Optimizing and simplifying the process of energy-efficiency estimation for urban redevelopment areas by using open source GIS solutions

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Key words: Energy demand, CO_2 emission, GIS, Python, Germany.

SUMMARY

With the emerging consideration of energy-efficiency and CO_2 reduction, neighborhood energy-efficiency concepts and implementation management have become more and more important for improving urban redevelopment projects in terms of cost-effectiveness and protection of environment and human health. Estimation of the energy consumption via energy simulation are the mandatory and preliminary factors before starting an urban planning project. This paper introduces the legal framework and the basic mathematical calculations for this objective. It demonstrates that Open-Source software components can be used efficiently to implement a user friendly and effective information technology (IT)-based support for the city planner to collect the necessary information of the urban infrastructure for energy demand calculation such as roof types and building height. Fundamental data like building footprints provided by state mapping agencies and municipalities are decoded and stored in advance using the PostGreSQL/PostGIS database management system (DBMS). For the data acquisition QField, the QGIS add-on for mobile devices, is expanded by a specifically implemented plugin which is optimized for user-friendliness, security, and performant data acquisition in the field including photographs for further documentation. The collected data are synchronized afterwards in the office with QGIS and the underlying DMBS for further analysis. The collected data and the processing results can be then used for a variety of maps to fulfill the required information needs.

SUMMARY (German)

Vor dem Hintergrund des voranschreitenden Klimawandels spielen auf kommunaler Ebene energetische Quartierskonzepte und ein damit zusammenhängendes sog. Sanierungsmanagement eine immer stärkere Rolle. Im Gebäudebereich müssen der Energiebedarf gemindert und die Energieeffizienz gesteigert werden. Die Wärmeversorgung im Quartier muss insgesamt effizienter gestaltet werden; darauf angepasste Lösungen für die Produktion und die Nutzung erneuerbarer Energien sind zu entwickeln. Im Rahmen der CO2-Bilanzierung, aber auch bei der energetischen Optimierung der Wärmeversorgung, liefern Open Source Anwendungen einen entscheidenden Beitrag im Zuge von Kostenkalkulationen und Wirtschaftlichkeitsanalysen. Grundlagendaten wie Gebäudegrundrisse, die von staatlichen Behörden bereitgestellt werden, werden hierzu entschlüsselt und in einem PostGreSQL/PostGIS Datenbank-Managementsystem (DBMS) gespeichert. Zur Datenerfassung wird QField, ein Tool um GIS-Daten im Gelände effizient bearbeiten zu können, um ein spezielles Plugin erweitert. Dies beinhaltet u.a. eine benutzerfreundliche Fotodokumentation der im Zuge der energetischen Stadtsanierung vor Ort via Tablet erhobenen Gebäude. Die gesammelten Daten werden anschließend im Büro mit QGIS synchronisiert und in der Datenbank für weitere energetische Analysen bereitgestellt. Mit den Daten können automatisch zahlreiche Karten generiert werden, wie z.B. zur Fern- oder Nahwärmenutzung, dem Einsatz erneuerbarer Energien oder einer klimagerechten Mobilität.

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1. INTRODUCTION

Increasing energy efficiency and reducing carbon dioxide emissions are key tasks to confront climate change and master the energy transition. The building sector as a whole, including residential and non-residential buildings, has a key function for the “Energiewende” – Germany’s transition towards a secure, environmentally friendly, and economically successful energy future – as such: It accounts for around 35 percent of final energy consumption and roughly one-third of greenhouse gas emissions (DENA, 2022). At the same time, energy consumption can be significantly reduced, and renewable energies can be effectively used for heat and cold generation. A sensible combination of both can generally help to develop solutions that may even include a virtually climate-neutral building stock by 2045.

While the switch towards renewables in the electricity sector has been remarkably successful, the development in other sectors has been less dynamic until now. According to the German Association of Energy and Water Industries (Bundesverband der Energie- und Wasserwirtschaft, BDEW), about 50% of the 43 million residential units in Germany use gas for heating, 25% for oil, and 14% for district heating, which is produced by thermal power plants (Figure 1). The rest of the units use wood, electric heating pumps, and electricity for heating purposes. Even now, one-third of all newly constructed residential buildings use gas for heating.

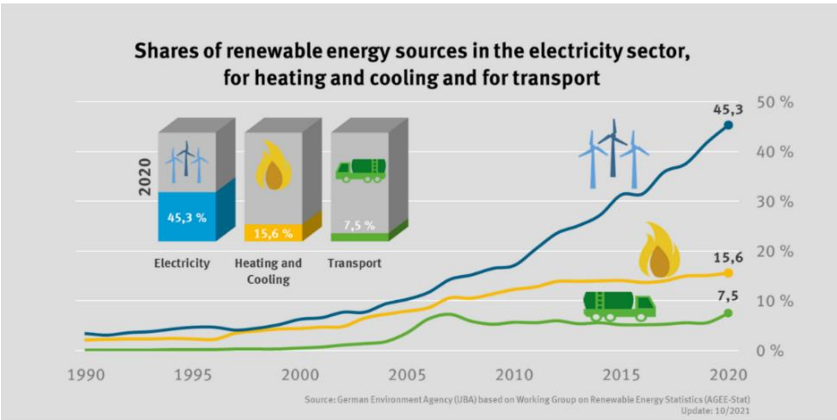

Figure 1. Development of renewable energy shares in Germany (November 2021) (AGEE, 2022)

Renewables are not yet playing a significant role in heating. According to recent figures by the German Environment Agency (Umweltbundesamt), renewables had a share of about 15.6% of total final energy consumption for heating (and cooling) purposes in the year 2020. When implementing climate protection measures in the building sector, the focus is increasingly on the district as the connecting level between individual buildings and the city as a whole. At the district level, synergies can be created, for example, in the conversion to district heating or serial renovation, which would be difficult to achieve at the individual building level.

1.1 Energy-efficient urban redevelopment in Germany

Local governments in Germany can step up their contribution to climate change action by linking various energy-efficient redevelopment measures with the various actors in urban districts. This requires an approach across all types of buildings that systematically combines energy efficiency improvements, renewable energy use, and the reduction of greenhouse gas emissions. The German Federal Government and the KfW Bankengruppe ("banking group"), a German state-owned investment and development bank, have been providing grants to support the development of such strategies and their implementation by local governments since 2011. With the KfW funding program 432 "Energetische Stadtsanierung" [energy-efficient urban redevelopment], neighborhoods have moved to the forefront as fields of action for climate protection (Friesecke et al., 2015).

The first funding module, creating an integrated neighborhood energy concept, analyzes the potential for energy saving and identifies goals and implementation strategies for the energy-efficient city. The concept with a funding period of one year contains statements concerning the cost, feasibility, and cost-effectiveness of redevelopment measures and describes procedures for monitoring success. In addition, it establishes a strategic basis for local governments to coordinate and synchronize regulatory measures and funding possibilities (BMI p.4, 2020).

Figure 2: The neighborhood in the center of the energy-efficient urban redevelopment process (BMI p.10, 2020).

The second funding module, the redevelopment management, supports the coordination and implementation of the formulated measures. The implementation management can be funded for three years. It is possible to increase the funding period from two years to up to five years.

Of the two funding modules, neighborhood energy concept and redevelopment management, 75 percent are subsidized with federal funds through the KfW Bank. The local government must provide the remaining 25 percent. Parts of it can also be covered by third parties (e.g., energy suppliers, housing companies, private owners).
Energy-efficient urban redevelopment focuses on six fields of action (BMI p.4, 2020).

- Energy-efficient redevelopment of the building stock
- Energy-efficient heat supply
- Energy-efficient electricity use
- Use of renewable energies
- Climate-friendly mobility
- Promotion of climate-conscious consumer behavior

Like every large urban development scheme, urban energy-efficient redevelopment requires collaboration by representatives of the municipality, the housing and property owners, and the energy industry. Associations and interest groups such as Haus & Grund, the largest association for private landlords and property owners in Germany, tenant associations, and the consumer advice centers act as multipliers and educational institutions, churches, and social welfare agencies.

By December 2019, 1,365 funding commitments had been issued to develop an integrated neighborhood concept or redevelopment management. Among these, 1,009 neighborhood concepts and 356 redevelopment management measures received a funding commitment.

1.2 Necessity of energy demand calculation

The KfW program 432 "Energetische Stadtsanierung" aims to stimulate investment in the building stock and technical infrastructure. But the program does not include its own funding regime. The requirement therefore is to develop financing models that take existing funding possibilities into account (BBSR, 2017).

Funding opportunities exist at the Federal level, in the form of KfW investment programs, with funding in the framework of the Renewable Energies Act (EEG, Erneuerbare-Energien-Gesetz) and the Power Heat Coupling Act (KWKG, Kraft-Wärme-Kopplungsgesetz), funding instruments of the Federal Office for Economic Affairs and Export Control (BAFA) and urban development funding, and at the level of the EU, the Federal states and the local governments. It should be noted that a wide range of funding programs can be used to implement measures in urban energy-efficient redevelopment.

1.3 Evaluation method for energy efficiency

Reliable data is an essential part of determining the energy requirements of buildings and related calculations. Nevertheless, most purchased data are outdated, coarsely resolved, and do not reflect reality. The following processes have been done to solve this issue.

The ALKIS data contains only the geometry of the field plan for our purposes. Nevertheless, this can be sufficient to calculate all relevant areas and volumes. For this purpose, field data capturing is required. Supplementary to this calculation, the following parameters are also surveyed to increase the reliability and accuracy of the data foundation needed for further computation in the energy plugin which will be discussed in section 2.3.2

- Verification building age classes (Baualtersklassen BAK)
- The number of stories
- Height of the floors, plinth height of the flap tile [m].
- Roof shape, roof angle [°].
- Number of attics/levels

Therefore, all relevant areas, including floor area, floor area without walls, facade areas, roof areas, gross volume, energetic volume, are measured by using QField (section 2.2.2). To increase accuracy assessment by 95 percent, on-site or online surveying by owners can be implemented. This surveying approach consists of the actual energy refurbishments carried out, the type and age of the heating system, energy sources, consumption of heating energy, and household electricity over the last three years. This data basis enhancement can improve the assessment accuracy by 95 percent.

This study aims to design an automated procedure to estimate the building's energy demand and CO2 emissions. To do so, the parameters according to (DIN, 2022) are calculated and determined in the building stock. Equation 1 represents the energy demand for heating of each building (Q_{ht}) is calculated from the total amount of heat demand for domestic hot water (Q_w), heat losses through transmission (Q_{tr}), heat losses through ventilation (Q_{ve}), heat gains through solar radiation (Q_{sol}), and heat gains through internal heat sources (Q_{int}).

$$Q_{ht} = Q_w + Q_{tr} + Q_{ve} + Q_{sol} + Q_{int} \quad (1)$$

Heat demand for domestic hot water ($\mathrm{Q_w}$) is calculated by equation 2. To calculate NUF as a parameter, the area of the building and the number of building-storey (Geschosse) is required ($NUF = area * 0.84 * (Geschosse + 1)$).

$$\mathrm{Q_w} = \mathrm{NUF} \times 12.5 \quad (2)$$

Q_{tr}, the heat losses through the transmission of the envelope area, can be estimated by equation 3. This formula is equivalent to the total envelope area containing the area of roofs, walls, windows, and cellar ceilings (A_{Ges}), total average U-Value of the building envelope (U_{Wert_Ges}), 0.024 is the conversion factor from Watt to kW per an hours a day, and Gt15-20 (IWU and DWD, 2022) is a long-term average of the respective weather station.

$$Q_{tr} = A_{Ges} \times U_{Wert\_Ges} \times 0.024 \times 1.2 \times Gt15\_20 \quad (3)$$

Equation 4 shows the formula of heat losses through ventilation (Q_{ve}). $\mathrm{c_{p,air}}$, the volume-specific heat capacity of air, is equal to $0.34 \frac{\mathrm{Wh}}{\mathrm{m^3K}}$. $\mathrm{n_{air,use}}$, average air change rate in an old and not refurbished building during heating season, is $3 \frac{1}{h}$. $\mathrm{n_{air,infiltr}}$, air change rate by infiltration, is $0.2 \frac{1}{h}$. $\mathrm{A_n}$ is the reference area of the building. $\mathrm{h_{room}}$ is the ventilation reference room height.

$$Q_{ve} = 0.024 \times \mathrm{c_{p,air}} \times (\mathrm{n_{air,use}} + \mathrm{n_{air,infiltr}}) \times \mathrm{An} \times \mathrm{h_{room}} \times \mathrm{Gt_{15-20}} \quad (4)$$

The formula of heat gains through solar radiation (Q_{sol}) can be reached from equation 5. F_{sh}, the reduction factor external shading, is 0.6. F_F, the frame fraction of the windows, is equal to 0.3. F_W, a reduction factor considering radiation of non-perpendicular to the glazing. $\mathrm{Fe_A}$ is the entire area of the windows. $I_{sol,j}$ ($\frac{\mathrm{kWh}}{\mathrm{a}}$) is the average global irradiation on surfaces with orientation j during the heating season (table 1)

$$Q_{sol} = F_{sh} \times (1 - F_F) \times F_W \times g_{gl,n} \times \sum_j (0.25 * \mathrm{Fe}_A \times I_{sol,j}) \quad (5)$$

Table 1. The average global irradiation on surfaces with orientation j during the heating season (IWU, 2022)

j	E	S	W	N
$I_{sol,j}$ ($\frac{\mathrm{kWh}}{\mathrm{a}}$)	271	392	271	160

Equation 6 represents the heat gains through internal heat sources (Q_{int}). The average thermal output of internal heat sources is 3 $\frac{\mathrm{W}}{m^2}$. $\mathrm{A_n}$ (m^2) is the reference area of the building. 222 is the number of heating days in Germany (duration of heating period).

$$Q_{int} = 0.024 \times 3 \frac{\mathrm{W}}{m^2} \times 222 \times \mathrm{A_n} \quad (6)$$

The amount of CO_2 according to the type of energy source (table.2) can be estimated from equation 7. HZ_NRG_f is the parameter changed relating to type of energy source

$$CO_2 = Q_{tr} \times \mathrm{HZ\_NRG\_f} \quad (7)$$

Table 2.The factor of energy source provider

Energy source	**HZ_NRG_f**
Natural Gas	0.2450 $\frac{\mathrm{kg}}{\mathrm{kWh}}$
Liquid Gas	0.2670 $\frac{\mathrm{kg}}{\mathrm{kWh}}$
Heating oil	0.3190 $\frac{\mathrm{kg}}{\mathrm{kWh}}$
Electricity	0.5650 $\frac{\mathrm{kg}}{\mathrm{kWh}}$
Wood	0.0190 $\frac{\mathrm{kg}}{\mathrm{kWh}}$

2. METHODOLOGY

2.1 Workflow development

The overall methodology is depicted in Figure 3 and comprises an intense requirements analysis, the data collection regarding base cadastral data, and building-related field data, which are evaluated in the Data Processing section.

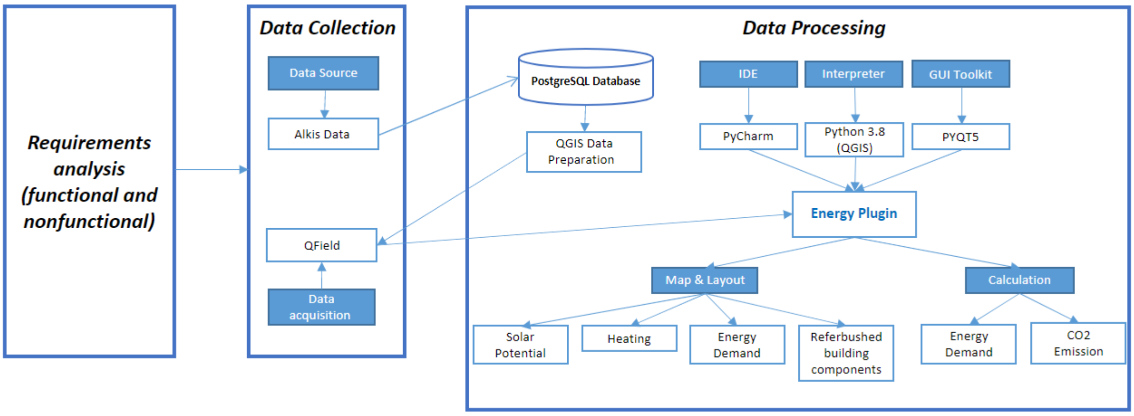

Figure 3. All the process from data collection, data processing, and results

2.2 Data preparation

2.2.1 Dataset

Official and Cadastral data (ALKIS) is the primary source of the data in the project. ALKIS, implemented in all states of Germany since 2015, combines and integrates data from the former cadastral map with the former property registry. In ALKIS, spatial and non-spatial related data were systematically kept together without redundancy. The Working Committee of the

Surveying Authorities of the States of the Federal Republic of Germany (AdV) has developed a technical concept for managing all official geodata (Seifert 2005, Adv 2019) ALKIS data is encoded in NAS-format, based on Geography Markup Language (GML) and Extensible Markup Language (XML), respectively. Governmental institutions provide data, i.e., state mapping agencies and municipalities. NAS data can be imported directly to the PostgreSQL database using norGIS *ALKIS* import software as PostGIS layers (norBit 2022) or opened in QGIS software by adding a vector dataset.

2.2.2 Mobile data preparation

QField allows working efficiently with GIS data on-site in the field. Its optimized user interface for Android devices hides the full power of QGIS under the hood (Opengis, 2019). In addition, a QField extension provides a chance to capture the relevant data related to the position of each building or land parcel according to the purpose of the projects. QField serves as a platform and user interface. However, most configurations must be done in QGIS desktop, preferably by Python programming. QGIS supports Python programming language, and PyQGIS is the Python environment in QGIS with a bunch of libraries such as Pandas and Numpy. Figure 4 shows the configuration of the layer attributes afterward presented on the QField interface, where city planners can apply them for assigning and editing the data on-site.

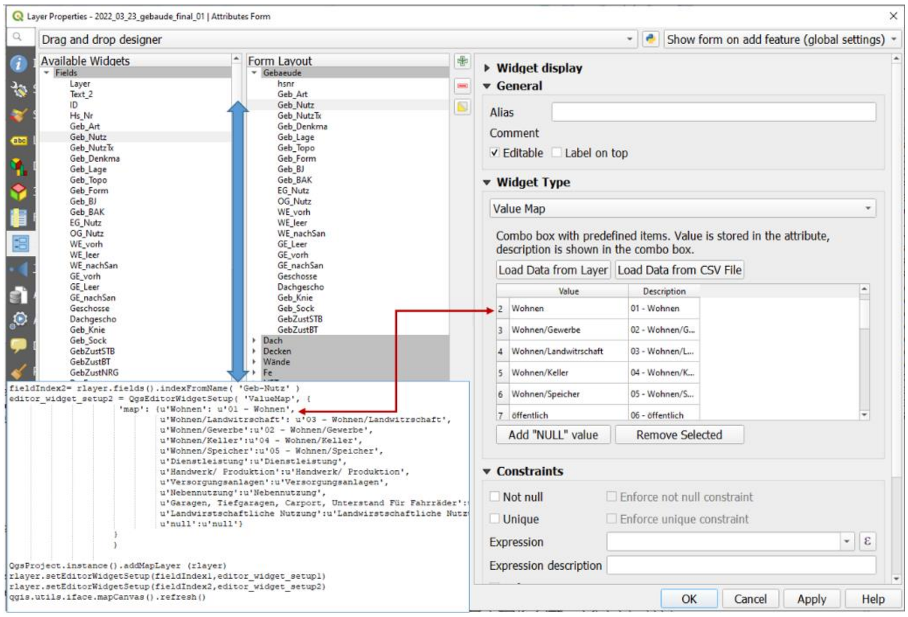

Figure 4. Widget type configuration in attribute form for feature attribute in QGIS desktop with python coding.

Furthermore, it proposes the possibility to configure certain widget types of attributes. Its *Value-Map* option is user-friendly and easy to use and offers different choices related to an attribute column. Some other presentation options, such as *value-Relation*, will ease the data capturing process on-site and make it more effective. For the monitoring process of the renovation measures, photos must be taken by the planners, which will be saved in a defined directory according to the chosen widget type (Ostadabbas et al, 2020).

The “Drag and drop designer” in the “form layout” section in attribute form configuration in QGIS provides an easy user interface for Mobile devices for better data accessing, sorting, and retrieving. Figure 5 represents the form layout design. The input form is divided into 11 pages according to their categories, two examples of which are building (Gebaeude) and roof shape (Dach).

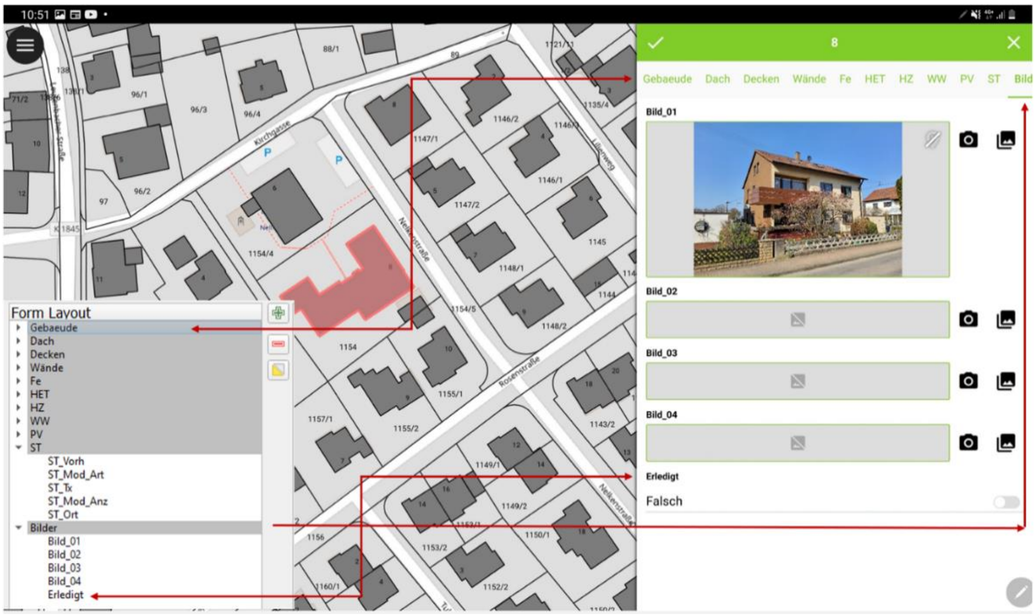

Figure 5. QField User interface and form layout design in QGIS

After specifying the QGIS project, the “Package for QField” must be configured to synchronize the relevant geodata for the device used on-site. After opening the QField application and loading the configuration file, the same geodata captured with Tablet and created before on the QGIS desktop will be shown on the QGIS desktop in the updated map and simultaneously updated in the PostgreSQL database. Currently, the QField application offers many of the well-known functionalities of the QGIS desktop, but is more straightforward and intuitive. Figure 5 shows the visualization of attribute form in QField, such as the categories and the field's name. To avoid measuring duplicate buildings by operators due to the immense number of buildings, "Erledigt", which means done, is used to show the operator whether the building has been documented or not.

2.3 Energy plugin code development for map creation

2.3.1 PyQt design

PyQt, the Python binding of the open-source software cross-platform graphical user interface (GUI) toolkit Qt, is integrated in QGIS, but can be utilized as well to support the graphical user interfaces for QGIS plugins (Siahaan, 2019). According to Figure 6, the user interface comprises four sections. The first section allows the user to load the raw data like the polygon of buildings, land parcels and labels with the correct symbology. Energy demand is calculated in the second part of the plugin using the data gathered using QField by field surveying (section 2.1.2). Essential formulas used for this calculation can be found in section 1.3. The next section is to group the output data into four areas: solar potential, refurbished buildings, heated buildings, and the energy demand of the buildings. Finally, the last part supports map layout generation (Figure 6). Using this plugin and interface will permit users to do the calculations and produce their maps in a couple of seconds.

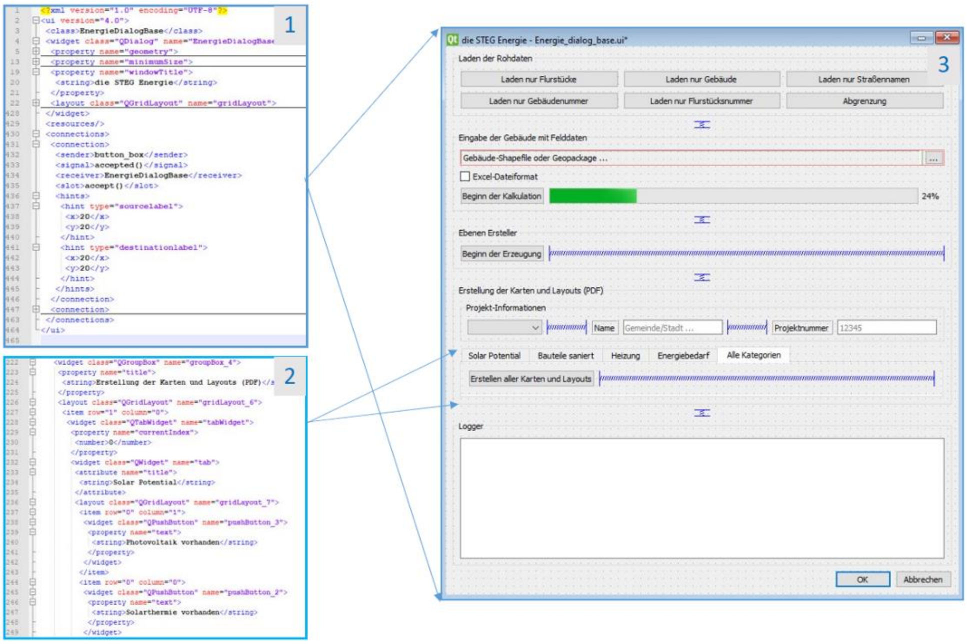

Figure 6. PYQT Design. Section 1 shows the source code of the GUI, section 2 shows a part of code showing tab menu, and section 3 is the main window

The red border in Figure 6 (section 1) illustrates the connection part of two core classes (which will be elaborated more in section 2.3.2) of the plugin generated automatically by the QGIS plugin builder. It helps plugin developers automatically apply the changes or modified items in the final user interface in the QGIS application. Figure 7 shows the preview of the *die STEG Energie* user interface created for the energy department (German language).

2.3.2. Code structure and plugin functionalities

The aforementioned GUI (Figure 7) is developed by utilizing the QGIS plugin builder. The foundation of this tool is based on object-oriented programming bundled properties and functionalities into individual objects. Two core classes are created automatically by the QGIS plugin builder. In the “die STEG Energie” plugin, the name of them are Energie and EnergieDialog. An instance of EnergieDialog is creates in the init function of Energie class as composition class (orange arrow or part 1 in figure 8). Supplementary to the former core classes, three other classes as composition class such as energy calculator (Figure 7. b), group layer generator (Figure 7. c), and map layout creator (Figure 7.d)), have been connected to two core plugin classes. Using this structure will facilitate further developments. To avoid redundancy and increase code performance, one or more pyqgis libraries have been rewritten into properties, static methods, instance methods, and class methods. This refactoring increases the readability, performance, and coding efficiency, which have a rudimental role for having clean code (Westra, 2014).

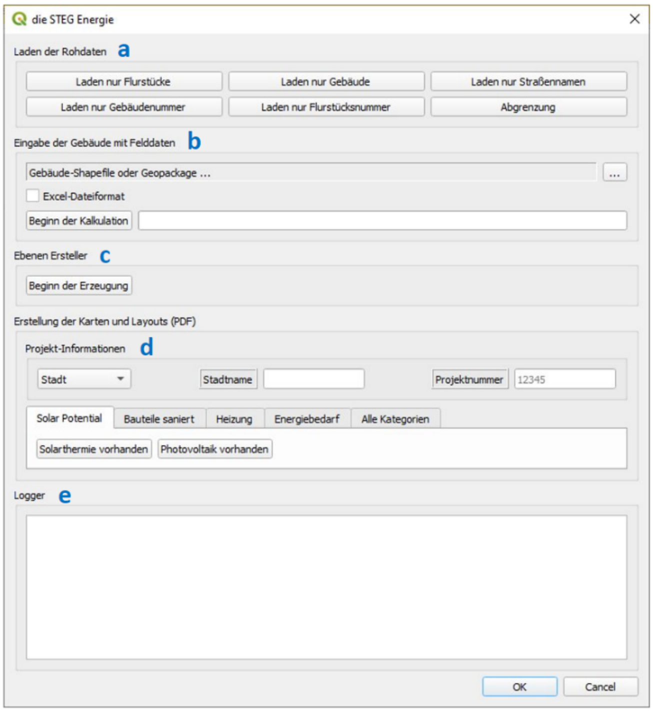

Figure 7. die STEG energy plugin (user interface). a) Import of raw data such as land parcels, buildings, labels as point features with their symbology. b) Energy calculation based on the data collected in QField. c) Generation layer group. d) Creation of maps and basic layouts in PDF format. e) Logging the comments and errors

According to Figure 8, some examples of properties, static methods, and instance methods used to increase the performance are minimum bounding box calculation and joining between QGIS temporary files. As mentioned in previous sections, the width and height of the buildings are required to calculate the area of walls, floors, facade, and the volume of the building. The minimum bounding box has been calculated to estimate these two parameters. Because most QGIS native algorithms output is stored in the temporary layer, a custom static function was used to implement a 1:1 joining attribute table (Westra, 2014).

At this step, all the requirements of buildings' energy demand calculations have been done. As shown in figure 8, the red arrow (section 2) indicates a part of the energy calculation. First, an object from the energy calculator class is created, and then from a function, the executor is invoked. All the formulas and parameters are stored in a list with the name of fields. Then these formulas recall in the field calculation function, and the results are stored in a new *.gpkg file. If any further calculation or parameters are required, the new parameters or formula will be added to the list or replace previous ones. Hence, the enhancement of building energy calculation will be straightforward in the future for energy department experts and plugin developers.

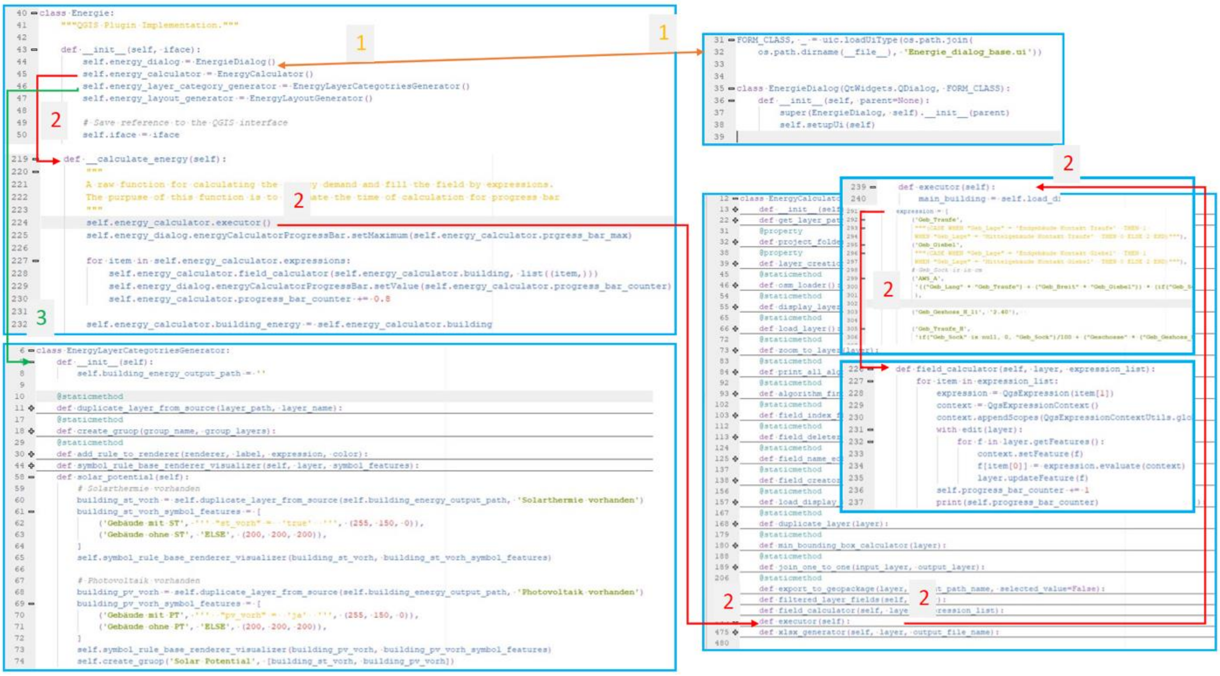

Figure 8: A part of plugin code. 1) The connection of Energy class and Energy Dialog (Generated for PYQT). 2) Energy calculation. 3) Group layer generator.

The same procedure has been applied to generate group categories and layouts. A list of rule base styling queries or grouping names is created by calling all the functions from their classes (green arrow or section 3 in figure 8). With this plugin, the energy expert users can calculate and visualize their output in some seconds. This process is summarized into four steps. Import raw data such as land parcel, buildings, and labels with their specific symbology (Figure 7. a). Energy calculation that the input comes from QField (Figure 7. b). Generate layer groups (Figures 7. c, and 9 show a sample of grouping and layouts). outs). Automatically create a series of maps in a PDF document for further evaluation and discussion with the stakeholders in the municipalities (Figure 7.d).

Figure 9 shows four samples of each group from a small part of the study area. Group 2, 3, and 4 represent the information gathering from field surveying, such as the number of houses using photovoltaic panels or the houses whose heating system has been refurbished. The results of the energy demand calculation are stored in group 1. Such categories or layers help city planners and energy experts to analyze the gathered and calculated values better.

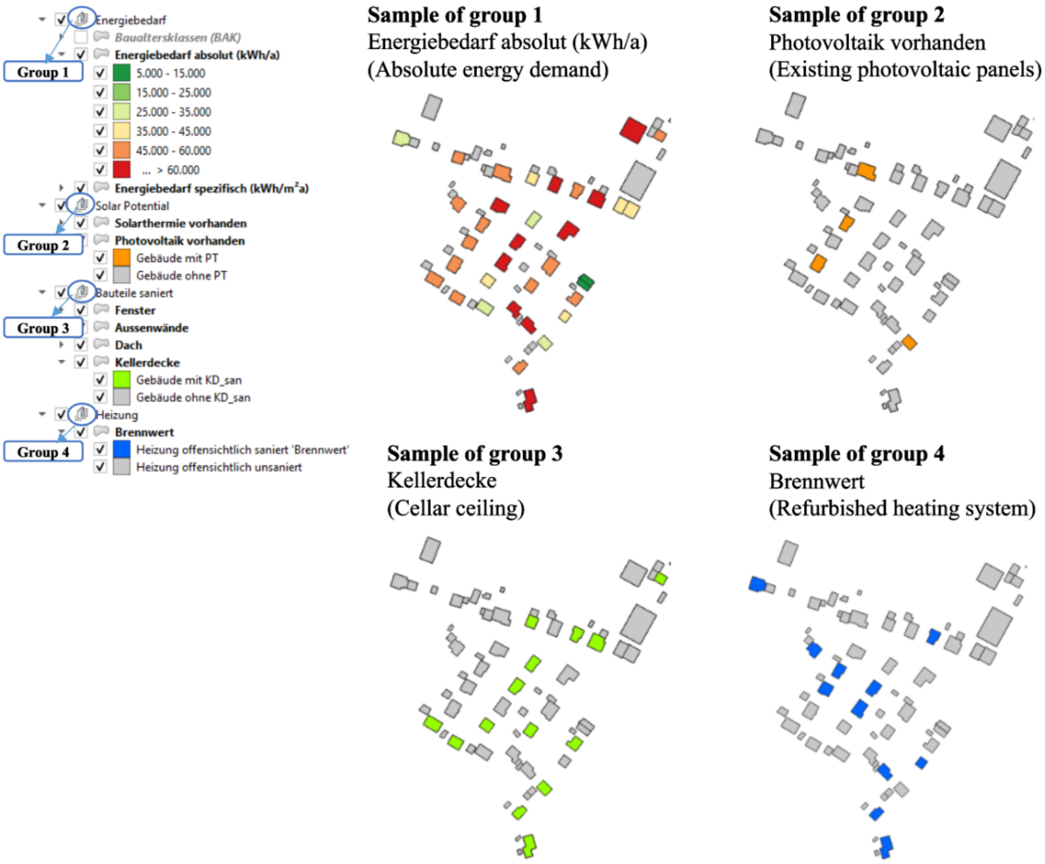

Figure 9: A sample of grouping layers and visualization for a small part of the study area. 1) The absolute energy demand for heating houses. 2, 3 and 4) Houses having photovoltaic panels, cellar ceiling, and refurbished heating system.

CONCLUSION

In most urban planning projects, estimating the energy demand of buildings and CO_2 emission has become one of the most significant factors to manage neighborhood energy-efficiency concepts. The approach used in this study aims to automate and simplify the procedure of energy demand calculation with the usage of open-source geospatial information software. The methods not based on GIS technology cannot prepare all requirements for energy demand calculation and estimating CO_2 emission according to costless software for gathering data, generating diverse types of maps with their specific symbology for different outputs, and implementing all the calculations in a couple of seconds for a large area. To solve this problem for the energy experts department, QField as open source plugin is used to gather field data as the input for the "die STEG Energie" plugin. This plugin provides all the prerequisites for better decisions and developing plans in the minimum time with minimal costs. Moreover, the source code of this plugin is based on object-oriented programming methods that will facilitate the implementation of further features in other fields of energy related evaluations. The approach described in this paper can be extended. To enhance the accuracy of the data collected in the, the data can be transferred from QGIS to a PostgreSQL database to make them accessible for the owners of the buildings via an online platform to let them update the data according to their specific more detailed knowledge about their properties. In addition, the LoD1 data based on the 2D cadastral floor plan, the estimated building height could be augmented to LoD2 data by adding standardized properties of roof type and precise building height for future projects and studies.

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