Open Source Tool for the Analysis and Simulation of Urban Energy Infrastructures

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***Abstract*—A rapid transformation of energy systems in cities is essential to tackle the global challenges caused by the climate change. Linking buildings to other urban energy sectors like heat and gas is of paramount importance for a synergistic utilization of the respective clean flexibility options such as heat pumps. This paper introduces an open source GIS-based tool, called *FlexiGIS-Grid* for setting up synthetic typologies of power, heat and gas networks in districts. It couples two open source models *FlexiGIS* and *rivus*. It has been found for the selected case study that the electrification of heat sector using heat pumps offers a cost-effective solution and can completely replace the need of natural gas as a fuel. However, distribution grid expansion is required to enhance the power network in order to meet the heat demand using heat pumps. Another key finding of this research confirms the feasibility of using hydrogen to substitute the dependency on natural gas resources, in which domestic heating technologies should be deployed to complement the hydrogen sector in satisfying the heat demand in the investigated district.**

***Index Terms*—open source, urban energy systems, OpenStreetMap, FlexiGIS, sector coupling**

I. INTRODUCTION

Urban areas are responsible for more than 75% of the world's energy needs [1] as two thirds of the global CO_2 emissions are emitted by energy sectors in cities [2]. For example, residential and commercial buildings consumed in 2018 about 60% of the global electricity [3]. Heat consumption accounts for 50% of the global final energy consumption in 2018 and emits 40% of the global CO_2 emissions [4]. Natural gas and other fossil fuels had a share of 32% and 12%, respectively, of the final energy consumption within the European households in 2019 [5]. At the same time, the urban potential for CO_2-free generation of electricity is restricted as the available local renewable energies in cities are in most cases limited. Thus, the coupling of different energy sectors at the urban level is one of the most important components of the energy transition in cities, which at the same time requires considerable changes in energy infrastructures such as electricity and heat networks.

Many cities in Europe have already decided to become climate neutral in the coming years. Copenhagen, for instance, plans to be climate neutral by 2025 [6], while the city of Oldenburg opted for climate neutrality by 2035 [7]. However on one side, there are still too few concrete concepts and strategies to achieve this goal. On the other side, energy system tools that can describe the transformation of energy infrastructures towards climate neutrality are already well established [8]. However, most available energy system tools lack a broad representation of all energy sectors at the district level. For example, the *oemof.thermal* tool which is part of the *oemof.solph* model only considers the heat sector [9] on different level including cities, other tools deal only with the electricity sector, such as the simulation program *Load profile generator* [10].

Various data models exist which deliver data sets of energy infrastructure, like SciGRID [11] for the power transmission networks or gas transport networks such as SciGRID_gas [12] and LKD-EU [13]. Most open source data models are based on publicly available data sets such as OpenStreetMap (OSM) and Transmission System Operators (TSOs) information. While the structure of the power transmission grids is well-known and is publicly available from different sources such as [11], electricity distribution networks are mostly not obtainable. Indeed, it is a challenging task to map the distribution grids infrastructures since components like cables and wires are located underground. Due to data privacy issues the data sets of low voltage level are also not procurable from the Distribution System Operators (DSOs). Moreover, distribution grids are in some cases operated by more than one grid operator which compete for power and gas consumers in the same city. This creates less incentives to share the data sets in order to preserve an economic advantage. An alternative is to generate urban networks data sets using heuristic approaches like eDisco or standard distribution network configurations such as Simbench. Due to the increasing integration of decentralized generation and the expected electrification of different energy sectors in cities, distribution grids design and planning is currently gaining more importance. Recently, some studies have addressed this topic and various methods and tools have been developed for obtaining datasets of distribution grids and their simulation. The author in [14] presented the development of synthetic low-voltage network models for representative settlement structures in Germany. A data-driven re-configuration approach is used in [15] to reconstruct grid topology. On the other hand, the authors in [16] developed an agent-based to simulate infrastructure components in the smart grid. The present paper aims to close the gap in modeling district sector-coupling (power, gas and heat) and spatial planning using Geographic Information Systems (GIS) techniques and open source data sets.

We chose an open source approach for various reasons which we will briefly list in the following. First, to allow access to high resolution data sets describing urban energy systems including the buildings and the grids infrastructure as well as the electricity generation and demand. Second, making energy data sets available for a wide range of stakeholders (not only scientists and modelers) to allow a transparent and meaningful debate about the current energy transition in cities. Third, as many technologies and scenarios exist in order to reach the energy transition goals, transparency in energy modeling and analysis is of paramount importance. Indeed, in order to foster the acceptance and implementation of energy efficiency and transition measures (which are needed from urban energy consumers), a high level of transparency is needed. The data generated in this contribution will be made available under a 3-Clause BSD License and the model will be available on the GitHub repository.

The absence of distribution grid typologies makes the estimation of the topology of network infrastructures of prime importance for planning future CO_2-free urban areas. This paper introduces a data-driven GIS-based open source tool for simulating power, heat and gas networks typologies using open source data sets. It addresses as well the following research question: What are the techno-economic implications and requirements of climate neutrality on the distribution networks? In addition, a scenario analysis for the future design of climate-neutral quarters is carried out using flexibility options such as heat pumps and new energy sources such as hydrogen. Four scenarios will be investigated, a reference scenario (status quo), climate neutral or CO_2-Free scenario, H_2 scenario and future scenario.

This article is structured as follows: The motivation and a related work are presented in Section I. The methodology and an overview of the coupled *FlexiGIS* and *rivus* tools are introduced in Section II. Section III presents data collection and the processing of the extracted geo-spatial and temporal data sets. In Section IV, *FlexiGIS-Grid* is showcased for the district of Wechloy in Oldenburg. The results and scenarios analysis are discussed in Section V, and finally Section VI concludes this paper.

II. METHODOLOGY

In order to address the aforementioned research question, this study introduces *FlexiGIS-Grid*. It aims to perform a soft-coupling of two developed open-source energy tools, namely *FlexiGIS* [17, 18] and *rivus* [19].

Soft-Coupling

FlexiGIS-Grid extracts OpenStreetMap data and converts it into sector-coupled multi-carrier networks. For the geo-processing feature of FlexiGIS-plugin has been coupled with the network optimization tool *rivus*. The overall workflow is illustrated in Figure 1.

In the first step, the required spatial data sets were processed, filtered and clustered in the FlexiGIS-plugin. The buildings and streets layers are processed to form the networks of edges and vertices in the respective district. The spatial parameters are treated here separately. In other words, locations are represented as vertices that are connected through edges in which demands are allocated. A single edge for instance replicates a street segment within the street network. A Mixed-Integer Linear Programming (MILP) problem is set up using Pyomo [20] by combining spatial, temporal and techno-economic data. The optimization is performed using the open-source solver *CBC* [21]. The results are summarized into an Excel sheet. The aggregated demands as well as optimized flows are presented and mapped per edge and commodity (energy carrier e.g. electricity, heat, hydrogen).

In order to deploy the output spatial data sets of urban infrastructures generated by FlexiGIS-plugin as input data into *rivus*, a number of preparatory steps have to be undertaken. These are illustrated in Figure 2. Spatial data in FlexiGIS is clustered into building and highway layers. First, these layers of different buildings categories are merged into one building layer, in addition to one highway layer. In a next step, the street network is converted into a network of edges and vertices. Finally, heat and power demands per building type are aggregated per edge. The upper limit of commodity supply is added to the selected source vertices. These vertices represent gas terminals and power substations for the selected district.

The methodology developed in this study as well as the scripts that conduct the soft-coupling and optimization have been published on GitHub [22]. A step-by-step installation process as well as simplified data sets to test the *rivus* component have been published as well.

Scenario description

This article investigates four scenarios. Table I explains the settings of the selected scenarios in terms of the investigated commodities/sectors and the respective adopted technologies and commodities costs. The *Reference* scenario does not feature any district heating networks and units as the status quo of the selected area reflects no installed district heating networks. In other words, heat demands are met through domestic gas heating. The *CO_2-free* scenario excludes the commodity natural gas since gas emits CO_2. Both scenarios *H_2* and *Future* feature *Hydrogen* which can be converted to heat or power in various processes.

To fulfill the energy demands, the model considers *Electricity*, *Heat* and *Gas (or H_2)* as its three basic commodities. Commodities are all goods represented by its energy content. They can be consumed directly or first converted into another commodities through processes. In general, scenarios are defined by altering the availability and the techno-economic descriptions of commodities or processes.

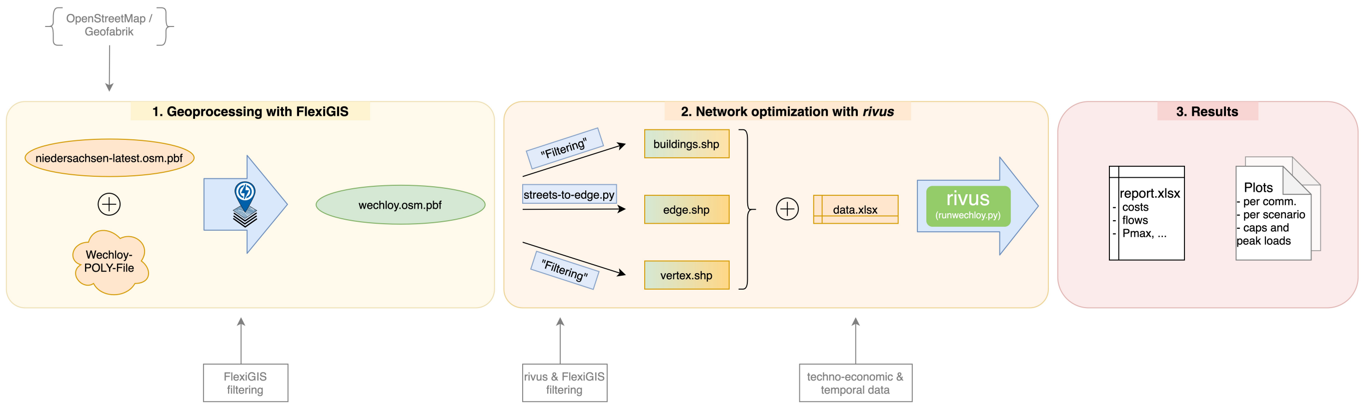

Fig. 1: Overview on the processing steps in *FlexiGIS-Grid*. Raw OpenStreetMap data is converted into sector-coupled multi-carrier networks. FlexiGIS is used to provide categorized building and highway layers on a district level. Spatial supply and demand data are generated with *rivus*. These are combined with temporal and techno-economic data to generate a MILP optimization problem. The solutions are cost-optimized multi-carrier grids.

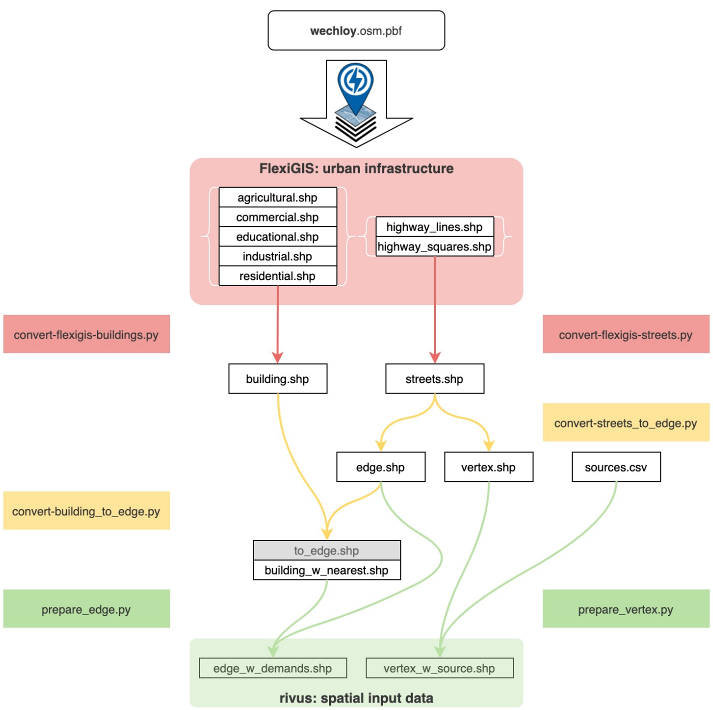

Fig. 2: A detailed description of the coupling between FlexiGIS and *rivus* is provided. The pre-filtered data is converted in three major stages. Technical compatibility is ensured in the red stage. Reduction of geo data is performed in the yellow stage. The final spatial demand and supply data is prepared in the green stage.

The investigated processes are listed in Table II. This table differentiates between domestic and district conversion processes. For heating purposes on a domestic level, for instance, heat pumps will be installed in a single household where electricity will be utilized to produce heat (E $\rightarrow$ H). On a domestic level, either power or gas (or H_2) commodities are converted to heat to meet the heat demand. On the other hand, on district scale Combined Heat and Power (CHP) units use gas to produce both electricity and heat for example.

TABLE I: List of the investigated scenarios

Scenario	**Adopted Technologies**	**Technologies costs**
Reference	power and gas	today's costs
CO_2-Free	power and heat	today's costs
H_2	power, H_2 and heat	today's costs
Future	power, H_2 and heat	future's costs

TABLE II: List of employed conversion technologies for the investigated commodities: Power or Electricity (E), Gas (G) and Heat (H).

Domestic	Process	**District**	Process
electric heating	E $\rightarrow$ H	CHP plant	G $\rightarrow$ E & H
gas heating	G $\rightarrow$ H	heat pump plant	E $\rightarrow$ H
heat pump	E $\rightarrow$ H	gas power plant	G $\rightarrow$ E
		gas heating plant	G $\rightarrow$ H

III. Data Collection

In this study, three types of data sets are required for the establishment of network typologies: spatial, temporal and techno-economic data sets. The data sources and collection are descried in following subsections. Figure 1 and 2 shows the workflow of data processing applied in this study.

Spatial data sets

The spatial layer of urban infrastructures is the foundation upon which the simulation of urban distribution grids is based. Using GIS data sets extracted from the OSM data base [23], FlexiGIS establishes the required underlying information for setting up the district energy networks. As depicted in Figure

2, geo-urban data sets of OSM elements *building, landuse* and *highway* were extracted and categorized. The location of power substations is also provided by OSM. The location of a gas pressure station has been estimated.

Temporal data sets

In *rivus*, the time domain is represented as a set of weighted time steps. These steps define respective scaling factors for the heat and electricity demand. The weight represents the duration in hours per year where these conditions apply. The time steps and their weights have been identified through a clustering process on heat and power time series for one year. In our case, five representative time steps namely *cold*, *dark*, *summer*, *peak-heat* and *peak-elec* have been found. The *cold* period lasts the longest with 3760 hrs at increased heat demand. The time periods *peak-heat* and *peak-elec* represent the respective peak load periods for electricity and heat. Their weight is comparatively small. Due to a lack of heat demand series, the time steps used in this study have been adopted from the original publication of *rivus* [19].

Techno-economic data sets

The power substation capacity was estimated based on FlexiGIS simulations of the aggregated electricity demand. The gas terminal capacity P_{Gas} was calculated using the following equation:

$$P_{\text{Gas}} = kP_{\text{Person}}N_{\text{Pop.}}$$

where $P_{\text{Person}} = 3500\,\text{kWh/a}$ [24], $N_{\text{Pop.}}$ is the population of a district and k is a security factor. The investment, fixed and variable costs of processes and commodities are provided by [25]. The implementation of hydrogen technology was based on previously defined gas processes for which the CO_2 output has been set to zero. The cost of hydrogen is based on [26].

IV. Case-Study

The authors selected Wechloy district in Oldenburg to apply the introduced *FlexiGIS-Grid* tool. Figure 3 depicts the underlying district infrastructure data sets. It illustrates urban data sets of building footprints areas, building portfolios and streets networks which have been extracted, filtered and geo-processed using FlexiGIS. Based on these GIS data sets, the typologies of electricity, gas and heat will be created for all selected scenarios.

V. Scenario Analysis

This section presents the key outputs of performing the optimization of different commodities and scenarios for the investigated Wechloy district. Figure 4 illustrates the synthetic simulated electricity, gas (or H_2) and heat networks typologies for all investigated scenarios. In addition, it depicts the required technological capacities for the respective process and/or commodity. The reference scenario attempts to emulate the current state of the urban energy infrastructures. Power and Gas networks are already constructed and under operation, however, district heat does not exist in Wechloy yet. As shown

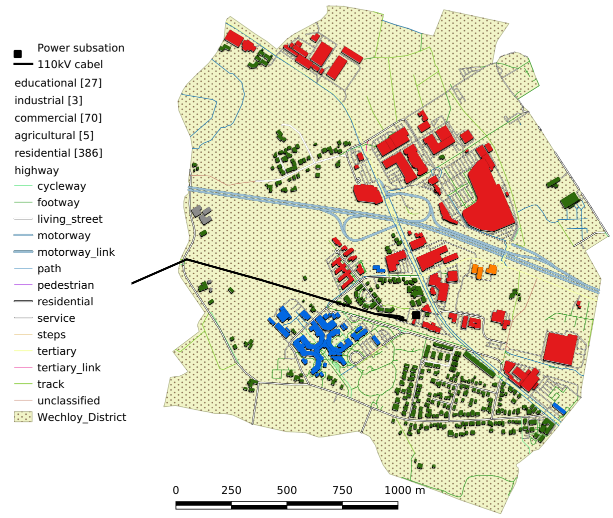

Fig. 3: A representation of urban infrastructures in the investigated district of Wechloy in Oldenburg including buildings, streets and the location of substation. Credits: QGIS and OpenStreetMap contributors.

in Figure 4 the power grid infrastructure is constructed to meet demand centers, for instance, the commercial neighborhood (see Figure 3) is provided with stronger power cables capacities as well as gas network pipeline. In this scenario the heat demand is met using the installed domestic gas heating devices.

On the other hand, a zero CO_2 scenario deactivates the gas sector as gas emits significant amount of greenhouse gases. In this case, domestic heating systems using heat pumps are able to cover the heat demand in the investigated urban area replacing the need for the gas networks. Hence, the optimization results showed no requirements to install domestic heating networks. However, the power distribution grid should be enhanced, as shown in Figure 4 to cope with the increased electricity demand for heat pumps.

Investigating hydrogen applications for heating in H_2 Scenario illustrates the feasibility of using alternative fuels instead of gas. In this scenario, domestic heating systems that use hydrogen as fuel should be considered, see Figure 4. The future scenario estimates a cost reduction of flexibility technologies and hydrogen costs while the costs of natural gas will be increased. It has been shown that gas sector would play no role in the future district energy systems, where the electrification of heat sector will be the optimal alternative.

Table III shows the technical and economical configurations resulting from the greenfield optimization of district systems under consideration of coupling power, gas and heat sectors. The following key findings have been observed:

- The reference scenario seems to be the most expensive one
- A climate neutral district would cost about the half of reference scenario

TABLE III: The resulted technologies and processes capacities, investment, fixed, variable and total costs of infrastructures in Wechloy optimized per scenario.

	Reference	**CO_2-Free**	H_2	**Future**
Installed Capacity[MW] Power/Gas/Heat	354/810/-	581,4/-/-	397,8/-/-	364/-/-
Process Capacity [MW] private/central	69,5/-	18,8/-	18,8/5,4	9,6/6,2
investment cost [m.€]	16,9	13,9	14,2	4,7
fix cost [m.€]	880,9	386,0	215,5	198,3
variable cost [m.€]	64,3	67,2	64,7	48,8
Total Cost [m.€]	962,1	467,1	294,4	251,8

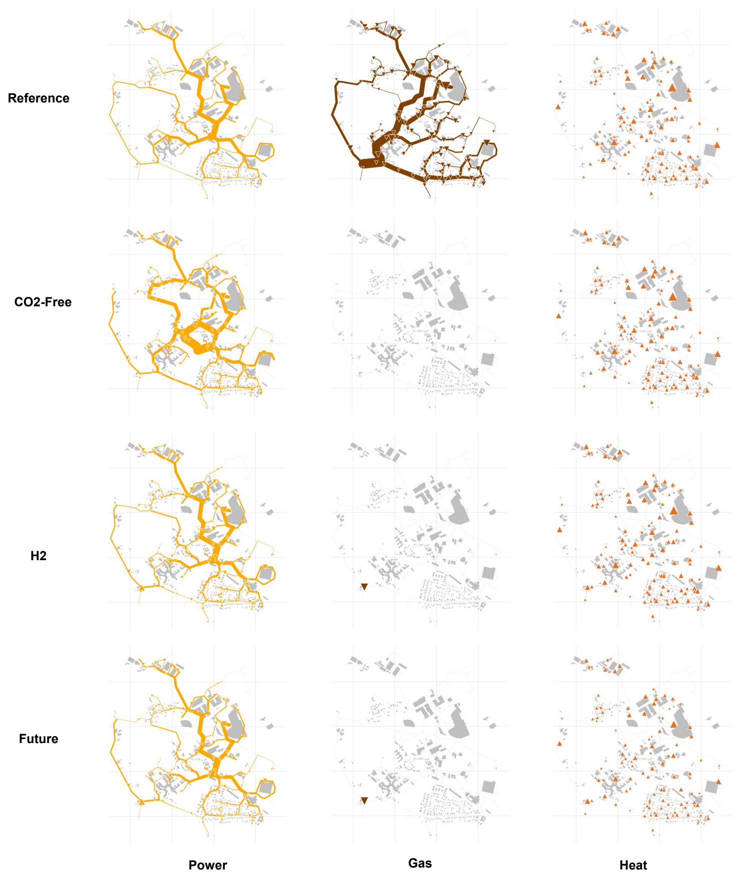

Fig. 4: The simulated power, gas (H_2) and heat networks for the four selected scenarios, the lines represent the network capacities and the symbols are the conversion unit capacities for Wechloy district in Oldenburg

- Deploying hydrogen on a district level for heat applications offers an attractive and cost-effective option to replace natural gas
- The cost reduction in the future scenario has a significant impact on the total system costs compared to all other investigated scenarios.

To summarise, the optimization results have shown that in order to achieve 100% CO_2 free from power, gas and heat sectors, we have two options: First, a complete electrification of the heat sector. The other alternative is using hydrogen besides heat pumps on domestic scale. A 100% electrification of heat sector using solely heat pumps leads to more investments on the expansion of the power grid capacities and the installation of heat pumps. However, the total costs of operating such systems will remain much lower than the gas networks as the gas prices are continuously increasing. Using hydrogen for heating purposes instead of natural gas can replace the needs on gas completely, the gas distribution infrastructure meanwhile leads to climate neutrality on the district level.

VI. Conclusions

Energy system models and scenarios are considered as valuable instruments to shape the transformation of urban energy systems towards climate neutral cities and districts. In this work, the authors introduced *FlexiGIS-Grid* an open spatial analysis tool that soft couples two open source models *FlexiGIS* and *rivus*. All scripts and codes related to this article can be found at the Github repository FlexiGIS_Grid. It aims to first simulate synthetic typologies of power, gas and heat networks. Second, it performs a scenario analysis of district networks under the consideration of sector coupling. Four scenarios were investigated in this study: reference, CO_2-Free, H_2 and Future scenario.

OpenStreetMap data sets were used in this study as a source of the underlying urban infrastructure data which served as the basis for modeling the distribution grids. Developing open source tools and models that are based on publicly available data is vital to enhance different energy actors to create data-driven decisions in designing future urban Energy Systems.

It has been proven for the case study that by which *FlexiGIS-Grid* has been applied that gas network might play a minor role in the future urban energy system in the light of the increasing prices of fossil fuels. On the other hand, green hydrogen as a clean source of energy would be an attractive commodity to completely replace natural gas. Hydrogen for domestic heating offers an attractive cost-effective solution on short and mid-terms. It has been also demonstrated that using a full electrification of the heat sector using heat pumps as a flexibility option could reduce the total costs although some investments should be done on expanding the distribution grid. Further work may consider including the transport sector and other flexibility options like e-mobility. Further improvements could be suggested to automate the modeling processes for more user friendly data geo-processing and for the analysis.

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