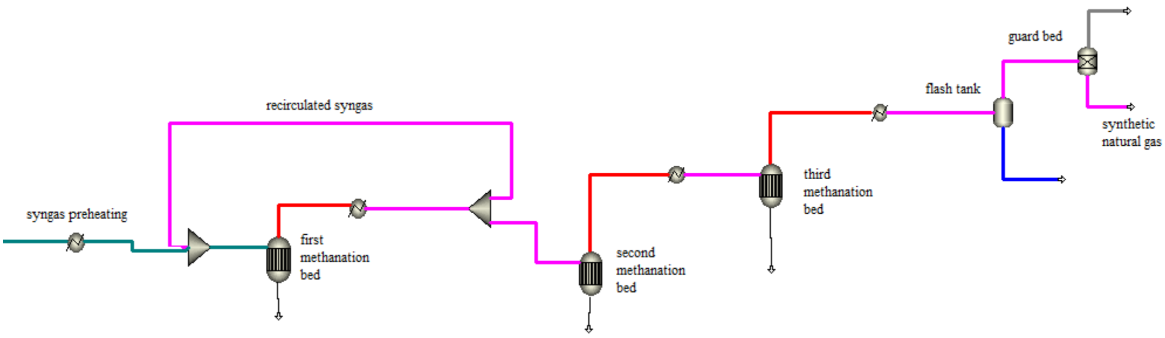


Figure 21. Aspen Plus® simulation flowsheet of the methanation unit for synthetic natural gas (SNG) production [27].

Table 3. Physical properties and process parameters of the biomass-to-SNG conversion process.

Parameter	Value
- Gasifier	
LHV of wet biomass [kJ/kg]	8,700
LHV of dry biomass (LHV) [kJ/kg]	17,000
Biomass ultimate analysis (mass basis):	47% C, 6% H, 45% O, 0% N, 0%S, 2% Ash
Biomass proximate analysis (mass basis):	14% FC, 84% VM, 2% Ash, 50% M
Syngas composition (mass basis)	53% CO2, 30% CO, 4% H2, 12% CH4
Flue gas composition (mass basis):	24% CO2, 4% O2, 72% N2
LHV of dry syngas [kJ/kg]	14,380
Syngas production efficiency [kW_{syngas} /$kW_{biomass}$]	0.728
High grade waste heat temperature [°C]	~870
Gasifier carbon efficiency (carbon outlet/carbon inlet)	~70%
Specific gasification unit cost [EUR/kW]	1,200
- Syngas purification section	
Carbon capture ratio [$t_{captured\ CO2}$ /$t_{dry\ biomass}$]	0.547
Carbon capture ratio (dry biomass LHV) [$t_{cap,CO2}$/MW_{wood}]	0.118
- Methanation section	
SNG to biomass ratio [t_{SNG} /$t_{dry\ biomass}$]	0.217
SNG production efficiency [kW_{SNG} /kW_{wood}]	0.624
- Overall process	
Electricity demand (biomass-to-SNG) [kW_e/MW_{wood}]	68
Waste heat between 60 °C - 800°C [kW_{th}/MW_{wood}]	340
Waste heat at high T (> 400 °C) [kW_{th}/MW_{wood}]	180

The main specifications for the gasification system used to approach a supplier are reported in Table 4.

Table 4. Datasheet used to approach a gasification system technology supplier.

Fuel characteristics:	• Wood chips.
Wood Category:	• Balanced mix of softwood and hardwood: stem wood, branches, bark, sawdust and recovered wood.
Wood quality and characteristics:	• Average water content 25-40%. • Density: 250-350 kg/m^3. • Energy content: 2.7-3.3 MWh/t. • Dried on site down to 20% water content before gasification.
Wood Demand:	• 85000 MWh/y roughly equivalent to 30000 t/y (90000 m^3/y).

Fuel storage, handling, and processing:

Raw wood storage	• Outside (covered) or in underground bunker, minimum reservoir of 3-5 days of operation.
Dry wood storage	• Short-term buffer, (12-24 h) between drying process and gasification, in biomass silos with automated feeding system.
Handling equipment	• Unloading bay for wood reception, preliminary studies on the feasibility of a supply chain based on railway transportation. • Wood screening unit, also in accordance with the type of waste wood that can be accepted. • The objective is to maximise the range of usable resources. • Feed conveyors, aiming to high level of automation.
Drying phase	• Belt dryer as optimal solution. • Target water content after drying: below 20%. • Simulation on steam drying at 120°C. • Open to every solution enabling the re-use of waste heat, either from the gasification process or the production site, even at lower temperatures.

Gasification reactor:

Reactor technology:	• Indirect gasification with steam, dual-fluidized bed reactor. Heat transferred by bed material recirculation. • Estimated temperature of the produced gas approx. 800-900°C.

Gasification agent:	• Steam.
Syngas composition (est. %vol.):	• H_2: 41%. • CO: 20%. • CO_2: 23%. • CH_4: 14%. • Others: 2%.
Gas purification equipment:	• The primary goal is to eliminate tars, particles, sulphur, and any other substances that could harm the catalytic elements. • Aim to optimize heat recovery during the cleaning process of the producer gas.
Potential waste heat sources	• Syngas cooling 17% of biomass LHV • Combustion gas cooling 10% of biomass LHV. • Additional waste heat recovery from hot air from dryer and water from the syngas scrubbing process. • Objective is to have a self-sustaining autothermal system, eliminating the requirement for additional external energy and generating surplus heat.
Operation mode:	• All year/only in winter.

Syngas upgrading for methanation:

Objective:	• Upgrading syngas to create sustainable natural gas (SNG) that meets the specifications of the natural gas grid.
Main equipment required:	• Syngas compression unit. • Guard-bed and water-gas shift reactor to adjust CO:H_2 ratio. • Reforming reactors, if needed. • CO_2 capture system (physical absorption). • Methanation unit.
Remarks:	• Waste heat valorization from methanation units at 400-500°C.

Due to the interest in thermally integrating the waste heat produced by the gasifier, it is key to identify the hot and cold streams able to exchange heat through all the biomass-to-SNG route. Those stream are summarized in Table 5. An integration with the waste heat streams of the aluminium remelting plant is also envisaged and those results are presented in the next section.

Table 5. Hot and cold streams for the biomass gasifier, syngas conditioning and methanation sections per MJ of processed wood.

Stream	Heat Load [kJ/MJ$_{wood}$]	T_{in} [°C]	T_{out} [°C]	Stream Type (HOT/COLD)
Gasification Unit:				
Syngas cooling	94	870	400	HOT
Flue gas cooling	111	890	100	HOT
Humidity cooling	138	120	30	HOT
Ash cooling	1	870	100	HOT
Scrubbing water cooling	110	65	30	HOT
Syngas compressor cooling 1	53	194	35	HOT
Syngas compressor cooling 2	12	155	35	HOT
Syngas compressor cooling 3	11	153	35	HOT
Biomass drying	146	25	120	COLD
Boiler feed water heating	15	30	121	COLD
Gasifier steam generation	84	121	121	COLD
Gasifier air preheating	45	30	400	COLD
Syngas upgrading unit:				
High temperature steam shift	26	416	200	HOT
Low temperature steam shift	18	260	106	HOT
Low temperature steam shift	14	106	30	HOT
CO_2 compressor cooling 1	1	83	35	HOT
CO_2 compressor cooling 2	2	96	35	HOT
CO_2 compressor cooling 3	2	96	35	HOT
Evaporator steam shift 1	10	25	242	COLD
Evaporator steam shift 2	17	242	242	COLD
Syngas preheating	19	35	242	COLD
Shift feed preheating	13	238	350	COLD
Methanation unit:				
Bed cooling 1	65	562	300	HOT
Bed cooling 2	15	414	200	HOT
Bed cooling 3	41	243	30	HOT
Methanator feed preheating	17	28	250	COLD

Based on the information of the heat streams, the composite curves of the biomass gasifier alone and the entire biomass-to-SNG route can be represented as shown in Figure 22a and b, respectively. These plots are relevant to determine not only the extent of internal waste heat recovery, but also the amount of waste heat available at corresponding temperature levels. The heating load is expressed in kWh/$t_{dry\ wood}$, where the specific lower heating value of wood is set as 4000 kWh/ $t_{dry\ wood}$. It is worth noticing that the drying process and the production of steam as a gasifying agent require 1000 kWh/ $t_{dry\ wood}$ (250 kJ_{th}/MJ_{wood}). This energy demand is nearly 25% of the embodied energy in the feed biomass, which highlights the importance of optimizing the waste heat recovery from the gasifier streams to improve the overall efficiency. Indeed, this study adopts a holistic approach in which all hot and cold streams in the process are considered as recoverable.

Through this strategy, the gasifier virtually achieves self-sufficiency, and the amount of energy required to cover the internal heating demands is balanced by internal char combustion (800 kWh/ $t_{dry\ wood}$). The cooling of the hot syngas prior to water scrubbing and the cooling of the flue gases are the most significant sources of waste heat at high temperature from the gasifier section. In fact, around 800 kWh/$t_{dry\ wood}$ can be recovered from these streams [29]. From the composite curves of the biomass-to-SNG route (Figure 23 b), an additional amount of waste heat is recoverable by intercooling the methanation beds. This recovered heat is partially utilized to generate steam at high temperatures for the gasification system and the water gas shift reactors (around 130 °C and 250 °C).

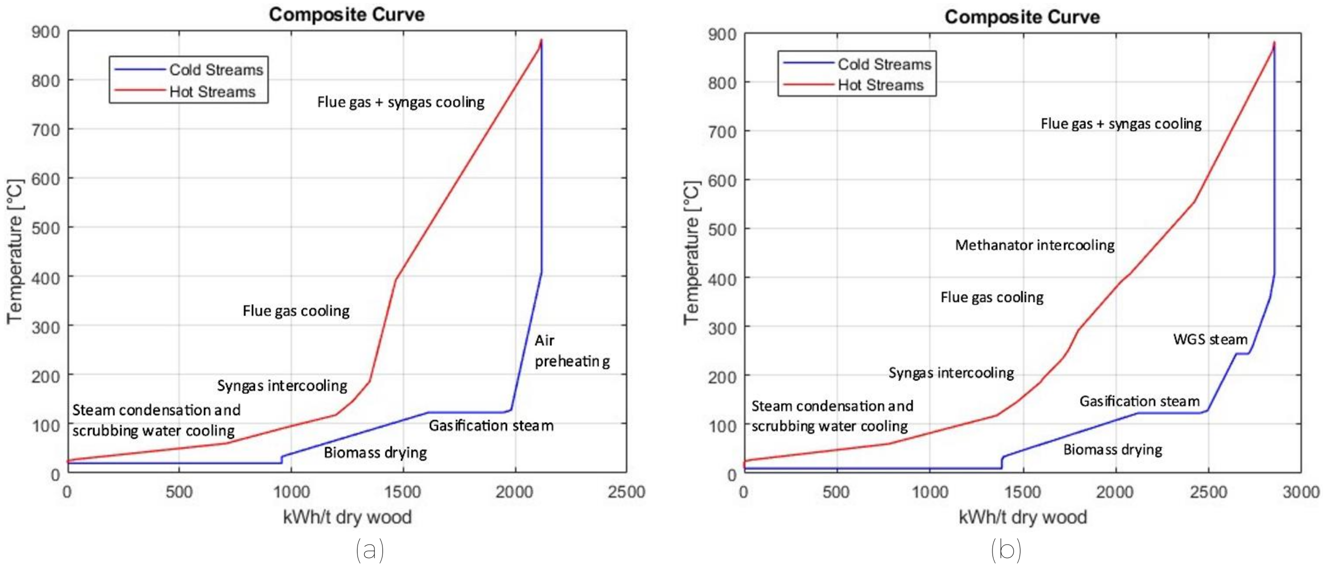


Figure 22. Composite curves of (a) wood gasifier and (b) biomass-to-SNG via methanation. Note that, in this figure, no steam network is used for cogeneration purposes yet, thus all the power used in the biomass-to-SNG section is assumed as imported.

The grand composite curve of the biomass-to-SNG production section is depicted in Figure 23. This plot is a representation of the cascaded heat available at certain temperature level and it can be built based on the cold and hot composite curves of Figure 23b. According to this plot, a large fraction of the waste heat is still available at relatively high temperatures (> 400°C, 800 kWh/$t_{drywood}$), which suggests the potential installation of a steam generation or a combined heat and power system, as it will be discussed later. An additional amount of the waste is available at lower temperatures (< 100 °C, 600 kWh/$t_{drywood}$), which could still be capitalized in a district heating network. In general, the energy efficiency of the SNG production process is around 64%, resulting in approximately 2400 kWh_{SNG}/$t_{dry\ wood}$. In addition to the biomass feedstock energy, around 7% of the energy embodied in the wood (LHV) is required in the form of electricity. As it has been previously discussed, electricity is utilized for grinding and chipping the biomass, as well as for operating the compression (e.g. for syngas and CO_2 compression) and pumping equipment of the biomass-to-SNG route. Apart from the inherent production of high grade waste heat streams, biomass conversion processes, such as gasification, can help capturing around 0.547 t_{CO2} per t_{DB}. Due to the biogenic origin of these emissions, if they are permanently sequestrated, an overall negative carbon balance could be achieved. Thus, the continuous operation of the proposed biomass gasification system, if assisted with CO_2 mineralization or injection, could help extracting CO_2 from the atmosphere. In fact, per kJ of wood input, the process has the potential to capture CO_2 emissions equivalent to burning around 0.6 kJ of fossil natural gas.

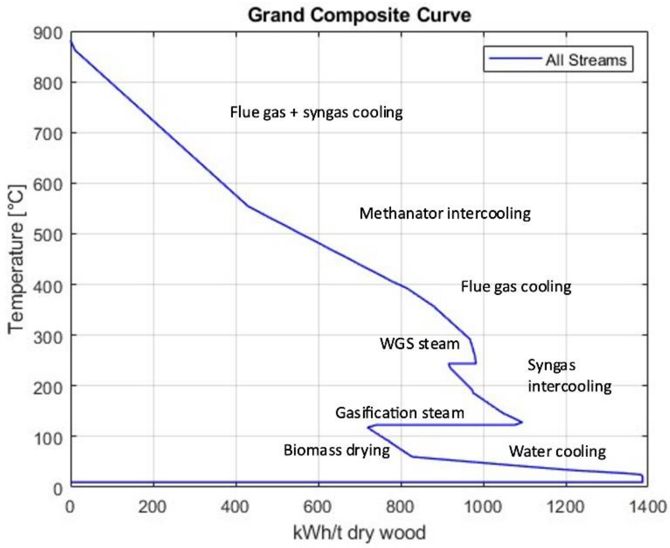


Figure 23. Grand composite curve of the biomass-to-SNG route. Electricity is considered as imported from the grid, thus no cogeneration unit is still evidenced.

It is important to realize that the direct heat exchange between the gasifier effluents and the aluminium in the Novelis plant is challenging, due to the characteristics of the hot gases (e.g. tar and particulate matter), which may require additional purification steps to meet the high quality standards of the finished aluminium product. For this reason, an indirect energy integration approach is identified as the most practical strategy to capitalize on the waste heat available through the biomass conversion and aluminium production systems.

In this regard, the energy demands of processes like: (i) the combustion air preheating for the Novelis furnaces, (ii) the biomass drying and the in-situ gasifying steam generation, (iii) the electricity generation and supply to the aluminium plant and (iv) the heating demand of the Sierre city could be partially meet by (a) the heat recovered from the cooling of the synthetic natural gas production units, (b) the flue stack gases of the furnaces and, to a lesser extent, (c) the aluminium casting water. Other identified integration solution is the use of the melter furnace stack gases to drive the sow drier furnace, in order to eliminate the fuel consumption in this latter technology. This approach directly competes with CHP (combined heat and power) generation, which calls for a systemic study to prioritize the best application for recovering the waste heat from the biomass conversion and aluminium production plants. Eventually, the residual heat from the industrial facilities can be readily upgraded via heat pumps driven by renewable electricity and anergy distribution networks, balanced by heat harvested from the surrounding environment (i.e. underground water).

Finally, by examining the grand composite curve of the biomass-to-SNG system (Figure 23), it could be argued that possibly other industrial sectors (e.g. chemicals, petro-chemicals, etc.) could make better direct use of the waste heat available at temperatures higher than those seen in the cogeneration systems. However, few applications are capable of enduring the harsh compositions of the gasifier effluents without needing a preliminary purification process or specialized heat exchangers. Also, aluminium and other heavy industrial sectors that process metallic solids count with much less options for heat supply in comparison to alternative users of the biomass energy. Actually, due to the technical and technological constraints imposed by the heat transfer mechanisms in the large reverberatory furnaces, aluminium remelting is less susceptible to electrification. Non-transferred plasma torches are among the proposed options for the aluminium melting decarbonization. Yet, their technological readiness level (TRL) and the associated heat transfer mechanism are not yet proven for the high temperature aluminium melting applications. In contrast, the chemical industries have at their disposition more compact heating appliances driven by electrical heating elements in controlled atmospheres and heat exchangers, rendering the utilization of the biomass waste energy less imperative.

5. BIOMASS UTILIZATION INTEGRATED TO THE INDUSTRY AND DISTRICT HEATING NETWORK

Hitherto, the analysis of the biomass energy conversion technologies focused mainly on the production of gaseous fuels, without elaborating on the potential to energetically integrate (directly or indirectly) those technologies into the Novelis aluminium plant and the city of Sierre. Hence, in this chapter, a comparison of different technological biomass conversion routes is performed encompassing from typical biomass energy uses, such as combustion in combined heat and power units or hot water boilers for district heating network; up to biomass gasification for simultaneous fuel and heat production (Figure 24).

Certainly, the limited woody biomass availability entails a stiff competition for this valuable resource. This contingency requires policymakers, local authorities, entities, and citizens to prioritize the most advantageous solutions for the entire biomass value chain, aiming to maximize the benefits for all the actors involved in the exploitation of biomass resources. Specifically, biomass energy could be used to supply heat at higher temperatures to the industrial applications, like aluminium production, whereas the waste heat produced in the aluminium solidification and furnaces could be cascaded down for its utilization in other applications at lower temperatures, such as a cogeneration or district heating networks. In this regard, process integration methods become fundamental to allocate the adequate amount of energy required by each consumer at the right temperature level, without significantly impacting the energy and material supply chain.

Clearly, by integrating more efficient energy technologies, the associated investment and the risk perception also increase, compared to the conventional biomass energy conversion systems. However, an economic feasibility study based solely on present market conditions may be misleading, in view of the upcoming energy transition policies and anticipated cost-effective deployments of those advanced energy systems, which will help displacing fossil resources and, thus, increase the industrial energy security and sustainability. In fact, new technological setups will be critical in scenarios of more stringent carbon taxations, as they can offset atmospheric emissions associated to the typical biomass energy use (e.g. direct biomass combustion), while helping to alleviate the environmental burden of the hard-to-abate heavy industries by enabling the production of negative emissions.

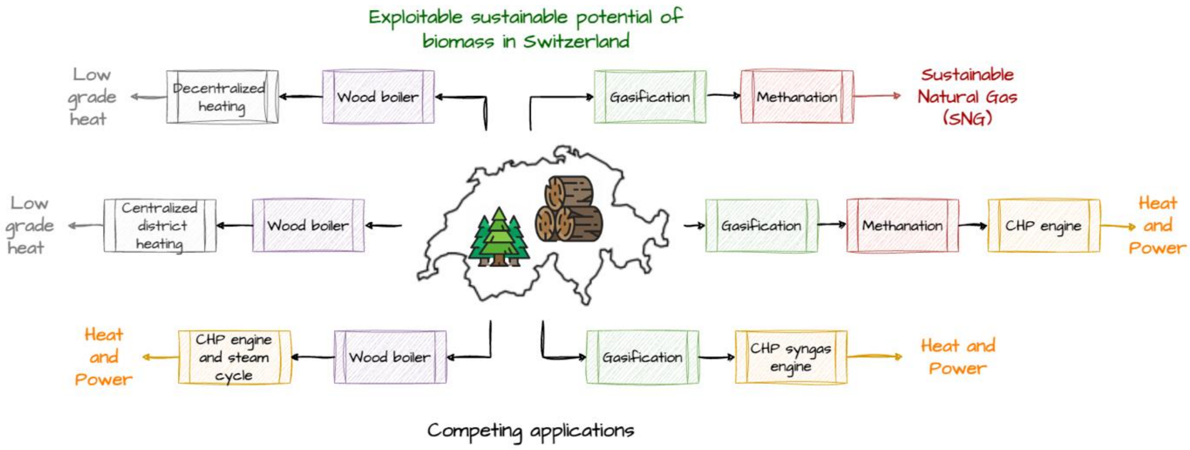


Figure 24. A schematic representation of the main competing applications for biomass energy use in Switzerland.

In this regard, a comprehensive comparison of different ways of using wood for energy has been conducted, focusing on factors such as energy efficiency, environmental impact, and cost-effectiveness. It is important to emphasize that, differently from previous studies that focused only on biomass energy conversion; the present study establishes a systemic view for the analysis of the industrial waste heat valorization and the potential heat supply to an urban agglomeration. This approach leverages the integration of energy technologies, such as heat pumps, anergy networks, carbon abatement and biomass-to-X energy systems, in lieu of only low efficiency combustion boilers. In order to fairly assess the performance of the existing and newly installed energy conversion systems, the boundary conditions that enclose them all must be carefully defined, as it will be discussed in the next sections.

5.1. Process integration scenarios for biomass energy conversion and district heating network

The industrial energy system is located in the Novelis cast house, which typically consumes around 420 kWh/t_{al} of natural gas and 25 kWh/t_{al} of electricity (excluding the rolling plant). It is located near the city of Sierre, which also has a need of space heating during the winter season. The Novelis rolling plant is excluded from the scope of this study due to its future electrification and so as to limit the wood utilization to the aluminium melter furnaces. In the rolling plant, the operating temperatures are much lower than those of the cast house, where the aluminium is actually melted and solidified into ingots that are processed in the rolling plant [1]. More details about the existing furnaces in the Novelis plant are shown in Figure 25 and 26. Thus, considering the SNG production efficiency (0.624 kW_{SNG}/kW_{wood}) and the gas consumption in the cast house, a wood gasifier with a maximum capacity of 720 kWh/t_{al} of SNG production could be adopted in the integrated biomass-to-SNG route.

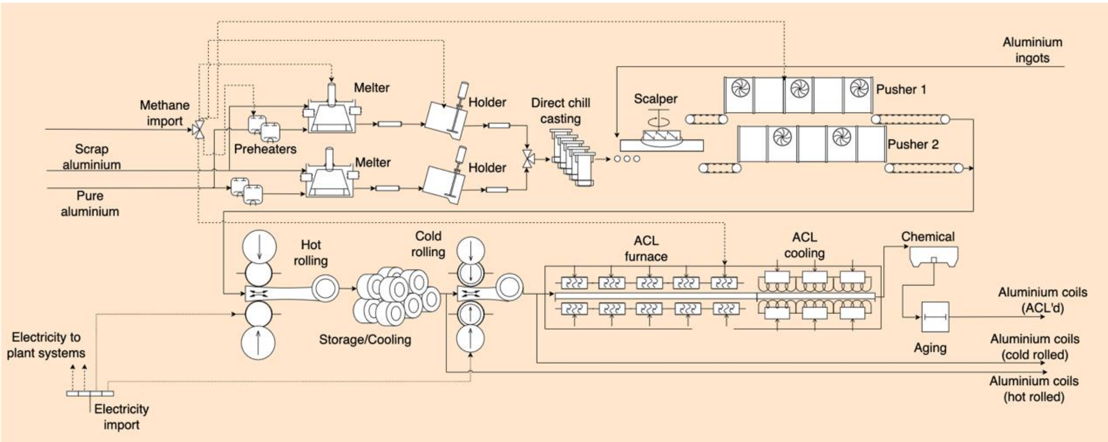


Figure 25. Process flowsheet of the Novelis aluminium plant [1].

A detailed design of a district heating network (CAD) in Sierre is in progress, and the NZL team as well as other official actors are actively assessing the technical and legal conditions for this project. Thus, in the present study, the city has been modelled as a simplified, low temperature heat requester for space heating purposes as if the CAD were already in place. In this way, the opportunity to recover waste heat from the Novelis aluminium plant can be analyzed since the early stages of the CAD design, thus allowing to inform local authorities about the best configurations for simultaneous biomass conversion and industrial waste heat utilization. Figure 27 shows the typical annual space heating demand for the city of Sierre obtained using REHO platform [30]. Two different district heating network concepts were studied. The first of them consists of a conventional, hot temperature water network, with respective supply and return temperatures of 65 °C and 40°C. A second design consists of a CO_2 anergy network operating between 15 °C and 13 °C [31]. More information on the assumed characteristics of the CADs is shown in Table 6. In this report, the water network (65°C-40°C) is the configuration adopted for distributing the heat produced by using the conventional biomass conversion technologies, since these setups are readily designed to produce and distribute hot water at specified temperature ranges. Clearly, a water anergy network could be a better solution for further exploiting the combustion enthalpy at lower temperatures. However, in this project, the anergy networks are limited to setups that employ heat pump systems in order to harness the low-grade industrial waste heat and the environmental heat to provide heat at suitable space heating temperatures.

For this reason, biomass-to-SNG routes were analyzed using two CAD alternatives, namely, a conventional water CAD (65°C-40°C) and an anergy CO_2 CAD (13°C-15°C) working across saturation states. The introduction of a low temperature anergy network allows to recover a larger amount of waste heat from the aluminium casting process and other waste heat streams from the gasification and syngas methanation units. Finally, it is worth mentioning that a water anergy network (~15°C) that recovers waste heat from the industrial site and the biomass energy conversion systems has been also studied, but those results are not listed on this report. The reason is that the performance of the two anergy networks is quite similar from an energy distribution point of view, but the CO_2-based setup allows to provide simultaneous heating and cooling services making use of the vaporization enthalpy of the working fluid. Moreover, the CO_2 network allows for more compact configurations and enhanced heat transfer properties (phase changing working fluid). These features confer to CO_2 networks more desirable characteristics in terms of costs and volume.

Unit	Energy consumption (kWh/tAl BSO)	Temperature level (°C)
Preheater	30 - 40	150 - 250 °C
Melter	350 - 500	700 - 750 °C
Holder	30 - 40	700 - 750 °C
Casting	180 - 200	700 - 50° C
Scalper	--	--
Pushers 1 & 2	190 - 250	400-550 °C
Hot rolling	50-70	300 - 450 °C
Storage /Cooling	--	500 - 100 °C
Cold rolling	40-60	50 - 150 °C
ACL	100-150	400 - 600 °C

Figure 26. Existing heating and cooling demands of the secondary aluminium plant. Energy consumption is given per tonne of aluminium processed in the pusher furnace (BSO) [1].

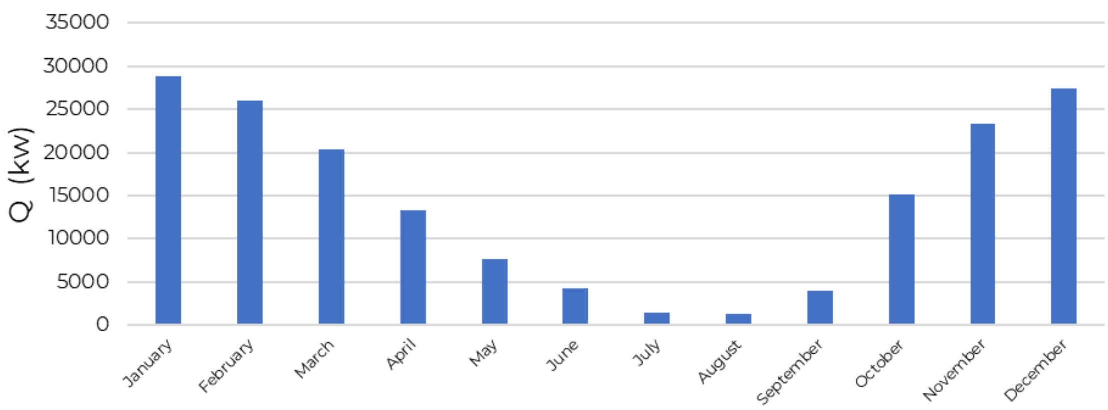


Figure 27. Estimated space heating demand of the city of Sierre [30].

Table 6. District heating network specifications.

Space heating	Value	Unit	Reference
Hot temperature	60	°C	Radiator temperature
Cold temperature	30	°C	Radiator temperature
Water District Heating Network:			
Supply temperature	65	°C	Based on [32]
Return temperature	40	°C	
Groundwater temperature	7.5	°C	[33, 34]
Specific cost heat pump	1000	CHF/kW_{th}	[35]
CO_2 anergy network:			
Supply temperature (CO_2 vapour)	15	°C	[31]
Return temperature (CO_2 liquid)	13	°C	[31]
Specific cost for decentralized HPs	1500	CHF/kW_{th}	[35, 36]

In this report, only SNG co-production is compared in more detail with the conventional biomass conversion routes. This approach aims to spotlight the suboptimal performance of the current uses of the valuable biomass resource to merely produce domestic heat and, in a lesser extent, electricity. On the contrary, the efficient use of biomass energy enables the defossilization of the energy and chemical sectors by co-producing waste heat, fuel and power, while cascading the waste heat to nearby urban agglomerations. The co-production of synthetic aviation fuel (SAF) and chemicals (e.g. methanol) based on catalytic reactions of syngas has been recently explored [12, 28, 28, 37]. Since those technologies are out of the scope of this project, an extended analysis is presented in the Annex A3.

Figure 28 shows the control volume adopted for the comparative analysis between (i) the conventional district heating systems using biomass combustion (thus, Novelis plant is fed by fossil natural gas only) and (ii) the integrated biomass gasification for the combined SNG, heat and power production. In the latter, the SNG produced is entirely consumed in the Novelis aluminium plant, thus no surplus SNG export is envisaged.

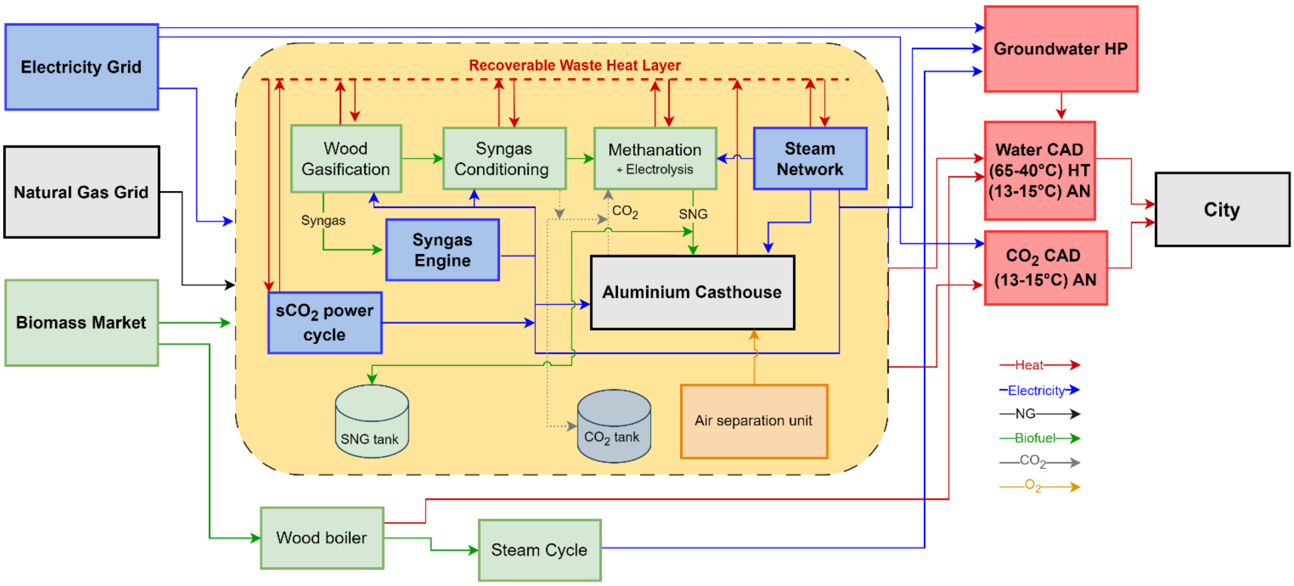


Figure 28. Control volume to for the comparative analysis of the biomass energy conversion routes, considering the Novelis aluminium plant and the Sierre city demands.

According to Figure 28, the energy demands of the Novelis cast house (sow drier, melter and holder furnaces) and the seasonal space heating demands of the city of Sierre are met by using either fossil natural gas, biomass or electricity imports. To this end, several energy technologies are leveraged, including biomass and syngas thermochemical conversion routes, cogeneration and steam network systems, supercritical CO_2 cycle, heat pumps (incl. groundwater), conventional and anergy CADs, electrolysis systems, air separation units (for Novelis oxycombustion furnaces), conventional wood boilers and gas storage tanks. Table 7 summarizes the various scenarios established for the comparative analysis. In total, 9 cases are considered (see also Table 7):

1. **SNG + water CAD:** The entire fuel gas demand of Novelis cast house is covered by the production of SNG via the biomass-to-SNG route. Waste heat from the biomass conversion unit as well as from the furnaces stacks and the casting water is released into a water district heating network (CAD) without any cogeneration of electricity. A large scale groundwater heat pump (HP) provide the remaining heating demand that the water CAD is not able to satisfy.

2. **SNG + cogeneration + water CAD:** Similar to case 1, in this case, SNG is also produced via the biomass-to-SNG route, but the waste heat from the biomass conversion unit and the cast house is valorized by integrating a steam network to cogenerate electricity and heat. Groundwater HP is also used to balance the space heating demand of the city.

3. **SNG + CO_2 CAD**: Similar to case 1 and 2, SNG is produced through biomass gasification, syngas purification and methanation, but the waste heat from the biomass conversion unit and from the plant are released to a CO_2 district heating network, instead of a water-based CAD, without any cogeneration of electricity.

4. **SNG + cogeneration + CO_2 CAD**: Similar to case 3, in which SNG is produced and a CO_2 network is implemented, but the waste heat is first valorized in a steam network (SN) for combined heat and power generation, before it is released to a CO_2-based CAD.

5. **Syngas for CHP engine + water CAD:** Differently from the previous cases in which the production of SNG is favoured, in this case, the biomass-derived syngas is used directly to run an internal combustion engine that produces combined power and heat. The heat is distributed to the city through a conventional water CAD. In addition, fossil natural gas is

imported from the grid to meet energy demands of Novelis furnaces. Only the combined heat and power production (CHP) engine is fed with syngas in order to prevent furnaces or central boilers to be fueled with a potentially toxic CO-rich fuel.

6. **Boiler for SN + water CAD**: In this case, biomass is directly burnt in a boiler to produce high temperature steam, which is fed to a steam network (SN) that generates power in a Rankine cycle. Heat is released to a water CAD, in which a HP compensates the remaining heat demand not provided by the water CAD. Novelis furnaces are fed with imported fossil natural gas.

7. **Only heating boiler**: Biomass is used only in a heating boiler to produce heat distributed through a conventional water CAD. Naturally, this case requires full import of electricity and fossil natural gas from the grid. As for the other cases, an underground HP complements the space heating demand that cannot be satisfied by the water CAD.

8. **OxySNG + sCO_2 + CO_2 CAD**: SNG is produced via biomass gasification and used to supply the heating demand of the Novelis furnaces. Differently from cases 1-4, the oxycombustion of SNG facilitates the separation of the CO_2 from the water in the combustion gases through condensation. The upgraded biogenic CO_2 stream can be readily commercialized or used to achieve negative emissions, if combined with sequestration (e.g. injection). A CO_2 district heating network is used and part of its power consumption can be generated by a waste heat recovery supercritical CO_2 power generation cycle.

9. **OxySNG + P2G + sCO_2 + CO_2 CAD**: Similar to the case 8, oxycombustion furnaces facilitate the biogenic CO_2 capture, which could be sequestrated to reach negative CO_2 emissions. However, the production of SNG could be boosted by reacting the biogenic CO_2 stream with hydrogen produced via water electrolysis in a methanation system. This so-called power-to-gas approach enables also the storage of renewable electricity in the form of liquefied gas, so that it can be used to supply both energy demands of Novelis plant and Sierre city even if a seasonal availability of biomass resources is expected. The oxygen production in the electrolyzer alleviates the load of a dedicated air separation unit (ASU) necessary to supply the oxycombustion furnaces. Next, waste heat is first valorized via a supercritical CO_2 power generation cycle, before being released to a CO_2 CAD at a lower temperature.

Table 7. Scenarios adopted for the comparative analysis between the conventional district heating system based on biomass combustion (Novelis plant based on natural gas) *versus* the integrated biomass gasification for combined heat, power and fuel production.

Description	Biomass conversion technology	Fuel production	Power supply technology	District Heating technology
SNG + water CAD	DFB Gasifier + Methanation	SNG	Full EE import	Water network (65-40°C)
SNG + cogeneration + water CAD	DFB Gasifier + Methanation	SNG	Steam network (balance EE import)	Water network (65-40°C)
SNG + CO_2 CAD	DFB Gasifier + Methanation	SNG	Full EE import	CO_2 network (13-15°C)
SNG + cogeneration + CO_2 CAD	DFB Gasifier + Methanation	SNG	Steam network (balance EE import)	CO_2 network (13-15°C)
Syngas for CHP engine + water CAD	DFB Gasifier	Syngas	Syngas ICE (balance EE import)	Water network (65-40°C)
Boiler for SN + water CAD	Biomass boiler	No	Steam turbine (balance EE import)	Water network (65-40°C)
Only heating boiler	Biomass boiler	No	Full EE import	Water network (65-40°C)
OxySNG + sCO_2 + CO_2 CAD	DFB Gasifier + Methanation	SNG for oxyfuel (+ASU)	sCO_2 cycle (balance EE import)	CO_2 network (13-15°C)
OxySNG + P2G + sCO_2 + CO_2 CAD	DFB Gasifier + Methanation + Electrolysis + Seasonal storage	SNG for oxyfuel (+ASU)	sCO_2 cycle (balance EE import)	CO_2 network (13-15°C)

DBF: Dual fluidized bed gasifier; CAD: fr. chauffage a distance (en. district heating network DHN); EE: electricity; SNG: Synthetic natural gas; P2G: Power to gas; ASU: Air separation unit.

In the Table 8, additional information is presented on the specific investment of the biomass gasification system, the syngas to SNG production units, and the steam network, based on the estimation procedure provided in Appendix A1.

Table 8. Specific costs of the gasification, the syngas to SNG production unit, and the steam network.

Parameter	Value	Unit	Reference
Specific investment cost $Cinv_{gasifier}$	1450	CHF/kW_{wood}	See Appendix A1
Specific investment cost $Cinv_{syngastoSNG}$	1191	CHF/kW_{SNG}	See Appendix A1
Specific investment cost $Cinv_{steamnetwork}$	2380	CHF/kW_e	[38]

Syngas derived from biomass gasification can be used as fuel to drive small (0.1-1 MW_{wood}) or even medium-sized cogeneration plants (5-20 MW_{wood}) [39–41]. Technical parameters and specific costs adopted for the syngas-fuelled engine are summarized in Table 9.

Table 9. Technical parameters and specific costs of the syngas cogeneration engine.

Parameter	Value	Unit	Reference
Syngas ICE electric efficiency	40	%	[42]
Syngas ICE heat efficiency	42	%	[42]
Specific Investment Cost $C_{Syngas\ ICE}$	890	CHF/kW_e	[43, 44]

The biomass boiler directly converts the chemical exergy of wood into heat. Combined heat and power production can be done in Rankine cycle fuelled with biomass. Table 10 shows the features of the

Table 10. Technical parameters and specific costs of a CHP plant based on a Rankine cycle integrated to a biomass boiler.

Parameter	Value	Unit	Reference
Steam pressure of Rankine cycle	50	bar	Based on typical operations of a CHP plant
Steam temperature of Rankine cycle	508	°C	
Turbine back-pressure	1	bar	
Specific investment Cost $Cinvbiomass_{CHP}$	1441	CHF/kW_{wood}	[45]

The simplest conversion alternative is a biomass boiler used only for producing hot water intended to be used in a hot water distribution network [46]. Despite its inefficiency and low versatility compared to other technologies, this option is included in the comparative analysis to highlight the need for implementing more efficient biomass energy conversion systems.

Table 11. Technical parameters and specific cost of a simple heating biomass boiler.

Parameter	Value	Unit	Reference
Boiler heat losses	5	%	-
Variable Investment Cost $Cinv_{biomass\ boiler}$	700	CHF/kW	[47]

A last solution is conceived as a hybrid between biomass-to-SNG and power-to-gas systems. It considers the seasonality of renewable electricity used to produce green hydrogen via electrolysis, which is later combined with biogenic CO_2 from woody biomass conversion steps to produce more SNG. The cast house melter furnace is assumed to operate in oxyfuel mode facilitating the capture of CO_2 [1]. The main assumptions of this scenario are listed in Table 12.

Table 12. Technical parameters and specific cost of a power-to-gas solution.

Parameter	Value	Unit	Reference
Electrolyzer type	Proton Exchange Membrane (PEM)	-	-
Electrolyzer Cost $Cinv_{Electrol}$	1200	CHF/kW	[48]
Electricity demand of air separation unit (ASU)	0.29	kWh/kgO_2	[49]

A selection of key performance indicators (KPIs), based on thermodynamic, environmental and economics metrics, are used to compare the nine biomass energy conversion cases. The results of energy demand, emissions and estimated costs are given per t_{AlBSO} produced in the Novelis Sierre aluminium plant (incl. the cast house and rolling plant). The energy demands reported encompass Novelis facility, district heating network (i.e. heat pumps), as well as energy consumption in the biomass conversion and ancillary units. The wood and natural gas specific energy consumption are differentiated. For the sake of comparison, the exergy values of biomass (B_{wood}) and SNG (B_{SNG}) are almost equivalent to the corresponding energy values multiplied by 1.12 [50] and 1.04 [51], respectively. Environmental metrics considering CO_2 emissions (direct and indirect) from the overall system are also calculated. Since a fraction of these emissions is biogenic, they are accounted for as circular emissions and are not considered in the net CO_2 emissions balance. On the other hand, net negative emissions result from sequestrating captured CO_2, thus additional benefits of the biogenic carbon management can be elucidated. Lastly, the operational (opex), the capital (capex) and the total (totex) expenditures account for both energy and non-energy related costs. Table 13 summarizes the energy prices, indirect emission factors and carbon credit used in the study of the proposed scenarios.

Table 13. Energy prices and environmental impact coefficients used in the comparative analysis of conventional and advanced biomass energy conversion.

Parameters	**Value**	**Unit**	**Reference**
Ind. Emission Electricity	23	g_{co2}/kWh	[52]
Ind. Emission Natural Gas	40	g_{co2}/kWh	Ecoinvent 3.10
Ind. Emission Wood	7	g_{co2}/kWh	From supply chain analysis
Biomass price	0.06	CHF/kWh	From supply chain analysis
Electricity price	0.15	CHF/kWh	NetZeroLab
Natural gas price	0.05	CHF/kWh	NetZeroLab
CO_2 Tax/Credit	100	CHF/ t_{CO2}	[53]

5.2. Results of the process integration scenarios

Figure 29 shows the energy flows of natural gas, electricity and wood that cross the control volume of the overall system shown in Figure 28. As expected, the biomass-to-SNG routes demand the largest import of biomass (720 kWh/t_{Al}) and electricity (up to 300 kWh/t_{Al}), but to the benefit of a complete replacement of fossil natural gas import. These figures can be compared to the cases in which biomass boilers and CHP systems are employed for direct biomass or syngas combustion, in which at least 430 kWh/t_{Al} of non-renewable natural gas are still needed to drive the Novelis cast house plant. In the case 5, in which biomass-derived syngas is used in a cogeneration engine, the electricity import is drastically reduced thanks to an increased efficiency of the cogeneration system. However, the biomass energy input is comparable to the amount of fossil natural gas input, indicating that this solution cannot help to shift the natural gas consumption and cut down the associated fossil CO_2 emissions.

On the other hand, it is worth noticing that the solution related to the case 4 has the lowest energy input among all the biomass-to-SNG production cases, even lower than those cases using conventional biomass energy conversion systems. It can be explained by the fact that biomass energy is first used to produce gas that can be consumed by the existing furnaces; then the waste heat generated through the biomass-to-SNG plant can be fully exploited to preheat the process streams, and co-produce the heat and power required through the overall energy system using a waste heat recovery steam network. The cogeneration system efficiently collects and exploits the high-grade waste heat available at higher temperatures, to only deliver it to the CO_2-based anergy CAD at the lowest temperature, so that it can be lastly upgraded by a series of heat pumps driven by the self-generated electricity.

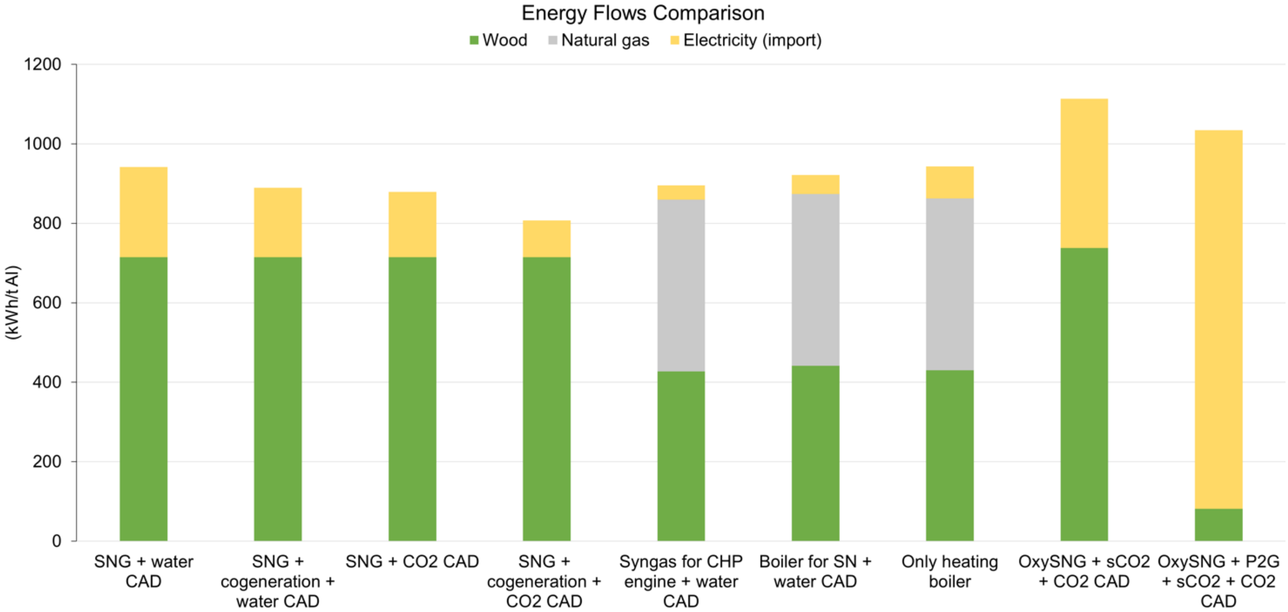


Figure 29. Energy inputs into the system for the set demands using different biomass energy conversion and utilization routes.

Table 14 gives further details about energy imports and power self-generation in the nine studies cases. As it was previously mentioned, the biomass-to-SNG production routes, when integrated to a steam network, exhibit a favorable power self-sufficiency. In fact, due to the syngas and the flue gas cooling, as well as the intercooling of other processing units, a high-grade waste heat source is available to produce combined heat and power. The integration of a CO_2 network to a biomass-to-SNG production route with a cogeneration system may reduce the overall energy requirement by 14% (case 4), compared to the solution in which biomass is only used in a combustion boiler (case 7, Table 14). Meanwhile, it is remarkable the energy consumption increase (28%) for the case 9, in which the power-to-gas approach aims to capitalize on the renewable electricity to boost the SNG production. However, more interesting is the fact that the need for biomass is drastically reduced by 89% in the same case, as the import of the woody biomass is limited only to the four colder winter months. The biogenic CO_2 is stored in liquid form so that it can be upgraded to fuel by capitalizing on the renewable electricity available during the remaining months.

For the sake of comparison, primary aluminium production reportedly consumes around 17000 kWh/t_{Al} mainly in the form of electricity. Meanwhile, in the best case, the cast house of Novelis, together with the city of Sierre and the ancillary systems, only consume < 1100 kWh/t_{al}, which is less than 10% of the energy consumption in the primary aluminium production process. This fact indicates the relevance of the circular economy and the importance of increasing the aluminium recycling rates as key decarbonization and energy efficiency strategies of the aluminium production sector. According to Szargut et al [50], the exergy of aluminium is 9 kWh/t_{Al} (800 kJ/$kmol_{Al}$, 27 kg/$kmol_{Al}$), implying that, theoretically, the minimum energy input to produce aluminium from the components in the environment is much lower (x10) than the actual energy input in the remelting process. In practice, efficiency pathways must rather observe the technical and legislation constraints, metallurgical recipes and other losses that increase the theoretical energy consumption. In any case, the results in Table 14 set a practical level-playing field to compare the expected energy consumption and the relative advantages of integrating more advances energy conversion systems. In fact, these results demonstrate the versatility of the integrated setups, vis-à-vis conventional biomass energy conversion systems.

Table 14. Comparison of the specific energy demands* (wood, electricity and natural gas) and the power self-generation for the nine selected biomass utilization applications.

Scenario	Wood demand	Natural gas demand	Electricity from grid	Power self-generation
	kWh/t_{Al}	kWh/t_{Al}	kWh/t_{Al}	kWh/t_{Al}
SNG + water CAD	715	0	228	0
SNG + cogeneration + water CAD	715	0	175	73
SNG + CO_2 CAD	715	0	165	0
SNG + cogeneration + CO_2 CAD	715	0	92	77
Syngas for CHP engine + water CAD	427	432	35	125
Boiler for SN + water CAD	441	432	48	86
Only heating boiler	430	432	81	0
OxySNG + sCO_2 + CO_2 CAD	738	0	375	84
OxySNG + P2G + sCO_2 + CO_2 CAD	82	0	953	72

** Neglecting the effect of the energy of plastic deformation embodied in the rolled product of aluminium and any other oxidative chemical reaction in the process, each unit of energy that is transferred in the form of heat needs to be evacuated, so that the metal eventually returns to the initial state of ambient temperature. Since all the exergy flows that leave the system are in the form of dissipated heat to the environment, virtually all the exergy that is imported with fuel and electricity is irremediably destroyed. For this reason, a classical efficiency definition, calculated as the ratio of the exergy output to the exergy input is not a representative indicator of the system performance. That is the reason for choosing the specific energy consumption (kWh) per t_{Al} as the suitable criteria to compare biomass energy conversion systems integrated to the aluminium plant and the city.*

All the integrated aluminium and biomass-to-SNG cases accomplish full replacement of the fossil fuel. An additional advantage of those configuration is that, when combined with the permanent CO_2 sequestration, they may generate biogenic CO_2 emissions. According to Figure 30, the net negative CO_2 emissions (-73 kg_{CO2} /t_{Al}) of the cases 1-4 can be compared to the net positive CO_2 emissions (120 kg_{CO2} /t_{Al}) associated to the cases in which less efficient biomass energy conversion technologies are contemplated. The case 8, based on the oxy-combustion of SNG and supercritical CO_2 power cycle, show the best results in terms of net CO_2 emission balances. In effect, a complete injection of all the captured CO_2 leads to record negative CO_2 emissions (-143 kg_{CO2} /t_{Al}), which is almost twice the values estimated for the other cases 1-7, as these latter do not include the injection of the CO_2 captured from the flue gases possible with the oxycombustion process and facilitated CO_2 separation. Anyhow, even though the emissions derived from the power-to-gas-based solution (case 9) are not fully net zero or net negative, it is interesting to note that they are five times lower than the current emissions of the Novelis plant based on fossil natural gas.

In the Table 15, the net negative emissions arise from injection of biogenic CO_2 emissions, which can offset indirect or direct fossil emissions from the overall system. However, as it is evidenced, case 9 is responsible for certain amount of indirect positive CO_2 emissions, due to the intensive import of electricity from the grid. Although this amount is still 4 times lower than the CO_2 emissions estimated for the conventional biomass energy conversion cases, this result underpins the need for electricity mixes with a larger share of renewable energy resources, so that scope 2 emissions do not impact negatively the decarbonization efforts of the industrial processes electrification. Table 17 details the breakdown of total, biogenic, fossil, capture and net CO_2 emission balances for the different biomass conversion and energy integration routes. It is with noticing that, the biogenic emissions are considered as net zero contributions, due to their nature of circular emissions. Thus, to calculate the net balance, they need to be subtracted from the total emissions. This assumption could be invalid in a scenario in which the production and use of the woody biomass is not anymore considered as renewable, since the CO_2 emissions released by the furnaces and biomass conversion process are not anymore offset by the replanted biomass.

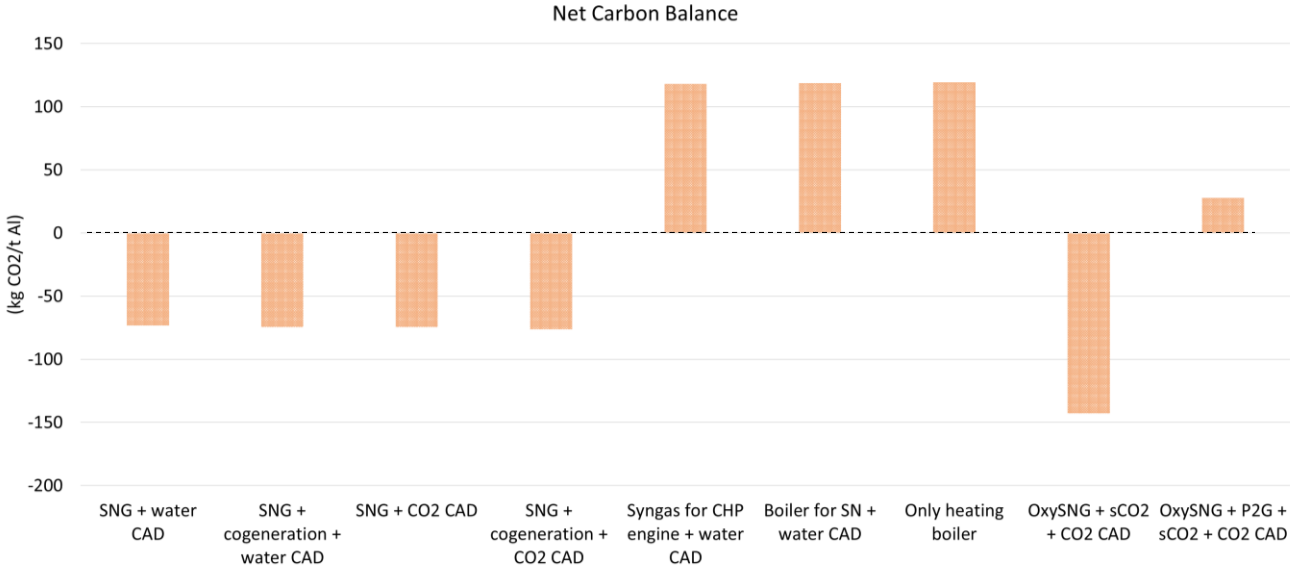


Figure 30. Net CO_2 emissions for the different biomass energy conversion and utilization routes, integrated to the aluminium plant and district heating network.

Table 15. Details of the environmental impact of different biomass energy conversion and utilization routes, integrated to the aluminium plant and district heating network.

Scenario	Total emissions (fossil + biogenic)	Biogenic emissions*	Sequestrated emissions	Net CO_2 balance
	kg_{CO2} /t_{Al}	kg_{CO2} /t_{Al}	kg_{CO2} /t_{Al}	kg_{CO2} /t_{Al}
SNG + water CAD	179	167	-85	-73
SNG + cogeneration + water CAD	177	167	-85	-74
SNG + CO_2 CAD	177	167	-85	-75
SNG + cogeneration + CO_2 CAD	175	167	-85	-76
Syngas for CHP engine + water CAD	269	150	0	118
Boiler for SN + water CAD	274	155	0	119
Only heating boiler	271	152	0	119
OxySNG + sCO_2 + CO_2 CAD	16	0	-159	-143
OxySNG + P2G + sCO_2 + CO_2 CAD	28	0	0	28

* Accounted as net zero emissions, thus subtracted from total emissions before calculating the net CO2 balance. The latter considers the additional subtraction of the sequestrated (injected) emissions.

Finally, the economic performance of the various cases is evaluated taking into account both the annualized operation and capital expenditures. As expected, Figure 31 shows that using wood boilers for low temperature heating applications leads to the lowest investment costs, while the costlier setup corresponds to the case 9 in which the power-to-gas systems are installed. The highest opex also corresponds to case 9, which is 2.5 times larger than the totex of the other alternatives. These results need to be taken with caution, as they do not reflect the cost evolution of the advanced energy technologies. On the other hand, despite being the most expensive, case 9 is also the only scenario that can store and capitalize on the CO_2 produced via biomass gasification to be used for producing fuel when inexpensive electricity is available in the summer season. Moreover, the system produces the oxygen required to operate the oxycombustion process, which proved to be a mature technology for reverberatory furnaces. The opex associated to electricity is one of the main challenges of the biomass-to-SNG routes integrated to the power-to-gas technologies, but it is important to highlight the reduced demand of scarce biomass resources compared to the other cases sparing an electrolysis system. Lower electrolyzer costs, internalized costs of reliability and energy security associated to storage capacity, as well as smart strategies of power consumption during periods of curtailment, may help improving the relative economic performance of this advances energy conversion system (case 9).

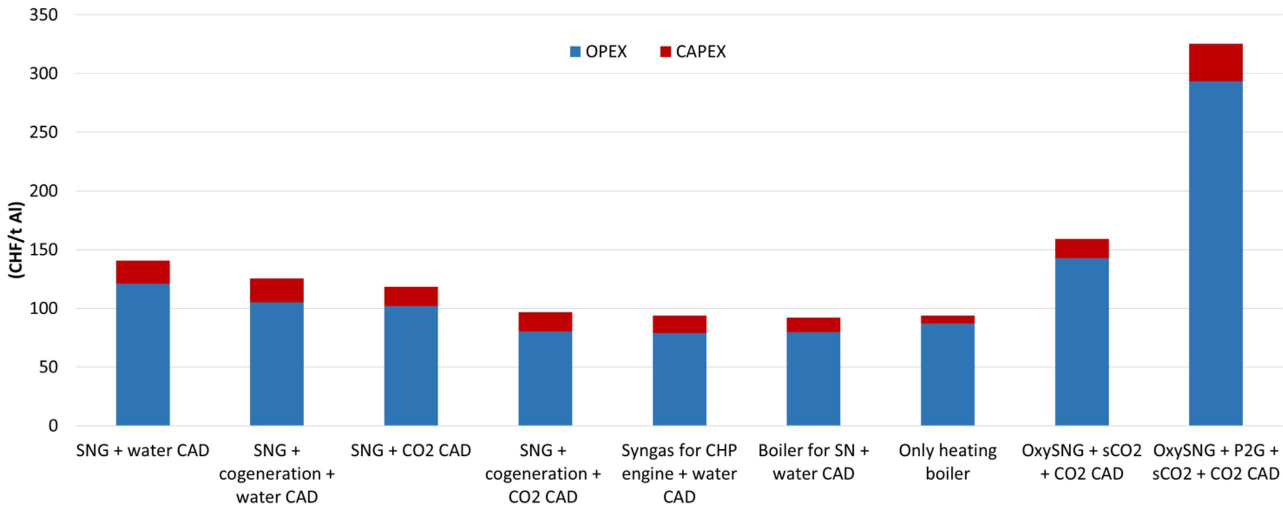


Figure 31. Annualized expenses for the different biomass energy conversion and utilization routes integrated to aluminium plant and district heating network.

Table 16 shows the breakdown of the capital, operational and total expenditures of different biomass energy conversion and utilization routes integrated to the aluminium plant and the district heating network. As it can be seen, in most of the cases, the major contribution to the total expenditures come from the operational share.

Table 16. Economic performance of the biomass energy conversion and utilization routes integrated to the aluminium plant and district heating network.

Scenario	Energy Opex	Carbon Credit (-) or Tax (+)	Capex	Totex
	CHF/t_{Al}	CHF/t_{Al}	CHF/t_{Al}	CHF/t_{Al}
SNG + water CAD	110	-7	20	123
SNG + cogeneration + water CAD	95	-7	20	107
SNG + CO_2 CAD	92	-7	16	100
SNG + cogeneration + CO_2 CAD	70	-8	16	79

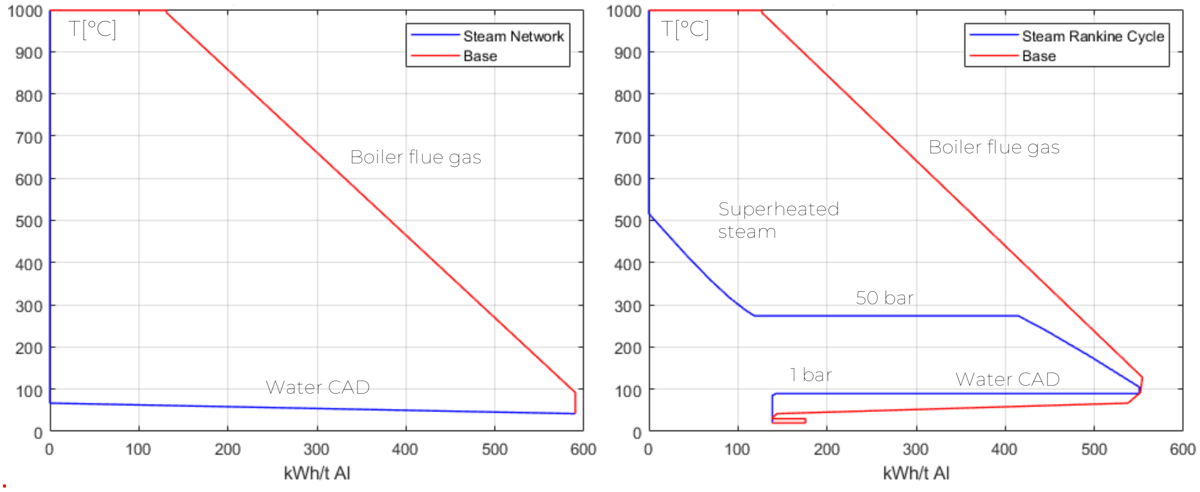
Scenario	Energy Opex	Carbon Credit (-) or Tax (+)	Capex	Totex
Syngas for CHP engine + water CAD	58	12	15	84
Boiler for SN + water CAD	63	12	13	87
Only heating boiler	72	12	7	90
OxySNG + sCO_2 + CO_2 CAD	157	-14	16	159
OxySNG + P2G + sCO_2 + CO_2 CAD	344	3	32	379

Figures 32-35 compare the integrated composite curves of the biomass energy conversion systems, starting from the basic applications, namely wood boiler for heat production only (Figure 32a) or for power generation using a Rankine cycle (Figure 32b); up to incorporating more advanced solutions, such as a biomass integrated gasification Rankine cycle linked to a hot water (Figure 33a) or CO_2-based district heating networks (Figure 33b). Figure 34 shows the integrated curves of the biomass-to-SNG route with oxycombustion furnaces in the Novelis plant, with a transcritical CO_2 cogeneration cycle and a CO_2-based district heating network. Finally, Figure 35 depicts the integrated curves of a biomass-to-SNG route with oxycombustion furnaces, a transcritical CO_2 cogeneration cycle, a CO_2 anergy network and seasonal liquefied CO_2/SNG gas storage, for (a) winter and (b) summer seasons. This case implements a power-to-gas SNG and CO_2 management system that reduces the biomass energy input to alleviate its overall demand. Biomass is harvested from April to October in Valais, Switzerland, and it could be stored to be used during the winter months.

If a wood boiler is used to supply only heat to the district heating (Figure 32a), the ranges of temperature of the hot water (40°C-60°C) are easily fulfilled by the hot combustion gases. However, it is also evident that the high-grade thermodynamic potential available in the flue gases is underexploited to merely produce low-grade heat for space heating purposes. This action contradicts the goal of the entropy minimization method, which relates the lost potential to excessively large driving forces in the energy conversion system. In effect, the Second Principle of the Thermodynamics states that, after the chemical energy of biomass is degraded into a warm water flow, the number of applications and the energy quality are irremediably reduced. Any attempt to upgrade the heat at higher temperatures to be used in other industrial and energy processes can be only at the expense of an external addition of energy and further irreversibilities.

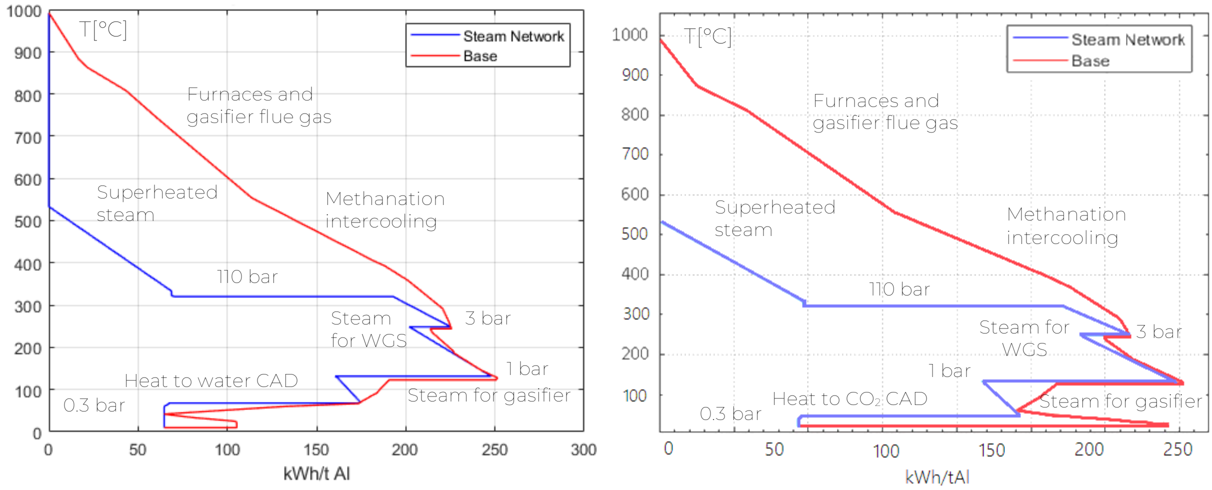
An additional solution aiming to palliate the irreversibility of the direct biomass combustion process is a combined heat and power production unit (Figure 32b). In the cogeneration unit, high pressure steam produced in a biomass steam generator (550 kWh/t_{Al}) allows to reduce the driving forces in the heat transfer process, as the biomass chemical energy can be first used to produce high quality electrical energy. The expanded steam leaving the steam turbine can still be used to supply heat to the Sierre city, whereas the power (~150 kWh/t_{Al}) can be used in the Novelis plant or in an underground water heat pump system. Again, the temperature of the backpressure steam is too low to be used elsewhere in the industrial plant; thus, an import of fossil natural gas is needed to supply the heat demand to the aluminium furnaces, with the corresponding net CO_2 atmospheric emissions.

Figures 33a and b illustrate the integrated curves representing the biomass-to-SNG routes, in which fuel, heat and power are simultaneously produced. Unlike the previous biomass utilization routes, the integration of a steam network/Rankine cycle with various pressure levels improves the performance of the steam production and utilization process, therefore reducing the associated irreversibilities. The preheating loads of the gasifier and the water gas shift reactants can be met by extracting steam from the extraction-condensing steam turbine at 3 bar and 1 bar, respectively, without incurring irreversible throttling or non-isothermal steam-water mixing, and generating around 60 kWh/t_{Al} of electricity.



(a) (b)

Figure 32. Integrated composite curves of wood boiler (a) for heating only or for (b) combined heat and power production in a Rankine cycle.



(a) (b)

Figure 33. Integrated composite curve curves of biomass-to-SNG production with cogeneration using steam network and (a) water district heating network and (b) CO_2 anergy network.

By applying the heat cascading efficiency principle, the waste heat from the gasifier effluents, the methanation unit and the furnace flue gases, that has not been converted into electricity or used to preheat the process streams, can still be fed to an anergy district heating network to distribute the low-grade waste heat from the condenser of the Rankine cycle (~70 °C) to the urban agglomeration. Apart from the waste heat from chemical reactions occurring through all the biomass conversion plant, the energy integration with the Novelis plant allows to capitalize on the waste heat available from the casting water, further reducing the amount of fuel or electricity consumed in the district heating network. This is particularly true for the case shown in Figure 33b (namely case 4), for which the anergy system is capable of recovering more heat due to the lower temperature of the phase changing CO_2 working fluid.

By examining Figures 33a and b, it could be argued that other industrial processes exploiting the waste heat at temperatures higher than those of a steam network should be prioritized, due to the lower thermal driving force and the direct heat exchange with the gasifier effluents. Certainly, the direct heat integration would be the best approach to profit from the waste heat derived from the gasification system. However, as it has been stressed, few processes and heat exchange equipment are capable to withstand the harsh composition of these streams, which will inevitably require a thorough purification process to remove the condensable tars and the particulate matter. These steps end up reducing the temperature ranges at which the waste heat is eventually available, making the cogeneration systems still attractive vis-à-vis other waste heat recovery systems at high temperatures. The use of regenerative material to recover the waste heat from the gasifier effluents also need to be carefully designed to about fouling and carbon deposition. The catalytic cracking of tars and the pre-reforming of SNG could help harnessing waste heat at higher temperatures, thus capitalizing on a higher thermodynamic potential of the gasifier effluents. Notwithstanding, it would also add more complexity to the overall energy system. All in all, using a steam cogeneration system is a good compromise between simplicity and versatility to satisfy the combined power and heat demands of the biomass-to-SNG plant, the Novelis aluminium plant and the Sierre city.

Other solutions integrate cogeneration units with a natural gliding temperature profile, known as internally recuperated transcritical CO_2 power cycles. Figures 34-35 show the integrated curves of cases 8 and 9, respectively, in which this technology is favoured over a steam network (Rankine cycle). Analogous to the CO_2 district heating networks, transcritical CO_2 power cycles are more effective in cases of limited space budget, as they are more compact and operate at higher pressures than steam networks. These cycles can also recover the water condensation enthalpy from flue gas at low pressure. Yet, as the distinctive plateaus of steam generation and extraction are not exploited, part of the thermodynamic potential clearly remains untapped.

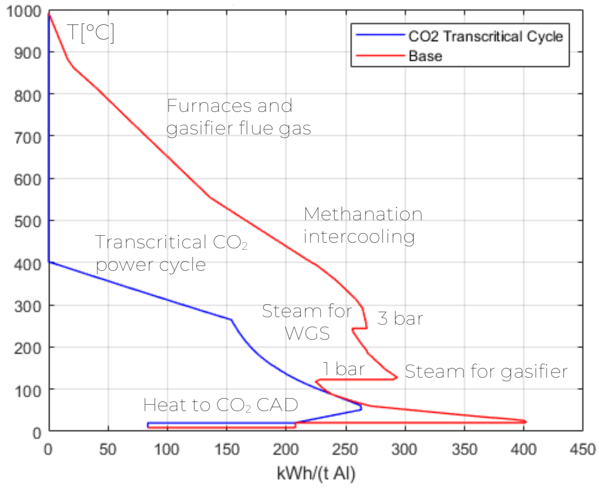
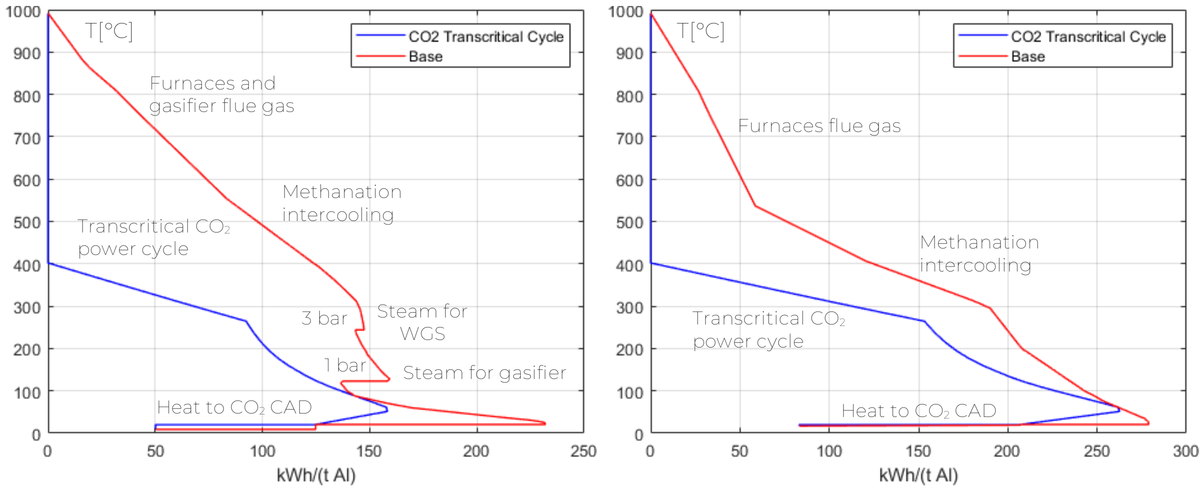


Figure 34. Integrated composite curve curves of biomass-to-SNG production with Novelis oxycombustion furnaces, transcritical CO_2 power cycle, and CO_2 anergy network.



(a) (b)

Figure 35. Integrated composite curves of biomass-to-SNG route with Novelis oxycombustion furnaces, transcritical CO_2 power cycle, CO_2 anergy network and CO_2/SNG seasonal liquefied gas storage: (a) winter season, (b) summer season.

The use of oxycombustion furnaces in the aluminium plant with the subsequent waste heat recovery from partial condensation of water slightly increases power self-generation. This effect helps compensating the lower temperature of the transcritical CO_2 power cycle. In fact, by using this technology, between 72-84 kWh/t_{Al} could be generated, in comparison to 73-77 kWh/t_{Al} generated in the steam networks, as it has been also reported in Table 14.

Finally, Figures 35a-b show the impact on the integrated curves of case 9 when adopting a power-to-gas system for two different periods representative of the (a) colder and (b) hotter seasons. In this case, biomass is only used from November through February, whereas the energy required by the overall system in the remaining days is produced by converting the captured and stored CO_2 and the hydrogen from water electrolysis into SNG. The latter is, in turn, used to fuel the Novelis furnaces and the CO_2 cogeneration cycle. The cascaded waste heat is eventually released to the CO_2 district heating network to be upgraded using heat pump systems. The max power capacity of the electrolyzer is 1223.02 kWh/t_{Al}, which in turn produces 933 kWh/t_{Al} of hydrogen (HHV). The methanator maximum capacity is 650 kWh/t_{Al} of SNG. The gasifier is consequently undersized, compared to the previous cases 1-4 and 8, only requiring a maximum biomass wood input of 251 kWh/t_{Al} during the operative months (less than 7 MW for an aluminium production of 27.8 t/h). Hence, maximum gasifier size is sharply reduced to less than one third of the minimum capacity for the previous SNG production routes [1]. Moreover, the integration of an anergy network for district heating purposes is competitive vis-à-vis a high temperature water-based network. The former technology has advantages in terms of compactness, enhanced heat transfer rates (e.g. pressurized and phase changing working fluid) and the possibility to harness heat from other actors in the CO_2 network, that may require not only heating, but also space cooling and refrigeration.

CONCLUSIONS AND PATH FORWARD

The main objective of this project was to develop a conceptual design of an integrated biomass gasification system with Novelis aluminium plant, and hence:

- Quantify the sustainable biomass potential for energy applications in Switzerland.
- Assess the obtainability of this resource and evaluate supply chain logistics.
- Model and simulate the biomass gasification system to be used in such application.
- Evaluate the operations on an integrated biomass gasification unit for producing synthetic natural gas to Novelis plant and cascading waste heat for district heating applications in the city of Sierre.
- Compare competing interests and deduce benefits of the proposed application in competition with other biomass uses.

Key project results indicate that exploitation of approximately one tenth of the sustainable biomass potential in nearby Cantons would suffice to meet the demands of the overall system during winter season. Energy consumption of the supply chain resembled in harvesting, drying, and transportation steps are calculated for different moisture content (MC) scenarios (natural vs. artificial drying). It was found that, energy consumed during biomass transportation varies minimally with MC, never exceeding 5% of the embodied energy in the biomass. Wood energy prices increase rapidly if transportation distances surpass a 90 km radius around Novelis plant. Finally, transportation costs alone could escalate from around 10 CHF/MWh_{wood} to over 30 CHF/MWh_{wood} for such large distances.

An energy conversion efficiency (based on LHV) of approximately 73% for syngas and 62% for SNG was estimated during the process modelling of biomass-gasification routes. In addition to the fuel production potential, waste heat availability was identified at ~18% for the SNG production route for which valorization opportunities are investigated. The exergy content of this waste stream can be exploited via cogeneration systems and district heating networks equipped with heat pumping systems. An important point to mention here is that direct heat integration of the gasification unit with the aluminium plant was found to be challenging due to the harsh composition of gasifier gaseous effluents and production rate requirements or practical limitations in the aluminium furnaces. Conversely, indirect heat integration between both the gasification and aluminium systems was found to exhibit multiple benefits.

Strategical benefits of using biomass for high temperature industrial applications are highlighted in the ability to achieve long term sustainable solutions that avoid reliance on imported fossil natural gas for such operations. In addition, the demonstrated strategy of cascading waste heat from the gasification units and aluminium furnaces to district heating systems at lower temperatures proved to be a suitable solution for meeting the energy demands of the different industrial and societal actors, while producing net negative CO_2 emissions.

The process integration study completed in this project revealed that biomass conversion routes can replace fossil natural gas in heavy industries, while different scenarios show varying energy and environmental performances. In particular, it was found that:

- The biomass energy conversion routes for SNG production demand the largest biomass (>720 kWh/t_{Al}) and electricity (100-300 kWh/t_{Al}) imports, but just to the advantage of replacing fossil natural gas.
- Carbon capture facilitates the separation of biogenic CO_2 emissions, which can be sequestered permanently, resulting in net negative CO_2 emissions (of up to -143 kg_{CO2}/tAl) compared to traditional scenarios of biomass conversion emitting more than +120 kg_{CO2}/t_{Al}.

- Systematic integration of waste heat recovery through the biomass conversion units and the aluminium furnace stacks using Rankine or transcritical CO_2 power systems can achieve up to 30% power self-generation.
- Case 4 (i.e. SNG + cogeneration + CO_2 CAD) presents the minimum energy consumption due to a more rational use of the biomass energy. This approach involves the integration to a steam network for combined heat and power production and anergy CO_2 district heating network that capitalizes on the low-grade waste. The total energy consumption of this configuration is 14% lower than the solution in which biomass is only used in a combustion boiler to supply heat.
- Direct biomass combustion (Case 7) holds the highest associated CO_2 emissions, due to the additional fossil natural gas consumption necessary to fuel the furnaces of Novelis Sierre plant.
- When power-to-gas technology and seasonal SNG/CO_2 storage is implemented, biomass input is drastically reduced (by 89%) as reported in Case 9 of this study. This approach aims to capitalize on renewable electricity available in the summer to boost SNG production, thus limiting import of the woody biomass to four colder months. The main challenges of this integrated route are the indirect emissions associated to the large electricity import.
- In Case 9, the installed power capacity of the electrolyzer was estimated at 1220 kWh_{ee}/t_{Al}, which in turn produces 933 kWh_{H2}/t_{Al} (HHV). A corresponding methanator capacity of 650 kWh_{SNG}/t_{Al} is required to convert the produced H_2 and captured biogenic CO_2 into SNG. The gasifier size for such system is sharply reduced to less than one third of other evaluated Cases 1-4 and 8. It is estimated at a maximum biomass input of 251 kWh_{DB}/t_{Al} during the operative months (less than 7 MW for a typical 27.8 t/h aluminium remelting plant).

Finally, an extended analysis presented in Annex, considering the integration of aluminium plant in an industrial cluster together with methanol and sustainable aviation fuels plants shows opportunities of industrial symbiosis for the processes decarbonization. Waste heat cascading combined with heat pumping solutions show a high degree of compatibility with future scenarios of decarbonization technologies and transition pathways.

Overall, the project reveals that biomass gasification holds significant potential for decarbonizing heavy industry applications. Expectedly, biomass gasification setups are footprint intensive and costlier than simpler biomass boilers. Moreover, the technology readiness level of some systems aggravates the risk perception, despite the efficiency and environmental benefits that more advanced technologies may have in the overall energy and industrial sector. However, an economic feasibility study based solely on present market conditions may be misleading, in view of the upcoming energy transition policies and anticipated cost-effective deployments of those advanced energy systems, which will help displacing fossil resources and, thus, increase industrial sustainability. In fact, new technological setups will be critical in scenarios of more stringent carbon taxations, as they can offset atmospheric emissions associated to the typical biomass energy use (e.g. direct biomass combustion), while helping to alleviate the environmental burden of the hard-to-abate heavy industries.

APPENDIX A0. PUBLICATIONS IN INTERNATIONAL CONFERENCES AND JOURNALS

The following publications in journals and conferences have been written during the time of the development of this report:

1) Florez-Orrego, D., Dardor, D., Germanier, R., Maréchal, F., A systemic study for enhanced waste heat recovery and renewable energy integration towards decarbonizing the aluminium industry. 36th Int'l Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS 2023, June 25th – 30th, Las Palmas de Gran Canaria, Spain.

2) Florez-Orrego, D., Dardor, D., Ribeiro Domingos, M., Germanier, R., Maréchal, F., Renewable energy integration and waste heat recovery for the production of sustainable jet fuel and decarbonization of industrial heating applications, AIChE 2023 Annual Meeting, November 5-10, 2023. Orlando (FL), United States.

3) Dardor, D., Florez-Orrego, D., Ribeiro Domingos, M., Germanier, R., MARECHAL F., Decarbonizing the production of primary aluminium using renewable resource, AIChE 2023 Annual Meeting, November 5-10, 2023. Orlando (FL), United States.

4) Ribeiro Domingos, M., Florez-Orrego, S., Teles, M., Maréchal, F., Alternative energy supply approach for industrial complexes and district heating networks based on biomass integrated gasification. 36th Int'l Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS 2023, June 25th – 30th, Las Palmas de Gran Canaria, Spain.

5) Florez-Orrego, D., Ribeiro Domingos, M., Maréchal, F., Techno-economic and environmental analysis of high temperature heat pumps integration into industrial processes. Sustainable Energy Technologies and Assessments, v. 60, 2023, 103560.

6) Andayesh, M., Florez-Orrego, D., Germanier, R., Gatti, M., Maréchal, F., Improved Waste Heat Management and Energy Integration in an Aluminium Annealing Continuous Furnace Using a Machine Learning Approach, Entropy MDPI, 2023, 25(11), 1486.

7) Florez-Orrego, D., Aimone, L., Dardor, D., Germanier, R., Maréchal, F., Comparative analysis of biomass utilization routes in industrial and district heating systems: integration of an aluminium industry and an urban agglomeration. 37th Int'l Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS 2024, June 30th – July 5th, Rhodes, Greece.

8) Florez-Orrego, D., Dardor, D., Aimone, L., Ribeiro Domingos, M., Germanier, R., Maréchal, F., Integration of renewable energy and reversible solid oxide cells towards decarbonizing the aluminium remelting production process. 37th Int'l Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS 2024, June 30th – July 5th, Rhodes, Greece.

9) Dardor, D., Florez-Orrego, D., Aimone, L., Germanier, R., Margni, M., Maréchal, F., Modelling The Effect of Future Uncertainty in Energy Prices on Decarbonization Pathways for Secondary Aluminium Production. 37th Int'l Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS 2024, June 30th – July 5th, Rhodes, Greece.

10) Florez-Orrego, D., Dardor, D., Ribeiro Domingos, M., Germanier, R., Maréchal, F., Renewable Energy Integration and Waste Heat Valorization in Aluminium Remelting Mills for the Co-Production of Kerosene and Methanol. 34th European Symposium on Computer Aided

Process Engineering / 15th Int'l Symposium on Process Systems Engineering (ESCAPE34/PSE24), June 2-6, 2024, Florence, Italy.

11) Dardor, D., Florez-Orrego, D., Ribeiro Domingos, M.E.G., Germanier, R., Margni, M., Maréchal, F., CO2 Capture and Management Strategies for Decarbonizing Secondary Aluminium Production. 34th European Symposium on Computer Aided Process Engineering ESCAPE34, June 2nd to 6th, 2024, Florence, Italy.

12) Florez-Orrego, D., Dardor D., Ribeiro-Domingos, M., Cortvriendt, L., Platteau C., Maréchal, F., A web-based decision support tool for the design and integration of industrial high-temperature heat pumps. 30th Symposium of the research program on heat pumps and refrigeration technologies of the Swiss Federal Office of Energy BFE-WP Tagung, Bern, Switzerland, June 26, 2024.

13) Florez-Orrego, D., Dardor D., Ribeiro-Domingos, M., Germanier, R., Marechal, F., Integration of renewable energy and reversible solid oxide cells towards decarbonizing the secondary aluminium production and urban systems. 2024 AIChE Annual Meeting - American Institute of Chemical Engineering, October 27th – 31st, 2024, San Diego, CA, USA.

14) Ribeiro-Domingos, M., Florez-Orrego, D., Maréchal, F., Systematic analysis on the energy transition pathways for sustainable natural gas production. 2024 AIChE Annual Meeting - American Institute of Chemical Engineering, October 27th – 31st, 2024, San Diego, CA, USA.

15) Aimone, L, Florez-Orrego, D., Dardor, D., Germanier R., Maréchal, F. Sustainable Biofuels Via Biomass Gasification Towards Fossil-Free Aluminium Production. 32nd European Biomass Conference & Exhibition - EUBCE 2024, June 24th - 27th, 2024, Marseille, France

APPENDIX A1. ECONOMIC EVALUATION OF THE SNG PRODUCTION ROUTE USING BIOMASS GASIFICATION

The economic evaluation of the biomass gasification system is a key step to fairly evaluate the feasibility of the SNG production. The operating costs and capital investments needed for the biomass conversion units are discussed in detail; however, the cost breakdown does not include auxiliary systems, such as the steam supply technologies.

A1.1 Capital expenditure estimation

The estimations of the capital costs required are conducted for a gasification plant with capacities of 10 and 20 MW_{wood}, respectively. Data and empirical correlations utilized are taken from chemical engineering manuals, academic literature, and technical reports from operating facilities.

Cost breakdowns are provided for the main units:

- Biomass storage and pre-treatment
- Gasification
- Syngas upgrading
- Methanation

Data from [54] and [45] are used to calculate the costs for biomass storage, feeding and pre-treatment (excl. drying) for 10-20 MW_{wood}. Similarities with the conventional biomass power plants help finding relevant literature data. However, expenses like site preparation may be site-specific. In addition, the construction of structures for biomass storage and handling includes various civil engineering works, whose Swiss costs might surpass reference costs from neighbouring European countries. It is worth mentioning that, since gasification is done at atmospheric pressure, the additional expenses for biomass lock hoppers required for pressurized gasification are avoided [55].

The cost of the drying unit considers a belt-conveyor dryer, for which correlations from [56] are used to compute the capital expenditure provided by manufacturers, such as Stela, Andritz, and Swiss Combi (Eq.A1).

$$I_{tot,dryer} = A_{dryer} \cdot \left[-3095 \ln\left(\frac{A_{dryer}}{480}\right) + 5838\right] \quad \text{(Eq.A1)}$$

where A_{dryer} is the cross-sectional area of a continuous working belt dryer (m^2). For the power capacity studied (10-20 MW_{wood}), the area A_{dryer} is estimated to be between 30 – 60 m^2, based on empirical correlations that take into account the dryer bed material height, residence time, and drying temperature [56, 57]. These results are summarized in Table A1.1

Table A1.1 Capital expenditure of biomass pre-treatment units for a 10-20 MW_{wood} gasifier.

Unit	**Capex**	
Biomass storage and pre-treatment	0.74-1.54	MCHF
Belt-conveyor dryer	0.45-0.77	MCHF

The total costs for gasification and pre-treatment units are calculated using scaling factors. The base cost, exponential factor and installation factor of each component are obtained from literature [58, 59] and the results are summarized in Table A1.2

Table A1.2 Capital expenditures and cost calculation factors used for a biomass gasification system with installed capacity of 10-20 MW_{wood}.

Unit	Capex (MCHF)	C_{base} (MCHF)	Base scale	Current Scale		Reference year	Exponential factor	Installation factor	Ref.
DFB-Gasifier	10-17	7.9	8	10-20	MW	2010	0.72	1	[58, 60]
Filtering	0.3-0.5	2	500	10-20	MW	2008	0.7	2.47	[58]
Water scrubber	2.9-4.7	2.5	9	2.7-5.4	m^3/s	2010	0.7	2.47	[58]
WGS-reactor	1.3-2	12.2	8819	60-120	kmol(CO+ H_2)/h	2002	0.65	1.81	[61]
Selexol CO_2 removal	1.5-2.4	63.3	9909	26-52	kmol CO2/h	2002	0.7	1	[61]

The additional costs to purchase the syngas and CO_2 compressors are determined using a logarithmic correlation, and then multiplied by material and installation factors, commonly employed to calculate capital costs of standard equipment in the chemical industry [62]. These costs are listed in Table A1.3

Table A1.3 Capital expenditures of gas compression systems for a gasification unit processing 10-20 MW_{wood}.

Unit	Capex	
Syngas Compressor	1.03 – 1.81	MCHF
CO_2 Compressor	0.40 – 0.76	MCHF

Lastly, the capital costs of a methanation plant are estimated. Specific cost for these plants ranges between 200-400 Eur/kW_{SNG} [63]. In this project, 300 Eur/kW_{SNG} is chosen based on the cost for the construction of a 5 MW_{SNG} SNG plant [64]. Following the example in [9], an additional contingency cost of 20% of the capital expenditure of the methanation and the syngas upgrading units is considered. This costs accounts for the relative novelty of these technologies, which may lead to an increased realization costs. In Table A1.4 the economic balance of the investment costs has been reported, while Table A1.5 reports the breakdown of the specific costs of the entire biomass-to-SNG production route, including subsections of gasification and methanation.

Table A1.4 Total investment costs for a biomass-to-SNG production section with a processing capacity of 10 – 20 MW_{wood}.

Unit:	**10 MW_{wood}**	**20 MW_{wood}**
	Values in MCHF	*Values in MCHF*
Biomass pre-treatment:		
Storage, grinding and handling equipment	0.74	1.54
Biomass dryer	0.45	0.77
Gasification Unit:		
DFB-reactor	10.07	16.59
Filtering	0.33	0.54
Water scrubber	2.90	4.71
Syngas Upgrading Unit:		
Syngas compressor	1.03	1.81
WGS-reactor	1.29	2.03
Selexol CO_2 removal	1.50	2.43
CO_2 compressor	0.40	0.76
Methanation Unit:	1.92	3.85
Contingency Cost	1.23	2.18
Total	21.88	37.46

Table A1.5 summarizes the specific total capital expenditures of the gasification, syngas purification and methanation system for SNG production (excluding steam network).

Table A1.5 Specific cost of a bio-SNG production system and its subunits.

Specific Cost	10 MW_{wood}	20 MW_{wood}	
$C_{gasifier+SNG\ production}$	2188	1860	CHF/kW_{wood}
$C_{gasifier}$	1450	1208	CHF/kW_{wood}
$C_{SNG\ production}$	1191	1052	CHF/kW_{SNG}

A1.2 Operational expenditure estimation

A simplified analysis of the operative costs of a biomass-to-SNG conversion unit is briefly discussed. It aims to estimate briefly the energy bill associated to SNG production, without considering any process integration with the gasifier, the aluminium plant or the city of Sierre. Therefore, these costs rely on the assumption that all the required electricity is purchased from the grid, and the excess heat is not commercialized in a district heating network. Raw feedstock is not necessarily the only expense that operators of a biomass gasifier face in practice. Costs of consumables used in the process, personnel, and required maintenance also constitute a significant portion of the operating costs of the system.

According to the initial analysis on wood availability in Switzerland, feedstock cost is ~0.06 CHF/kWh. The total demand for wood in the studied system may vary from 40 GWh/y for a 10 MW_{wood} gasifier operating only (4000 h/y) up to 175 GWh/y for a 20 MW_{wood} gasifier that produces year-round. Consequently, for a price of 0.06 CHF/kWh, the yearly feedstock cost can range from 2.5 MCHF/y to more than 10 MCHF/y, depending on the size and type of operation planned. The energy input required by the gasification system includes not only wood, but also electricity (6-7% of the chemical energy of wood). Considering an electricity price of 0.15 CHF/kWh, as per current tariffs from Novelis, the electricity costs represent a significant operating expense, ranging between 0.4 – 1.7 MCHF/year.

The main consumables costs explicitly considered in the operational expenditure (OPEX) estimation include the replacement costs for the material (olivine) in the bed reactor and wastewater treatment after the water scrubber. Consumption rates and prices of olivine are reported in [65]. The resulting total costs are relatively small compared to other expenses, possibly due to the reported low costs of olivine (150 CHF/t). In addition, a wet scrubber for particulate and tar removal represents an important cost. Cost of wastewater treatment is considered equivalent to the cost of fresh water from the grid at 3.5 CHF/m^3. Thus, for a specific water consumption of approximately 2.5 m^3/h per MW_{wood}, wet scrubber operational costs range between 0.35 – 1.5 MCHF/y. According to [66], wastewater treatment is a high operative costs. Solutions including an oil-based scrubber, as the OLGA process [67, 68], might reduce the operational costs, allowing a more efficient tar removal process with the opportunity of also of recycling the spent scrubbing fluid into the gasifier. Alternatively, researches [69] also focused on the purification and cleaning of wastewater treatment from water scrubbing using bio-char from gasification and pyrolysis of biomass, as active carbon, reducing the waste treatment cost.

Other expenses for component and material replacement are estimated as a percentage of the investment costs, considered as maintenance costs. These expenses include ash disposal, catalyst replacement, boiler chemicals, and generic maintenance of mechanical components. Maintenance costs are estimated to be 4% of the investment for the gasifier section. Yet, for the SNG production unit, this relative cost is increased to 5%, accounting for the expenses for solvent replacement for CO_2 removal. Lastly, labour costs are accounted for estimating the continuous operation of the gasifier, as it is assumed that one operator is consistently required, with an additional one needed for feedstock shipments reception. In total, six operators are expected to be employed to ensure the uninterrupted operation of the plant, with an annual salary of 80,000 CHF per operator. Table A1.6 shows a summary of the operating expenses for a biomass-to-SNG production route.

Table A6: Operation and maintenance (labour) costs for a biomass-to-SNG production unit for a gasifier capacity between 10 – 20 MW_{wood}.

	Operating and maintenance expenses (MCHF/y)	
Plant Capacity	10 MW_{wood}	20 MW_{wood}
Feedstock (c_{wood}=0.06 CHF/kWh)	4.8	9.6
Electricity import (c_{el}=0.15 CHF/kWh)	0.8	1.6
Wet scrubber make up water	0.7	1.4
Maintenance	0.9	1.6
Labour	0.5	0.5
Opex	**7.7**	**14.7**
Opex (without wood and electricity)	**2.1**	**3.5**

A1.3 Simplified sensitivity analysis of the cost of the energy resources on the total cost of a biomass-to-SNG production route

The break-even costs of SNG are estimated under the assumption that the gasifier operates for the majority of the year. In this simplified sensitivity cost analysis, the additional waste heat recovery from gasifier is not included; therefore, a higher and more conservative total operating cost is expected. From Table A1.7, it can be seen that a final cost of SNG production via biomass gasification route is around 3 times the cost of wood in case of low-electricity prices (0 – 150 CHF/MWh). In fact, for the energy prices assumed for wood (40- 60 CHF/MWh) and electricity (150 CHF/MWh), the price of SNG ranges between 140 – 170 CHF per MWh. However, it must be born in mind that using the waste heat for domestic heating purposes adds an additional revenue of 2.63M CHF/y, assuming 2cts per kWh. Further sensitivity analyses are being done using considering other uncertainty parameters, such as market costs, energy prices, maintenance expenses, and yearly operative time, as well as expected lifespan for the plant, but those results are out of the scope of this report.

Table A1.7: Conservative prices of (in CHF/MWh)* of SNG production unit for a gasifier capacity of 10 – 20 MW_{wood}.

		Price of wood [CHF/MWh]			
		40	**60**	**80**	**100**
Price of Electricity [CHF/MWh]	**0**	124	156	188	220
	150	140	172	204	236
	300	157	189	221	253
	600	189	221	253	285

* Interest rate of 6% and lifetime of 40 years are assumed, an annual operating time of 8000 hours is assumed in this simplified sensitivity analysis section.

APPENDIX A2. COMPARISON OF NON-INTEGRATED WOOD UTILIZATION SYSTEMS

A simplified assessment of the standalone efficiency of the biomass energy conversion systems is discussed in this section. The analysis does not take into account integration with the aluminium production plant, or the total heating demands of the city of Sierre, but rather it considers a limited amount of biomass (10 MW) that can be utilized in competing applications. In the first scenario, the production of SNG through gasification is prioritized, while in the next the generation of electricity through combined heat and power systems is preferred. In a final one, the production of heat for district heating is favoured. Figure A2.1 below summarizes these potential routes.

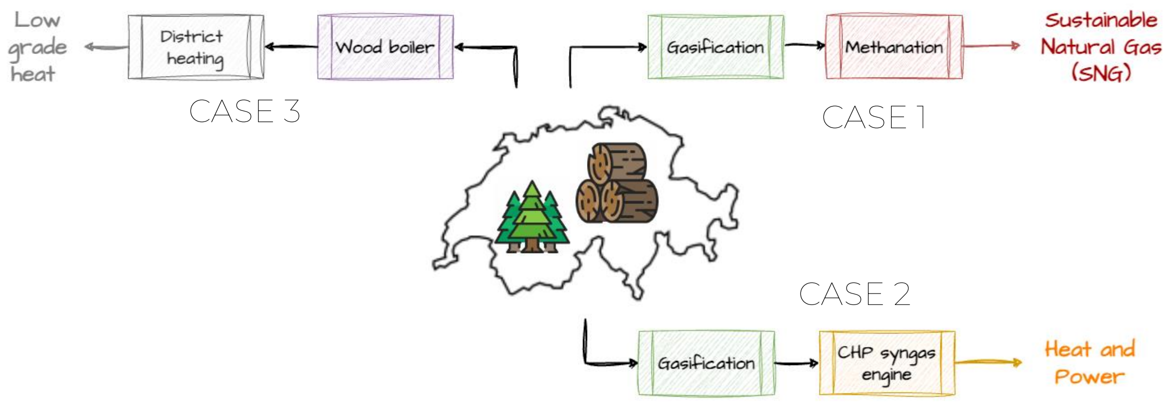


Figure A2.1: Competing applications for biomass utilization.

For each scenario, the total amount of fuel (SNG), domestic heat and electricity that can be produced is firstly calculated. As a result, the highest amount of SNG that can be produced is 6.2 MW for the Case 1 (Figure A2.1). Similarly, the highest amount of heat and power per 10MW of wood that can be produced is 8.5 MW_{th} for the Case 3 and 2.33 MW_{ee} for Case 2, respectively. As each scenario requires equal amounts of utilities (fuel, heat and power), if any of them are not provided by the biomass energy, an additional amount of fossil natural gas or electricity is imported from the Swiss grid. Heat demand can be in any case balanced by groundwater heat pumps with an assumed coefficient of performance of 3.

Tables A2.1 Wood transformation routes energy flows.

			Natural gas	Domestic heating	Electricity
Scenario	**Biomass conversion technology**		(MW)		
1	Gasification + SNG production	Produced	**6.2**	1.7	0
		Imported	0	6.8	2.9
2	Gasification + CHP cogeneration in a syngas engine	Produced	0	4.5	**2.9**
		Imported	6.2	3.9	0
3	Wood boiler + district heating	Produced	0	**8.5**	0
		Imported		0	2.9

The combination of thermodynamic, environmental, and economic metrics can help in the decision-making process to optimize the utilization of wood for energy, shedding light on both the potential benefits and drawbacks of implementing a SNG production process at an industrial scale. The concept of exergy, derived from a combination of the First and Second Laws of thermodynamics, is used to assess the quality of the energy conversion processes.

In this simplified analysis, the exergy and energy efficiency are calculated based only on a control volume that includes biomass conversion technologies (e.g. gasification, combustion, etc.). Tables A2.2 shows a comparison between various biomass utilization routes, in terms of energy and exergy efficiency, as well as environmental and economic performances. The use of wood combustion only for district heating misleadingly displays the highest efficiency (~ 85%). However, taking into account that the quality of the chemical energy in the biomass is degraded to low grade waste heat (40 – 65°C), the exergy efficiency of this configuration is actually the lowest (5%). From an environmental point of view, prioritizing the transformation of woody resources into SNG reduces the CO_2 footprint by 90%, compared to the traditional biomass conversion solutions. The opex of the energy system is similar for all options, while the capex of the SNG production case is expectedly the highest, followed by CHP and simpler wood boilers. In view of this, the utilization of only a capex criterion for selecting the best biomass energy conversion technology typically ignores any benefits in terms of energy and environmental impact, in scenarios of biomass scarcity or stricter environmental regulations.

Table A2.2 Simplified comparison of the wood conversion routes: thermodynamic, environmental and economic indicators.

	Energy efficiency	**Exergy efficiency**	**Scope 1 and 2 emissions**	**Opex**	**Capex**
1	79%	57%	198	5752	1444
2	75%	29%	1578	5046	1122
3	85%	5%	1610	5888	462

APPENDIX A3. EXTENDED STUDY: BIOMASS GASIFICATION FOR COMBINED ALUMINIUM, POWER, HEAT, CHEMICALS AND SUSTAINABLE AVIATION FUEL PRODUCTION

The extended analysis shown in this Annex aims to assess the integration of a biomass-to-SNG route to supply heat to the Novelis aluminium plant, while exploring other synergies between the chemicals and the metallurgy industry, in order to decarbonize hard to abate industrial processes using renewable energy resources. Like the aluminium industry, the aviation transportation sector heavily depends on non-renewable energy resources, which hinders its energy security of supply [70]. Methanol is an intermediate molecule for other chemicals production, like olefins, amines, acetic acid, dimethyl ether and formaldehyde; but it can be also used as an alternative to SNG for long term storage applications due to its liquid form, or even as shipment fuel. Thus, more efforts should be done to defossilize these critical sectors on which others sectors rely, including cargo, food packaging, automotive industry, polymers and chemicals synthesis.

The production of sustainable aviation fuel (SAF) is carried out via catalytic Fischer-Tropsch (FT) process [28]. In this process the syngas production via biomass gasification is purified to achieve a $CO:H_2$ ratio of 1:2 and compressed up to 41 bar. The low temperature Fischer-Tropsch reactor (200-240°C) filled with iron catalyst ensures high selectivity for paraffin and heavy linear waxes. A polymerization reaction yields a large variety of products with different carbon chain lengths, such as n-olefins, n-paraffins, oxygenated products, and branched chain hydrocarbons [70]. The selectivity of the products depends on several reaction parameters, e.g. temperature, pressure, catalyst and reactor type. The probability of chain growth via addition of a monomer to the initiator is given by a chain growth probability (α) defined by an Anderson-Schulz-Flory (ASF) distribution [28]. A direct product is diesel-cut, whereas hydrocracking of the waxes yields further kerosene- (C_9-C_{16}) and diesel-cut (C_{15}-C_{20}) mixtures. The hydrocarbons in the naphtha range (C_5-C_{12}) are rather straight chain and need further treatment to increase their branching and achieve high-octane rating.

On the other hand, for producing methanol, the purified syngas is compressed to 90 bar and is heated up by the reactor effluent in a feed-effluent heat-exchanger, before it is fed to a methanol synthesis loop. The methanol synthesis occurs in an isothermal reactor operating at 90 bar and 210 °C [70]. The reactor outlet stream is a gaseous mixture of methanol, water and unconverted reactants. This mixture is cooled and flashed twice, first to 30 °C and 45 bar, and then to 3.5 bar, in order to separate the condensable products and the non-condensable reactants. The latter fractions are recycled in order to achieve higher conversions. The condensed stream continues to a distillation column at atmospheric pressure, in which methanol is produced (99% wt.). To avoid the built up of inerts, a fraction of the non-condensable stream is continuously purged [70]. Selected results are discussed for a scenario of energy integration between:

(i) A secondary aluminium processing plant producing 250 kt/y,

(ii) A FT liquids production plant producing 4.08 kt_{diesel}/y (or 0.01675 t_{diesel}/t_{Al}); 9.40 $kt_{naphtha}/y$ (or 0.0386 $t_{naphtha}/t_{Al}$), as well as 17.57 $kt_{kerosene}/y$ (or 0.07215 $t_{kerosene}/t_{Al}$ or 863 $kWh_{kerosene}/t_{Al}$),

(iii) A methanol plant producing 26.35 kt/y (or 0.1082 $t_{methanol}/t_{Al}$ or 611 $kWh_{methanol}/t_{Al}$).

For these production rates, the total biomass energy consumption is 681.77 GWh/y (or 2799 $kWh_{biomass}/t_{Al}$), whereas the total import of the electricity reaches 1096.52 GWh/y (or 4500 $kWh_{electricity}/t_{Al}$). The diesel consumption in the aluminium plant is 0.23 kt/y (or 0.00094 t_{diesel}/t_{Al}). It is worthy to notice that the self-power generation using a sCO_2 cycle for waste heat recovery through the aluminium remelting and the chemical plants is 167.39 GWh/y (or 687 $kWh_{electricity}/t_{Al}$), which represents around 15% of the total power import. For the sake of comparison, the power consumption of the aluminium plant is 68.07 GWh/y (or 279 $kWh_{electricity}/t_{Al}$) [70]. Notably, the power demand of the electrolyzer is dominant (1080.76 GWh/y or 4434 $kWh_{electricity}/t_{Al}$, max. 170 MW), which is explained by the intensive production of hydrogen and the CO_2 conversion to value-added products in a power-to-gas approach. Hydrogen and oxygen production in the electrolyzer amount 19.65 kt/y (or 0.0807 $t_{hydrogen}/t_{Al}$) and 157.20 kt/y (or 0.6455 t_{oxygen}/t_{Al}), respectively [70].

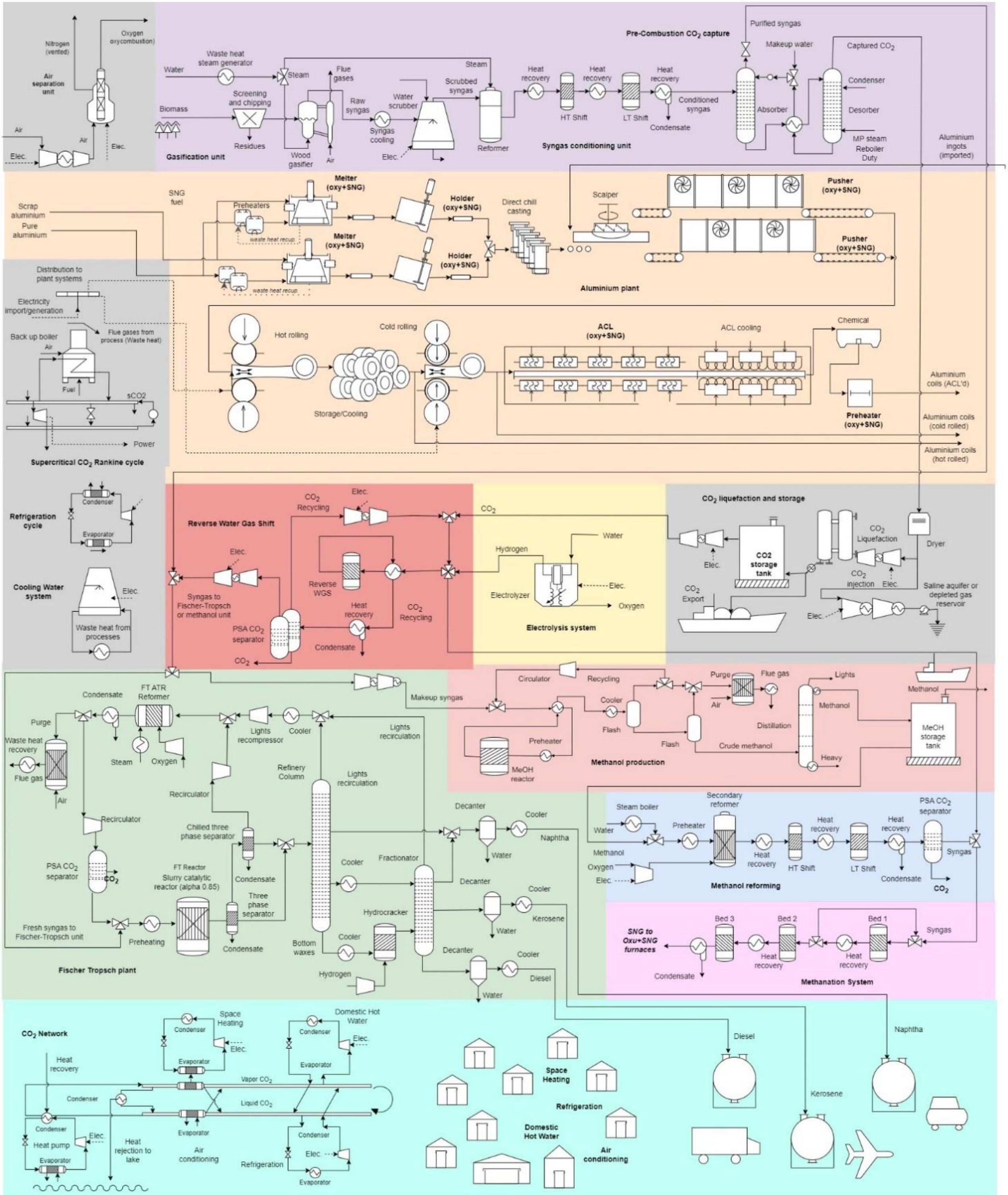


Figure A3.1. Flowsheet of the integrated aluminium, sustainable aviation fuels and methanol production industrial cluster, including power-to-gas-to-power system, a seasonal energy storage system and a district heating network [70].

Oxygen production from an auxiliary air separation unit (24.22 kt/y or 0.1008 t_{oxygen}/t_{Al}) is necessary, especially during winter months, in order to balance the oxygen (and hydrogen) requirements. In fact, the venting of surplus oxygen (77.40 kt/y or 0.3178 t_{oxygen}/t_{Al}) and nitrogen (99.55 kt/y or 0.4088 $t_{nitrogen}/t_{Al}$) is estimated, i.e. no enabling oxygen storage, in spite of the intensive oxygen utilization in the oxycombustion furnaces. The CO_2 processed in the reverse water gas shift is estimated as 95.15 kt/y (or 0.3907 t_{CO2}/t_{Al}). Meanwhile, the methanator processes 26.53 kt/y of CO_2 (or 0.1089 t_{CO2}/t_{Al}) and 4.82 kt/y of hydrogen (or 0.0198 $t_{hydrogen}/t_{Al}$) to yield 134.01 GWh/y (or 550 kWh_{SNG}/t_{Al}) of synthetic natural gas, which along with 65.37 GWh/y (or 268 kWh_{SNG}/t_{Al}) of synthetic natural gas produced by a methanol reforming unit, supplies the fuel consumption to the oxycombustion furnaces of the aluminium plant. It is worthy to notice that no CO_2 injection or mineralization is necessary, as all the captured and separated CO_2 is processed by the overall system, and stored to produce value-added products. This is done only when the cost of electricity is more favorable during the summer period [70]. A complementary behaviour of loading and offloading is observed between the methanol and the CO_2 storage tanks (see Fig. A3.2).

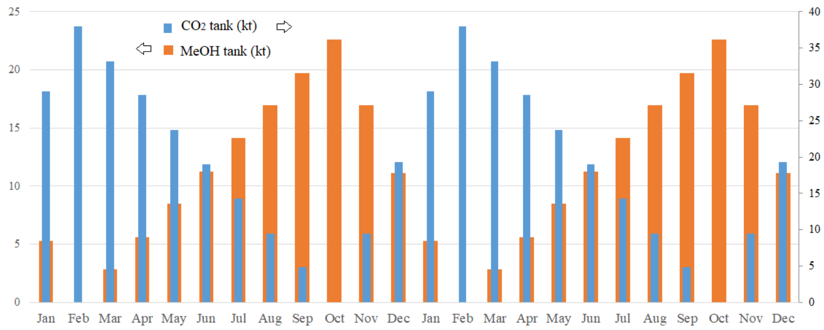


Figure A3.2. Annual evolution of the storage levels of CO_2 and methanol tanks [70].

Interestingly, the syngas production for chemicals and fuels production is evenly divided by the reverse water gas shift and the gasification systems, which are respectively 66.40 kt/y (or 0.2727 t_{syngas}/t_{Al}) and 64.06 kt/y (or 0.2630 t_{syngas}/t_{Al}) of syngas production, totalizing 130.46 kt/y (or 0.5357 t_{syngas}/t_{Al}) of syngas. As for the biogenic CO_2 emissions at the gasifier stack (75.12 kt/y or 0.3085 t_{CO2}/t_{Al}), they represent the dominant source of emissions of the integrated energy systems, followed by the also biogenic CO_2 emissions from the offgas flare of the Fischer-Tropsch unit (13.41 kt/y or 0.0551 t_{CO2}/t_{Al}) and the CO_2 emissions from the purge gas flare system in the methanol production unit (3.65 kt/y or 0.0149 t_{CO2}/t_{Al}). The total environmental emissions based on the direct and indirect CO_2 emissions of the integrated system amount 177.50 kt/y (or 0.7288 t_{CO2}/t_{Al}).

The indirect fossil CO_2 emissions, which arise from the supply chains of the biomass and electricity imports, are estimated as 9.57 and 68.67 kt/y (or 0.0393 t_{CO2}/t_{Al} and 0.282 t_{CO2}/t_{Al}), respectively. In other words, due to the intensive electrification strategy, and in view of the emissions intensity of the electricity consumed, a relatively high share of fossil emissions (44% of 177.50 kt/y, or 0.2915 t_{CO2}/t_{Al}) could be expected. Therefore, the indirect emissions still remain the main challenge in the power-to-gas energy systems. However, it must be also noted that they are still much lower than when operating the chemical plants based on fossil natural gas on a standalone basis. This fact demonstrates the interrelation between the energy systems and the industrial sectors, and the need to orchestrate a coordinated decarbonization strategy for all the renewable energy conversion routes to actually achieve sustainable net zero targets. In this way, as long as that the energy inputs are derived from renewable energy resources, the fossil fuel dependency and emissions could be virtually avoided [70].

APPENDIX A4. SURVEYS WITH BIOMASS SECTOR SPECIALISTS IN VALAIS

The Net Zero Lab team conducted some surveys in 2023 with practitioners and other actors involved with the biomass value chain in Valais in order to gather more information than that reported by WSL, including:

- Olivier Bourdin: Forest guard, Direction of the Triage Forestier du Cône de Thyon,
- Florian Rong: Independent engineer, Manager Ecovalbois
- Prof. Stéphane Genoud, Noemi Imboden, HES-SO Valais Energy Management Lab.

Figure A4.1. Ecovalbois biomass collection, pre-treatment, and storage facilities. Photos taken during the visit to Ecovalbois.

The key highlights from the discussion with Mr. Olivier Bourdin include internal insights to the situation of biomass extraction and utilization in the Canton of Valais:

1- Biomass is under-utilized in Valais and currently some wood just rots in the forest after being cut.
2- Soleil Vert is a project aiming to recover non-problematic waste wood and wood from landscape maintenance.
3- There is an untapped potential of lower quality biomass (i.e. with higher moisture content and low grain size) that should be considered, such as needles (spikes) that are present in abundance at the truck port.
4- The main obstacle to utilization of more biomass is cost of production and technical limitations. Currently, subsidies enable utilization of 120,000 m^3 of wood in Valais. An increase in market price should drive an increase in exploitable potential after the utilization of protection forest subsidies and residual waste biomass. If the efficiency of harvesting techniques is enhanced, up to 20% of the branches could be also recovered, thus increasing the utilization amount.
5- In contrast to the Swiss plateau, wood can only be harvested between April and November in the Canton of Valais.

6- High quality wood (e.g. *plaquette de bois*) is almost fully exploited in Valais (at least those harvested thanks to national subsidies). Thus, some margins of improvement remain available only for lower quality biomass as aforementioned in points 1 and 3.
7- Logistics (i.e. transportation and drying) consume 5-6% of the energy content of the biomass (based on lower heating value).
8- Wood price fed to boiler is around 6 franc cents per kWh, but other factor can influence this price, at it has been seen during the energy contingency of 2022-2023.

The outcomes of the site visit to Ecovalbois and the discussion with Mr. Florian Rong can be summarized:

2- Ecovalbois was founded since 2007 with the aim of creating a network between biomass producers and consumers to eventually achieve the limits of biomass potential in Switzerland.
3- Currently only 30% of wood utilization goes to energy applications in Valais.
4- WSL woody biomass potential is a conservative estimate, in fact the real potential is somewhere between the sustainable and the additional sustainable potential limits, rather than only the sustainable one.
5- Hardwoods (feuillus) are starting to take over from softwoods (réesineux). As for hardwoods, there is less potential for construction wood, but more for energy wood as it can be exploited earlier in its lifetime.
6- Industrial scale biomass utilization installations allow for higher efficiency of 90%, compared to small local applications (about 60% efficiency).
7- Increased price of biomass drives an increased financially exploitable potential in Valais and other parts of Switzerland.
8- Costs of up to 8 ct/kWh are reported after previously stable values of 5.2 – 5.6 ct/kWh, which indicates increasing market prices.

Similar discussions were held with Prof. Stéphane Genoud, who answered to few questions presented by the Net Zero Lab members during a meeting and are summarized as follows:

Question 1. What is your reaction on the WSL data?

« Concerning the data from the WSL, we had several meetings with the association "Forêt Valais" and the canton of Valais regarding the availability of energy wood and the feedback we received was that the data available from the WSL is not completely accurate. This is because the growth rates and, thus, the possible harvest data in Valais are different from those in other regions of Switzerland. This is especially true because we are at a higher altitude and the forests in the region are quite steep. In addition, about 90% of the forest in the Valais is protective forest, which protects the local population from avalanches and rock falls. In order for the State of Valais to have more accurate data, the LiDAR data produced by the Swiss Confederation will be purchased by the cantonal government and studied. Subsequently, the canton will carry out a study of the energy wood potential at the cantonal level. This is expected to be completed by the end of the year (n.b. 2023)»

Question 2. From your point of view, what is the major application for forest wood in Switzerland? Can you provide percentages for the competing applications?

« In Switzerland, forestry statistics are compiled every year, in which the use of wood is shown in statistics under the following Link. It shows that in 2021 about 40% of the wood harvested in Switzerland was used as energy wood. »

Question 3. What is currently and what should be the major energy utilization route for wood consumption? Combustion for heating? Gasification? Others? Please provide examples and percentages if known.

« Until today, the majority of wood is used for combustion for heating. More information about the uses of wood is found in the "Annuaire La forêt et le bois 2022" . On pages 75 and 76 uses of Swiss wood and on the following pages (77-82) the energy uses of wood. The complete wood energy statistic are found under the following Link »

Question 4. How do you define the ecological restrictions on utilizing your biomass resources? And how do you prioritize your market (end users)?

« According to the national legal basis, only as much wood can be removed from the forest each year as it will grow back, in order to ensure biodiversity and post-harvest development. The second basis is the fact that the forest area cannot decrease (see Guide de la forêt Valaisanne). In the first analyses that we made, we assumed that the energy wood would be made available or sold to the local population. This is because about 90% of the forests in Valais belong to the Burgergemeinden. The Burgergemeinden is a non-profit organisation that manages the property of the citizens. They therefore act in the best interests of the population. It is also the Burgergemeinden that have joined forces and founded forestry companies to manage the forests. In our project, we have set ourselves the goal of managing the forest as a common good, based on the theory of Dr. Prof. Elinor Ostrom. With this in mind, the forest should serve as a livelihood for its owners and not be sold for profit. However, I have to admit that a discussion might be needed to define which is the prioritised use of the forest, whether it makes more sense to offer the wood to the local population, whose conversion efficiency might be lower, than to industrial partners, who could use more energy or save more CO_2 with the same amount of biomass. »

Question 5. Do you think that in Valais or Switzerland, there would be a supplier able to supply industrial partners? And if so, which could be the maximum continuous supply based on your experience/studies?

« The problem with current planning is the lack of coordination and availability of information. Even though there is an energy strategy at the cantonal level that sets out the broad guidelines for the energy supply of the future in Valais, there is a lack of concrete local planning and application regulations. In the first studies we carried out, no municipality had enough wood energy potential to produce the share of wood energy that is currently produced on the communal territory by non-renewable heating systems. The municipalities we studied were Zermatt, Annivier, Riddes, Chamoson, Leytron, Saillon and Saxon. Actually, these are all municipalities with a large forest area and a rather small number of inhabitants. In addition, the demand for energy wood is strong today. Many projects are planned with sawn wood heating, without the availability of local energy wood having been clarified beforehand. We have been in contact with an engineer who has studied the planned projects in the field of district heating with wood and the availability of wood, and he has come to the conclusion that there is not enough local wood to satisfy the demand. In order for the question of maximum continuous supply to be defined, the canton's study of the available energy wood potential must be completed. As also mentioned during our meeting, "Forêt Valais" assumes that a large part of the local forests will not survive the climate change (extremely dry and hot summers). Their strategy is therefore to remove more trees from the forest in the coming years. This is so that the value of the forest can be exploited and, at the same time, new tree species can be planted that are suited to the new climate. Forêt Valais therefore expects that the supply of energy wood will increase in the coming years and that wood will eventually be available for industrial use. It should also be noted that, according to an estimate by the canton, about 3.5 times less wood is currently being removed from the forest each year than is growing back. After consultation with forestry operations,

they do not agree to take wood out of the forest for purely energy wood purposes. If, however, we manage to strengthen the value chain, build more with wood and also promote industrial wood, more waste wood will inevitably be produced at the same time, which can be used as energy wood. »

Question 6. To validate national biomass potential data, do you have access to reliable information of used vs. total potential biomass in the Valais besides of WSL data?

« As mentioned above, the canton of Valais is currently in the process of obtaining LiDAR data and will analyse it. We also have access to the "Système d'Information Forestier du Valais". This shows the logging and forest stand planning for each forest district. In addition, the logging carried out in the last few years and the forest area treated can be seen. »

APPENDIX A5. HYPOTHETICAL DIRECT HEAT INTEGRATION OF THE ANNEALING CONTINUOUS LINE (ACL) AND THE BIOMASS GASIFIER (NO SNG PRODUCTION)

A simplified analysis aimed to assess the feasibility of the direct heat integration between the biomass gasifier effluents and the aluminium in the annealing continuous line (ACL) at Novelis rolling plant. This preliminary analysis did not incorporate the downstream SNG production section. The results are graphically shown in Figure A5.1, including not only the aluminium needs, but also the energy needed to compensates the wall losses and the hot gas escaping from the ACL furnace. The total heating load of the ACL is around 2000 kW, which closely matches the waste heat available at high temperature (500 °C) from the wood gasifier effluents (20 MW_{wood}). The integrated composite curve demonstrates the theoretical feasibility of heat exchange between the two processes, but it does not highlight the impact of the harsh compositions of the syngas and flue gas produced in the gasifier, which could compromise the quality of the finished aluminium products. In this regard, an intermediate stream could be necessary to exchange heat between the aluminium and gasifier effluents, which increases the need for heat transfer equipment and the space budget near the ACL furnace. Thus, in view of the possibility of electrifying this furnace, further research into the integration between the ACL and the gasifier have not been further pursued.

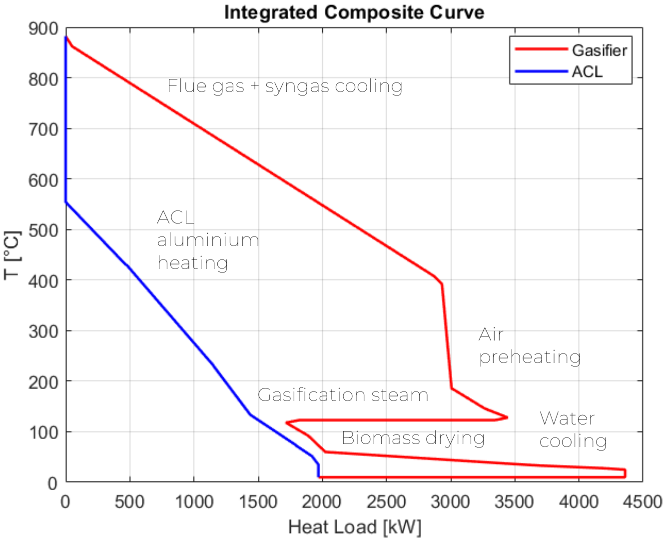


Figure A5.1. Integrated composite curve showing the hypothetical potential for the direct heat integration between the aluminium heating furnace (ACL) and the biomass gasifier effluents.

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