Process analysis of a biomass-based quad-generation plant for combined power, heat, cooling, and synthetic natural gas production

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Abstract:

A new concept for upgrading distributed co-generation plants to quad-generation plants, which combine the production of power, heating, cooling and synthetic natural gas (SNG), is designed and analyzed. Five cases with SNG production ranging from 0 to 100 % of total energy outputs are designed to simulate different modes of operation. The quad-generation system is simulated using ASPEN PLUS and described by simulating different portions of the system. This paper also describes the new process, which is of particular interest for improving the total first law efficiency. With this system, it is possible to increase the efficiency of natural resource utilization, minimize the environmental impact in distributed generation, and, by providing flexible operation, better support the integration of intermittent renewables such as wind power. Straw is used as a biomass feedstock for this simulation. The net energy efficiency is used to evaluate the performance of the quad-generation system. The results show that the most efficient case of the proposed system is providing 89.8 % net energy efficiency, which is almost 7.6 % higher than the lowest efficient case. Based on the flowsheet simulation, this energy assessment compares the proposed quad-generation system to the existing district heating system.

Key words: Quad-generation, Process integration, Straw, SNG.

1. Introduction

The increasing demand for energy, environmental concerns, and trends toward the deregulation of energy markets have become integral parts of energy policy planning. Flow-based energy resources are largely incompatible with the current energy infrastructure, and a new and more complex structure is required to produce a more sustainable energy system [1]. The development of energy-efficient production technologies has made cogeneration and tri-generation possible [2, 3] and now, the development trend is moving towards quad-generation and poly-generation. Meeting the future demand for power, heat, cooling, and bio-fuels with highly limited and fluctuating resources will require carefully planned allocation of the available renewable resources and a highly flexible system. All of these aspects have added new dimensions to energy planning. One of the renewable resources that could fulfill all of these demands is biomass, and one of the most efficient ways of utilizing this biomass is gasification [4, 5]. Thus, this study proposes and studies a novel hybrid configuration for a biomass-based quad-generation system. It shows how the plant owners can utilize their total capacity by producing different fuels according to the local demands.

In Denmark, there are a substantial number of biomass-fired district heating plants, and approximately 10 straw- or wood-chip-fired decentralized combine heat and power (CHP) are also in operation. The rest of the decentralized CHP plants are fuelled by natural gas. One in three of the decentralised DH plants and one in seven of the decentralised CHP plants use environmentally friendly biomass fuels such as straw, wood chips, wood pellets, and wood waste). But the majority of rest of the plants - use natural gas as a fuel [6]. From this starting point, a scenario framework has been suggested in which the Danish system is converted to 100 percent renewable energy sources (RES) by the year 2060, including reductions in space heating demands by 75 percent [7]. The European Commission has also developed political strategies to increase the share of renewable and sustainable energy in fulfilling the overall energy demand [8, 9].

Biomass conversion can be divided into two main pathways: thermochemical conversion and biochemical conversion [10].The main thermochemical pathway for dry biomasses can be divided into combustion, gasification and pyrolysis [11]. Gasification converts the biomass into a syngas that can subsequently be used to generate heat and power or converted into fuels or other chemicals [12]. In this study, the existing methodology is replaced by gasification as it is one of the most efficient conversion methods.

The most stable state-of-the-art gasification technologies combined with the possibilities of cogeneration through the gasification of biomass have been described and compared in a Danish context [1], and it has been shown that the thermal gasification of biomass is both highly flexible and efficient. There are a number of scientific publications that address some novel concepts for polygeneration system design and energy analysis using different input fuels [13, 14]. These papers found that system integration with gasification technology made a significant contribution to the improvement of performance. The concepts of polygeneration and energy integration have been described using various examples of systems [15-17], and some papers have published the mathematical modeling and simulation of polygeneration energy systems [18-22]; however, these papers focus on the evaluation of new plants and technologies concerning the configuration design of the processes. With the aim of achieving higher efficiency and lower emissions, innovations in both power generation technologies and process integration strategies were taken into account in the development of a fully integrated plant [23-26]. The high efficiency of small-scale biomass gasification quad-generation based on gas engines provides an opportunity for converting natural gas fired heating plants into efficient quad-generation plants that have not been used previously. Natural gas-fuelled gas engine quad-generation plants can either be converted into pure biomass-based plants or dual fuel plants, operating on producer gas, natural gas or mixtures of both. The main advantage of the conversion of such plants is that the gas engine is already installed, and this is normally a major part of the total investment. For high chemical conversion and effective energy utilization, a new biomass-based quad-generation system using existing gas engines and an additional synthesis unit for power, heat, cooling and SNG production is proposed in this paper.

Research into large-scale investment planning to convert existing plants to quad-generation energy systems is limited, albeit clearly crucial for strategic policy-making in regions and countries. This paper includes different scenarios according to the fuel demands of the specific plants and attempts to provide an overview of possible technical outcomes of a new green field quad-generation system regarding fuel production efficiency. It also endeavors to select the best case among the possible alternatives, in accordance with explicit technical objectives, i.e., efficiency.

2. Scope of this work

The Brovst district heating plant (DHP) is one of the district heating plants in the Jammerbugt municipality in Northern Denmark. Fig. 1 shows the heat production of the Brovst DHP. Scenario-1 represents the existing capacity of the Brovst DHP and assumed that is constant. The distance between the heat production curve and scenario 1 line embodies the free capacity. In the summer, especially from June to August, heat production is lower than in the rest of the year as it has less heat demand. During this period, it is necessary to shut down heat production from the engine. The motivation of this work is to utilize this free capacity between the plant capacity and the actual production by upgrading the existing system to quad-generation. It will also be possible to scale up the production like scenario 2 in fig. 1. Scenario 2 line represents the extended capacity for the quad-generation. Scenario 2 includes power, heat, cooling, and fuel demand and also constant energy demand. Feedstock selects 100 ton of biomass per day according to satiate the energy demand which represents in scenario 2 (own calculation) from fig. 1. The district heating requirements are based on historical requirements from an existing Brovst DHP, while the district cooling requirements are loosely estimated based on what could be the space cooling requirements of the area's commercial buildings. By installing a quad-generation system, the plant can satisfy public demand for heat while also producing power, cooling and SNG according to the demand and the market value of each. The use of fossil fuels is also associated with many concerns, among which are the security of the supply and the resulting air pollution. One of the ways to reduce the transportation sector's dependency on fossil fuels is to use biofuels from quad-generation plants. In this region, a large amount of power is produced by wind farms, but the output is variable according to the availability of wind. In cases of excess power production from wind, the excess can be utilized to produce H_2 for CH_4 synthesis. Therefore, a quad-generation power plant can be used in conjunction with wind energy because it has flexible output.

3. Process description

3.1 Description of existing plant:

The Brovst DHP uses natural gas for the production of heat and power. Heat demand is approximately 37,200 MWh/year. The system inside the dotted line in Fig.2 represents the existing plant. Presently, it has two natural gas generator sets with an output of 3.1 MW of power and 4.1 MW of heat together, with the power being sold to the national grid. It also has two condensing hot water boilers with a total of 8.15 MW of heat production. A 1600 m^3 storage tank has also been installed in this plant.

3.2 Description of proposed quad-generation plant:

A quad-generation system is proposed, as described by the flowsheet in Fig. 2. The process is described by the following steps:

1. The biomass is gasified in the presence of air.

2. The syngas leaving the gasifier will be cooled and cleaned by a gas cleanup unit. The particulate matter is removed from the raw syngas exiting the gasifier using a cyclone collector and a candle filter system.
3. One of the streams from the syngas cleanup unit will be sent to the engine for power and heat production, while a compression heat pump is introduced. It is a flexible compressor-driven unit able to produce both cooling and heating.
4. The synthesis gas can contain a considerable amount of methane and other light hydrocarbons, representing a significant part of the heating value of the gas. Therefore, another stream from the gas clean-up section enters the CH_4 synthesis section to be converted to CO and H_2 driven by the addition of steam over a catalyst at high temperatures. Subsequently, it maintains a proper H_2:CO ratio for methane synthesis. In the water-gas shift reaction, CO and H_2O are converted to CO_2 and H_2.
5. In the methanation reactor, CO and H_2 are converted to CH_4 and H_2O in a fixed-bed catalytic reactor. It reqires H_2 from external sourse. In this system H_2 is produced by electrolysis process. Because methanation is a highly exothermic reaction, the increase in temperature is controlled by recycling the product gas or using a series of reactors. After gas upgrading, SNG is ready for applications.

As the heat demand varies during the year, there is a need for different case studies for the best utilization of total capacity. Therefore, the above system is designed for five cases based on output ratios. And also this system is flexible to switch one case to other case according to demand in different seasons.

- SNG-0: In this case, natural gas is replaced by bio-syngas and the gasification unit, with 100 % of the bio-syngas is used in the combined cycle to generate power, heat and cooling and no bio-syngas is used for SNG production. .

- QUAD-75: In this scenario, 75 % of the bio-syngas is converted to generate power, heat and cooling and 25 % of the syngas is converted to H_2-rich gas is used in methane synthesis for SNG production.
- QUAD-50: In this scenario, 50 % of the bio-syngas is used to generate power, heat and cooling, and the other 50 % of the syngas is converted to H_2-rich gas to be used in methane synthesis for SNG production.
- QUAD-25: In this case, 25 % of the bio-syngas is used for power, heat and cooling generation and 75 % of the syngas is converted to H_2-rich gas to be used in methane synthesis for SNG production.
- SNG-100: All of the syngas is used in methane synthesis for SNG production.

4. Model simulation

The ASPEN PLUS process simulation software is used to model the systems evaluated in this paper. It offers a variety of thermodynamic property methods for process simulations. Some investigations conducted on biomass gasification [20, 27, 28] have shown that ASPEN PLUS is capable of predicting performance under diverse operating conditions. The Peng Robinson equation of state with the Boston-Mathias alpha function (PR-BM) has been used to estimate all of the physical properties of the conventional components in the gasification process [29, 30]. The alpha parameter in this property package is a temperature dependent variable that improves the correlation of the pure component vapor pressure at very high temperatures. For this reason, this property package is suitable for simulating gasification processes that involve fairly high temperatures. 'HCOALGEN' and 'DCOALIGT' are selected for the enthalpy and density property models, respectively, for both biomass and ash.

Regarding the process simulation, the following assumptions have been made:

- The process is in steady state and isothermal.
- This process is made-up to occur instantaneously at equilibrium with volatile products mostly made of H_2, CO, CO_2, H_2O, CH_4, and C_2H_4 [31, 32].
- The electricity and steam for gas cleanup unit is extracted from gas engine (CHP unit)

The process design parameter assumptions for the simulation are summarized in Table 1. The overall process is divided into different sections, which are described below.

4.1 Biomass Drying:

Biomass is specified as a non-conventional component in ASPEN PLUS and is defined in the simulation model using the ultimate and proximate analysis. Part of the moisture portion of the non-conventional component representing the biomass materials (Table 2) in ASPEN PLUS is converted to conventional liquid H_2O in a stoichiometric reaction (RSTOIC) block. Air is pumped into the dryer. The moisture from biomass is evaporated in a countercurrent heat exchanger block using the process steam as a heat source. A small heat loss is modeled in the condensate return line and is assumed to be 2 % of the dryer thermal load. A FLASH2 block is used to separate the exhaust vapors from the biomass material, and dried product (DRYBIOM) exits the dryer with 10 % moisture content.

4.2 Gasification Unit:

Fig. 3 shows processes diagram for gasification unit. ‘DRYBIOM’ from the drying unit enters the ‘BIOMASS’ block at near-atmospheric pressure and the component yield of this block has to specify. It moves through an equilibrium reactor ‘DCOMBIOM’ and mix of air in a ‘MIXER’. The stream continues to a RGIBBS block. It separates tar components from the stream. A description of the different ASPEN PLUS reactor blocks are given in Table 3. The gasification reactions occur in (‘DCOMBIOM’) according to the reaction set shown in below.

$C + 0.5O_2 \longrightarrow CO$	(1)
$C + CO_2 \longrightarrow 2CO$	(2)
$C + H_2O \longrightarrow CO + H_2$	(3)
$C + 2H_2 \longrightarrow CH_4$	(4)
$CO + 0.5O_2 \longrightarrow CO_2$	(5)
$H_2 + 0.5O_2 \longrightarrow H_2O$	(6)
$CO + H_2O \longrightarrow CO_2 + H_2$	(7)
$CH_4 + H_2O \longrightarrow CO + 3H_2$	(8)
$H_2 + S \longrightarrow H_2S$	(9)
$0.5N_2 + 1.5H_2 \longrightarrow NH_3$	(10)

Raw syngas is produced from 'GASIFIER' with temperature 1100 ^{o}C and 25 bar. Then, the ash is separated from the syngas and flow into cleanup unit.

4.3 Gas cleanup unit:

After the synthesis gas leaves the gasifier, it must be processed for further use. First, the synthesis gas passes through a gas cooling heat exchanger block, 'SYN-HTX', which generates process steam. The gasification of these biomass fuels will produce components such as H_2S, and NH_3, which can be harmful to equipment and produce pollutants during synthesis gas combustion. Next, the gas passes through a wet scrubber, 'H2SABS', to remove sulfur matter. After that the stream continues to block 'CO2ABS' where it can produce 'CO2RICH' stream and CO_2 is separated through block 'B1'. The next stage in gas processing is the selective removal of harmful components through 'N2STRP' block (Fig.4).

4.4 Power, heat and cooling production unit:

Clean syngas from the gas clean-up section enters the gas engine, where it combusts in 'COMBA' with air from 'AIRSPT' (Fig. 5). The stream continues into an expander ('EXPN1') and burns in a reactor ('BURN') in the presence of air. The flue gas is used to run 'EXPN2' and 'EXPN3'. The total work from all the 'EXPN's are combined in 'WORKMIX' and are split (80:20) again into two streams, with 20 % of the produced power used for the cooling system and the exhaust gas from 'EXPN3' used for district heating purposes. District heating water from the users (make-up water) returns as 'DHWIN1' and 'DHWIN2' and is heated by heat exchangers ('B3' and 'B2'). Both 'DHWOUT1' and 'DHWOUT2' outputs from the heat exchangers are utilized for the district heating system.

4.5 SNG production unit:

The 'SYNGASOT' stream leaves the gas cleanup mix with additional hydrogen 'H2IN' in the 'MIXER' block and continues to the methanation reactor, 'METHANT'. Additional H_2 feed is necessary to provide CO/H_2 ratio. Fig. 6 shows the CH_4 synthesis process. In the methanation reactor, CO and H_2 are converted to CH_4 and H_2O in a fixed-bed catalytic reactor.

$$CO + 3\,H_2 \longrightarrow H_2O + CH_4 \tag{11}$$

The produced CH_4 still has some impurities, so it enters a separator unit, 'CO2REMOV', where the CH_4 is separated from CO_2.

4.6 System evaluation criteria

The net energy efficiency (NEE) of the quad-generation system can be defined as [12, 20]:

$$\eta = \frac{\sum E_{products}}{\sum E_{feedstocks}}$$

$$= \frac{E_P}{\left(E_{in} + E_{inH_2}\right)} + \frac{E_H}{\left(E_{in} + E_{inH_2}\right)} + \frac{E_C}{\left(E_{in} + E_{inH_2}\right)} + \frac{E_{SNG}}{\left(E_{in} + E_{inH_2}\right)}$$

$$= \eta_P + \eta_H + \eta_C + \eta_{SNG}$$

where E_P, E_H, E_C and E_{SNG} are the output energies from power generation, heat production, cooling energy and the SNG process, respectively. E_{in} represents the total biomass energy input to this quad generation plant which includes power and heat input during gas cleanup unit, and E_{inH_2} is the hydrogen energy input to the SNG synthesis process. η is the net energy efficiency, and η_P, η_H, η_C and η_{SNG} are the power, heat, cooling and SNG efficiencies, respectively. The efficiency is calculated on the basis of the lower heating value (LHV). The amount of energy required for CO_2 separation is not included in this efficiency calculation.

5 Results and discussion

The detailed energy consumptions for a quad-generation plant are shown in Table 4. For 100 tons per day of biomass input, SNG-0 utilizes 7625 kg/h syngas for power, heat and cooling production, while QUAD-25 uses 2287.5 kg/h for power, heat, and cooling production and 5337.5 kg/h for SNG production. The necessary amount of air for power production is reduced from SNG-0 to QUAD-25, as this case produces less electric power from the gas engine. The amounts of H_2 necessary for CH_4 synthesis are 66.24, 52.41, 42.31 and 35.76 kg/h for SNG-100, QUAD-25, QUAD-50 and QUAD-75, respectively, which are equivalent to 2.23 MW, 1.76 MW, 1.41 MW and 1.2 MW and it is presented by the LHV of H_2. H_2 is generated from an external source, but the increase of H_2 does not compensate for the energy loss those results from the smaller amount of carbon (C) in the syngas for CH_4 synthesis. Energy input required for the H_2 production is not included in the efficiency calculations. Additionally, the flow rate of make-up water is 3 tons/h for each case. The SNG-100 case has the highest CO_2 capture ability mainly because of its maximum ability to convert CO to CO_2. This results in the most energy loss and the lowest percentage of CO_2 emissions in the exhaust.

Fig.7 shows the energy balance for the quad-generation system. It also indicates the amounts of the four outputs from the SNG-0, QUAD-75, QUAD-50, QUAD-25, and SNG-100 cases. It should be noted that the amount of syngas produced from the gasifier has been kept constant for all of the cases. According to the different amounts of syngas utilization, this process produces approximately 49.728, 73.595, 95.22 and 134.34 m^3/h of SNG for the QUAD-75, QUAD-50, QUAD-25 and SNG-100 cases, respectively. Simultaneously, it generates 11.1, 8.6, 6 and 5 MW of heat in the SNG-0, QUAD-75, QUAD-50 and QUAD-25 cases, respectively. Twenty percent of the power generation from the quad-generation plant is used for the cooling system. The SNG-0 case does not produce any SNG, as all the syngas is used for power, heat and cooling production.

The primary measure of energy efficiency for a power plant is the feedstock to net power production to the feedstock ratio, but because the waste heat generated in the quad-generation plant is used for heat production, cooling, and SNG production, this measure is not an accurate representation of the efficiency of quad-generation plants. In this case, the net energy efficiency also includes the efficiency of the biomass used by all of the individual outputs. In Fig 8, the entire individual energy efficiency factor for the quad-generation plant can be observed. It also shows that the power efficiency for SNG-0 is 22.5 %, while the efficiency for QUAD-25 is 6.9 %, which is relatively low as it uses less syngas for power production. In the case of heat utilization, heat production efficiency is higher than the other output efficiencies. The heat production efficiencies are 24.47 %, 29.37 %, 42.1 % and 54.34 % for QUAD-25, QUAD-50, QUAD-75 and SNG-0, respectively. Fig. 8 also shows the cooling efficiency, which is the least efficient for all the cases, as it produces a smaller proportion of cooling relative to the total output. For SNG production, the efficiency increases gradually from QUAD-75 to SNG-100. For the SNG-100 case, fig. 8 does not show the power, heat and cooling efficiency as there is no production for this case. Similarly, fig. 8 does not include the SNG efficiency for the SNG-0 case.

Temperature, pressure, mass and mole flows of different streams are listed in table 5 which refers to the numbers used the process diagram (fig. 2). The data from QUAD-50 case has reflected in this table. For an input of 4167.67 kg/hr of straw input, 657.35 kg/hr of SNG can be produced. Stream 1, biomass composition is analyzed in table 2. Stream 3, syngas has more mole components like H_2S, NH3, S and the values are 14.15, 31.73, 0.29 kmol/hr respectively. Stream7 and 8 represents the electricity to the grid and heat pump respectively.

Efficiency for different cases with individual power, heat, cooling and SNG production are showed in fig. 8. It also presented the net energy efficiency (NEE) of five different cases. It can be observed that with increasing SNG production, the change trend of NEE is like "M". The lower NEE is also a result of transforming chemical energy into thermal energy, which is poorly converted to electrical energy, instead of transferring chemical energy to electrical energy. This means that the larger the power production shares, the lower the efficiency will be with respect to SNG production. It also reflects the more SNG production gives higher SNG efficiency for this system. The NEE for SNG-100 is relatively low as it captures the highest amount of CO_2 of all the cases.

Fig. 9 shows a complete comparison of the input and output products of a quad-generation plant and the Brovst DHP. Here input is included both biomass and H_2. The SNG-0 case is more appropriate for the winter as the demand for heating rises in this season, while the QUAD-25 case would be more appropriate in the summer because it can produce more SNG and still produce some power, heat and cooling. In the case of excess power production from wind and a lower price for heat from other heating plants, SNG-100 would be a good option for a quad-generation plant. A life cycle analysis and economic analysis have also done for quad-generation plant. It is found that Quad-generation offers significant CO_2 reductions and energy efficiency improvements, while the economic feasibility is jeopardized by high investment costs [34, 35]. In case of more heat production from quad-generation plant, it may serve the nearby localities as the municipality considered a joint distribution and production network. As described in the scope of the research, it is possible to utilize the maximum capacity of the plant by selecting different case studies and reducing the gap between the production and capacity curves

6 Conclusion

The quad-generation processes for the production of power, heating, cooling and SNG were modeled and compared in terms of design and energy efficiency analysis. One of the advantages of this design is that the plant authority does not need to build storage for SNG as they already have access to the national natural gas grid. In this context, a process that converts biomass into SNG, which is equal in quality to fossil-derived natural gas, has been investigated. Such a product could easily be injected into the national gas grid to benefit from the existing distribution network for transport applications. With the increasing market share of gas engines in the transport sector, fossil fuels could therefore be partially substituted by a renewable fuel that is neutral in greenhouse gas emissions.

As the Danish Government aims to derive more of its energy from renewable fuels, this type of integrated quad-generation approach could be applied for any of the heating plants in other municipalities. This modeling approach can be used by other investigators who aim to change their operation strategies and plant designs from fossil fuel-based to renewable resource-based energy systems.

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Figure Captions:

Fig.1 Heat demand and total capacity over a year for the Brovst DHP

Fig.2 Simplified scheme of the proposed quad-generation system

Fig.3 ASPEN PLUS model for the gasification unit

Fig.4 Gas clean-up model

Fig.5 Power, heat and cooling production model

Fig.6 SNG synthesis process

Fig.7 Energy balances of the SNG-0, QUAD-75, QUAD-50, QUAD-25 and SNG-100 cases for one hour of operation.

Fig. 8 Power, heat, cooling and SNG efficiencies for five cases

Fig. 9 Comparison of a quad-generation plant to an existing district heating plant

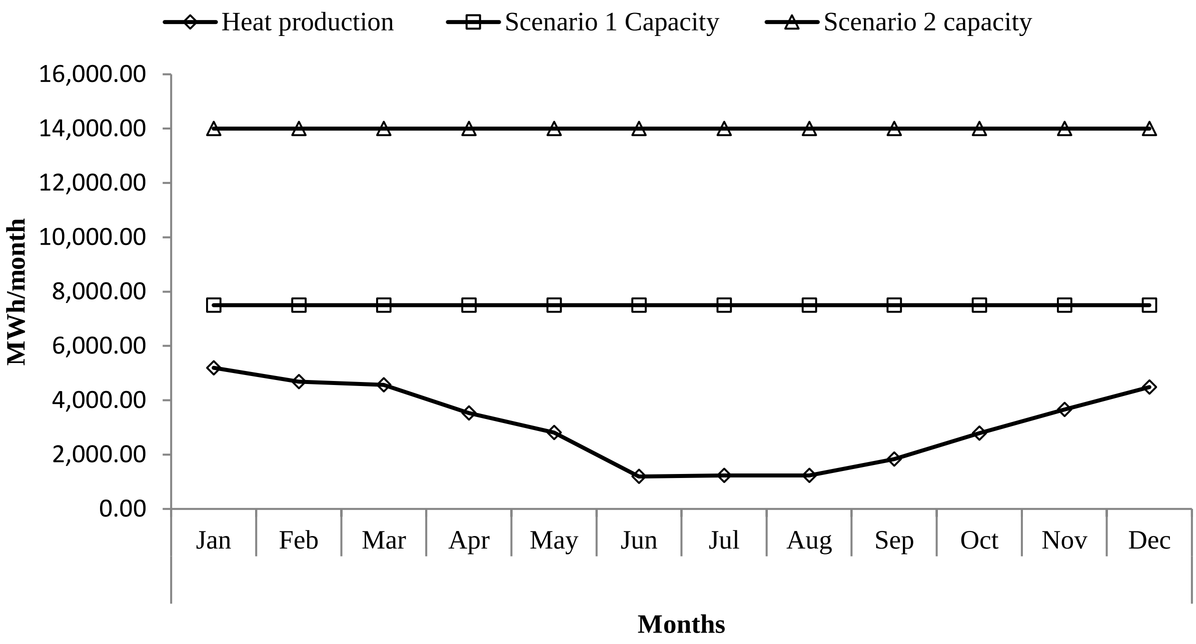
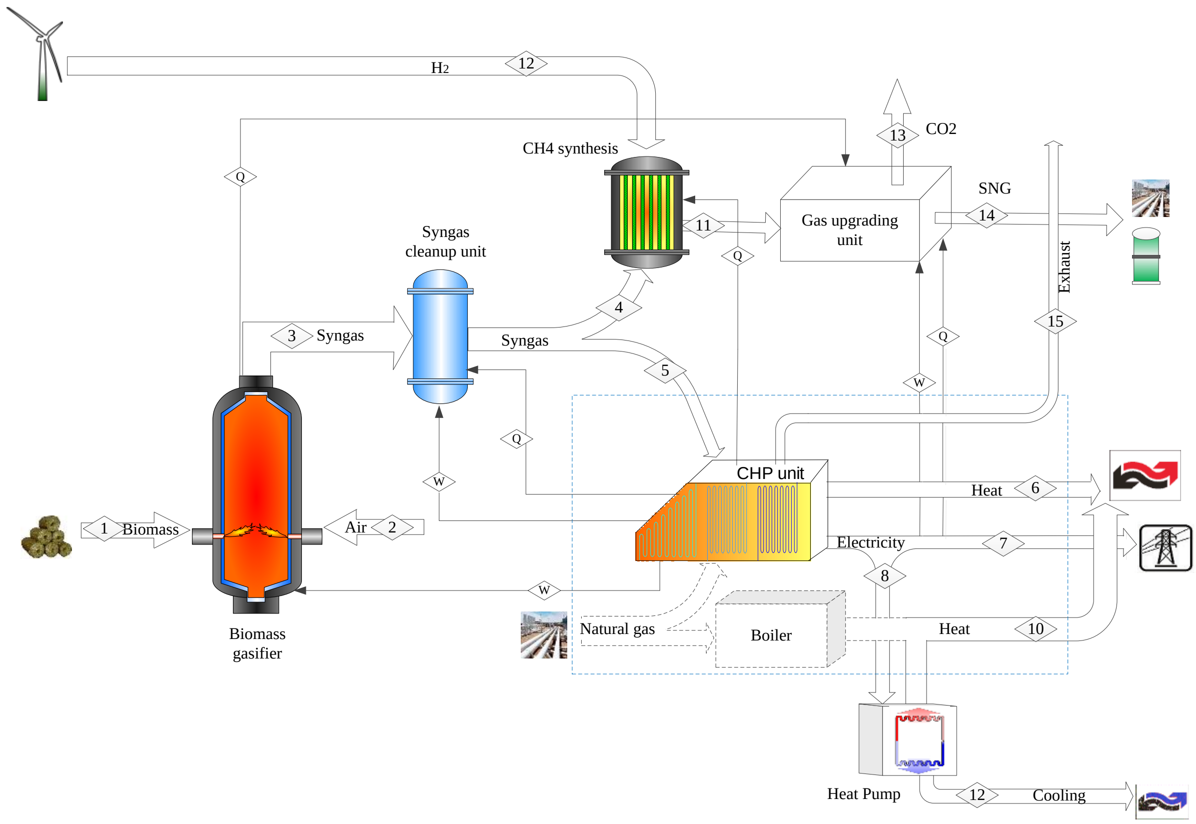


Fig.1 Heat production and total capacity over a year for the Brovst DHP



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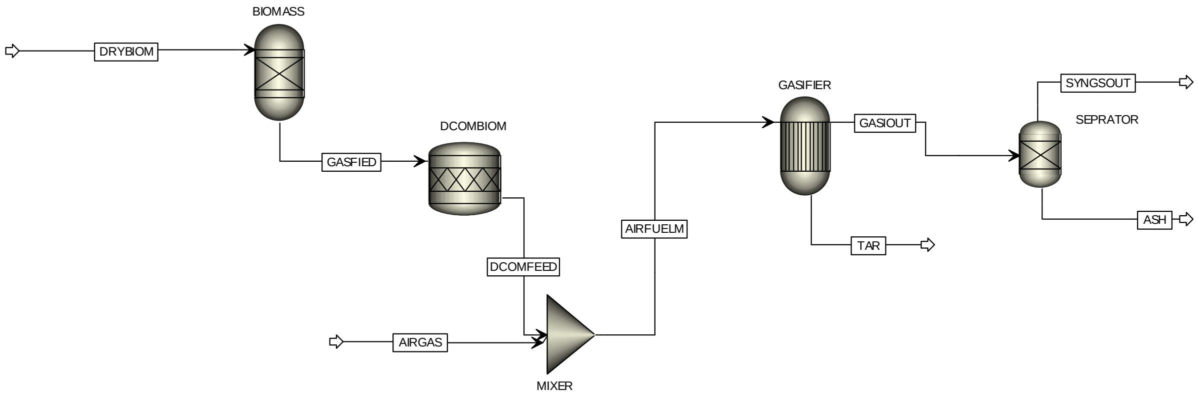

Fig.3 ASPEN PLUS model for the gasification unit

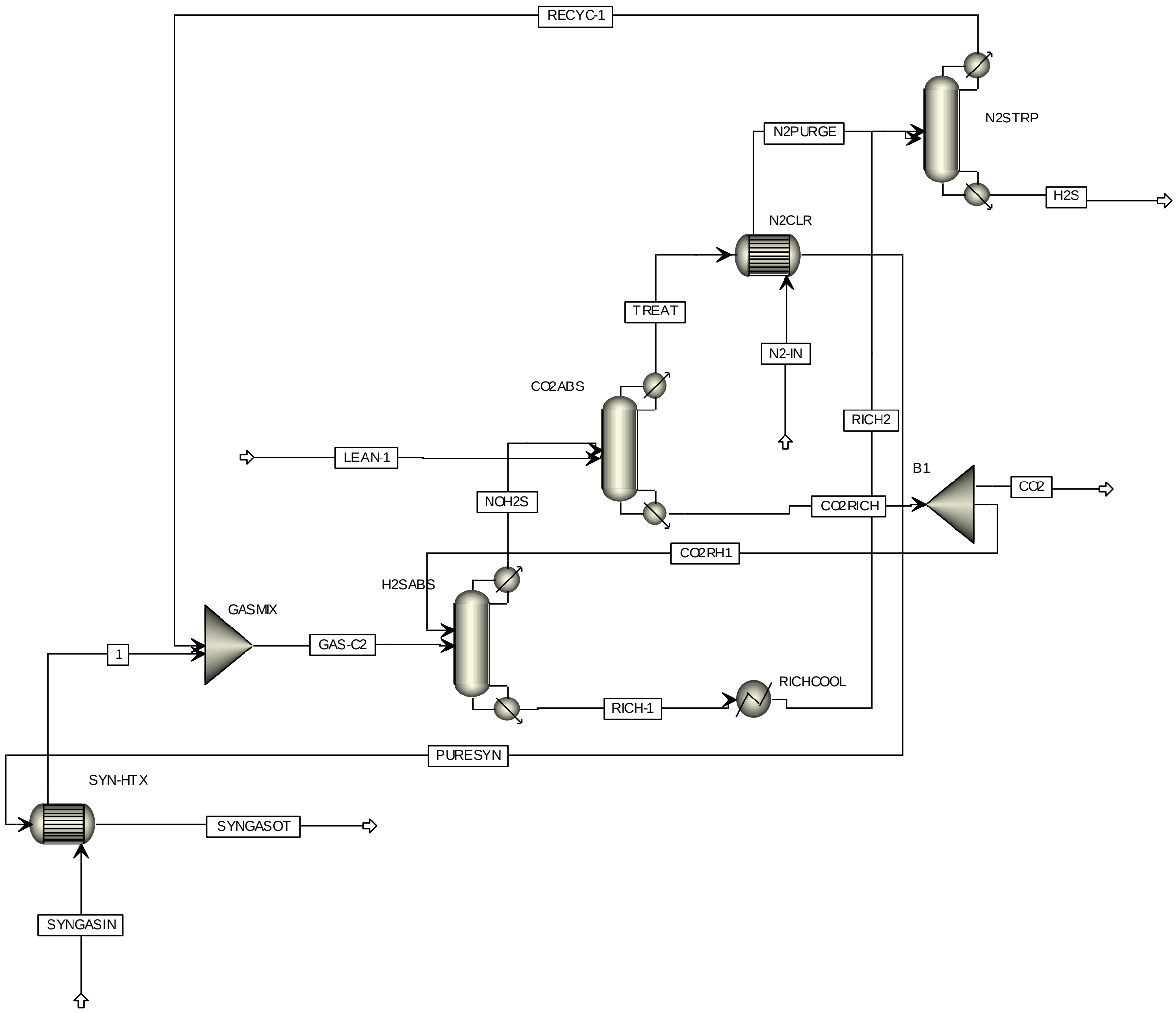

Fig.4 Gas clean-up model

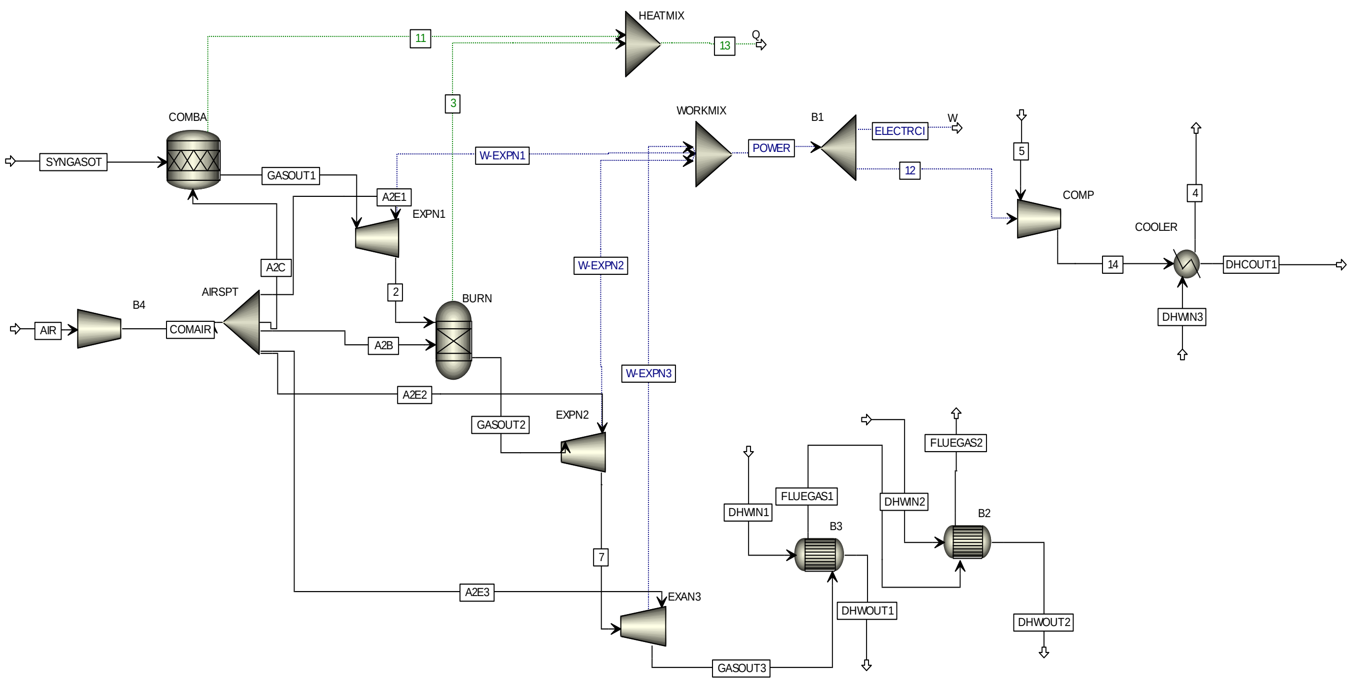

Fig.5 Power, heat and cooling production model

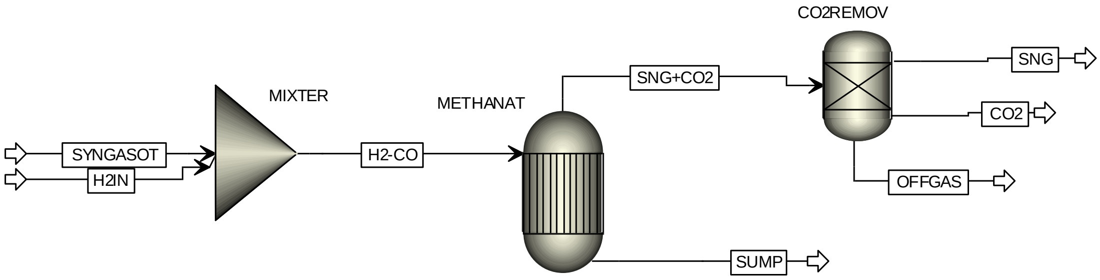

Fig.6 SNG synthesis process.

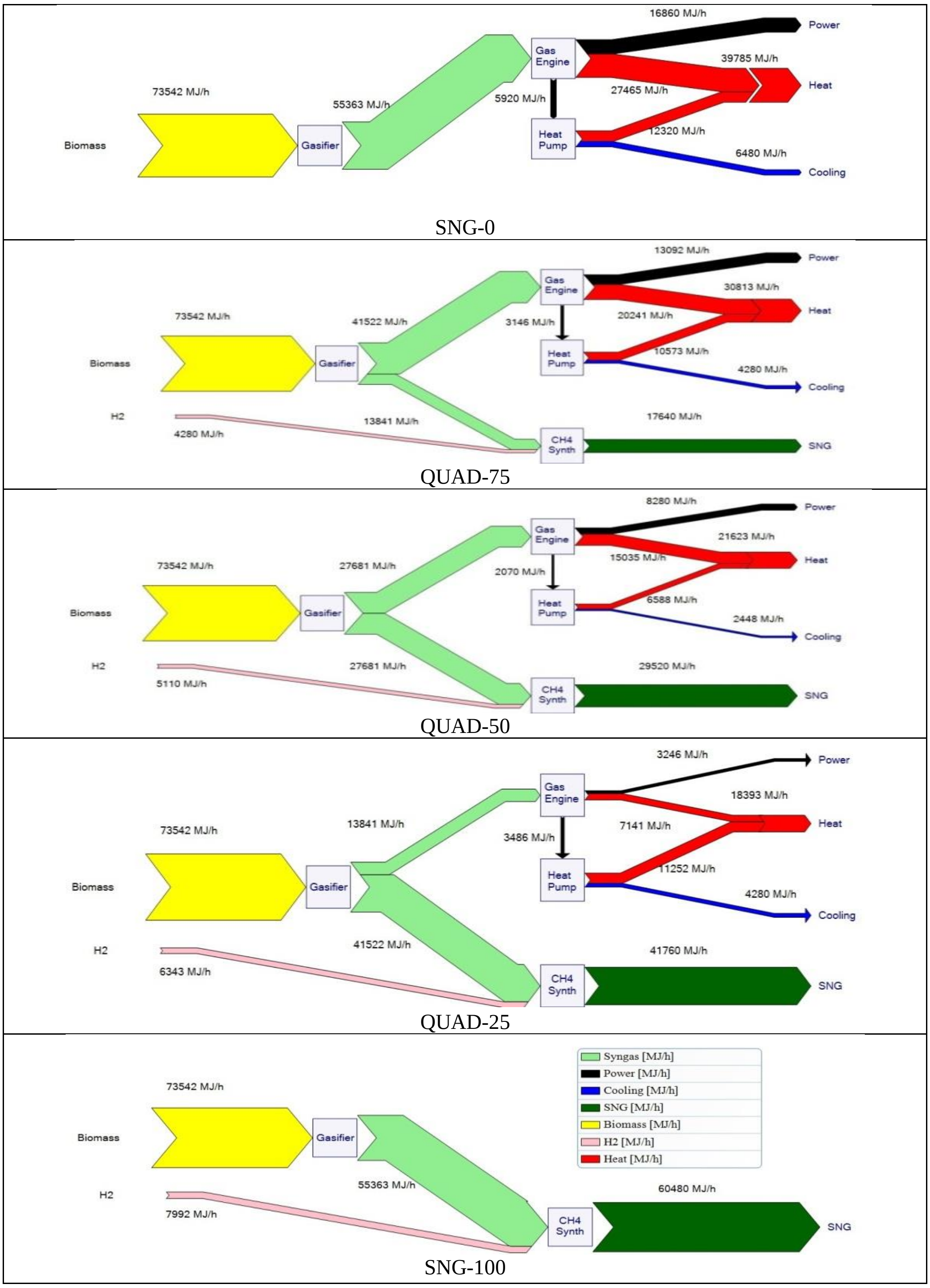

Fig. 7: Energy balances of the SNG-0, QUAD-75, QUAD-50, QUAD-25 and SNG-100 cases for one hour of operation.

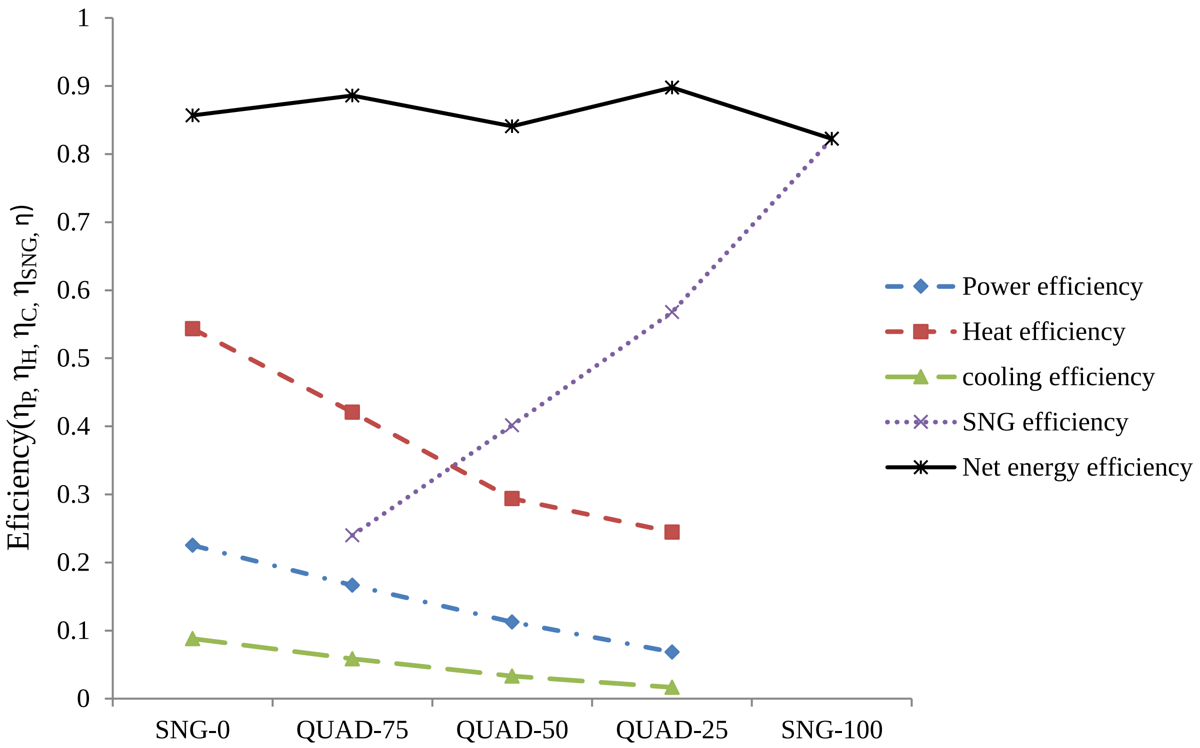

Fig. 8 Power, heat, cooling and SNG efficiencies for five cases

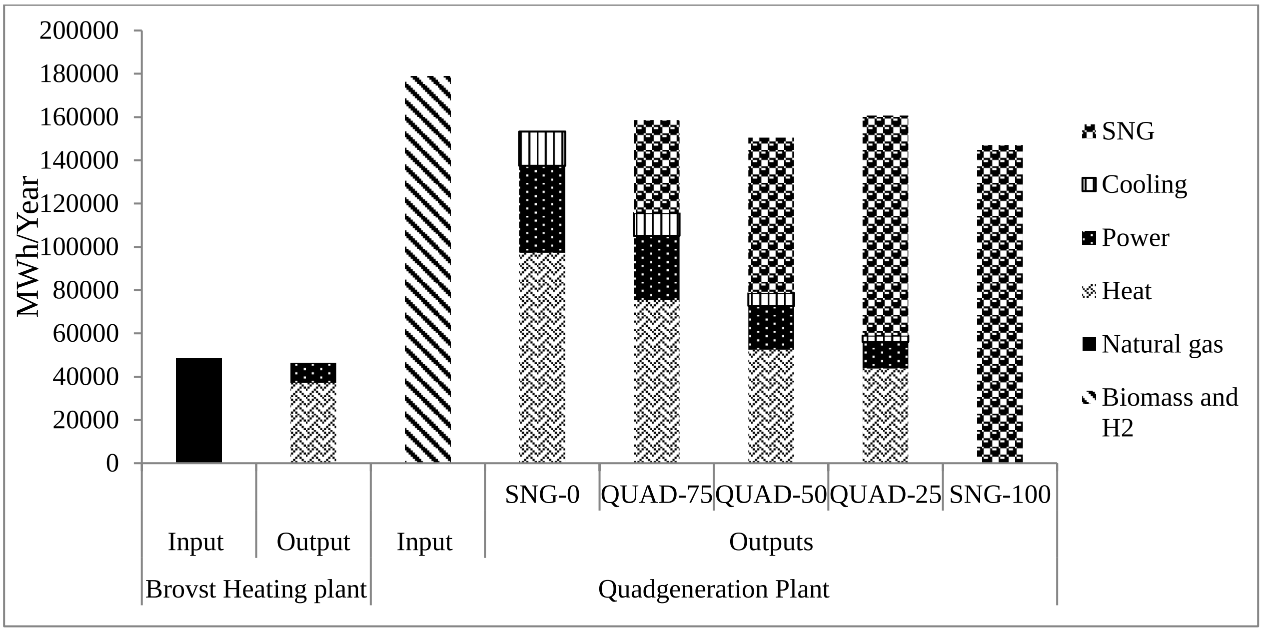

Fig. 9 Comparison of a quad-generation plant to an existing district heating plant

Table captions:

Table 1: Process design parameter assumptions for simulation

Table 2: Biomass characteristics (DM: dry matter; DAF: dry ash free) [32]

Table 3: Description of the reactor blocks utilized in the simulation

Table 4: The material balance, power, heat, cooling and SNG produced, and utilities of five cases

Table 5: Parameters of the main points of the quad-generation system

Table 1: Process design parameter assumptions for simulation

Item	Unit	Value
Gasification unit		
Temperature	°C	1100
Pressure	bar	25
Air for gasification	t/h	96
Gas cleanup unit		
CO_2 removal	%	95
Sulphur removal	%	95
Electricity [30]	kJ/mol (CO^2 + H_2S)	1.9
Steam [30]	kg/mol (CO^2 + H_2S)	6.97
Power, heat and cooling unit		
Gas engine inlet temperature	°C	650
Gas engine inlet pressure	bar	25
Air for gas engine	t/h	100
Isentropic efficiency of expanders	%	90
Isentropic efficiency of main compressors	%	88
Mechanical efficiency main compressor	%	98
recycled water for heating	kg/h	2000
recycled water for cooling	kg/h	1000
SNG synthesis unit		
SNG synthesis temperature	°C	270
SNG synthesis pressure	bar	20

Table 2: Biomass characteristics (DM: dry matter; DAF: dry ash free) [33].

Properties /Biomass		Straw
LHV(MJ/kg)		17.65
Ultimate Analysis (DAF)	C	48.39
	H	6.15
	O	44.68
	N	0.58
	S	0.09
	Cl	0.30
Proximate Analysis (DM)	VM	77.36
	FC	19.25
	Ash	5.58

1 Table 3: Description of the reactor blocks utilized in the simulation

Block ID	Aspen floowsheet Name	Description
RYIELD	BIOMASS	Yield reactor-converts non-conventional biomass to conventional components by using FORTAN statement.
RSTOIC	DCOMBIOM	Specify operating conditions, reactions, reference conditions for heat of reaction calculations, product and reactant components for selectivity calculations
MIXER	MIXER	Mix of air and decomposed biomass feed from DCOMBIOM and feed to GASIFIER.
RGIBBS	GASIFIER	Specify reactor operating conditions and phases to consider in equilibrium calculations
SEPRATOR	SEPARATOR	Separates gases from ash by specifying split faction.

Table 4: The material balance, power, heat, cooling and SNG produced, and utilities of five cases

Items	Units	SNG-100	QUAD-75	QUAD-50	QUAD-25	QUAD-0
Feed stocks						
Biomass	t/day	100	100	100	100	100
Syngas for Power, heat and cooling	kg/h	7625	5718.75	3812.5	1906.25	0
Syngas for SNG	kg/h	0	1906.25	3812.5	5718.75	7625
Air for gasification	t/h	96	96	96	96	96
Air for gas engine	t/h	100	80	60	40	0
Make up water	t/h	3	3	3	3	3
H_2 input	kg/h	0	36.76	42.231	52.41288	66.241
Waste Product						
Ash	Kg/h	138	138	138	138	138
CO_2 capture during gas cleanup	Kg/h	326.98	326.98	326.98	326.98	326.98
CO_2 capture during SNG production	Kg/h	0	131.78	156.23	182.565	204.682

Table 5: Parameters of the main points of the quad-generation system

Stream	Temperature (°C)	Pressure (bar)	Mass flow (kg/h)	Mole flow (kmol/h)								
				N_2	O_2	CO	H_2	CO_2	H_2S	CH_4	H_2O	C_2H_4
1	25	1.01	4167.67	-	-	-	-	-	-	-	-	-
2	25	1.01	1000	32	96.015	-	-	-	-	-	-	-
3	1205.10	28	7209.68	32.66	98.24	16.84	86.87	16.84	14.14	21.7	59.04	0.4
4	650	25	7625	-	10.2	19.35	56.66	0.84	0.71	18.66	41.02	0.4
5	650	25	3812.5	-	10.2	19.35	56.66	0.84	0.71	18.66	41.02	0.4
6	90	1.01	2000	-	-	-	-	-	-	-	55.51	-
7	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-
9	5	1.01	362.35	-	-	-	-	-	-		55.35	-
10	95	1.01	502.72	-	-	-	-	-	-	-	15.63	-
11	614.58	1.01	7689.24	-	-	6.49	0.04	37.86	.02	48.68	36.47	0.49
12	100	1.01	42	-	-	-	31.87	-	-	-	-	-
13	270	20	257.29	-	-	6.49	0.043	37.86	8.35	-	67.64	0.49
14	270	20	657.35	-	-	-	-	-	-	30.24	-	-