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Modeling Urban Street Lighting Infrastructure Using Open Source Data Sets

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Abstract

Streetlights in urban settings have been increasingly ubiquitous assets in cities worldwide. The illumination of street networks accounts for a major and growing burden on the environment, municipalities's budgets and power supply systems. The global demand for street lighting is expected to increase by 80% by 2030 compared to 2005. This paper introduces an open source GIS-based tool to simulate urban street infrastructures and calculate the electricity demand for streetlights. Furthermore, different scenarios of operating street lighting systems using local available renewable energy resources and flexibilization technologies are investigated. Using solely open source data sets, this research confirms the possibility of replicating realistic urban street infrastructures. The extracted OpenStreetMap geospatial road networks for the case study of the city of Berlin is validated against available public data sets. It is found that, a self sufficient streetlight system, 100% renewables, for the investigated case study requires significant investments in renewables and storage technologies. The developed tool, called FlexiGIS-light, establishes a strong basis for further analysis and discussion for the planning of sustainable and integrated street lighting systems in urban areas.

1 Introduction

The worldwide environmental campaign "Earth hour" engages millions of stakeholders to turn-off indoor and outdoor lights (e.g. streetlights) for one hour per year. While the main intention was to draw attention towards the environment, it did contribute to the reduction of the global electricity consumption by an average of 4% [1]. Global challenges such as the urbanization require, however, systematic and collective decarbonization of all energy sectors in cities [2]. The accelerated growth of urban population will force all energy infrastructures to grow in order to address the increasing energy demand. For instance, the global electricity demand to illuminate public streets will increase by 80% by 2030 [3]. According to the German Energy Agency (dena), the largest consumer of electricity in municipalities is streetlights [4, 5]. Germany consumes around 4TWh/year electricity for lighting streets, bridges and squares. This requires the operation of more than 9 million streetlights, which results in the emission of more than two million tons of CO2 and costs municipalities the sum of 760 million Euros [3]. Therefore, the decarbonization and integration of street lighting sector is vital.

The human footprints can be observed from space though cities lights. Earth images from space illustrate how world populations settled down following geography by means of streetlights. Unlike daytime, political boarders and urban street networks can be recognized from space through artificial lights. Researchers have been using satellite images from the International Space Station (ISS) to capture urban divide extracting data sets about urban development like in [6]. Figure 1 demonstrates, for instance, how the city of Berlin is still divided into West and East although it had been united since decades. "Berlin Wall" can be easily seen from space (white arrow in Fig. 1) because two different streetlights systems are still operating. Around 225.000 public streetlights illuminate more than 18.328 km of paths and streets in the capital city in 2019, of which 197.500 Km are electric lights and the rest are still operated using gas [7].

Fig. 1 Urban streetlights in Berlin from space. ©NASA

Urban energy models can help city planners address the aforementioned challenges by offering relevant insights into the planning and operating of sustainable solutions [8]. However, there is a lack of transparency as the underlying modeling and data sets are usually not publicly available [9, 10]. In this context, open source data sets provided under appropriate open source licenses like OpenStreetMap offer many advantages. It enhances cooperation between researchers and provides easy access to data which is relevant for research. Opening-up data produced by publicly financed projects and its respective scenarios can lead to more social acceptance and open the debate such as to obtain plausible strategies. Open energy modeling allows for a constructive exchange across the boundaries of science, politics and social stakeholders [11]. When energy models are integrated in Geographic Information System (GIS), a realistic representation of urban energy infrastructure is possible. Moreover, inter-dependencies between different relevant layers of information are revealed and consequently taken into account in the modeling [12].

Previous contributions investigated the feasibility of using

LED technologies to improve the efficiency of streetlights like in [3, 13]. Recent studies focus mainly on controlling and intelligent systems of street lights for the applications of smart cities like in [14] and [15]. The authors in [16] introduced a methodology to calculate the street lights electricity demand and to determine the losses in the system. streetlights powered by renewable energy sources (RES) have been tested for remote areas [17, 18], but such applications are mainly stand-alone and location-specific. StreetlightSim [19] model was developed to simulate traffic patterns and adaptive networked streetlights. In this framework, modular tools to assess the potential integration of local urban renewable could support city planners. Nevertheless, most established relevant models did not offer transparent and transferable versions and did not integrate GIS techniques to simulation real world urban street light infrastructures.

The transition toward urban sustainability should address all sectors including street lighting system. It does make sense to investigate the contribution and feasibility of integrating local urban RES and flexibility options in planning sustainable street lighting infrastructure. Within this context and based on the aforementioned, this work addresses the following research questions:

- How can GIS combined with open source data, like OpenStreetMap (OSM), be used to produce reliable urban road infrastructure data sets?
- How to model existing and future public street light infrastructures and how to characterize their electricity consumption?
- To what extent can the street lighting infrastructure become an energy self-sufficient system?

To answer these research questions, this paper introduces an open source GIS-based tool called FlexiGIS-light. The tool is a further development of the FlexiGIS model [12, 20]. FlexiGIS-light aims at establishing a realistic urban street infrastructure derived from the OSM database, simulating the electricity demand and finally investigating different energy scenarios. The originality of this research lies in the following points. First, it applies GIS techniques to simulate a realistic and reliable urban streetlights infrastructure. This work adopts an open source approach where the developed tool as well as the involved data sets are made publicly available. A simplified model to simulate the street lighting electricity demand is provided and introduced. Scenario analysis of different streetlights operation modes is then performed to investigate the potential of urban renewable energy resources to meet streetlights demand.

This paper is structured as follows: Section 1 presents the motivation and a related literature review. An overview of FlexiGIS-light is introduced in Section 2. The collection and processing of the extracted geospatial and temporal data sets are presented in Section 3. In Section 4, FlexiGIS-light is showcased for the city of Berlin for different street lighting modes for two scenarios. The results and discussion are presented in Section 4 and finally Section 5 concludes the article and provides an outlook of future developments and analysis.

2 FlexiGIS-light overview

FlexiGIS-light is a modular open-source GIS-based tool for modeling urban road network infrastructure. It extracts the topology of road network from OSM, simulates the electricity consumption of streetlights and finally investigates different energy scenarios. This section introduces the model and its workflow. A GIS-Desktop plug-in of FlexiGIS-light is also available. The tool and its plug-in are licensed under the open source permissive software license BSD-3-Clause.

The main packages and steps of FlexiGIS-light model are visualized in Figure 2 as a Directed Acyclic Graph (DAG). It illustrates the model key modules, workflow, rules and inter-dependencies.

2.1 Extraction of road infrastructure data

The First step is the geo-processing of the road infrastructures using the OpenStreetMap database. In order to replicate the underlying urban street network topology, FlexiGIS-light provides two options to process the data sets using: osmosis and osmfilter. Both options process the OSM data for the OSM data elements *highways* which is represented as nodes and ways [1]. Both OSM processing tools offer commands for reading, writing, sorting and merging geo-data sets. Applying changes to data sources is one of the main features of osmosis. Osmosis can also generate and dump large data sets from/into local databases. Unlike osmosis, osmfilter allows faster geo-processing of OSM data especially with *o5m* format. A short comparison of both tools is introduced in Table 1.

	OSMOSIS	**OSMfilter**
Tool	java multi-platform	command-line tool
Data format	all incl .pbf	only .osm/.o5m
Data size	relatively big data	smaller data sets
Openness	yes	yes
Processing time	slow	fast
Database	data export to PostgreSQL	does not require local database

Table 1 Short comparison between osmosis and osmfilter

Following the extracting and processing of the OSM *highways* raw data sets, the resulting relevant data are clustered based on their type (see Figure 4 for an overview of the data types considered by the tool). Required urban street's geometries like length and area are determined and then fed-into the next step of the model, where the temporal data sets are prepared.

2.2 Modeling streetlights electricity requirements

This step simulates the electricity demand and supply of streetlights.

2.2.1 Simulation of streetlights load profiles: The characterization of urban road electricity consumption is based mainly on the underlying road network topology and the required illumination per unite area. The extracted and geo-processed OSM data sets include the location, type, OSM object ID and the area of the respective street and/or

[1] More information about OSM data structures on the OSM-Wiki

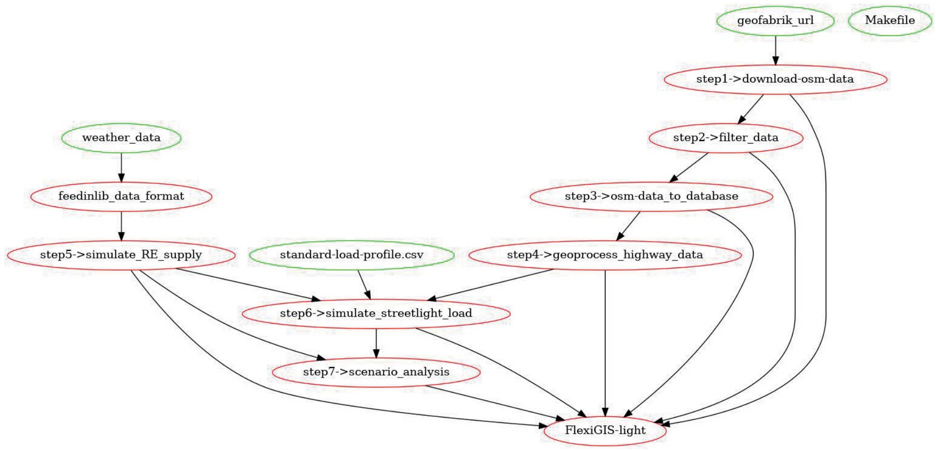

Fig. 2 Directed Acyclic Graph (DAG) graph illustrating FlexiGIS-light workflow.

square. The types of extracted road objects are shown in Figure 3. In this research, the time series of load profiles $L_{\mathrm{st}}(t)$ are simulated with hourly time steps for the extracted streets and squares using the following equation:

$$L_{st}(t) = \sum_{j} \Gamma_{st\,j}(t) * A_{st\,j} * \varepsilon_{st} \tag{1}$$

where, $L_{\mathrm{st}}(t)$ is the time series of electricity demand as a function of time (t). $\Gamma_{st\,j}(t)$ represents the normalized Standard Load Profile of the corresponding streetlight mode (see 2.3). A_j is the area of respective street j in square meters, the area of each urban road and square were already calculated in the first step 2.1. The parameter ε_{st} represents a measure of the electricity usage intensity for each street type. In other words, $\varepsilon_{st(j)}$ [W/m^2] describes the required streetlight power to illuminate a unite square meter of each urban object j and is calculated as follows:

$$\varepsilon_{st(j)} = E_{v(j)} * A_{(j)} / \eta_V \tag{2}$$

Where $E_{v(j)}$ represents the illuminance (*1 Lux (lx) = 1 lumen (lm) / Area (m^2)*) which is defined as the illuminance produced on a square meter surface by a luminous flux of *1 lm* uniformly distributed over that surface [21].
The value of the respective *Lux* depends on the urban street type, i.e. different streets and squares need different light level requirements. The lighting level for parking squares, for example, differs from the lighting intensity of primary streets. Depending on the local traffic situation and the respective road dimension, an illuminance level between 2-15 Lux is recommended [22]. η_V is the luminous efficacy, here it equals to *683 [lm per Watt]* [23]. A_{st} is the unit square area to be illuminated.

2.2.2 Simulation of renewable power generation:

The estimation of urban renewable power generation is performed using the open source tool *feedinlib* [24]. *feedinlib* is part of the *oemof* framework and can be used also as a standalone tool. Time series of the electricity equivalent from solar and wind resources are generated for the case study with an hourly resolution and normalized to their average values.

2.3 Scenario Analysis

This step utilizes simulated streetlight requirements to analyze three different operating schemes for two scenarios.

- **Mode-1**: urban streetlights operate for whole night (i.e. from sunset to sunrise)
- **Mode-2**: lights operate from evening till ca. midnight. A break in between is applied until early morning. Roads are then illuminated till it becomes bright.
- **Mode-3**: depending on the street portfolio, main roads are illuminated all-night while other secondary streets follow Mode-2.

The street lighting system is investigated under the integration of renewable power generation from local RESs using the *oemof* tool [25]. The first scenario considered, RE-scenario, investigates the potential and feasibility of integrating RESs into street light systems using today 's costs and storage technologies. On the other hand, Future-scenario investigates the impact of a potential cost-reduction by 2030 on the design street lighting system. The next section elaborates on the data sources for the simulation of the streetlights infrastructure for the selected case study.

3 Data collection and processing

Three types of data are collected and processed: geo-spatial, temporal and techno-economic. All data are collected solely from publicly available and freely accessible sources.

3.1 Spatial database

The source of geo-referenced raw data set of the streetlights infrastructure is the open-source OpenStreetMap database. The data sets are downloaded for Germany and filtered for the case study (Pre-selected OSM data sets for different regions is available from Geofabrik). FlexiGIS-light then processes the extracted data in different steps (see Figure 2). The outputs are the clustered OSM road infrastructures data sets, where exemplary data is shown in Figure 3 and 4.

3.2 Temporal data sets

For the calculation of streetlights consumption and renewable power generations, two main data sets are needed: weather and electricity load information.

3.2.1 Meteorological data sets:

The ECMWF ERA5 data sets are used [26] (downloaded from the Climate Data Store (CDS) database). The weather data sets have an hourly

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resolution with a spatial resolution of 25x25km for a period of one year. The data set contains wind speed at 100m and 10m height. Solar radiation parameters and temperature are at 2m height.

3.2.2 Load profiles for streetlights: The standard load profiles (SLP) are representative load profiles developed by the German Association of Energy and Water Industries (BDEW) [27]. In this case, the streetlights standardized synthetic load profiles adopted by the EWE grid operator after they normalized to 1000KWh/year were used [28].

3.3 Economic data sets

The required economic parameters of wind, PV and storage technologies, such as investment and variable costs, are taken from the International Renewable Energy Agency (IRENA) report [29]. The same report predicts a technology cost decrease by 58% for PV and 61% for Li-ion battery storage by 2030 [29] for the future scenario.

4 The case Study

After obtaining the necessary data sets, the FlexiGIS-light tool is used to investigate the case of the city of Berlin. The first step of FlexiGIS-light is executed and a road infrastructure of the traffic network in Berlin is obtained. The geo-referenced data sets of streets, squares and other relevant street components like bus stops, traffic signals etc. are extracted (see Figure 3). The street objects types are categorized and other relevant geometric parameters like areas are processed.

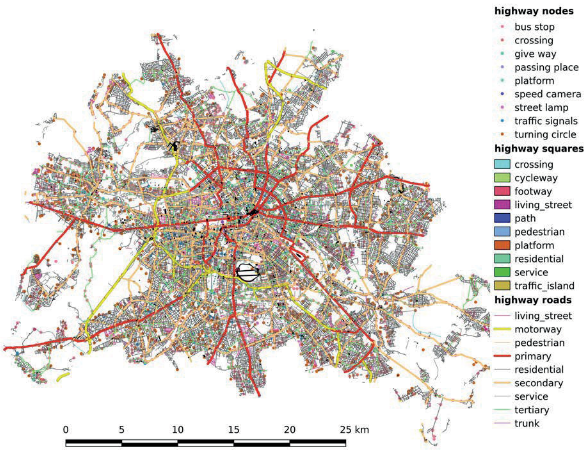

Fig. 3 Extracted road Infrastructure in Berlin using the first step of the FlexiGIS tool. Credits: OpenStreetMap contributors, QGIS Desktop.

Results and implications

Figure 4 shows a zoomed area of the clustered geo-data sets of different road infrastructure portfolios like primary streets (red lines) and pedestrian squares (blue polygons). The validation against public data sets provided by the Federal Agency for Cartography and Geodesy (BKG) [30] has proved a high completeness degree of OSM street network data sets.

In the next step, the times series of the aggregated electricity demand are simulated for three different operation schemes

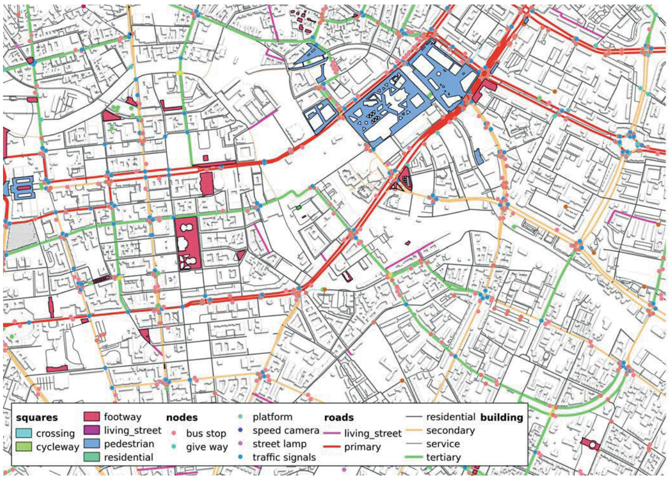

Fig. 4 Zoom of the extracted road Infrastructure in Berlin using FlexiGIS. Credits: OpenStreetMap contributors, QGIS Desktop.

(see 2.3). A sample hourly time series for three arbitrary and consecutive days is shown in Figure 5. As the main component of street lighting system is lamps that operate during dark hours and turned-off at day, streetlights patterns are similar in all modes. Assuming that all streetlights in Berlin are eclectic lamps (no gas), the total averaged simulated electricity demand for streetlights in Berlin is found to be 0.3TWh/year. This accounts for 2,3% of the total electricity consumption in 2019, which amounts to 13,3 TWh according to Stromnetz-Berlin [31]. The variation of the streetlights schemes for the road types in Mode-2 & 3 has a marginal impact on the total demand and consumption patterns (see Figure 5).

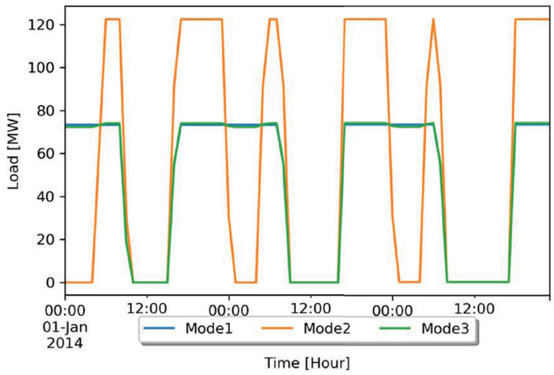

Fig. 5 Times series of streetlights demand for three modes for arbitrary and consecutive days in January.

As expected, for the three modes, load peaks occur as soon it gets dark and drop as soon as the sun rises. While the solar PV power behaves diametrically to the load, the wind generation fluctuates continuously regardless of the sun position.

In the next step, the resulted time series of normalized solar, wind and streetlight loads are used to investigate different scenarios of RE power generation mixes. The standard deviation of the residual load is calculated for different mixes. Minimum values of standard deviation indicate lower magnitudes of the back-up and storage capacities required to balance the residual loads [32, 10]. Figure 6 illustrates the different mix scenarios considered for the three street lighting modes. Note that, the required balancing energy

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from storage is at its maximum for a 100% only-solar scenario.

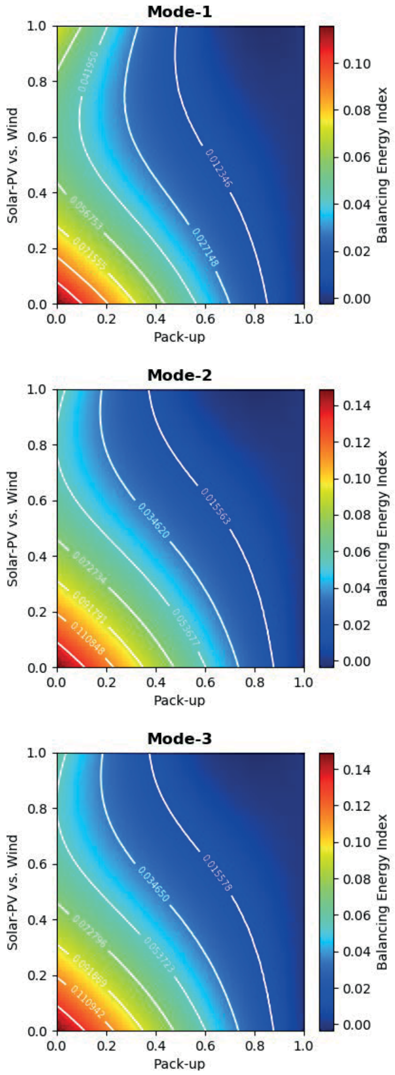

Fig. 6 Configurations of renewable power generation mix for the three streetlights operating modes in Berlin.

In order to analyze the results presented in Figure 6, it is necessary to comment on the street light load time series in Figure 5. Obviously, the best combinations of local RESs at minimal cost values are heavily in favor of wind. 100% only renewables-based street light systems require maximum back-up and storage investments. Any contribution from the distribution grid will reduce the balancing needs from other resources. As illustrated in Figure 6, the simulated power generation mix scenarios are relatively similar for the three operation modes. The reason behind this behavior is the somehow similar streetlights profiles and patterns for all investigated modes. Nevertheless, Mode-1 would offer a minimal balancing energy at the best power mix from a weather perspective compared to other modes. It seems that, the relatively small variation of the load in Mode-3 (occurred in the early hours when streetlights in secondary roads turned-off) does not cope very well with the local RE fluctuations causing a slightly increase in the fluctuations of the residual and, therefore, a slight increase in the required balancing energy compared to mode-1.

Using the optimization framework *oemof*, the optimal required power capacities at minimum system costs are

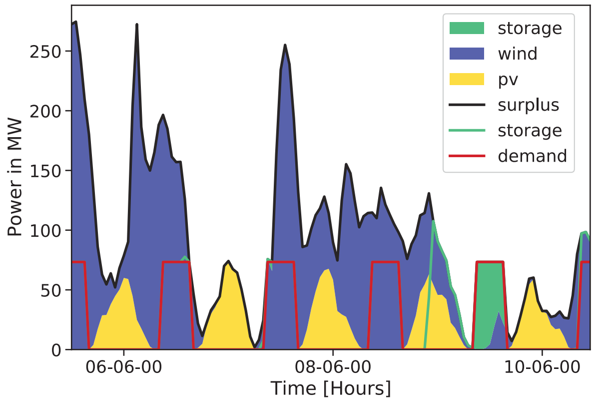

Fig. 7 Exemplary times series of energy balance at min investment costs simulated for Berlin's streetlights for few arbitrary nights in June using *oemof (dispatch mode)*. The streetlights demand (red) is met by available local RE like wind (dark blue).

investigated for a street lighting system only relying on RES. The optimization problem is solved with an hourly resolution for one year. The cost function is defined such as to match the streetlights electricity demand using only locally available RES (within the administrative borders of the city of Berlin) while minimizing the total system costs. The optimization was conducted for an investment period of 25 years with an interest rate of 7%. Exemplary result for few arbitrary nights in June for the RE-scenario are shown on Figure 7. The hourly time series illustrated the optimal distribution and operation of renewable and storage capacities to locally meet the streetlight demand. In case of overproduction, the surplus electricity (black curve) during the day can be stored in batteries to cover the demand at night hours. On the other hand, the deficit generation in the absence of wind and/or solar will be covered by the stored energy (green area). In this work, the storage capacity is optimized to fill-in the maximum gap between demand and supply which justify the higher costs of storage investments. Other case studies with limited local RESs and/or high streetlights demand might have to consider back-up capacities or import power from the national grid to compensate the deficit power generation and to reduce the storage costs.

Considering today technology costs, the obtained generation and storage capacities and total required investments of the 100% renewable streetlight system are presented in Table 2.

	RE Capacity [MW]	**Required Storage [GWh]**	**Total Cost [million €]**
Mode-1	304	5.3	223
Mode-2	508	5.1	243
Mode-3	307	5.3	223

Table 2 Resulting system costs and required generation and storage capacities for the investigated RE-scenario for the city of Berlin using oemof.

The investigation of the Future-scenario shows that, the total system cost is reduced by approx. 55% for Mode-1 & 3 and 54% for Mode-2 compared to the RE-scenario. Also, installing slightly more storage capacities by 2030 reduces wind turbines installations and decreases the investments costs. A total investments of around 100 [million €] with installing 292MW wind and 5GWh Li-ion battery is necessary for a 100% renewable street lighting system by 2030 in Berlin.

5 Conclusions

Using open source data, a realistic urban road infrastructure was extracted and simulated using the FlexiGIS-light tool. The use case of the city of Berlin was considered in this investigation. As FlexiGIS-light is modular by design, it can be applied for other use cases and for other cities and regions. However, the quality of the input data depends heavily on the OSM data sets quality for each region and city. The potential power generation from local solar and wind resources was calculated and a linear optimization was performed to investigate the feasibility of operating street light system utilizing local renewables and battery storage.

A self-sufficient street lighting infrastructure based only on local available renewable power generation can be realized. From weather perspective and also cost function point of view, the optimal configuration of power generation was in favor of wind resources. In all cases, additional investments are required to install renewables and storage capacities.

Further developments of the FlexiGIS-light would investigate the impact of coupling street light with other urban sectors such as transport. It will also be interesting to investigate the multi-purpose usage of street lighting infrastructure during day hours for other applications such as plug-in station for e-mobility. Other parameters could be included in the simulation of street lighting network like the distance between streetlight poles (usually designed based on the street dimensions e.g. width), the designed height of light pole and the light technology.

6 References

[1] S. J. Olexsak and A. Meier, "The electricity impacts of earth hour: An international comparative analysis of energy-saving behavior," *Energy Research & Social Science*, vol. 2, pp. 159–182, jun 2014.

[2] F. Kraas, C. Leggewie, P. Lemke, E. Matthies, D. Messner, N. Nakicenovic, H. J. Schellnhuber, S. Schlacke, U. Schneidewind *et al.*, *Humanity on the move: Unlocking the transformative power of cities*. German Advisory Council on Global Change, January 2016.

[3] C. SCHILLER, T. KUHN, M. BOELL, and T. KHANH, "Energieeffiziente strassenbeleuchtung einsparpotenziale identifizieren und erschlieÃ§en," *LICHT*, vol. 61, no. 10, 2009.

[4] dena, "Strassenbeleuchtung mit leds und konventionellen lichtquellen im vergleich," *Deutsche-Energie-Agentur*, 2016.

[5] A. Ożadowicz and J. Grela, "Energy saving in the street lighting control system—a new approach based on the EN-15232 standard," *Energy Efficiency*, vol. 10, no. 3, pp. 563–576, aug 2016.

[6] M. Kuffer, K. Pfeffer, R. Sliuzas, H. Taubenbock, I. Baud, and M. van Maarseveen, "Capturing the urban divide in nighttime light images from the international space station," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 11, no. 8, pp. 2578–2586, aug 2018.

[7] V. u. K. berlin.de Senatsverwaltung fÃijr Umwelt. Oeffentliche beleuchtung in berlin zustaendigkeiten. [Online]. Available: https://www.berlin.de/senuvk/bauen/beleuchtung/de/zustaendigkeiten.shtml

[8] J. Waldorf, "Eine chance fÃijr kommunen durch eine zukunftsweisende beleuchtungssanierung," *Vortrag des ZVEI in MÃijnchen*, sep 2008.

[9] A. Alhamwi, W. Medjroubi, T. Vogt, and C. Agert, "Modelling urban energy requirements using open source data and models," *Applied Energy*, vol. 231C, pp. 1100–1108, dec 2018.

[10] J. Ranalli and A. Alhamwi, "Configurations of renewable power generation in cities using open source approaches: With philadelphia case study," *Applied Energy*, vol. 269, p. 115027, jul 2020.

[11] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, and I. Staffell, "The importance of open data and software: Is energy research lagging behind?" *Energy Policy*, vol. 101, pp. 211–215, feb 2017.

[12] A. Alhamwi, W. Medjroubi, T. Vogt, and C. Agert, "GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas," *Applied Energy*, vol. 191, pp. 1–9, apr 2017.

[13] P. C. Veena, P. Tharakan, H. Haridas, K. Ramya, R. Joju, and T. S. Jyothis, "Smart street light system based on image processing," in *2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2016, pp. 1–5.

[14] B. R. Prakash, S. Megha, M. K. Francis, S. Niharika, and M. Megha, "Intelligent management of street lights using internet of things and power management," in *2019 International Conference on Smart Systems and Inventive Technology (ICSSIT)*, 2019, pp. 279–283.

[15] O. Yaman and M. Karakose, "New approach for intelligent street lights using computer vision and wireless sensor networks," in *2019 7th International Istanbul Smart Grids and Cities Congress and Fair (ICSG)*, 2019, pp. 81–85.

[16] G. Ereu and J. Mantilla, "A methodology to determine electrical energy consumption in street lighting systems," in *2006 IEEE/PES Transmission & Distribution Conference and Exposition: Latin America*. IEEE, 2006.

[17] A. Al-Fatlawi, S. R., T. Ward, and N. A. Rahim, "Technical and economic analysis of renewable energy powered stand-alone pole street lights for remote area," *Environmental Progress & Sustainable Energy*, vol. 33, no. 1, pp. 283–289, apr 2013.

[18] M. A. D. Costa, G. H. Costa, A. S. dos Santos, L. Schuch, and J. R. Pinheiro, "A high efficiency autonomous street lighting system based on solar energy and leds," in *2009 Brazilian Power Electronics Conference*, 2009, pp. 265–273.

[19] S. P. Lau, G. V. Merrett, A. S. Weddell, and N. M. White, "Streetlightsim: A simulation environment to evaluate networked and adaptive street lighting," in *2014 IEEE Asia Pacific Conference on Wireless and Mobile*, 2014, pp. 66–71.

[20] A. Alhamwi, W. Medjroubi, T. Vogt, and C. Agert, "Development of a GIS-based platform for the allocation and optimisation of distributed storage in urban energy systems," *Applied Energy*, vol. 251, p. 113360, oct 2019.

[21] ICE. International electrotechnical commission. [Online]. Available: http://www.electropedia.org

[22] P. L. Pro. Led strassenbeleuchtung aussenbeleuchtung beleuchtung strassen leitfaden led planung beschaffung. [Online]. Available: https://www.premiumlightpro.de

[23] R. Baleja, K. Sokansky, T. Novak, T. Hanusek, and P. Bos, "Measurement and evaluation of the road lighting in mesopic and photopic vision," in *2016 IEEE Lighting Conference of the Visegrad Countries (Lumen V4)*. IEEE, sep 2016.

[24] U. Krien, G. Plessmann, S. GÃijnther, B. Schachler, S. Bosch, and C. Kaldemeyer, "feedinlib (oemof) - creating feed-in time series - v0.0.12," *Zenodo*, Jan. 2019.

[25] S. Hilpert, C. Kaldemeyer, U. Krien, S. GÃijnther, C. Wingenbach, and G. Plessmann, "The open energy modelling framework (oemof) - a new approach to facilitate open science in energy system modelling," *Energy Strategy Reviews*, vol. 22, pp. 16–25, nov 2018.

[26] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers *et al.*, "The era5 global reanalysis," *Quarterly Journal of the Royal Meteorological Society*, vol. 146, no. 730, pp. 1999–2049, 2020.

[27] bdew. German association of energy and water industries. [Online]. Available: https://www.bdew.de/energie/standardlastprofile-strom/

[28] EWE. Network access to the power distribution network. [Online]. Available: https://www.ewe-netz.de/marktpartner/strom/lieferanten

[29] I. R. E. Agency, *Electricity Storage and Renewables: Costs and Markets to 2030*. IRENA, 2017.

[30] F. A. f. C. GeoBasis-DE / BKG and Geodesy. Wfs digitales landschaftsmodell. [Online]. Available: https://www.bkg.bund.de/

[31] stromnetz. Zahlen, daten und fakten. [Online]. Available: https://www.stromnetz.berlin/uber-uns/zahlen-daten-fakten

[32] L. v. Bremen, K. Knorr, B. Lange, and S. Bofinger, "A full renewable power supply scenario for europe: The weather determines storage and transport," in *8th International Workshop on Large Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, Bremen*. energynautics, 2009, pp. 0–0.