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Geothermal Energy and Biomass Integration in Urban Systems: a Case Study

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ABSTRACT

Heating, electricity and transportation are the three components of urban systems final energy consumption. Geothermal energy and biomass are two promising renewable energy resources that can be used for the production of heat, electricity and biofuels, thus allowing a reduction of fossil fuel consumption and of the associated greenhouse gas emissions. The goal of this paper is to assess the potential for the integration of geothermal energy combined with biomass in the energy system of a city, taking into account the consumption of fossil and renewable resources, costs and environmental impact.

Several process options are available for both resources. For geothermal energy, deep aquifers and EGS (Enhanced Geothermal Systems) are considered, for both separate production of heat and electricity, and cogeneration. For biomass, besides the option of direct combustion, conversion to biofuels by a set of alternative processes (pyrolysis and gasification) is included in this study. The use of pinch analysis and optimization allows the evaluation of possible hybrid energy conversion systems integrating geothermal with biomass.

The European city of Lausanne (Switzerland) is used as an example case study. The heat demand of the city is partially satisfied by a district heating network. The complete urban energy system is modeled in order to account for the potential competition and synergies between different energy carriers and technologies for the same end-uses. A set of "ad hoc" scenarios is developed with the goal of assessing the interest of geothermal and biomass within the long-term strategic energy planning of the city.

1. INTRODUCTION

Extending recent trends to 2050 ("6DS" scenario), greenhouse gas (GHG) emissions are expected to increase by 60% compared to 2011. Avoiding the consequent catastrophic effects for climate change would require a 50% reduction compared to todays levels [1]. Fossil fuels account for more than 80% of the world primary energy consumption and for the majority of anthropogenic GHG emissions. Thus, substitution of fossil fuels with renewable energy sources, such as geothermal and biomass, is one of the key actions to tackle climate change. In the year 2008, geothermal energy and bioenergy, in particular woody biomass, accounted for 0.1% and 10.2% of global primary energy supply, respectively. Geothermal energy is projected to cover 3% of the global electricity demand and 5% of the global heat demand by 2050. Bioenergy demand is expected to increase threefold in the same timeframe [2]. Today about 50% of the world population lives in urban areas, with a projected increasing trend. Urban systems account for about two-thirds of global primary energy consumption and for 71% of global energy-related GHG emissions [3].

1.1 The case study of Lausanne

The European urban system of Lausanne (Switzerland, 137000 inhabitants) is taken as an example case study in this work. Figure 1 shows the energy flow Sankey diagram of the city for the year 2012. The final energy consumption is broken down into its three components: heating (59.5%), electricity (23.1%) and transportation (17.3%). Fossil fuels (oil and natural gas) account for 59% of the urban system's primary energy consumption, covering the largest share of the demand in the heating and in the transportation sector. A district heating network (DHN), covering 20.5% of the heating demand, is powered by fossil fuel boilers, a waste water treatment plant (WWTP) and a municipal solid waste incinerator (MSWI) cogeneration power plant. Electricity demand is mainly satisfied by hydroelectricity (79.9%), followed by nuclear (7.3%), and smaller contributions from other renewable energies. There is currently no deployment of deep geothermal technologies, while biomass accounts for 2.5% of the primary energy consumption, with 15.4 kt (1 kt = 10^6 kg) of local woody biomass burned in the MSWI in the year 2012 out of a total potential estimated in the range of 50-100 kt/year.

The planned expansion of the DHN of the city as well as the phasing out of nuclear power plants in Switzerland [4] present opportunities for a wider deployment of these two renewable resources as fossil fuel substitutes. Various energy conversion options are considered. Geothermal heat can be harvested from aquifers or high-depth Enhanced Geothermal Systems (EGS). The extracted heat can be the hot source for electricity production in organic Rankine cycles (ORC), for cogeneration in Kalina cycles, or can directly supply the DHN. Considered options for woody biomass are combustion in boilers for heat supply (with or without drying), and conversion to biofuels such as bio-oil for heating (pyrolysis) and synthetic natural gas (SNG) (gasification), the latter allowing as well for substituting fossil fuels in the transportation sector.

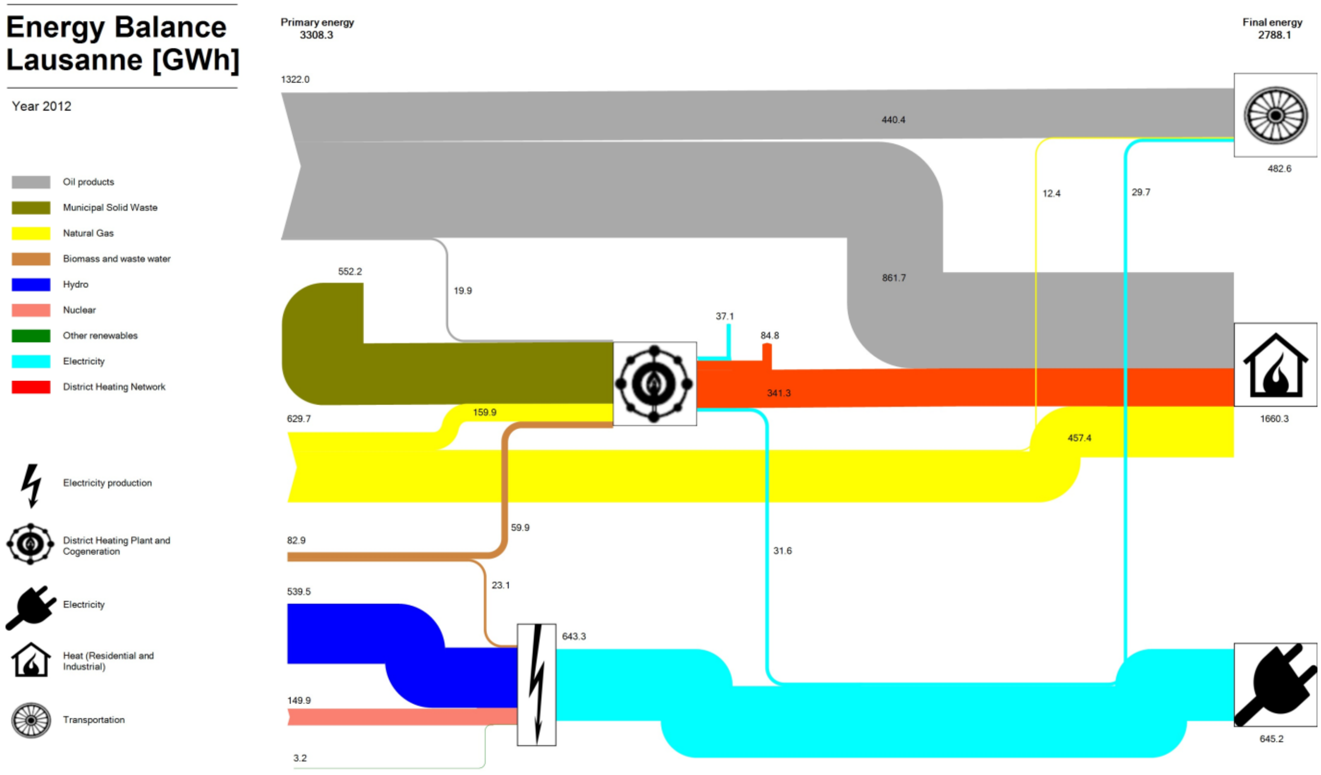

Figure 1: Energy flow Sankey diagram of the city of Lausanne (Switzerland) for the year 2012.

1.2 Literature review

Gerber et al. [5] have applied multi-objective optimization for the evaluation of geothermal integration in a urban system taking into account total yearly cost and environmental impacts. The urban system is modeled in its entirety (only decentralized heating is excluded) and one year is broken down into a set of independent periods with different heating requirements. Woody biomass conversion technologies (dryers, boilers, gasifiers) are also included in the model, although no heat integration is considered with geothermal technologies. Alberg Østergaard et al. [6] have applied the EnergyPLAN model [7] to design a 100% renewable scenario for a Danish city, mostly based on the use of biomass, geothermal and wind power. Low-depth resources in combination with absorption heat pumps are considered for geothermal, whereas the quantity of biomass previously dedicated to individual residential heating is converted to production of biogas and SNG. Thus, in that work only a subset of the possible energy conversion technologies is considered, and no possibility for heat integration is taken into account.

Integration and hybridization with geothermal and solar resources have been identified as a strategic research priority for biomass in Europe [8]. Hybridization has been applied to the production of electricity in ORCs, with geothermal heat used for biomass drying and preheating, and biomass supplying the remaining heat requirements at higher temperature. This is the case for a 35.5 MW_e installation in California, USA [9]. A hybrid geothermal-natural gas-biomass conversion system has been proposed for the Cornell University campus (USA), evaluating the use of excess geothermal heat alone for electricity production with an ORC during the summer, and in combination with biomass for heating production during the winter [10].

1.3 Goals and structure of the paper

The goal of the present work is to develop a complete model of the urban system to map the current situation (year 2012) and to preliminarily evaluate the interest of integrating woody biomass and geothermal energy in the future energy strategy, taking into account cost and environmental impact as performance indicators. Heat cascading and the introduction of storage in the multi-period problem formulation allow for evaluating the possible configurations of biomass-geothermal hybrid systems, focusing as well on the potential for the utilization of excess geothermal heat during the summer.

Firstly, the methodology adopted for developing the urban system model and for calculating the key performance indicators of each scenario is presented together with the computational framework (section 2). The various technology models are then described in detail in section 3. The model is initially applied to the 2012 situation and then to a set of future scenarios (year 2035) with different combinations of geothermal and biomass conversion technologies, leading to preliminary conclusions that can be used as guidelines for the future energy strategy of the urban system.

2. METHODOLOGY

2.1 Urban system model

Figure 2 depicts the overall model developed for the urban system. Each technology model corresponds to a "unit", which is characterized by input and output "streams". Streams are associated with two types of "layers": "Resource Balance" and "Heat Cascade". Each layer of type "Resource Balance" corresponds to a mass or power balance in the system. As an example, all the natural gas (NG) imported or produced by the gasification units needs to be consumed by the units having this resource as an input. Thermal streams belong to the "Heat Cascade" layer. If a unit has multiple thermal streams, only the net heating requirement and/or excess are shown in the figure. Each "location" has its own heat cascade, i.e. heat exchange is allowed only between units belonging to the same location. All technology models are described in detail in the next section. In order to capture seasonality issues, the year is split into four different periods for the analysis, as shown in Table 1.

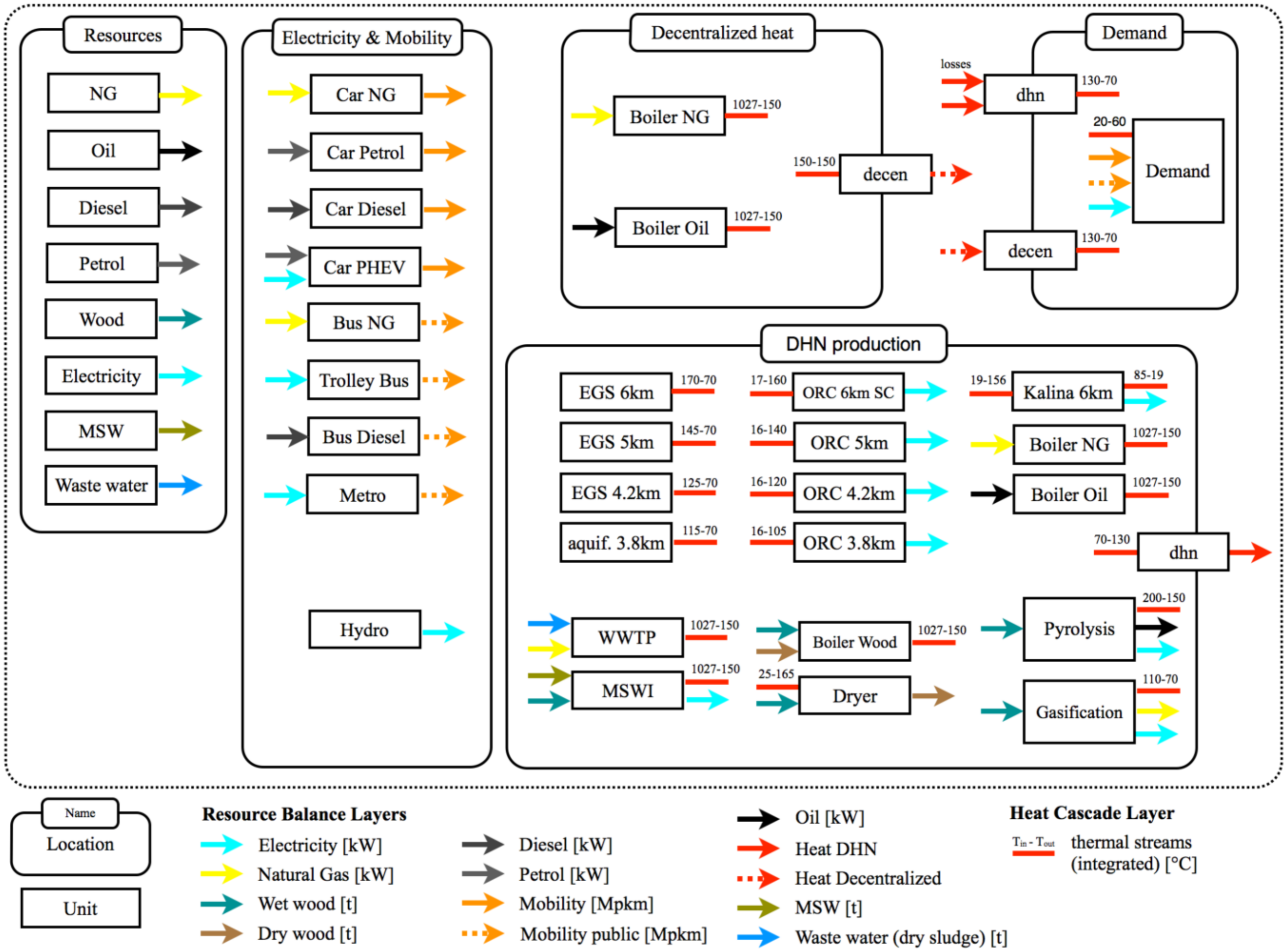

Figure 2: Urban system model overview (mobility is expressed in millions of passenger-km [Mpkm]).

Period	Months	Duration [h]
Summer	June to September	2928
Winter	November to March	3624
Mid-season	October, April, May	2208
Peak	-	0.01

Table 1: Definition of the four periods of the multi-period problem.

2.2 Performance indicators definition

Different scenarios for the urban system, corresponding to different technology choices and relative sizes, are compared based on two performance indicators, the total yearly cost of the energy system and the CO_2-equivalent emissions.

The total cost of the system C_{TOT} [MCHF$_{2012}$/year] is defined as the sum of the total investment cost $C_{INV,an}$, annualized based on the equipment lifetime n_{tech} and the discount rate i (6%), the yearly operating cost C_{OP} and the yearly costs for operation and maintenance $C_{O\&M}$ (1). $C_{INV,an}$ is the result of the contributions of all the technologies (*tech*) including the existing ones, in order not to penalize new technologies. C_{OP} is the total cost related to resource consumption (*res*: electricity imports and fuels). $C_{O\&M}$ is the sum of the operation and maintenance costs (excluding fuels and electricity imports) of all the technologies in the energy system.

$$C_{TOT} = C_{INV,an} + C_{OP} + C_{O\&M} = \sum_{tech} \frac{i(i+1)^{n_{tech}}}{(1+i)^{n_{tech}} - 1} C_{INV,tech} + \sum_{res} C_{OP,res} + \sum_{tech} C_{O\&M,tech} \tag{1}$$

A similar approach is used for the calculation of the environmental impact calculated with a Life Cycle Assessment (LCA) approach. Due to the central importance of GHG emissions, the chosen impact assessment method is the "IPCC 2013 Global Warming Potential (GWP) – 100 years" [11]. The total yearly emissions of the energy system Em_{TOT} [kt$_{CO2\text{-}eq}$/year] are defined as the sum of the emissions related to the construction of the energy conversion technologies $Em_{constr,an}$, allocated to one year based on the technology lifetime, and the emissions related to operation Em_{OP} (2). The latter are the emissions associated to the fuels (from cradle to combustion) and to imports of electricity. The main source of environmental impact data is the Ecoinvent database [11].

$$Em_{TOT} = Em_{constr,an} + Em_{OP} = \sum_{tech} \frac{Em_{constr,tech}}{n_{tech}} + \sum_{res} Em_{OP,res} \tag{2}$$

This definition of the energy system performance indicators presents the advantage of avoiding the need of assuming prices for electricity and fuels produced within the system boundaries. From the environmental impact assessment point of view, with this approach there is no need of adopting the concept of avoided emissions, as the emissions from the residual fossil resources consumption are automatically accounted for in the final indicator.

2.3 Calculation framework

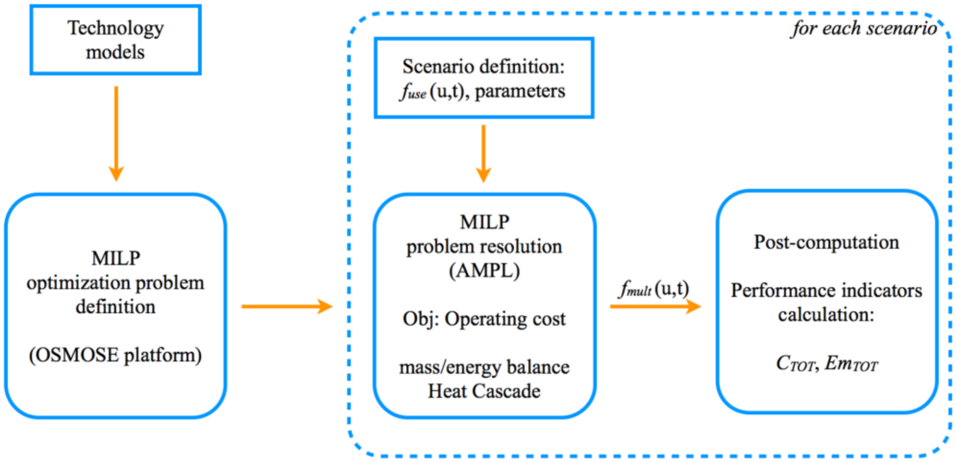

Figure 3: Calculation framework methodology.

Figure 3 shows the calculation framework used for the evaluation of the different scenarios. The previously defined urban system model is translated into a multi-period Mixed-Integer Linear Programming (MILP) problem (common to all scenarios) with the OSMOSE platform [12]. The key variables of the MILP problem are f_{use} (u,t) and f_{mult} (u,t). f_{use} (u,t) is a binary variable defining the use of a unit u in the period t. The models of all the units presented in Figure 2 are defined with a default size. f_{mult} (u,t) is the multiplication factor defining, in each period, the actual size of the units' streams relatively to the default size. The upper limit of this variable is defined by the parameter f_{max} (u), corresponding to the maximum size of each unit.

For each scenario, only a defined subset of units is available, i.e. for all the other units f_{use} (u,t) = 0 for all t. This scenario definition is added to the original MILP problem, which is coded in AMPL [13]. The MILP problem has as key constraints the balancing of the "Resource Balance" layers and the heat cascade definition according to the formulation as in [14]. Solving the MILP problem optimizes the operation of the energy system for one year, with the objective of minimizing the operating cost. The output of interest is f_{mult} (u,t), which is used within a post-computation function to calculate the performance indicators. The maximum value of f_{mult} (u,t) over t is taken into account for the calculation of the installed capacity of each technology.

3. TECHNOLOGY MODELS

This section details the unit models presented in Figure 2, with the key data for lifetime, efficiency, cost and emissions. The data refer to the default size of the units ($f_{mult} = 1$). The total investment cost of a unit can be broken down into a fixed cost ($C_{INV,1}$) and a variable part ($C_{INV,2}$) linearly proportional to f_{mult} in the size range considered for each technology. The cost is expressed in Swiss Francs (CHF), and currency conversion values of 0.923 CHF/USD and 1.2 CHF/€ are assumed for 2012.

3.1 Resources

Table 2 shows the data for the resources in the energy system. For the cost, average data have been taken for Switzerland in the year 2012. Cost of imported resources is taken at the border of the city, i.e. the profit made by intermediate service providers is not taken into account if the service providers are property of the City of Lausanne. The MSW is considered free of charge as it would need to be collected anyway. For the year 2012, the electricity import mix is assumed to be equal to the actual mix presented in section 1.1. For the future scenarios (with nuclear phase out), 20% of the import mix is attributed to natural gas combined cycles, and the remaining share is supplied by renewables with a repartition based on the energy strategy of the urban system.

Resource	LHV [MJ/kg]	Cost [CHF/kWh]	GWP [kg_{CO2-eq}/kg]
Natural Gas	45.7 [15]	0.07	3.015 [11]
Oil	42.6 [16]	0.098	3.49 [11]
Petrol	44.15	0.205	3.82 [11]
Diesel	42.8	0.194	3.46 [11]
Wet wood (50% wt)	8.3* [17]	0.05	0.041 [11]
Dry wood (15% wt)	15.8* [17]	-	-
MSW	12.3 [18]	0	0.52 [11]
Sludge (WWTP)	2.97 [18]	0	0
Elec. Import	-	0.16	-

Table 2: Data for resources: lower heating value (LHV, *on a wet basis), cost and environmental impact.

3.2 Demand and district heating network

The energy demand of the city is divided into heating, electricity and transportation. Table 3 shows the values calculated for the end-uses in energy services for the City of Lausanne based on the available data. For electricity and heating, average power values are considered for the different periods in order to account for the seasonal variation in energy demand. Transportation is assumed to be constant over the different periods, with a share of 19.5% attributed to public transportation (year 2012).

Heating demand is partly satisfied by a DHN. For the year 2012 the total length of the network is 100 km, with an investment cost of 3000 CHF/m and an operation and maintenance cost of 8 CHF/m/year. As shown in Figure 2, the units “dhn” and “decentralized” are used to transfer heat from the respective locations of heat production to the heat demand cascade. In the model definition, the ratio between centralized and decentralized heat production is maintained constant by fixing the f_{mult} of the “dhn” unit. The feeding temperature of the DHN is 130°C, the return temperature is 70°C, and heat losses in the network are assumed to be 15%.

Period	Electricity [MW]	Heating [MW]		Transportation [Mpkm]	
		DHN	Decentralized	Private	Public
Summer	59.46	18.07	59.81	207.0	852.7
Winter	83.02	63.73	210.9	207.0	852.7
Mid-season	77.13	31.11	102.3	207.0	852.7
Peak	124.7	108.5	410.85	207.0	852.7

Table 3: Characterization of end-uses in energy services for the City of Lausanne.

3.3 Geothermal

3.3.1 Resources

The City of Lausanne does not present particularly favorable geological characteristics in terms of geothermal resources. The geothermal gradient in the area is 0.03°C/m. In this work, deep aquifers and EGS are considered. For aquifers, data for the Malm and the Muschelkalk aquifers [19] are considered at a depth of 2 km and 3.8 km, respectively. The 2 km aquifer is not included as a model in this case study as its temperature level is too low in comparison to the temperature of the city’s DHN. For EGS drilling costs are updated with recent values available from the software environment GEOPHIRES [20]. Table 4 shows the key data for the considered resources at different depths with the following characteristics: depth, water expected mass flow rate, pumping power, total heat extracted, temperature at well (T_{well}), reinjection temperature (T_{inj}), total investment cost (including stimulation, exploration and drilling), and cost for operation and maintenance. Emissions related to drilling are calculated in the post-computation phase according to the LCA methodology presented in [21]. The project lifetime is assumed to be 30 years for all the considered resources.

Resource	Depth [km]	Mass flow [kg/s]	Pump [kW]	Heat [kW]	T_{well}/T_{inj} [°C]	C_{INV} [MCHF]	$C_{O\&M}$ [MCHF/y]
Malm	2	25 [19]	30.1 [20]	3780 [22]	65/29 [22]	9.64 [20]	-
Muschelkalk	3.8	13.5 [19]	3.5 [20]	2552 [22]	115/70 [20]	21.79 [20]	0.398 [20]
EGS	4.2	100 [20]	1231 [20]	22841 [20]	125/70 [20]	37.93 [20]	1.407 [20]
EGS	5	100 [20]	1180 [20]	31241 [20]	145/70 [20]	49.16 [20]	1.832 [20]
EGS	6	100 [20]	1053 [20]	41793 [20]	170/70 [20]	64.74 [20]	2.405 [20]

Table 4: Data for geothermal resources: deep aquifers and EGS.

3.3.2 Energy conversion cycles

The energy conversion cycles associated with the identified resources are taken from the optimal configurations presented in [21]. For electricity production, ORCs are considered for the resources deeper than 3.8 km with a single-loop configuration, while a supercritical (SC) cycle is chosen for the 6 km EGS. The high temperature of the city's DHN does not make it an optimal solution for cogeneration with geothermal resources. For this reason, only a Kalina cogeneration cycle at 6 km is chosen, being the only one with temperature levels able to partially satisfy the network demand. Table 5 details the working fluid and the electrical efficiency of the different cycles. Investment costs are calculated in the post-computation phase based on the equipment cost functions available in OSMOSE [12]. As for the resources, environmental impacts are calculated with the LCA methodology presented in [5]. The electrical efficiency ε_{el} is calculated as the ratio between the net electricity produced by the cycle and the heat power extracted from the geothermal resources (see Table 4). $C_{O\&M}$ is assumed to be 5% of the total investment cost per year.

Cycle	Fluid	ε_{el} [-]
ORC SC 6 km	R134a	18.1%
ORC 5 km	R134a	14.9%
ORC 4.2 km	R134a	13.1%
ORC 3.8 km	R134a	13.2%
Kalina 6 km	NH_3/H_2O	12.3%

Table 5: Data for geothermal energy conversion cycles for electricity production (ORCs) and cogeneration (Kalina).

3.4 Woody biomass

Table 6 shows the key data for woody biomass conversion technologies. For each technology model, inputs and outputs with respect to the layers defined in Figure 2 are associated to a negative and a positive sign, respectively. The wood boiler is modeled to be powered with either wet wood (humidity 50% wt) or dry wood (humidity 15% wt). The wood boiler model presented in [5], realized with the flowsheeting software Belsim VALI [23], is used in order to calculate the variation of efficiency between the combustion of wet wood and dry wood. Results give an efficiency (with respect to the respective wood LHVs on a wet basis, reported in Table 2) of 90.2% for dry wood combustion, decreasing to 87.15% for wet wood. The wood air dryer model in [5] is modified by lowering the air temperature to 165°C. The pyrolysis model is based on average values for the technologies from producers' catalogs. The gasification to SNG model is also taken from [5], and it represents an optimal thermo-economic design.

Model	Wet wood [t/h]	Dry wood [t/h]	Heat [kW]	Electricity [kW]	NG [kW]	Oil [kW]
Wood boiler	(-22.6)	(-11.48)	45403			
Air dryer	-5.785	3.403	-3106	-229.8		
Pyrolysis	-9.5		900	200		15300
Gasification	-8.675		3433	364.3	13424	

Table 6: Data for mass and energy balances of woody biomass conversion technology models.

Table 7 details the cost and environmental impact data assumed for the aforementioned wood conversion technologies at their default size ($f_{mult} = 1$). For the wood boiler, $C_{O\&M}$ = [0.01, 0.015] CHF/kWh of heat produced is assumed. For the other technologies, $C_{O\&M}$ is assumed to be 5% of the total investment cost per year. The environmental impacts for the air dryer, the pyrolysis and the gasification units are calculated based on the volume of the reactors according to the LCA methodology in [24]. For the cost of the dryers, data obtained from producers are used. For the gasification unit a linear interpolation is performed between the values available in [25]. For the pyrolysis, the upper limit of the cost range reported in [26] is assumed.

Model	Lifetime	$C_{INV,1}$ [MCHF]	$C_{INV,2}$ [MCHF]	GWP [$t_{CO2\text{-}eq}$/unit]
Wood boiler	25	1.302 [5]	9.75 [5]	99.96 [11]
Air dryer	50 [11]	0	1.07	76.16
Pyrolysis	25	0	10.44 [26]	181.1
Gasification	25	0	36 [25]	27.98

Table 7: Data for cost and environmental impact of woody biomass conversion technology models (with reference to the technology size in Table 6).

3.5 Mobility

Based on information available from various sources in the City of Lausanne [27], a model for mobility in the urban system is developed. Specific mobility demand is estimated to be 7735 pkm/capita/year. Table 8 details all the data for the mobility models for both public and private transportation in the city. Total mobility demand in 2012 is estimated as 1060 Mpkm, with a 19.5% share of public transportation. For the future scenarios (year 2035), as detailed in the next section, specific mobility demand is assumed to remain constant and the share of public transportation to increase up to 28.5%.

For the cost model, investment and O&M costs are neglected, while emissions related to unit construction are included in the assessment of the environmental impact indicator.

Type	Technology	GWP [$t_{CO2\text{-}eq}$/u]	Year 2012			Year 2035		
			[MJ/pkm]	pkm [%]	[p/v]	[MJ/pkm]	pkm [%]	[p/v]
Public	Metro	324.3	0.338 [27]	47.9%	63	0.338	41.8%	63
	Trolley Bus	32.43	1.354 [27]	31.4%	13	0.704	35.1%	25
	NG Bus	32.43	3.13	8.17%	9	1.76	8.46%	16
	Diesel Bus	32.43 [11]	2.94 [27]	12.5%	8	1.47 [27]	14.6%	16
Private	Petrol car	6.79 [11]	1.774 [11]	75.3%	1.6 [28]	1.548	50%	1.6 [28]
	Diesel car	7.21 [11]	1.535 [11]	24.4%	1.6 [28]	1.381	40%	1.6 [28]
	NG car	6.79 [11]	1.751 [11]	0.44%	1.6 [28]	1.648	5%	1.6 [28]
	PHEV* car	7.59 [11]	0.78/0.2^{el} [11]	0	1.6 [28]	0.64/0.16^{el}	5%	1.6 [28]

Table 8: Data for the mobility model. Fuel economy [MJ/pkm], CO_2-eq. emissions related to construction ("u": unit), relative share and average occupancy [person/vehicle] for private and public transportation for the City of Lausanne for the year 2012 and for the year 2035 scenarios. (*PHEV: plug-in hybrid electric vehicle with fuel petrol/electricity).

3.6 Other technologies

Large-scale gas and oil boilers, providing heat to the DHN, are modeled with an efficiency of 87.5% (on a LHV basis) for the year 2012, increased to 95% for the 2035 scenarios. For the cost and emission assessment, the same assumptions as for the DHN wood boiler are used (Table 7). The large-scale centralized boiler is the only technology assumed to be able of burning bio-oil produced with the pyrolysis unit. For decentralized natural gas boilers an efficiency of 95% is assumed, together with $C_{O\&M}$ = 0.03 CHF/kWh and investments costs of 0.08 CHF/kWh of heat produced [29]. For decentralized oil boilers an efficiency of 85% is assumed, together with $C_{O\&M}$ = 0.04 CHF/kWh [29] and investment cost equal to centralized boilers. For both types of decentralized boilers, lifetime is assumed to be 20 years and emissions related to construction are 0.702 $t_{CO2\text{-}eq}$/unit for a 55 kW_{th} unit [11].

The MSWI of the city is a cogeneration power plant, burning in 2012 161 kt of MSW and 15.4 kt of wet wood, with a mass flow input rate assumed to be constant over the year. For the same year, the total net output of the power plant is 63.2 GWh_e (of which 26.1 GWh_e used for electricity supply in the City of Lausanne) and 256 GWh_{th} sent to the DHN. The maximum efficiency of the power plant is calculated as 81.9%. In the model, the amount of electricity produced during the different periods is set as constant, and the heat available is calculated as the difference between the total output and the electricity produced, this in order to calculate the amount of available excess heat in summer. The total investment cost of the power plant is 144 MCHF. Emissions are calculated in the post-computation for the different components of the power plant using data from [11] with a 30 year lifetime.

For the WWTP the model includes only the boiler for the combustion of the dry sludge obtained from the waste water. The input to the boiler is 1.106 kg/s of dry sludge and 560 kW of natural gas for the combustion process. The total energy efficiency of the power plant is calculated to be 60.2% and the heat produced is delivered to the DHN. Lifetime is 25 years and total investment cost is 9.9 MCHF (fixed size). In the various scenarios both the combustion of the dry sludge and of the MSW are considered as a requirement of the energy system, therefore the multiplication factor f_{mult} of these technologies is fixed to the 2012 value.

Due to its dominant share in the electricity production of the city, hydroelectricity is also included in the urban system model. The installed capacity for the city of Lausanne consists of three Kaplan turbines, each with a plate capacity of 31 MW_e, with the plan of installing an additional unit. The multiplication factor of the technology is set in order to match the actual capacity factor in the different seasons and the technology is given priority for electricity supply in the model. $C_{O\&M}$ are 0.003 CHF/kWh, lifetime is 40 years, investment cost is 5300 CHF/kW and emissions are 0.0035 $kg_{CO2\text{-}eq}$/kWh [30].

4. SCENARIOS

The first goal of the developed model is to map the current energy system of Lausanne (year 2012). Then, in order to evaluate the integration of the considered biomass and geothermal technology options, a set of "ad hoc" scenarios is defined for the year 2035. Some simplified assumptions are made about the evolution of the Lausanne energy system between 2012 and 2035:

- Population growth: a 0.7% yearly rate is assumed for the demographic growth, increasing the urban system population from 137000 inhabitants in 2012 to 161000 in 2035.
- Demand in energy services: the specific demand per capita in energy services for electricity and transportation is assumed to remain constant, with the share of Mpkm provided by public transportation increased to 28.5% in 2035 and fuel efficiency evolution as in Table 8. The total heating demand is assumed to remain constant due to the balanced effect of population growth and building efficiency. The DHN is assumed to have a yearly increase rate of 2%, leading to a total length of 150 km in 2035.
- Electricity production: as previously detailed, the installation of a new 31MW_e Kaplan turbine is considered.
- Gas and oil boilers: an increase of efficiency from 87.5% to 95% is assumed for DHN boilers. For decentralized boilers, an increased share of the heat demand is satisfied by natural gas boilers (60%), with 40% satisfied by oil boilers.

#	Year	Woody Biomass	Geothermal
0	2012	15.4 kt/y MSWI	-
1	2035	15.4 kt/y MSWI	-
2	2035	15.4 kt/y MSWI	3.8 km direct use
3	2035	15.4 kt/y MSWI	4.2 km direct use
4	2035	15.4 kt/y MSWI	6 km Kalina
5	2035	15.4 kt/y MSWI	5 km ORC
6	2035	100 kt/y Boiler (wet)	-
7	2035	100 kt/y Boiler (dry)	-
8	2035	100 kt/y pyrolysis	-
9	2035	100 kt/y gasification	-
10	2035	100 kt/y pyrolysis	4.2 km direct use
11	2035	100 kt/y pyrolysis	4.2 km ORC
12	2035	100 kt/y pyrolysis	6 km Kalina
13	2035	100 kt/y gasification	5 km direct use
14	2035	100 kt/y gasification	6 km Kalina
15	2035	100 kt/y gasification	3.8 km ORC
16	2035	100 kt/y Boiler (dry)	6 km ORC
17	2035	100 kt/y Boiler (dry)	4.2 km direct use

Table 9: Lists of scenarios considered for the evaluation of geothermal and biomass options.

Table 9 lists the scenarios considered for the evaluation of the different options for geothermal and biomass. Scenarios 0 and 1 assess the base case reference scenarios for the years 2012 and 2035 respectively, with 15.4 kt/y of wet wood burned in the MSWI and no geothermal installation. Scenarios 2-5 evaluate different options for geothermal addition to the 2035 base case scenario, without changing the use of wood. From scenario 6 on, the use of wood is increased to its maximum potential (100 kt/y). First (scenarios 6-9) different options for biomass conversions are evaluated with reference to the 2035 base case scenario: combustion in the DHN wood boiler (wet or after drying), pyrolysis for bio-oil production for the DHN oil boiler, gasification for SNG production. Scenarios 10-17 evaluate different combinations of biomass and geothermal technology options in order to account for heat integration possibilities. In scenarios with geothermal conversion cycles, as a simplifying assumption the cycles are assigned a fixed multiplication factor for all the periods. For biomass technologies, storage of resources is allowed across the different periods.

4.1 Results

Scenario 0 assesses the performance indicators for the City of Lausanne in the year 2012, leading to a total yearly annual cost of 382.3 MCHF/year and total emissions of 656.3 $kt_{CO2\text{-}eq}$/year. Figure 4 shows the results for the year 2035 scenarios listed in Table 9. In agreement with the performance indicators definition (section 2.2) Figure 5 shows the breakdown of the total emissions and total annual cost for the urban system. The GWP 100a indicator is the sum of the emissions from equipment construction ("Transport", "Hydro" and "Other" technologies, including geothermal and biomass) and from resources (fuels and electricity import). The total annual cost is the sum of the annualized investment and O&M costs (MSWI, WWTP, DHN, hydro, fossil fuel boilers, geothermal) and of the cost of resources (in the figure, "Wood" includes the costs of both the technology and the resource).

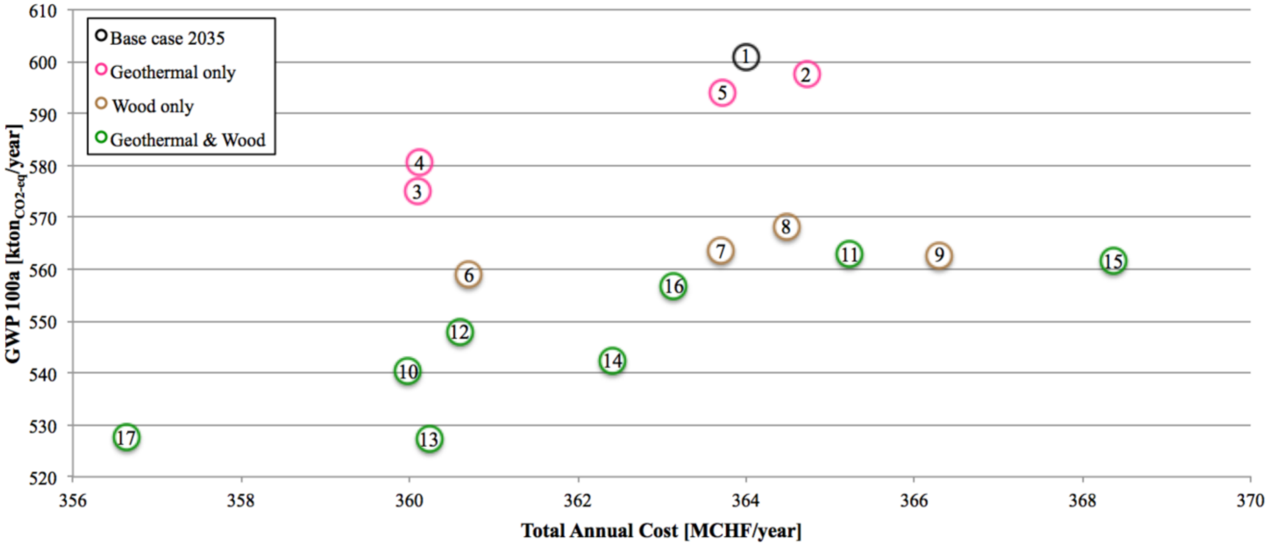

Figure 4: Results of scenarios 1-17 (year 2035) in Table 9 with respect to total annual cost and GWP 100a performance indicators.

Scenario 1 is the base case reference for the year 2035 with a total annual cost of 364 MCHF/year and total emissions of 601 kt$_{CO2-eq}$/year. In this scenario, higher costs are due to the increased size of the DHN and to the increase in electricity demand, partly satisfied by the installation of an additional hydroelectric turbine. The total annual costs are, nonetheless, lower compared to 2012. This is explained by the possibility of fully using the MSWI heat production capacity during the summer period, combined with an increase in efficiency and a higher share of public transportation. In the 2012 scenario, in fact, the summer demand of the DHN is substantially lower than the heat production capacity of the MSWI cogeneration plant. This additional heat is enough to completely cover the DHN demand for the year 2035 during the summer period. In scenario 1, the remaining part of the total DHN yearly demand (689.9 GWh) is satisfied by the WWTP (16.35 GWh) and by a centralized natural gas boiler (313.8 GWh). The full exploitation of the MSWI heat production is also the main reason for the decrease in CO_2-eq. emissions, together with the decreased share of decentralized oil boilers. The different electricity import mix and the higher electricity demand increase the impact of imports from 3.6 kt$_{CO2-eq}$/year in 2012 to 25.7 kt$_{CO2-eq}$/year in 2035.

Scenarios 2-5 evaluate different options for the deployment of geothermal technologies. For a direct use of the geothermal heat in the DHN, the 4.2 km EGS installation (scenario 3) is more advantageous than the 3.8 km Muschelkalk aquifer (scenario 2), due to the much lower capacity of the latter although with comparable investment costs (see Table 4). In scenario 3, the 4.2 km EGS allows for reducing the use of the DHN natural gas boiler to 204 GWh/year, although there is no use for the geothermal heat in summer due to the contribution of the MSWI. The option of a 6 km Kalina cogeneration power plant (scenario 4) presents higher total costs and emissions compared to the previous solution, due to higher investment costs only partially balanced by a reduction of natural gas consumption in the DHN boiler and of electricity imports. The high temperature of the city DHN limits the interest of a geothermal cogeneration option for the city. Scenario 5 evaluates the option of a 5 km ORC for electricity production (30 GWh$_e$/year). The option does not seem of interest, as the annual cost savings in electricity imports are comparable to the investment and O&M costs for the geothermal drilling and the electricity production power plant.

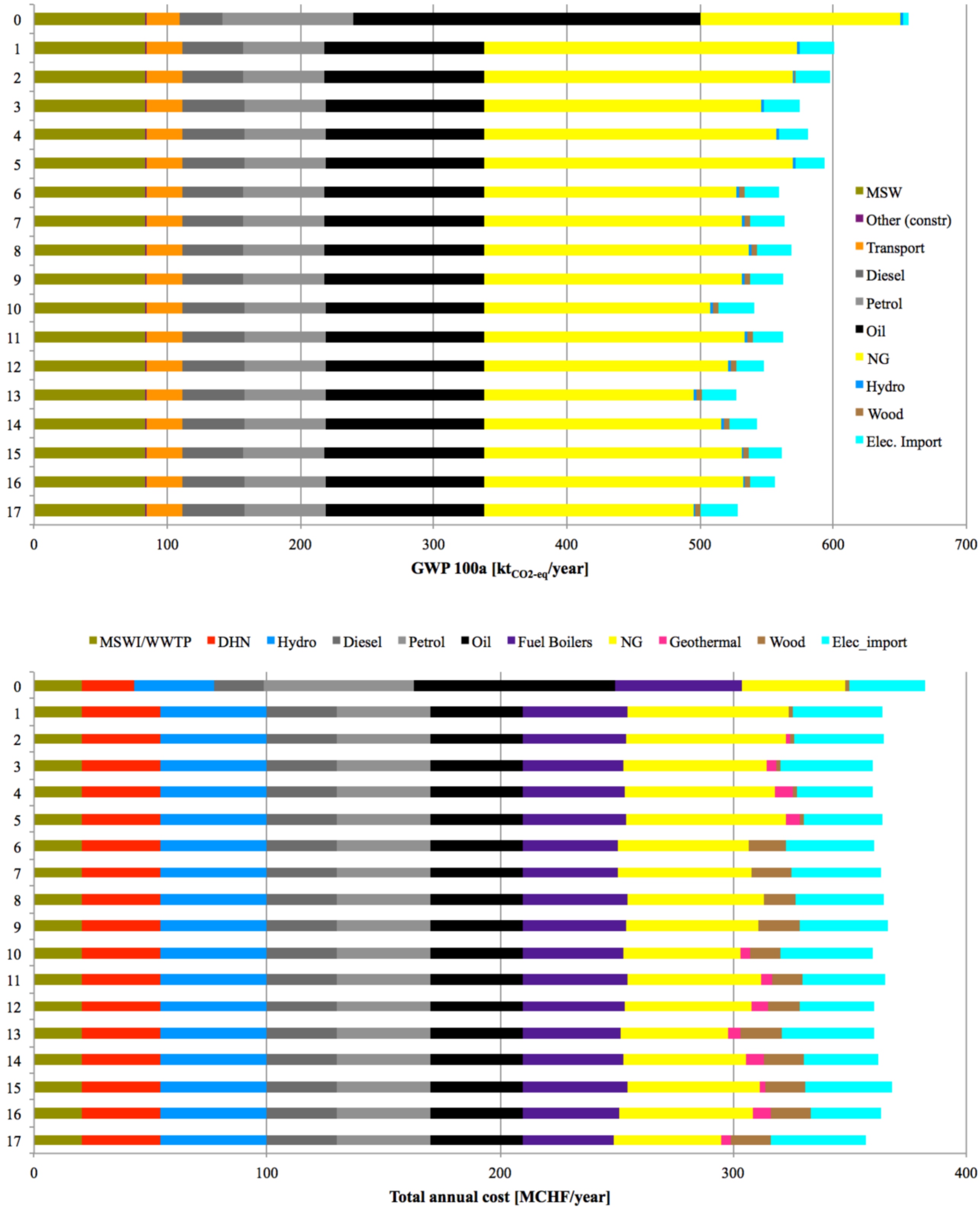

Figure 5: Breakdown of the different contributions to the two performance indicators for the different scenarios: total environmental impact (GWP 100a) and total annual cost of the urban energy system.

Scenarios 6-9 evaluate different options for the deployment of biomass conversion technologies, assuming the maximum potential of 100 kt of wet wood. The direct combustion of wet wood in DHN boilers (200.9 GWh/year) allows for a reduction of the centralized fossil fuel boilers heat production to 131 GWh/year, with a 7% reduction of the urban system global emissions. In the absence of excess heat availability in the system, it is not interesting to industrially dry the wood prior to combustion (scenario 7), as the gain due to the increased efficiency of burning dry wood (+ 15.7%) is lower than the total cost of the dryer (including production of additional heat requirements). Scenario 8 evaluates the conversion of wood to bio-oil through pyrolysis for combustion in DHN boilers. The lower efficiency of the process (153 GWh/year of heat production at the bio-oil DHN boiler) compared to the direct combustion leads to worse values for both performance indicators, while the annual investment costs are slightly higher compared to scenarios 6 and 7. The option of SNG production by wood gasification has a better performance in terms of environmental impact due to the higher efficiency (155 GWh/year of SNG production and 39.6 GWh/year of heat), in trade-off with substantially higher investment costs.

Scenarios 10-17 evaluate various options for the integration of biomass and geothermal technologies. The coupling of pyrolysis with direct use of geothermal heat (scenario 10) allows for a strong reduction of the heat production by the natural gas boiler, limited to 54 GWh/year in the winter period with the consequent savings in CO_2-eq. emissions. For ORC and Kalina options (scenarios 11, 12), results are similar to the previous scenarios for the same technologies, shifted by the contribution of pyrolysis. Similar considerations can be drawn for the combination of geothermal and gasification technologies (scenarios 13-15). In this case, the option of using direct heat from a deeper EGS (5 km, scenario 13), allows for achieving the lowest environmental impact (527.4 $kt_{CO2\text{-}eq}$/year), due to the almost complete replacement of fossil fuels in the DHN supply. The potential cost savings are limited by the high investment cost of this scenario, which presents as well a substantial share of geothermal heat losses in summer.

Scenario 17 proposes a possible way to use the excess geothermal heat in summer through process integration. As in scenario 3, a 4.2 km EGS is deployed for direct use of heat. The excess heat available in summer in the DHN, partly from the MSWI (at higher temperature) and partly from the geothermal resource, is enough to satisfy the heat requirements of an air dryer as the one presented in Table 6 (100kt/y of wet wood dried during summer). In this way, the wood drying process acts as a seasonal storage solution for the otherwise wasted geothermal heat. The more efficient combustion of dry wood in winter allows a fossil fuel free DHN, with emissions very close to the best case of scenario 13, as well as lowest total annual costs (356.6 MCHF/year, -2% compared to scenario 1) due to the lower investment requirements.

CONCLUSIONS

A complete urban energy system model is realized for the European City of Lausanne (Switzerland) to assess the current situation of the energy system (year 2012) and the possibilities for biomass (combustion, pyrolysis, gasification) and geothermal energy (deep aquifers and EGS for direct use, cogeneration, ORCs) integration in the future energy strategy.

A set of scenarios is evaluated for the year 2035 in order to assess the feasibility of the various options in terms of the total annual cost of the city and the global GWP environmental impact. In particular, pinch analysis and process integration are applied to evaluate the use of excess heat in summer. The option of direct use of heat in the district heating network results to be the most interesting deployment of EGS for the city, while the cogeneration option is limited by the high temperature of the network specific to this case study. Results suggest the interest of using the excess of geothermal heat in summer for integration in the biomass drying process. The storage of geothermal energy in form of dry wood for combustion in winter allows a complete replacement of fossil fuels for the district heating network supply.

Future work involves the refinement of the methodology for urban system modeling, including all indicators in the MILP formulation. A more detailed analysis of the case study is envisioned, including estimates for storage, transportation and heat exchanger network cost. Impact of uncertainty is also expected to be taken into account in the optimization framework.

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