Energy Building Stock Simulation and Planning for Small Municipalities

A Web-based Urban Energy System Model for Potential Analysis and Citizen Participation

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Abstract: City planning for sustainable energy and development goals in small municipalities suffers from unresolved complexities, insufficient data and prohibitive cost. We propose a low-cost urban energy system for building stock assessment and urban energy planning by combining archetype-based dynamic energy demand and coverage simulation with incentive-based citizen participation as a means to improve data quality. Combining a white-box based physical approach with multi-dimensional archetypes for individual building energy demand and supply estimation with statistical top-down validation and calibration, we obtain an energy simulation method that requires less data on the building stock than other typical methods.

1 INTRODUCTION

Changing energy use is a physical necessity. The Paris Climate 2015 established moderate goals for this transition until 2050. In spite of efforts around the globe, progress is dramatically slower than necessary and time is running out.

In small cities, resources, expertise and data may not be as abundantly available as in large "Smart Cities". Consequently, city planners struggle to implement effective measures to pursue their sustainability goals. This paper aims to highlight a feasible approach of energy simulation through archetype classification on the example of the city of Korneuburg, Austria. The city of around 13 thousand inhabitants aims to achieve their self-proclaimed goal of energy self-sufficiency by the year 2036 (Stadtgemeinde Korneuburg, 2014).

The first step to this end is to establish certainty of the current energy usage: Once known, cities can develop roadmaps from the current to the desired situation. This encompasses all emission-related aspects of energy usage such as mobility, buildings and industry.

City planners need a framework to predict energy demands and coverages for entire cities and compare possible effects of future measures (Sousa et al. 2012). Examples of such projects are abundant (see Tardioli et al., 2015, Caputo et al., 2012), and yet it remains difficult to generalize the approaches to small cities. A number of factors limit the usage of such tools: First, the required data for the framework may not be readily available and its aggregation cost-prohibitive or hindered by privacy concerns (Ballarini et al., 2011 and Ballarini et al., 2014). Second, the expertise required to operate such tools may not be available within smaller administrative bodies. Finally, the resources required to sustain complex energy estimation and planning systems may not be available.

Typical approaches and solutions fall in one of three categories: (i) High-accuracy physical energy estimation tools that incorporate all energy aspects of a city. They tend to be expensive, as they require detailed and extensive physical data and expertise (engineering method), (ii) well established tools for narrow areas of city planning such as heating demand estimation, grid planning, etc. Their ability to visualize energy system states and changes are therefore limited. And (iii): Holistic city planning solutions –typically trading detail for accessibility.

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Existing research on quantifying a city's building stock energy system focuses heavily on demand estimation, specifically heating energy demand. A holistic city simulation must also include methods of quantifying *how* these energy demands are met, and their corresponding greenhouse gas emissions. Finally, existing building stock should be compared to varying future scenarios. The energy framework for small municipalities is required to answer: What energy usage and associated emissions are attached to the current building stock? Which saving potentials are available and where? What could happen if we assume certain transition rates (which can represent political measures)? The energy framework is also required to provide a number of technical and practical features and constraints to be feasible in a non-scientific context: Data management: Possibility to integrate different data types, and versioning of this data, user-friendly interfaces: Comfortable, intuitive and robust design

The importance of the last two points cannot be understated. It must be ensured that data aggregation can continue on the running system and can be done in an economically feasible way.

2 METHODOLOGY

Three key components form the proposed energy framework are: (i) An energy database, (ii) an energy building simulation engine and (iii) a web-based front-end user interface, later referred to as the "web-platform". The focus of the following section is to describe the energy simulation method. Thereafter, a brief overview on the data model and web platform is given.

2.1 Energy Simulation

According to (Swan and Ugursal., 2009) and (Tardioli et al., 2015), large scale building stock energy simulation can be classified into three categories: White-box based approaches employ physical energy models on a city scale, typically extrapolating from single buildings through distribution, archetype or sample methods.

Black-Box based approaches use statistical methods such as regression, decision trees and artificial neural networks to estimate energy consumption based on existing data (Tardioli et al., 2015). Although physical models have their merit in obtaining detailed results for specific buildings, the amount of parameters and computation time required usually prohibits their use for city scale application (Kavgic et al., 2010, Keirstead et al., 2012, Pervez et al.,2014). A purely black-box based approach (as employed Humeau et al., 2013 and Powell et al., 2014) extrapolating from existing data is not sufficient, as there is no data on future, more efficient buildings to extrapolate from. Finally, grey-box based approaches can be seen as a combination of both white- box and block-box based techniques.

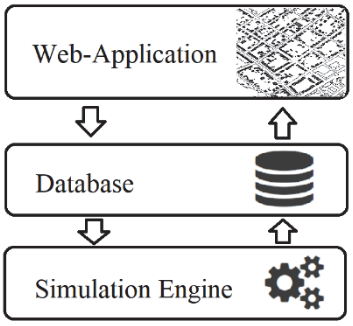


Figure 1: The components of the implemented energy web-platform and their interaction.

For single building simulation, and more so for estimation of future building and plot potentials, a physical approach is necessary. It is however virtually impossible to collect sufficient data on each building to apply physical methods individually (Ballarini et al., 2011 and Ballarini et al., 2014). Instead, the first important modelling decision is to appropriate each building from the building stock with a virtual building type, typically referred to as an archetype (Swan and Ugursal, 2009), designed to reflect determining features such as

- Surface-to-Volume ratio (compactness)
- The share of solar transmitting surfaces on the building envelope and their orientation
- The thermal transmission properties (of building materials)
- Usage of the building (for residential, commercial and other purposes)
- Energy system (including all energy uses such as heating, cooling, (de-)humidification, end-use, etc.)

The relative influence of these parameters have been extensively investigated and discussed: (Schüler et al., 2015) found through statistical regression analysis on 57.000 buildings in Geneva that microclimate, which they describe through the parameters of average building height, horizontal density and average irradiation, play an important role. (Aksoezen et al., 2014) argued that the most influential building parameters on energy demand are

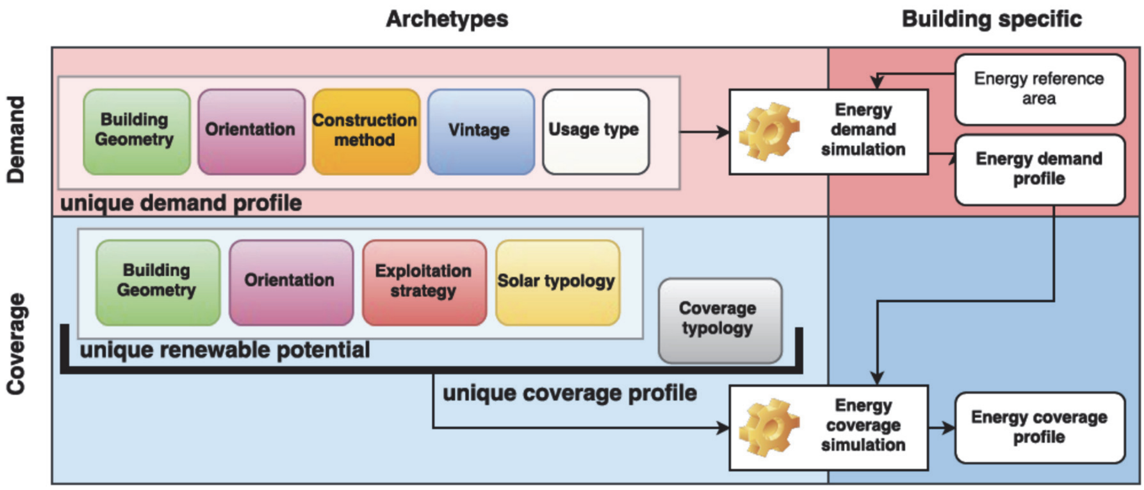


Figure 2: Energy simulation data model divided in demand archetype classification (light red) and building energy demand calculations (dark red), as well as coverage archetype combination from parameters on the renewable energy potential of the building and common coverage typology through conventional energy systems (grey box).

compactness and building age. In any case, archetypes allow direct control over the trade-of between modelling effort and model accuracy (Korolija et al., 2013).

The energy simulation method proposed in this work is combining data from the geoinformation system of the municipality of Korneuburg, statistical data on city quarters and archetypes to quantify the energy use intensity of the building stock (compare Caputo et al., 2012 for a detailed description of this approach).

The archetypes developed in this study divide between **demand archetypes** and **coverage** or supply **archetypes**. The demand archetypes are characterized by the combinations of (i) typical building geometries, (ii) typical physical properties of the thermal hull, (iii) typical usage profiles, (iv) construction method and (v) orientation of the building (as can be seen in Figure 2). Typical physical properties are assumed according to vintage of the building as surveyed in (Zelger and Waltjen, 2009) and reflect typical building materials from a certain time. The parameters of building construction method and usage type follow the same categorization in this source.

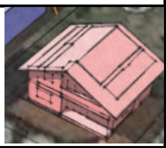
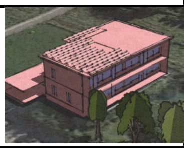
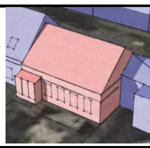
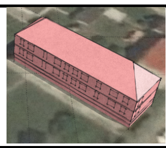
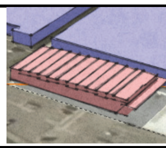
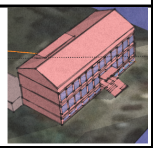
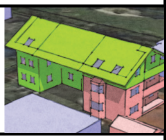
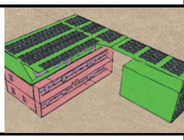
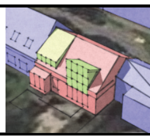
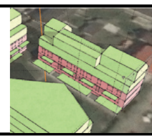
Similarly to (Kazas et al., 2015), the orientation parameter was quantified into eight equally sized segments, as can be seen in Figure 3. Since orientation could only be derived from GIS building footprints, it was defined by the direction of the largest building façade. As there is no possibility to distinguish between a building and its rotation by 180° from a rectangular building footprint alone, the two cardinal directions opposite each other cannot be distinguished with this method and subsequently, orientation of archetypes can only be equally distributed between the two. For the most part, this is of no concern, as archetypes are mostly, but not generally, mirror symmetrical and thus invariant to 180° rotation. However, for highly unsymmetrical building geometries this approach is not directly applicable.

One of the key predictors of a building stock's energy demand is building age: As pointed out by (Aksoezen et al., 2014), the dependency of heating energy demand on building age is non-linear. However, a statistical approach with archetypes allows for estimations with low margins of error.

In the case of Korneuburg, data on building age was available as a statistical distribution for around hundred districts ("sub-zones") with five to fifty individual buildings each from (Galosi et al., 2012).

Since the data model needs to depict not only present but also future conditions, the coverage simulation is required to factor in energy demand, coverage systems, as well as renewable energy potentials on site. To this end, we employed coverage archetypes, that are similar yet more numerous than the energy demand archetypes described above, and combined from two parts: The first part is a parametric typology of "common" coverage systems such as gas or oil powered heating systems. They are "common" in the sense that they typically cover the energy demand of the building stock, but this is purely semantical. The methodological distinction to the other parametric types is that opposed to the latter, the "common" coverage systems do not have any constraints in their application

Table 1: Geometric types constituting the building stock of the city of Korneuburg, as well as possible densification variants.

Geometry	Detached single family house	Modern double family house	Attached Single family house	Multifamily house	Retail	Office
Building stock						
Gross floor areas [m²]	209	418	108	760	750	510
Densifi-cation variants					Retail and Office Densification geometry types currently in development	
Gross floor areas [m²]	500	662	162	1064		

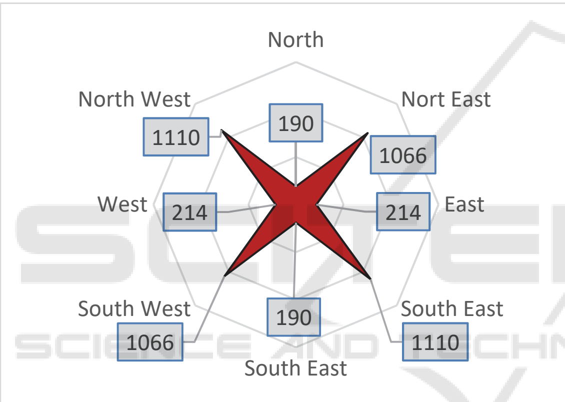


Figure 3: Distribution of building orientations in Korneuburg. Most parts of the city align with the river Danu be (flowing from North West to South East).

Not so for the group forming the "unique renewable potential" (Figure 2). These parameters determine to extent to which renewable energy potential can be used for any given building. The "solar" parameter describes different rulesets that determine which areas of a building geometry type can be used for solar energy. These rules are not specific to certain building geometries. However, since surface suitability for solar usage depends heavily on building geometry, specific solar type rulesets with certain geometries in mind can yield better results than generic rules. Figure 4 shows how three different solar ruleset types are applied to two different geometries.

Since the orientation of the building archetype's geometries is unknown and statistically distributed, it is necessary to distinguish between areas of technical solar potential (the last step of solar ruleset types) and the actual feasibility of these potential areas due to irradiation depending on orientation. All roof and façade potential areas are divided in primary areas (with the highest irradiation of the roof or façade areas respectively) and secondary areas (the rest). In a last step, the actual feasibility is determined by combining the possible orientations with a certain

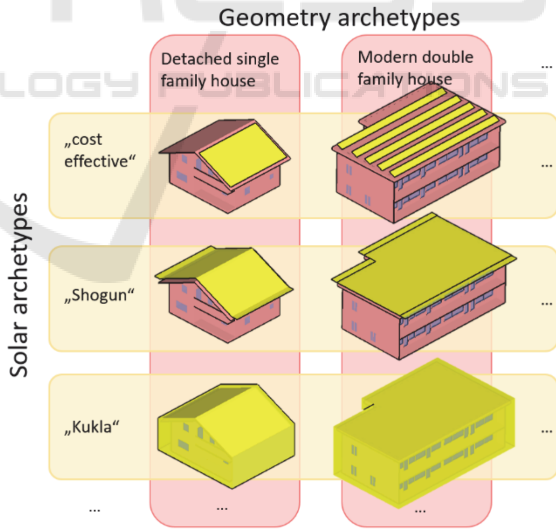


Figure 4: Exemplary application of three solar typologies onto different building geometries: The "cost effective" typology classifies 90% of the south-most facing, sloped roof surface, and/or 40% of horizontal roof areas at optimal orientation (tilt and azimuth) as solar potential. "Shogun" classifies all roof areas (automatically adding 1m wide canopies), and the hypothetical "kukla" typology assumes all building surfaces as solar potential (resulting solar potential areas in yellow).

"exploitation strategy", which determines the share of primary and secondary roof and façade surfaces actually used, as well as which technology, thermal, photovoltaic or hybrid is being applied to each. Figure 5 shows primary and secondary areas for different orientations.

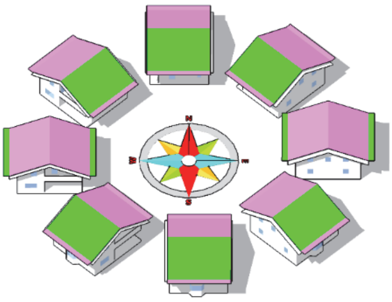


Figure 5: Primary (green) and secondary (purple) solar roof potential areas for different orientations according to an exploitation strategy.

The resulting simulation method for individual buildings provides dynamic calculation methods for thermic building simulation in a single thermal zone and yields energy usage, energy supply, humidity and temperatures in a quarter-hour resolution, as well as primary energy balances and greenhouse gas emissions. It was developed upon (Rondoni, et.al. 2015), which was validated using a TRNSYS reference model.

For the purposes of city-scale scenarios, the calculation is separated in two steps: First, the detailed energy demand of all predefined archetypes is calculated. Then, results are aggregated according to the spatiotemporal distribution of these archetypes throughout the city and the years of the scenario to obtain a city estimate. The building stock is derived from the archetypes to match its actual energy reference area. Area-specific values are assumed to equal those of their corresponding archetype. The results can be compared to top-down energy use data from the local energy supplier to calibrate the archetypes and their distribution throughout the city.

The last important feature of the energy simulation method is future energy scenarios. This is accomplished through virtual "measures", which is a transition rule with the following parameters: (i) a building parameter such as geometry or energy system to transition, (ii) a filter that determines which archetypes should be affected, (iii) a target value for the parameter, and (iv) a transitioning rate per year and (v) a timespan in between years.

2.2 Database and Web-platform

As (Swan and Ugursal, 2009) and (Kavgic et al., 2010) have pointed out, it is generally difficult to obtain reliable information from end-users and residents due to privacy and collection issues and cost. As (Aksoezen et al., 2014) put it: "There is a missing link in practically all models between the estimated energy consumption and the real energy consumption".

The approach of this study is to make the results of the simulation available to the end-users and residents themselves on a dedicated web-platform. Here, the citizens are incentivised to voluntarily partake in the data collection in two ways:

First, the web platform offers detailed simulation of individual buildings, also in virtual refurbishment variations as a service to residents. They can use this service to explore the opportunities for their own home. Since it is in their self-interest to obtain as reliable results as possible, they are incentivised to produce as detailed information about their building as possible.

The second incentive is through collaborating on a common goal. As projects such as Wikipedia have impressively shown, members of a community have an innate desire to contribute in a meaningful way towards a common goal. In the case of the web platform of the particular city of Korneuburg, the goal is to achieve municipal energy self-sufficiency by 2036 (Stadtgemeinde Korneuburg, 2014). It is important to point out, that this goal was not imposed by the city administration or other government, but rather was the result of an inclusive development project by citizens, politicians and other stakeholders to shape the roadmap into the city's future.

3 RESULTS

With this city energy model it is possible to quantify and visualize the building stock's energy demand (Figure 8), energy use intensity and greenhouse gas emissions (Figure 7). Furthermore, future scenarios can be evaluated by adjusting the existing archetypes and transitioning them with archetypes that reflect future, more energy-efficient buildings. Different densification strategies can also be examined (Figure 6), as well as the quantitative effect of retrofitting measures. For the goal of energy-autonomy, as in the case of Korneuburg, it is possible to investigate different mixes of archetypes, whether they are sufficient to meet the goals and how possible transitioning roads require different rates of retrofitting and other energy policy measures.

Citizens are incentivised to visit the energy web platform, as they can investigate their city for themselves and discover the (im)possibilities of certain futures. By providing examples of best-practice buildings, the web platform aims to connect the overarching goals of a city to the individual action space of their residents. If they decide to, they can even provide detailed data on their own building, such as energy audits, archetypical information and energy bills – thus improving the database, which is primarily based on statistical assumptions (Figure 9).

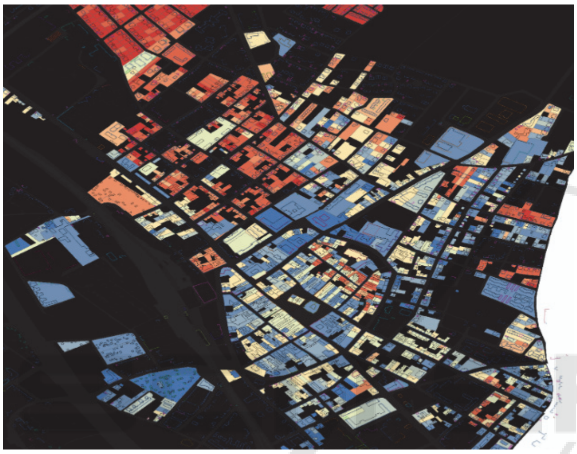


Figure 6: Densification potential of plots within existing density regulations from high (red) to low (blue).

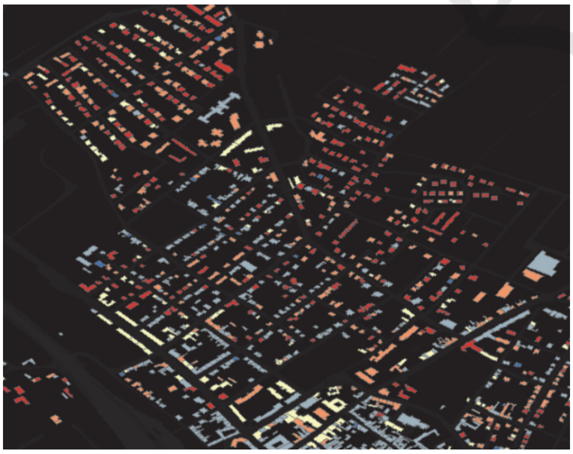


Figure 7: Greenhouse gas emissions per building and year from blue (< 40 kg CO_2equiv./m²a) to red (> 180 kg CO_2equiv./m²a).

Since resource efficiency is a major concern, the data model is able to combine different datasets. Apart from user input, it is also possible to incorporate measurement and sensory data, which can be used to validate the underlying modelling assumptions. A role-management system enables control over rights and privileges of all participants. Municipal energy planners can then use the platform to maintain their building energy data.

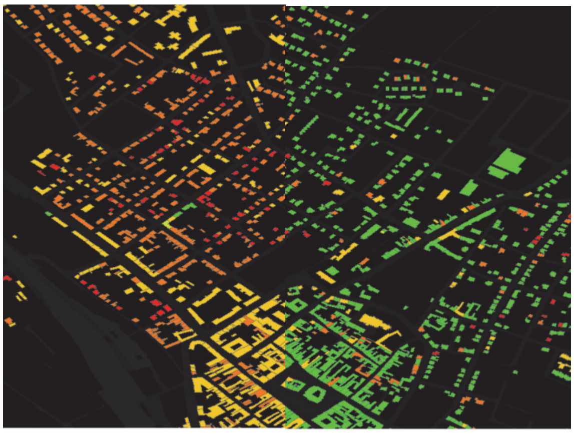


Figure 8: Heating energy demand from green (< 15 kWh/m²a) to red (> 150 kWh/m²a) for the existing building stock (left) and a future city scenario with 80% of the building stock retrofitted to passivhouse standard (right).

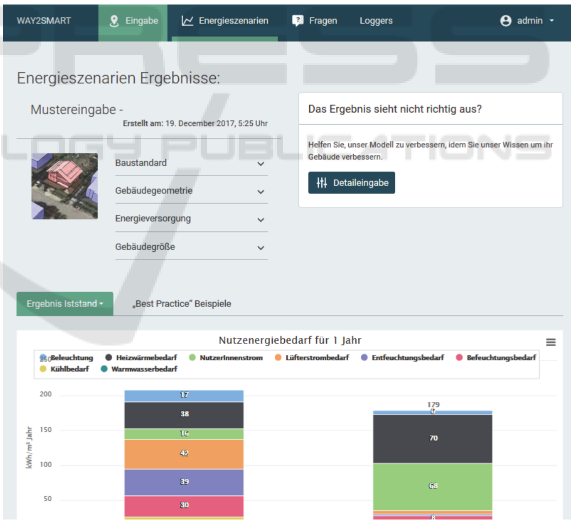


Figure 9: Web-platform user interface for detailed building simulation and result presentation.

4 DISCUSSION

With this approach we aim to combine the strengths of top-down statistical methods (i.e. bridging the gap between simulation and reality and giving insight in user behaviour), and engineering methods, which are the only ones capable to evaluate the impact of new building solutions (Swan and Ugursal, 2009). The number of archetypes derived in this study from building parameters is around 58 excluding and 180 including the orientation parameter. For comparison, (Mata et al., 2014) compiled 593 archetypes including residential and non-residential buildings in France, Germany, Spain and the UK.

The current implementation of the simulation method focuses on the individual building. In reality, a plot can and often does house multiple buildings. Their energy demand can still be calculated separately, however their potential for renewable demand coverage and densification through refurbishments are interconnected. The potential of ground heat pumps for example depends on the area of unsealed land, which remains when subtracting the building's footprints from the plot area.

Another example is densification: Construction laws impose thresholds on building density for plots of land. However, the plot specific densification potential cannot be algorithmically allocated to each building. This suggests plots instead of buildings to constitute the central aggregation point for data. This will require the development of plot archetypes, which in turn can be comprised of various building archetypes.

One notable example of an energy web-platform is the "energy app" developed by the city of Glasgow (Glasgow City Council, 2015). Although the method of building stock estimation is different, it incorporates similar features for citizens to explore and interact with – especially the interactive 3D online map.

3D based methods, most notably CityGML, have demonstrated great potential for integrating GIS and other georeferenced data (e.g. LIDAR) with energy metadata for energy simulation purposes, as (Agugiaro, 2014) demonstrated for the city of Trento. (Monsalvente et al., 2015) developed a „modular physical [building simulation] model in INSEL", which can be generated automatically and connects directly to the CityGML open source standard. However, its physical model can only be employed for buildings with a level of detail (LOD) of at least two, which includes roof shapes. Since roof geometry is not commonly obtainable data in small municipalities, the proposed approach in this paper focuses on building footprints, which correspond to a building LOD of zero, in combination with a small number of geometric archetypes.

However, obtaining a sufficient number of archetypes can be challenging for larger cities, or cities with a very diverse and heterogeneous building stock. However different, the approaches are not mutually exclusive, as the building input data for energy demand are very similar (compare Wate and Coors, 2015). The authors aim to develop our simulation method to be compatible with the CityGML standard, and it's energy application domain extension (ADE).

5 CONCLUSIONS AND OUTLOOK

Combining a white-box based physical approach with multi-dimensional archetypes for individual building energy demand and supply estimation with statistical top-down calibration capabilities, we obtain an energy simulation method that requires less data on the building stock than other typical methods. Nevertheless, further refinement on archetypes and distributions will be necessary.

Once the platform opens up to a wide base of users from the municipality, it will be interesting to study the actual engagement of the users, as well as the quality and quantity of their supplied data.

As with most projects on building stock, data collection and processing is time-consuming and error-prone. We fully agree with the suggestion of (Keirstead et al., 2012) for "a centralized repository for cities' energy related data". We believe that open source standards such as CityGML are necessary and need to be developed and put to use faster in order to meet our goals in the future. To this end, we aim to develop our simulation method to be compatible with the CityGML standard, and it's energy application domain extension (ADE).

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