Grid based energy system setup optimisation with Rivus in dedicated regions

Fabian Hofsäß[1], Maurizio Santin[2], Massimiliano Condotta[3], Markus Biberacher[1], Damiana Chinese[2], Giovanni Borga[3]
[1]Research Studio iSPACE
Schillerstraße 25, 5020 Salzburg, Austria
Phone: +43 662 90 85 85 222
E-Mail: fabian.hofsaess@researchstudio.at
[2]DPIA, Università di Udine
Via delle Scienze, 206, 33100 Udine
Phone: +39 0432558024
E-Mail: damiana.chinese@uniud.it
[3]Università Iuav di Venezia
Santa croce Dorsoduro 2196, Cotonificio veneziano,30123 Venezia, Italy
Phone: +39 0412571271
E-Mail: condotta@iuav.it

SUMMARY

Within the project *IDEE* (Integrated Design Efficient Energy systems in urban regions) the expertise of four cross-border (Italia & Austria) research centres and one public authority is bundled up to support the planning of new setups or the extension of existing setups in grid based sustainable energy systems for pilot regions inside the project areas. A special focus within the project is the optimization of network topologies in district heating setups. First scenarios on possible system setups for the pilot regions have been calculated outlining the topology of optimal pipe setups as well as the load of (Heat-) pipes at different time steps with the objective to minimise overall system costs.
Keywords: District heating, Optimization, Network calculation, MILP

INTRODUCTION

The heating systems of residential and commercial buildings in urban areas are mainly supplied from grid based energy systems: natural gas grids typically feed boilers, power grids may feed different types of heat pumps and resistance heating, and district energy systems, directly supply users with heat carriers. District heating systems, in particular, are generally recognized (Lund et al., 2016, Hast et al., 2018) to be an essential part of decarbonisation and renewable energy strategies, at least in continental Europe (Finney et al., 2012).
However:
- the market penetration of different grids is different in cities, in urban and rural areas (Soltero and Chartegui, 2018), as well as across Europe (Werner, 2017), particularly on the two sides of the Alps;
- it is recognized (Köfinger et al., 2016, Lund, 2017) that, with decreasing heating demand of building stock, district heating networks need to evolve into so called 4th generation district energy, i.e. into smart and low temperature systems, to remain competitive with other technology options.

In this context, the *INTERREG* project *IDEE* aims to develop integrative planning tools, which allow the quantification of complex correlations appearing in grid based systems. In particular, the project objective is to identify least costs systems for achieving emission reduction and energy efficiency improvements in Austrian and Italian program areas and to the dedicated pilot regions Maniago, Feltre and Salzburger Seenland.
Optimization based on mixed integer linear programming (MILP) has been recognized as the most widely applicable approach to support district heating systems planning (Sameti and Haghighat, 2017). In the last decade, GIS have also been increasingly used for managing all data relevant for district

energy, such as heating demand (Finney et al., 2012) and costs of connecting different urban areas with different grids (Möller and Lund, 2010, Nielsen and Möller, 2013).
Integrating GIS and MILP has thus emerged as a state of the art methodology for grid based energy systems planning; however, only a few recent models are reported in literature.
Delmastro et al. (2016) integrate GIS and optimization by using a modified version of the Steiner algorithm, typically used for power grids, in order to produce optimized layouts for district heating grids taking into account demand as a quali-quantitative importance factor.
Unternährer et al. (2017) focus on large urban areas with a high number of buildings and propose a combination of preliminary clustering algorithms and minimum spanning trees.
While previous models mainly aim at network layout optimization, the model *RIVUS*, developed by Dorfner (2016) adds the sizing of energy conversion processes, and thus allows a more comprehensive evaluation of alternative urban energy systems. Moreover, unlike previous models, *RIVUS* is an open source model, implemented in Python, and it enables simultaneous modelling of different energy grids (gas, power and district energy).
For these reasons, *RIVUS* was chosen as a starting point for the development of *IDEE* methodological framework and its application in the project pilot areas.

METHODOLOGY

Preliminary panels and discussions with stakeholder of pilot areas highlighted a strong interest in district heating which is perceived as a means to promote energy and economic savings and, most evidently, to reduce local air pollution. Interest for CO2eq emission reduction has been mainly expressed in Austrian pilot regions, which belong to the Climate and Energy Model Regions of the Klimafonds program. Besides economic information, decision makers thus mainly require information on air emissions. However, a literature review performed at the beginning of the project (Chinese et al., 2018) has highlighted that in district energy planning models greenhouse gas emissions are commonly taken as a proxy for overall environmental impact. Just a few studies take other air pollutants (Genon et al., 2009, Fang et al., 2013, Li et al., 2016) and environmental impact categories into account (Oliver-Sola et al., 2009, Ghafghazi et al., 2011, Bartolozzi et al., 2017): such studies show that sometimes trade-offs arise between reducing global emissions, i.e. greenhouse gases, and local emissions, such as NOx, SOx and particulate matter. RIVUS structure is suitable to evaluate several energy and material flows (commodities), up to now, however, only calculations of CO2eq has been reported for some German case studies (Dorfner, 2016).

RIVUS MODEL IMPLEMENTATION FOR ECONOMIC AND ENVIRONMENTAL ANALYSIS

RIVUS has the objective to identify minimum cost scenarios for grid based heating infrastructures through Mixed-Integer-Linear-Programming (*MILP*). The cost function is build up out of investment, fix und variable costs. Costs have to be paid for the network grid, for the supplied energy and for technical processes.

$$\sum cost = \sum inv + \sum fix + \sum var \qquad (1)$$

There are two types of technical processes, domestic (hub) and central processes. Each one has a specific investment cost (€/kW), but only the central process has an additional fixed investment cost (€), which accounts for size-independent investment costs. The network grid has fixed investment costs (€/m) and variable investment costs (€/kW/m). Each purchase energy unit is also part of the cost function (€/kWh), and additional specific fixed costs (€/kW) and variable costs (€/kWh) can be introduced to account for further operational expenses such as maintenance.

In *RIVUS*, the complete process chain with all relevant commodity transformation processes, related efficiencies and costs are considered. All estimated demands are either satisfied through a grid based supply system (e.g. district heating, natural gas or electricity) which is tied to the topology of the (advanced road) infrastructure or satisfied through an alternative predefined option. The status-quo of the existing grid based energy infrastructure is considered as starting point for any optimized system setup. The model identifies the least cost system setup which satisfies all geo-localized demands by either through a connection to the district heating grid or local supply options (etc. heat pumps).
The *RIVUS* model provide as output the optimal system setup as snapshot for one specific year; to opportunely weigh long term investment costs stretching over *n* years with the interest rate *i*, the equivalent annual cost method is used, multiplying present investment costs by the annuity factor *ANF*:

$$ANF(n,i) = \frac{(1+i)^n * i}{(1+i)^n - 1} \qquad (2)$$

RIVUS separates the energy demand in different time scopes. For each declared time scope, the amount of hours and the fraction of the energy demand has to be declared. In the upcoming scenarios, the four original time scopes specified in *RIVUS* have been used for Salzburger Seenland; for northern Italy, the duration curves calculated in Chinese et al. (2018) have been used.
The outcome of the *RIVUS* is a cost optimal system setup for the energy supply. Related emissions are not part of the objective function but part of user set absolute constraints in the model. Emission values for CO_2eq, NOx, SO_2 and particulate (PP) in combustion processes have been incorporated into the model within the *IDEE* project. Emission factors related to net heat generation based on the IINAS database (2018) have been assumed. For local pollutants, such as NOx, SO_2 and particulates, only direct emissions were accounted for. Since emissions of greenhouse gases are global, a life cycle oriented approach was taken, providing also an assessment of life cycle CO_2 emissions as reported in Chinese et al. (2018). Credits for avoided remote electricity production have been assigned, and subtracted from direct CO2eq emissions, in case cogeneration systems are chosen as an energy source for municipal systems. Emission factors for the national energy mix of Italy and Austria were obtained from Chinese et al. (2017).
Centralized woodchip boilers and woodchip based ORC - CHP systems have been considered as sources for district energy systems. Heat recovery from nearby process industries was also considered for Italian case studies: in that case, it was assumed that no additional emissions occurred when connecting the system to district heating.
Based on local conditions, it was chosen to examine electric resistance heating as alternative to district heating in the Austrian case study, while natural gas heating has been taken as the alternative option for Italy.
Electricity domestic heating does not produce local pollution and only the CO_2 equivalents of the Austrian energy mix are hence considered. For natural gas, direct emissions for boilers up to 1 MW are evaluated. Indirect life cycle emissions were also evaluated for CO2eq, but bounds are always set to direct emissions only.

GIS PREPROCESSING AND NETWORK GRID MODELLING

For Austrian pilot regions, the location and capacity of existing power plants are derived from Open Government Data (SAGIS, 2018), for Italian regions information on existing power plants is obtained from the RSE Atlas (GSE atlas, 2018) and integrated with local information on available energy or waste heat sources.
All data are collected and administrated in a database, which is linked to the *RIVUS* model (Havasi, 2017).

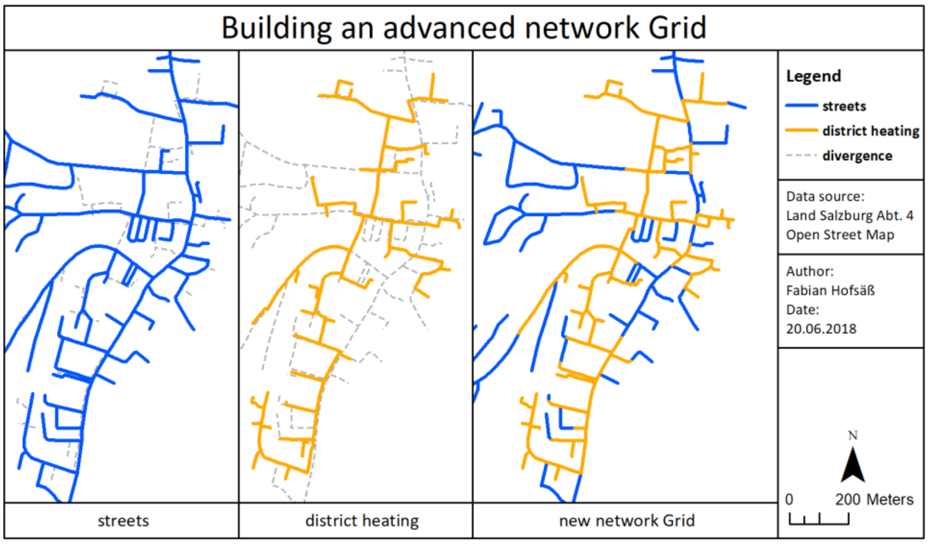

Figure 1"progress of fitting two networks together"

Open Street Map data have been proven an appropriate data source to serve as base layers for describing the building and infrastructure stock. The existing road network is considered as indicator dataset for future grid based supply infrastructure and is therefore the foundations of the grid based solution. Embedding the current supply infrastructure like heat pipes to the existing road network has been made by a semi-automated progress. The status-quo of the existing district heating network for the Austrian project area has been provided by Land Salzburg. The selected heat pipes are snapped to the road network. Thus, an advanced road network with new major grid lines is built.

ESTIMATING ENERGY DEMAND

One of the key aspect in Designing Efficient Energy systems in urban regions is to estimate, with accuracy, the energy demand of building stock i.e. the energy flows to be delivered to each single building.

Generally, for the assessment of the annual energy use for space heating and cooling of a residential or non-residential building is used the European standard formula (European Committee for Standardization, 2008):

$$QH,nd = (QH,tr + QH,ve) - \eta H,gn\ (Qin + Qsol) \qquad (3)$$

This method includes the calculation of the heat transfer by transmission and ventilation of the building and the contribution of internal and solar heat gains to the building heat balance. The result is the annual energy that is required by a building.

We decided to use this method to calculate the energy demand of each single building to be implemented in *RIVUS*. Of course, it is not possible to run a simulation for each and every building in a city. The solution is to apply a characteristic transmission loss, ventilation loss, internal gain and solar gain value to each edifice of the city, which depends on the building functional typology, dimension and technological features that are related to building age. The characteristic energy demand value of each single building is then calculated according to the formula (3) by multiplying a characteristic energy loss or energy gain (in kWh/m^2y) by a geometric parameter which is specific for the building (in m^2). It is done for each individual building in considered area with regard to the specific geometry of each single building.

The characteristic energy loss or energy gain values (in kWh/m^2y) are deduced from a series of dynamic energy simulation runs on a set of typical buildings selected among different building typologies. The dynamic simulations have been done using the software Energy Plus (2018) developed by the US Department of Energy and the graphic interface Design Builder Software Limited.

The geometric parameters of each single building are based on land registry data and national census databases and processed with GIS tools. Geometric information on buildings layouts and information about floors numbers and functional typology is derived from the cadastre. Information about buildings age come from elaboration of national census data, where available, integrated with the results of local surveys performed during the project.
A detailed description of the methodology applied to the Italian case studies can be found in (Condotta, 2018)
For the Austrian side, a similar modelling of typical buildings using the method described is still under development. For the present analysis, the estimates of building energy demand in the project area are calculated using indicators based on gross floor area, which are based on building age and building type (Rehbogen et al., 2018).

MODEL APPLICATION AND SCENARIO DEFINITION

A showcase of the described integrative approach has been performed for Feltre (Italy) and Seeham (Austria). Both Scenarios have similar settings, but different demands, sources and topology.

Scenario "Feltre"
As many Italian towns, Feltre currently hasn't any district heating system and relies almost 90% on natural gas. The current analysis for Feltre takes into account two technology options to meet domestic heat demand: domestic boilers fuelled with gas and district heating. In particular, district heating is assumed to be connected to a biomass boiler using woodchips and/or to a waste heat recovery from a metallurgical company located in the industrial area. The base scenario set up for Feltre aims at system cost minimization with no additional constraint: in this case, *RIVUS* identifies the existing natural gas network, whose infrastructure costs are assumed to be sunk, plus a small district heating network as the least cost option, due to the low cost of biomass. In terms of total CO2 emissions, this probably corresponds to the current situation of Feltre, since wood combustion in domestic ovens is the second energy source after natural gas.
Two follow-up scenarios are hence evaluated with the additional constraint of reducing total CO2 equivalent emissions from the entire system by 20% and 40%, respectively. A set of potential locations for new biomass boilers was defined based on the availability of land to build new plants, leaving the selection of the minimum cost layout (including combinations of existing natural gas and new district energy systems) to the optimization procedure implemented in *RIVUS.*

Scenario "Seeham"
The Base scenario, for the village "Seeham", represents a notional status quo of the district heating network. In a pre-processing step, the energy supply through the current district heating network was identified for the first Scenario. The follow-up scenarios are limited by a decrease output of the emitted CO2 equivalents of the Base scenario. The reduction steps of the CO2 are set, as for Feltre, to 20 and 40 percent. Electric resistance heating is assumed to be the only alternative to biomass based district heating in Seeham: as a result, the model outcome shows a high potential in upgrading the district heating network. To limit the enlargement of the district heating network in the scenarios to similar targets as in Feltre, costs of the heat pipes were first artificially increased. Once corresponding layouts had been obtained, regular market prices of heat pipes were then assumed to evaluate actual costs of modelled scenarios.

RESULTS

For a first evaluation of the results obtained in combining GIS-tools with MILP, a simplified plot showing only the layout of DH networks is provided in Figure 3.

For Feltre, two new DH-boilers built in the base case scenario would be sufficient to supply most buildings with district heat. However, there is still a lot of natural gas used for domestic heating especially in times where the demand is significantly high, as it is in “peak” and “high”-load timesteps. By decreasing the CO2 limit the Waste-Heat recovery in the south of Feltre is the best price option for the heat peak demand. As soon as the CO2 limit is further decreased the CO2-free Waste-Heat recovery is chosen to meet energy demand all over the year, completely substituting biomass boilers and thereby decreasing also local pollutants such as particulate and SOx, as shown in Figure 2.

The Seeham Base scenario is reflected by the current installed DH-network. By decreasing the CO2 limit some branches are installed in the near distance to the current network. The output of last scenario shows an ambitious build of DH into the west of Seeham. As soon as a breakpoint is exceeded the DH-network supplies a large part of west Seeham. As shown in Figure 3, this gives an image of the potential of the housings for DH in the west.

Scenario	System costs [k€]	Percentage [%]	District Heating Supply [MWh]	Waste Heat Supply [MWh]	Domestic Heating [MWh]	District Heating pipes length [m]	Percent of supplied buildings in the area [%]	Energy loss [%]
Feltre Base	2069	100	41892	0	2488	16813	99	6.46
Feltre 80% CO2	2305	111	42399	1436	950	17673	99	7.09
Feltre 60% CO2	2388	115	37325	7493	71	17673	99	7.14
Seeham Base	1495	100	3869	0	6729	4002	35	10.52
Seeham 80% CO2	1307	87	5874	0	4932	4971	50	9.75
Seeham 60% CO2	1135	76	7941	0	3074	6235	66	10.10

Table 1 “*RIVUS* Output and Benchmark numbers for the scenario Seeham“

In Table 1 the System cost of Feltre compared to Seeham are cheap if the amount of energy is considered. The costs for DH is for both the same, but the cost for the alternative domestic heat supply is not, in fact electric heating is three times more expensive than gas heating. As a result, the system costs in Seeham decrease when the DH system is expanded. In all scenarios, the amount of heat supplied through DH-networks is increasing, however, this requires higher investments in Feltre.

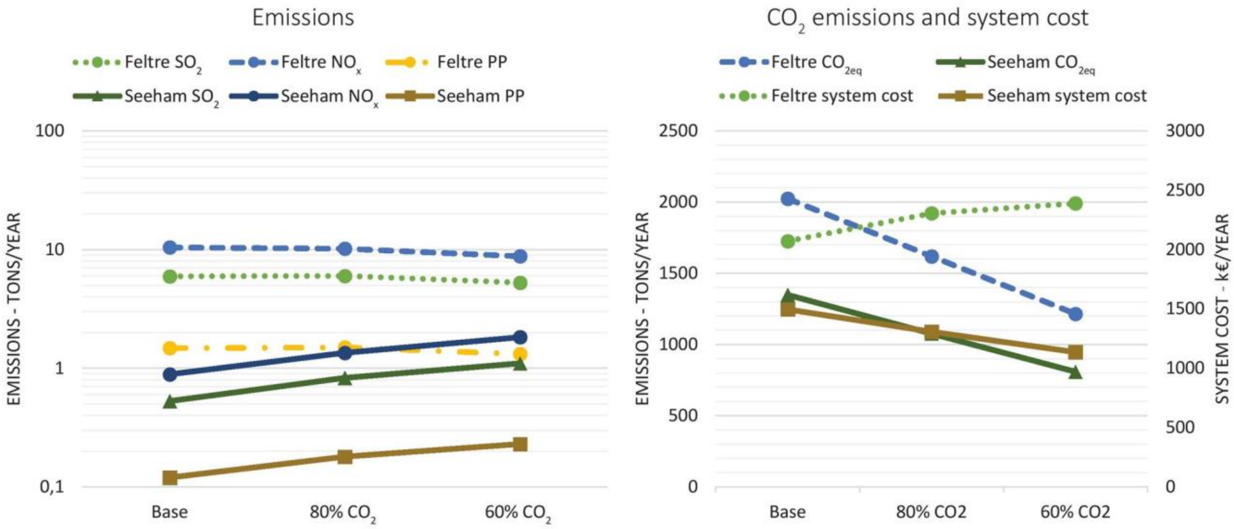

Figure 2 "Summary chart for Feltre and Seeham with all the pollutants evaluated and the systems cost"

In Figure 2 the environmental performance of energy systems in Feltre and Seeham is compared. Regarding the results about Feltre, it can be noted that with the increase of the CO2 reduction constraints a reduction of the air pollutants is reached, in all cases thanks to the incorporation of Industrial Waste Heat into the system, with a more extensive use in the 60% scenario.

For Seeham, the substitution of electric heating with biomass based DH results in higher local pollution (SO2, PP and NOx) when more ambitious CO2 reduction targets are set. From the economic point of view, contrary to Feltre, the system cost is decreasing with the reduction of CO2 emissions.

CONCLUSIONS

In this paper, scenarios on possible system setups for Feltre and Seeham have been calculated outlining the topology of optimal pipe setups as well as the load of heat pipes at different time steps with the objective to minimize overall system costs and setting also CO2 emission reduction constraints. It has been shown that district heating is an opportunity to reduce air pollutants especially if coupled with industrial heat recovery. On the other hand, based on available data, biomass boilers reduce the total amount of CO_2 emitted but the emissions of other pollutants such as SO_2, NOx and PP are increased. From the economic point of view, it has been shown that the reduction of emissions of CO_2 leads to an increase of the system cost in the Italian case study, due to higher costs of low emission options, while costs decrease in the Austrian case study, mainly due to the high costs of resistance heating, which was taken as only alternative. Considering the current state of the market, more realistic results are expected to be obtained for both cases if low temperature alternatives are incorporated into the system, such as heat pumps, e.g. instead of resistance heating, or solar heating, as an alternative or complement to industrial waste heat recovery. Further work in this direction, as well as more detailed sensitivity analysis, is planned to be performed in the scope of the *IDEE* project.

ACKNOWLEDGEMENTS

This research was funded by the European Regional Development Fund - Interreg V-A Italia - Österreich 2014-2020 – Axis 1.1 project IDEE ITAT1007 – CUP G22F16000860007

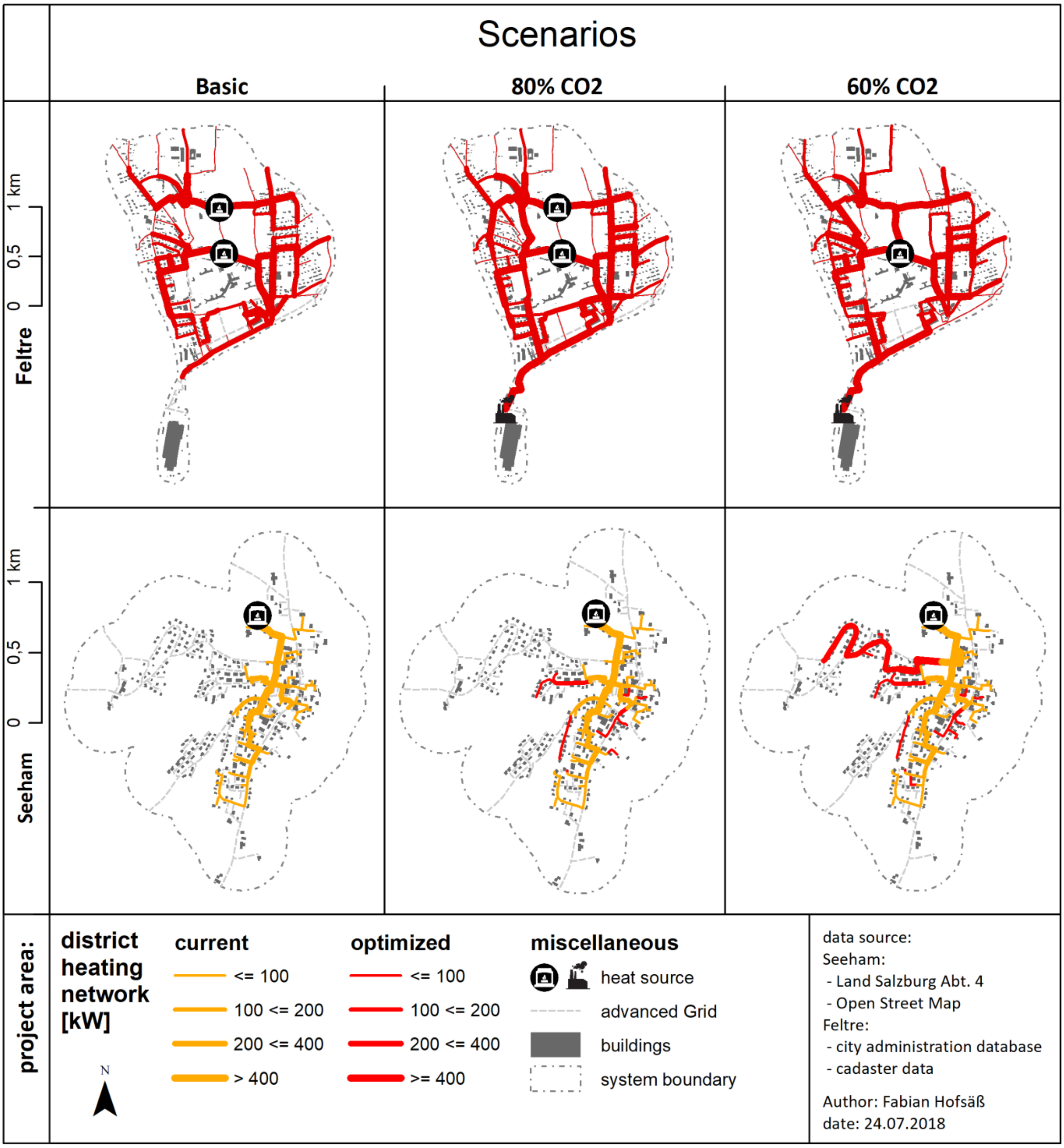

Figure 2"Scenario Feltre & Seeham"

REFERENCES

Bartolozzi I., Rizzi F., Frey M., Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy, *Renewable and Sustainable Energy Reviews*, Volume 80, 2017, Pages 408-420

Chinese, D., Santin, M., Saro, O. (2017) Water-energy and GHG nexus assessment of alternative heat recovery options in industry: A case study on electric steelmaking in Europe, *Energy*,Volume 141,2017,Pages 2670-2687

Chinese, D., Santin, M., Angelis, A., Saro, O., Biberacher, M. (2018), What to do with industrial waste heat considering a water-energy nexus perspective, *Proceedings of the eceee Industrial Efficiency Conference*, Berlin, 2018

Condotta, M., Borga, G. Urban energy performance monitoring for Smart City decision support environment. In *Techne special Issue 01/2018*, Firenze University Press, Firenze, Italy.

Delmastro, C., Mutani, G. & Schranz, L. (2016), The evaluation of buildings energy consumption and the optimization of district heating networks: a GIS-based model, *International Journal of Energy and Environmental Engineering* 7: 343

Dorfner, Johannes; Open source modelling and optimization of Energy Infrastructure at urban scale. Ph.D. Thesis, Technical University of Munich, 2016,

European Committee for Standardization (2008). ISO – "International Organization for Standardization, Standard ISO EN 13790/2008: Energy performance of buildings – Calculation of energy use for space heating and cooling".

Fang H., Xia J., Zhu K., Su Y., Jiang Y., Industrial waste heat utilization for low temperature district heating, Energy Policy, Volume 62, 2013, Pages 236-246

Karen N. Finney, Vida N. Sharifi, Jim Swithenbank, Andy Nolan, Simon White, Simon Ogden, Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping, Energy Conversion and Management, Volume 62, 2012, Pages 165-175

Genon, G., Torchio, M. F., Poggio, A., & Poggio, M. (2009). Energy and environmental assessment of small district heating systems: Global

Ghafghazi, S., Sowlati, T., Sokhansanj, S. et al. Life cycle assessment of base–load heat sources for district heating system options, *The International Journal of Life Cycle Assessment (2011) 16: 212*

Aira Hast, Sanna Syri, Vidas Lekavičius, Arvydas Galinis, District heating in cities as a part of low-carbon energy system, *Energy*, Volume 152, 2018, Pages 627-639

Havasi, K., (2017), *Open Source Project Advancement for Spatial Energy Infrastructure Optimization*, Master thesis, Technical University of Munich

M. Köfinger, D. Basciotti, R.R. Schmidt, E. Meissner, C. Doczekal, A. Giovannini, Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies, *Energy*, Volume 110, 2016, Pages 95-104

Li Y., Xia J., Fang H., Su Y., Jiang Y., Case study on industrial surplus heat of steel plants for district heating in Northern China, *Energy*, Volume 102, 2016, Pages 397-405

Mohammad Sameti, Fariborz Haghighat, (2017), Optimization approaches in district heating and cooling thermal network, *Energy and Buildings*,Volume 140,2017,Pages 121-130

Bernd Möller, Henrik Lund, Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system, *Applied Energy*, Volume 87, Issue 6, 2010, Pages 1846-1857

Steffen Nielsen, Bernd Möller, GIS based analysis of future district heating potential in Denmark, Energy, Volume 57, 2013, Pages 458-468

Oliver-Solà, J., Gabarrell, X., & Rieradevall, J. (2009). Environmental impacts of the infrastructure for district heating in urban neighbourhoods. *Energy Policy*, 37(11), 4711-4719.

Rehbogen, Strasser, Koblmüller, Mostegl, Schardinger, Biberacher, Zach, (2018) *Integrierter Wärmeplan Zentralraum Salzburg - Umsetzungsplanung für die Wärmewende der Energie-Vorzeigeregion Salzburg* Endbericht heatswap_Salzburg Energieforschungsprogramm FFG

Mohammad Sameti, Fariborz Haghighat, Optimization approaches in district heating and cooling thermal network, *Energy and Buildings*, Volume 140, 2017, Pages 121-130

V.M. Soltero, R. Chacartegui, C. Ortiz, R. Velázquez, Potential of biomass district heating systems in rural areas,

Energy, Volume 156, 2018, Pages 132-143

Unternährer, J., Moret, S., Joost, S., Maréchal F., (2017) Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy, *Applied Energy*, Pages 749-762

Sven Werner, International review of district heating and cooling, *Energy*, Volume 137, 2017, Pages 617-631

Internet based sources:
https://energyplus.net (EnergyPlus, requested on 26.07.2018)
https://atla.gse.it/atlaimpianti/project/Atlaimpianti_Internet.html (GSE atlas, requested on 26.07.2018)
http://www.iinas.org/gemis.htm (IINAS, requested on 26.07.2018)
http://www.SAGIS.at (SAGIS, requested on 26.07.2018)