Journal of Civil Engineering and Urban Planning (2026)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2026.080218
ISSN 2616-3969 Vol. 8 Num. 2

GIS-Enabled Archetype Modelling of Urban Building Energy Demand in Severe-Cold Xining, China

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Keywords: Geospatial analysis; Building archetypes; Heating demand; Severe cold climate; Heat recovery

Abstract: Cities frequently have adequate geographic building inventories but insufficient information to specify detailed energy models for individual properties. This study examines a GIS-driven, archetype-based workflow for central Xining, a high-altitude Chinese city in a severe cold zone. Fifteen representative building types were constructed using local parameter assumptions and generated through a structured JSON-to-Ruby/OpenStudio pipeline for EnergyPlus calculation. Of 60,304 mapped footprints, 20,342 were classified into usable archetypes, accounting for 64.4% of the reported floor area. The classified stock has modelled annual space-heating demand of 3.79 TWh, electrical consumption of 3.96 TWh, and domestic hot-water gas use of 0.65 TWh. Simulated heating requirements differ substantially by occupancy, particularly for ventilation-intensive public buildings. Introducing 60% sensible heat recovery in relevant public functions reduces the modelled heating demand by 20.3%. A residential floor-area comparison agrees with a statistical benchmark within 5.8%, although heating indicators remain non-equivalent in scope and were not calibrated. The framework is useful for transparent scenario screening, provided classification gaps and statistical boundaries are explicitly acknowledged.

1. Introduction

1.1 Research context

Urban energy planning requires information about where buildings are located, how they are used, and how their thermal and electrical needs respond to operating conditions. A city may possess reliable maps of its building footprints while lacking the construction details and metered consumption records needed to create an individual simulation for every property. The resulting mismatch between abundant geographic information and scarce engineering information is a persistent problem in bottom-up urban building energy modelling (UBEM). In a physics-based approach, the consequences of a change in envelope performance, ventilation strategy, or equipment operation can be examined explicitly. However, this analytical flexibility is useful at metropolitan scale only when the required input data can be assembled consistently. Reviews of building-stock modelling distinguish engineering-based simulations from more aggregated

statistical descriptions and emphasize that model complexity must be compatible with data availability [1,2].

Archetypes provide a practical connection between a mapped urban inventory and building performance simulation. Rather than assuming that each property has a unique and completely observed configuration, the stock is organized into groups with comparable functions and relevant physical characteristics. Each group receives a reproducible set of envelope properties, internal gains, schedules, and service assumptions. Simulated energy intensities can then be associated with the mapped buildings belonging to that group. This approach does not eliminate uncertainty; it makes the assumptions visible and permits the same modelling procedure to be repeated. Work on GIS-based archetype identification and automated city-level simulation illustrates the value of linking spatial records to standardised engineering descriptions [3,4].

Cold-climate settlements create a particularly demanding application. Space heating operates over a substantial part of the year, and differences in thermal insulation, outdoor-air supply, and occupancy patterns can produce large differences between building types. In a city where several uses coexist within one block, treating a structure as entirely residential or entirely commercial may further obscure the processes driving energy demand. Consequently, useful urban estimates require more than a single average heating intensity. They need a transparent classification, a clear accounting boundary, and an explanation of how assumptions made for representative models are extended to the wider building population.

1.2 Case-study motivation and research gap

Xining, the capital of Qinghai Province in northwestern China, provides an illustrative case. The investigated urban area lies in a high-altitude environment, approximately 2,295 m above sea level, and is classified as severe cold climatic zone 1C in the source study. It contains a diverse building population with substantial low-rise housing and incomplete land-use descriptions. These features create two interrelated challenges: many building records cannot immediately be associated with a reliable functional type, and energy performance must be represented using assumptions appropriate for local climate and construction practice. The study therefore addresses the operational feasibility and interpretive limits of an archetype-based framework rather than claiming that every urban building has been individually surveyed.

Previous urban simulation workflows have demonstrated how municipal databases can support automated energy models, including EnergyPlus-based retrofit analysis [4]. Their applicability is nevertheless influenced by the consistency of building attributes and the extent to which archetype parameters reflect a particular climate. The methodological contribution in the present case is a compact inventory of fifteen types combined with a scripted model-generation route and a geographically referenced scaling procedure. This differs from a building-by-building calibration exercise: the objective is to establish an auditable stock representation and compare a defined ventilation intervention with a documented baseline. The manuscript therefore evaluates model generation, mapped-stock coverage, energy-use contrasts, and the suitability of existing statistical information for validation as separate questions.

1.3 Objectives and scope

The research has four linked objectives. First, it documents the conversion of an urban footprint inventory into a set of buildings with usable energy-model classifications. Second, it describes how representative residential, public, and mixed-use models are parameterised and executed using OpenStudio and EnergyPlus. Third, it reports the distribution of space-heating, electrical, and domestic hot-water energy across these categories and applies the resulting intensities to the

mapped stock. Finally, it explores a heat-recovery scenario and examines the interpretation of discrepancies between model estimates and published heating statistics.

Three qualifications frame the analysis. The mapped and classified subset is the empirical basis for the principal city totals; estimates for unclassified floor area represent extrapolation, not directly simulated buildings. A successfully completed simulation demonstrates numerical operability but does not, by itself, establish agreement with measured consumption. Moreover, comparisons with district-heating statistics can be informative only when their geographic coverage, building population, and supply-versus-demand boundaries are considered. Keeping these distinctions explicit makes the results more useful for planning and establishes a defensible basis for later field validation.

2. Materials and methods

2.1 Study area, building inventory and data boundaries

The spatial focus is central Xining, Qinghai Province, at approximately 36.72 °N and 101.75 °E. The working GIS inventory contains 60,304 building footprints after the removal of 1,245 polygons with areas smaller than 20 m². For the modeled inventory, the source reports a combined floor area of 93.75 million m². This value should be understood as represented floor area, rather than as a claim that the sum of two-dimensional footprint polygons alone equals that amount. Each building is treated as a spatial object that can carry geometry, estimated storey count, and, when available, a functional label. This representation makes it possible to compare classification coverage in terms of both the number of objects and the floor area that they represent.

The threshold applied to very small polygons was intended to keep the modelling inventory focused on buildings for which an archetype representation is meaningful. Its effect on the total area is not separately quantified in the source material, so no area-loss estimate is introduced here. Likewise, the geographic boundary of the analysed districts is not redefined beyond the stated central-city study area. The observations and simulated results reported below refer to that documented inventory. They should not be treated as a census of every building in the whole administrative municipality.

Height information was converted into an estimated number of storeys by rounding the ratio of building height to 3.0 m. This operation is computationally straightforward but has consequences for floor-area allocation. Buildings with atypical floor-to-floor heights, mechanical service levels, high lobbies, or stepped roof forms may be assigned too many or too few storeys. The original inventory does not provide an independent, parcel-level verification dataset for this conversion. Accordingly, storey count is treated as an inferred attribute and the potential geometric bias is carried into the uncertainty discussion rather than being presented as a measured quantity.

2.2 Weather information and archetype parameter sources

Hourly weather input was taken from the Chinese Standard Weather Data (CSWD) record associated with WMO station 528660. A consistent annual weather file is essential because relative differences among archetypes are meaningful only when the models experience the same external climate. The climate description is therefore used uniformly for the individual simulations. The reported results represent performance under the adopted weather record and specified operating assumptions; they are not an observed time series for all properties in Xining. Variability among actual years, spatial weather differences inside the city, and local microclimatic effects were outside the documented simulation exercise.

Engineering attributes were drawn from a local parameter library that differentiates existing

conditions from a code-oriented parameter tier [5]. This two-tier organization is important for interpreting retrofit comparisons. Parameters describing the present stock provide the reference condition, whereas values chosen for a compliant or improved configuration define a contrasting engineering scenario. Neither tier automatically reproduces the construction history of each mapped building. Published work on automated GIS-to-energy workflows informs the generation procedure, while the local library supplies case-specific parameter choices [5,6]. A relevant national heating and ventilation design standard is GB 50736-2012 [7]. The central numerical and categorical modelling assumptions are listed in Table 1.

Table 1. Principal inputs and modelling assumptions documented for the Xining archetype workflow.

Parameter or input	**Specification retained from the source**
GIS footprint inventory	60,304 retained polygons after a minimum 20 m ²screen
Represented floor area	93.75 million m ²for the full working inventory
Storey estimation	Round(building height / 3.0 m)
Weather	CSWD, WMO station 528660
Building archetypes	Fifteen functional types, P01-P15
Model-generation environment	JSON input, Ruby automation, OpenStudio 3.8
Dynamic simulation	EnergyPlus 24.1, six timesteps per hour
Envelope and leakage	Code-derived U-value targets; 0.2 m simplified opaque layer; 0.5 ACH infiltration
Heating representation	Ideal heating demand; assumed conversion efficiency 0.90; 15 October to 15 April
Domestic hot water	Gas heater efficiency 0.80; 50 ℃ delivery; 5-80 L per person per day
Scenario intervention	60% sensible heat recovery in relevant public functions

2.3 Development of the fifteen building archetypes

Fifteen archetypes, identified as P01 through P15, represent the modeled building classes. The categories are low-rise housing (P01), office-hotel (P02), hospital (P03), residential-retail (P04), large office (P05), large hotel (P06), school (P07), small office (P08), small inn (P09), retail-office (P10), retail-hotel (P11), shopping centre (P12), retail (P13), restaurant (P14), and high-rise housing (P15). This modest number of templates was selected to provide a manageable classification rather than a detailed taxonomy of every architectural variation. For each archetype, the representative prism geometry was assigned using the median dimensions from its corresponding sample. Median-based abstraction reduces the impact of extreme footprints, but it also suppresses differences in aspect ratio, roof configuration, and facade exposure within a category.

Functional classification influences more than the name assigned to a geometry. It determines the schedules, occupant-related gains, ventilation assumptions, water-use characteristics, and, where applicable, envelope properties used by the simulation. Residential and public buildings need not respond to the same heating controls or outdoor-air requirements. For a mixed-use archetype, the functional components are therefore represented separately instead of applying a weighted average set of parameters to the complete structure. Maintaining this distinction avoids assigning residential operating conditions to a public floor or vice versa. It is particularly important when the intervention being assessed changes ventilation heat losses only in selected occupancies.

Thermal transmittance targets for residential construction were associated with DB63/T 1626-2020, and values for public buildings with DB63/T 1627-2018, for the respective building functions [8,9]. The full U-value table is not available in the present study record and has not been reconstructed without supporting measurements. The analysis consequently identifies the relevant construction standards and their role in model generation without claiming unverified material conductivities. The distinction is consequential: an archetype model can be reproducible in concept while its full numerical reproduction still requires the accompanying parameter files.

2.4 Thermal envelope and representation of floors

The automated geometry-generation procedure distinguishes the ground floor, repeated intermediate floors, and top floor. Interior levels that share the same thermal specification are represented using zone multipliers. This arrangement limits the number of explicitly simulated thermal zones while maintaining distinct treatments for the roof and the ground-contact floor. If all floors were duplicated without distinguishing their exposure, the model could attribute roof losses or ground heat exchange to levels that do not experience those boundary conditions. The adopted grouping is therefore a purposeful simplification, though it cannot represent differences between individual intermediate floors.

Opaque building elements were represented with a 0.2 m material layer selected to meet the prescribed thermal transmittance and provide an effective heat-storage response. This is a modelling abstraction, not an assertion that all walls in the study region physically consist of one homogeneous material. The specified U-value primarily governs conductive losses, whereas the thermal capacity assumption influences transient temperature changes and load profiles. For windows, a simplified glazing construction includes the specified U-value, solar heat-gain coefficient and visible or solar transmittance as defined in the archetype parameters. Because the source does not include orientation-specific glazing statistics or measured facade characteristics, further claims about detailed solar-gain calibration would not be justified.

Simplification has advantages and limitations at the urban level. Standard constructions help isolate differences associated with use and control patterns, and repeated floors make simulations more economical. At the same time, variations in insulation ageing, thermal bridges, air leakage, shading, window operation, and occupant behaviour may cause an actual building to depart from its archetype. These effects are most appropriately addressed by measured data and sensitivity analysis in a later model-refinement stage. They are not corrected retrospectively by assuming a single universal adjustment factor.

2.5 Occupancy, internal loads, ventilation and service systems

Building operation was represented by a complete set of annual schedules spanning 8,760 hours. The schedules describe typical temporal variation in occupancy, lights, equipment and relevant service demands for each functional type. Their purpose is to distinguish uses with different daily and seasonal occupancy profiles. A single yearly schedule cannot capture the full diversity of behaviours in schools, hotels, offices and households; nevertheless, consistent schedules permit a controlled comparison between archetypes. No building-level time-use survey or high-resolution metered schedule was supplied for independent calibration, so these profiles should be interpreted as standardized input assumptions.

An infiltration level of 0.5 air changes per hour was assumed. Infiltration is an important component of heat balance in severe cold conditions because incoming outdoor air must be warmed to the indoor condition. Unlike deliberate ventilation, infiltration arises from envelope leakage and pressure-driven exchange, and a constant value is necessarily an approximation. Ventilation rates

for certain public functions are comparatively high in the archetype models. The parameter library specifies approximately 10-12 m ^{3}of outdoor air per square metre of floor area per hour for schools and restaurants, which explains why these categories have particularly elevated baseline heating demand. The stated rate is treated as a model input and not as a field measurement at all facilities.

Space conditioning was simulated through an ideal-load heating formulation. The calculated useful heat was subsequently related to fuel input using a heating efficiency of 0.90, as defined by the simulation procedure. The heating season extends from 15 October to 15 April. Mechanical cooling was omitted from the reported study. This choice confines the interpretation of results to the modelled services and should not be read as evidence that every public or residential building in the area uses no cooling in practice. In particular, simulated annual electricity refers to the loads represented in the archetypes rather than an independently audited account of all actual end uses.

Domestic hot water was represented as a separate service. The model assumes gas-fired water heating with an efficiency of 0.80, a delivery temperature of 50 ℃, and water-use allowances ranging from 5 to 80 litres per person per day across occupancy types. This formulation permits differences between residential, hospitality, catering, and other functions to affect annual gas use. However, daily per-capita norms cannot reproduce every seasonal, behavioral or institutional pattern. For reporting, domestic hot-water gas is kept distinct from useful space-heating demand and electricity. This separation reduces ambiguity when comparing fuels and avoids silently combining quantities defined at different energy-system boundaries.

2.6 Automated model generation and computation

Archetype specifications were stored in JSON format and translated into OpenStudio models by a Ruby-based generation process operating through the OpenStudio 3.8 command-line environment. Four parameter modules are defined in the automation process, following the general modelling framework cited in [6]. The structured-input approach separates parameter definition from model assembly. It also allows a change in an archetype attribute to propagate through the generation procedure without manually rebuilding every geometry or schedule. This is the principal operational benefit of using a scripted pipeline for a compact set of representative buildings.

Each generated model was simulated with EnergyPlus 24.1 using six timesteps per hour. The study reports 28 completed simulation runs across the assessed configurations, with no fatal errors and no unmet-load hours. This operational check indicates that the models were executable under the selected solver settings and load assumptions. It does not constitute a comparison with independently observed building energy use, and it does not establish that the schedules or constructions describe the real stock accurately. A complete run-by-run manifest is not available for establishing which archetype-scenario pairs contributed to the 28 reported executions; the simulation total is therefore not interpreted as proof of an exhaustive factorial comparison.

A replicable application of the process would archive the archetype JSON files, the generation script, model outputs, the weather file, and the code versions together. This record is particularly valuable when contrasting current-state and heat-recovery cases because otherwise a change in template settings could be mistaken for an intervention effect. The software route and solver settings reported here correspond to those used in the Xining modelling workflow. Archival and additional quality-control procedures are identified as suggested improvements rather than completed analyses.

2.7 Spatial aggregation and alternative coverage assumptions

For each classified building, annual simulated energy intensity is associated with its selected archetype and multiplied by the floor area attributed to that building. The resulting building

estimates are then aggregated over the mapped, labelled subset. Conceptually, a stock total equals the sum of category-specific intensity multiplied by corresponding floor area. This accounting relationship is straightforward, but the classification and area estimates underlying it are not error-free. The total must therefore be interpreted together with its coverage fraction and the specified system boundary.

The study reports two scales of results. The primary estimates cover 20,342 footprints with usable types and represent 64.4% of the mapped floor area. Separately, a whole-inventory scenario allocates the otherwise unclassified area using the shares of represented archetypes. That scenario is an extrapolation based on assumed composition, not a measurement of the properties that lack labels. A simple proportional increase in the labelled subset's total is not necessarily identical to the reported result because redistribution across category shares can change the weighted energy intensity. To avoid obscuring this distinction, the principal conclusions focus on the classified stock, while the extended estimate is explicitly identified as conditional.

2.8 Scenario configuration and validation framework

Two configurations are examined: a current-state case and a case in which public-building ventilation incorporates sensible heat recovery at 60% effectiveness. The adoption of heat recovery is linked in the original study to the heating and ventilation standard GB 50736-2012 [7]. The 60% value is applied as a scenario parameter and does not imply that every affected building has been independently checked for compliance. The intervention applies to the relevant public functions; residential parts of mixed-use buildings retain their original natural-ventilation treatment. Envelope geometry and the reported electrical and hot-water inputs are otherwise held constant in the comparison.

Model assessment is separated into three levels. The first is execution quality, assessed through solver completion and absence of severe calculation errors. The second is geometric plausibility, assessed through comparison of calculated residential floor area with the figure provided in the statistical yearbook. The third is comparison of heating intensity with the yearbook's reported district-heat indicator. These tests do not have equivalent evidential strength: a geometric agreement does not validate consumption, and the yearbook comparison is not a calibration exercise unless compatible boundaries and independent adjustment rules have been established. This study did not tune parameters to force a match with the yearbook. Instead, the discrepancy is described and interpreted as an indication of the limits of direct statistical comparison.

3. Results

3.1 Classification and spatial coverage

Among the 60,304 mapped footprints, 20,342 could be assigned a usable energy archetype. This is 33.7% of the inventory by count but represents 64.4% of its reported floor area. The difference between those coverage percentages shows that buildings with usable labels are, on average, associated with more floor area than those without usable labels. It also illustrates why reporting only the percentage of classified objects would misrepresent the amount of building stock actually included in the energy calculation. The classified fraction remains substantial, but it cannot be treated as the entire city.

The remaining inventory consists of 36,851 records awaiting verification, 3,049 categorized as other uses, and 62 industrial records. These counts sum to the 39,962 footprints without a modelled archetype. The classification information does not establish that all three groups should receive the same energy characteristics, and industrial buildings are especially difficult to represent using

residential or public-building assumptions. Their exclusion from the main totals therefore avoids assigning an obviously inappropriate template. At the same time, the unclassified population is large enough that its unknown use composition can materially influence a whole-inventory extrapolation.

The 64.4% floor-area share corresponds to approximately 60.38 million m ²when applied to the reported inventory total of 93.75 million m ². This value is calculated from rounded coverage figures rather than obtained from an additional building table. Accordingly, its precision should not be overstated. Table 2 summarises the categories reported for the spatial matching process and clarifies the distinction between directly classified and unclassified buildings. These results identify classification coverage as a primary determinant of the credibility of city-level totals.

Table 2. Functional-label coverage of the working GIS building inventory.

Inventory class	Building count	Interpretation
Usable archetype label	20,342	33.7% of footprints; 64.4% of represented floor area
Pending verification	36,851	Not included in the primary classified-stock total
Other uses	3,049	No justified mapping to the fifteen templates
Industrial	62	Outside the scope of the residential and public archetypes
All mapped footprints	60,304	Working GIS inventory after the polygon-area screen

3.2 Differences in simulated energy intensity

The energy profiles of the fifteen archetypes reveal substantial variation across occupancy functions. The source assessment reports a residential comparison value of 45.5 kWh/m ²per year and a high-rise housing intensity of approximately 43.2 kWh/m ²per year; corresponding category-level figures include 123.6 for offices, 89.3 for retail, and 228.4 for schools. The smallest reported value is 17.2 kWh/m ²per year for the small-inn archetype, whereas the restaurant reaches 293.7 kWh/m ²per year, above the school category. These numerical comparisons illustrate the importance of reporting type-specific values rather than compressing all building uses into one residential-oriented indicator.

Ventilation requirements provide a plausible explanation for the prominence of schools and restaurants in the heating results. Fresh outdoor air becomes an important thermal load when indoor occupancy and hygiene requirements are high, particularly in the prolonged heating season of a severe cold city. By contrast, buildings with smaller outdoor-air quantities or shorter occupied periods can experience lower annual heating requirements even if their geometry or external construction is not dramatically superior. This interpretation is consistent with the model specification, but it does not represent an independent attribution analysis obtained by varying one parameter at a time. A full sensitivity experiment would be required to quantify the contribution of ventilation separately from setpoint, schedule, geometry, and envelope.

Electricity and domestic hot-water gas show different patterns because they depend on other end-use characteristics. For example, the reported annual electrical intensity is 36.7 kWh/m ²for schools and 196.3 kWh/m ²for hospitals. The spread is consistent with differences in operating hours and internal service loads, although the source lacks equipment-by-equipment monitoring data with which to test that explanation. For domestic hot water, the archetypes add approximately 6-29 kWh/m ²per year of gas energy. Figure 1 displays the contrasting service intensities for the fifteen representative types and makes clear why heat, electricity and water heating should be analysed individually.

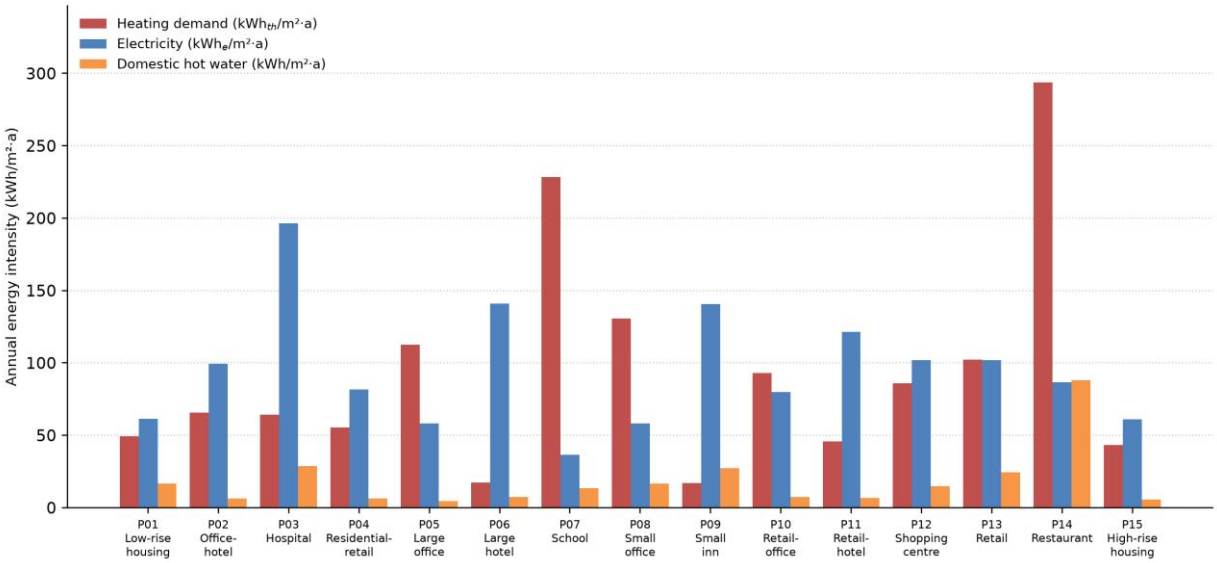

Figure 1. Simulated annual energy intensities for the fifteen archetypes, separated into space heating, electricity, and domestic hot-water gas.

3.3 Energy demand of the labelled building stock

Applying the archetype intensities to the classified inventory yields annual totals of 3.79 TWh for modelled space heating, 3.96 TWh for electricity, and 0.65 TWh for gas supplied to domestic hot water. A combined coal-equivalent indicator of 1.08 million tonnes is also reported; this secondary measure is interpreted cautiously because its conversion factors and precise energy-accounting convention were not available for independent verification. The three service totals should not be interpreted as an inventory of every fuel flow in Xining; they are the aggregate of the end uses and buildings represented by the selected archetypes.

Residential functions account for 56.8% of the reported heating total. Schools make a notably disproportionate contribution: they represent 6.3% of the modelled floor area but 23.1% of heating demand. This pattern is consistent with the high school heating intensity and indicates that area shares alone are insufficient for identifying potentially influential building categories. A small category can be important for heating policy when its per-area demand is large. Conversely, a large area share may dominate the aggregate even where its annual intensity is moderate. Both mechanisms matter when selecting targeted efficiency measures.

The relative composition of energy types is shown in Figure 2. The figure should be read as an aggregation over the 20,342 labelled buildings, not the complete GIS inventory. Under the separate extrapolation procedure described earlier, the estimated heating amount for the whole represented inventory rises to 6.62 TWh per year. The gap between 3.79 and 6.62 TWh highlights how strongly conclusions about absolute city totals depend on treatment of the unclassified stock. The larger value is useful as an illustrative scenario, but its uncertainty cannot be removed by a high simulation-completion rate.

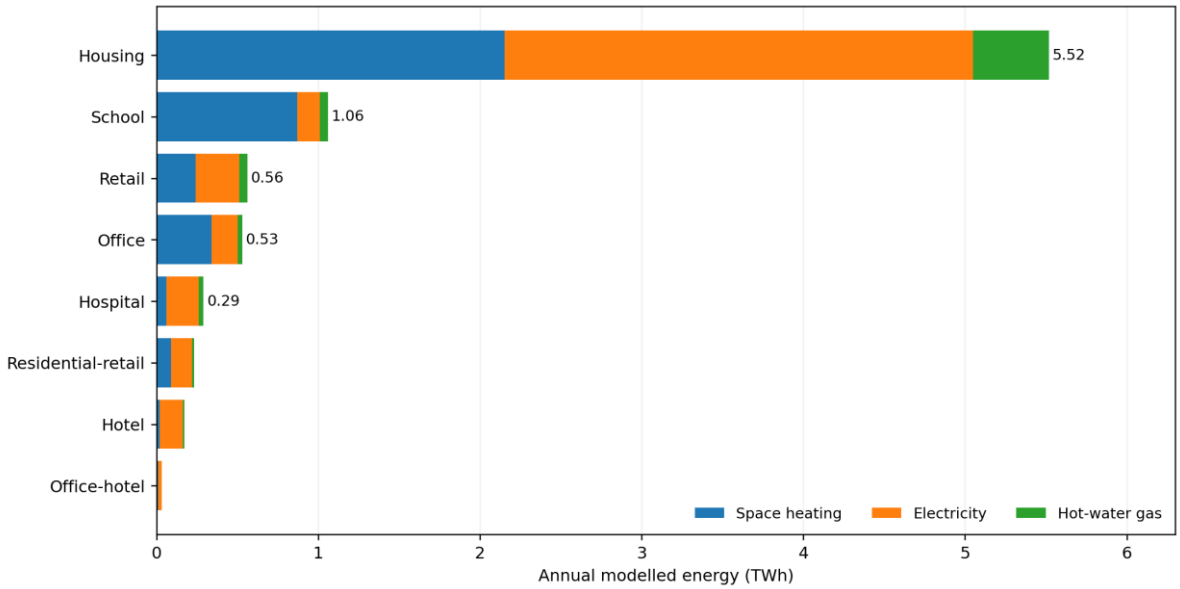

Figure 2. Annual modelled energy by broad building function in the classified stock (TWh; category values reconstructed from rounded values in the original chart).

3.4 Comparison with external heating statistics

The analysis compares its residential floor-area calculation with a yearbook figure for district-heated housing. The modelled residential area is 47.32 million m², whereas the corresponding statistical figure is 44.75 million m². The modelled value is therefore about 5.8% higher, taking the yearbook area as the denominator. This degree of agreement provides a limited geometric plausibility check. It cannot establish that the distribution of building ages, insulation levels, heating hours, or occupants has also been recovered correctly.

The statistical benchmark for delivered district heat is 131.5 kWh/m²per year, calculated from the cited 2024 yearbook quantity of 2,746 × 10⁴ GJ and 58 million m² of reported area. The modelling outputs include 45.5 kWh/m²per year as a residential useful-heating indicator and 50.5 kWh/m²per year for its source-side energy indicator. Figure 3 additionally shows a model-wide, all-type figure of 62.8 kWh/m²per year. These are three distinct quantities, and comparing each directly with the same statistical reference leads to different percentage gaps. Relative to 131.5, the corresponding shortfalls are approximately 65.4%, 61.6%, and 52.2%. Using one explicit denominator for each comparison makes the otherwise easily confused numerical gaps transparent.

The differences should not automatically be interpreted as evidence of a deficient simulation. Published district-heat transactions may include distribution boundaries and a building population unlike the insulated reference models. Available descriptive information indicates that the statistical stock includes many buildings constructed before 2000, while the archetypes reflect more protected envelope conditions. More importantly, a source-side heat sale and a building-level calculated useful heating requirement are not equivalent metrics. Adjusting model input values until these numbers coincide would disguise the mismatch in accounting scope instead of resolving it. The comparison is therefore diagnostic and descriptive, not a calibrated validation outcome.

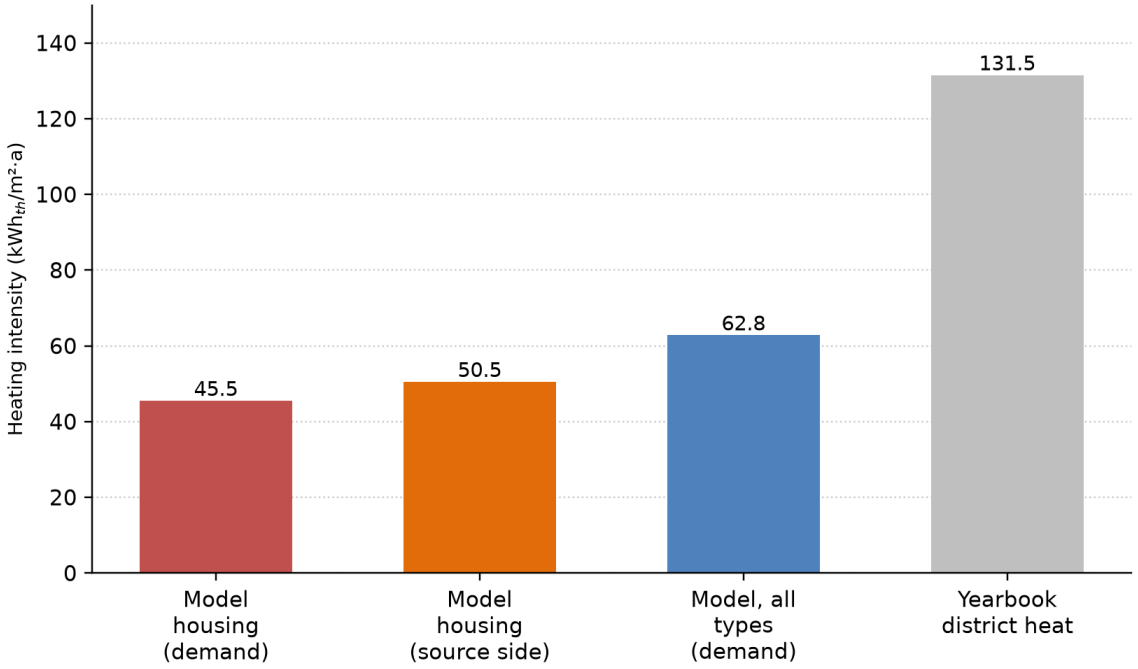

Figure 3. Distinct simulated heating-intensity indicators compared with the yearbook district-heat benchmark of 131.5 kWh/m ²per year.

3.5 Effect of sensible heat recovery

For the public-building heat-recovery configuration, total simulated space-heating demand in the classified stock declines from 3.79 to 3.02 TWh annually. This corresponds to a decrease of approximately 20.3% using the unrounded values reported in the source. The intervention does not alter the stated electricity or domestic hot-water quantities in the modelling comparison. Hence, the outcome specifically describes the change in simulated heating demand under a 60% sensible heat-recovery assumption, not an independently calculated saving in total final energy, costs or carbon dioxide emissions.

The relative response is not uniform. For the school archetype, heating intensity changes from an annual 228.4 kWh/m ² to 103.1 kWh/m ²; the restaurant likewise declines from 293.7 kWh/m ² to 129.8 kWh/m ². These large reductions are consistent with the relatively high amounts of outdoor air specified for those uses. Mixed residential-commercial configurations exhibit a more moderate decline, approximately 21% under the tested assumptions, because the residential component does not acquire the same heat-recovery system. This distinction is important for intervention design: the effective savings of a mixed-use stock depend on the functional shares served by the technology, rather than solely on the nominal recovery effectiveness.

The comparison supports heat recovery as a potentially influential thermal strategy for the represented public archetypes. Nevertheless, the study does not quantify fan-energy penalties, heat-exchanger bypass operation, frost protection, capital costs or maintenance impacts. None of these can legitimately be inferred from a scenario that holds electricity unchanged. The reported reduction is best described as a modelled heating-demand potential under the specified simplified operating conditions. Practical implementation and whole-system energy benefits require additional equipment-level assessment.

4. Discussion

4.1 Contributions and meaning of the urban estimates

The principal value of the study lies in the relationship between limited city data, reproducible thermal representations, and clearly defined aggregation. The framework can translate a large geographic inventory into an energy assessment without pretending that every individual building is known in detail. Because the same library is applied consistently, type-to-type contrasts are more interpretable than a collection of independently assembled single-building calculations. The use of separate functional specifications inside mixed-use archetypes further helps identify why an intervention produces unequal effects across the stock. These features make the approach useful for screening and policy comparison even before comprehensive metering becomes available.

Its predictive claims must nevertheless be bounded. The simulation results are conditional on a particular weather record, model library, and inventory. They indicate expected behavior under those conditions, not a direct measurement of energy transactions. The fact that all reported simulations terminate successfully is a necessary technical requirement but says little about the validity of individual assumptions. In a similarly cautious sense, agreement with a published floor-area figure supports the approximate geometry while leaving consumption behavior largely untested. The best-supported interpretation is therefore a transparent engineering scenario analysis of a classified urban subset.

4.2 Geometric, classification and operating uncertainty

The largest visible data limitation is incomplete archetype coverage. Roughly two-thirds of building objects are not mapped to a usable energy type, even though these objects account for a smaller proportion of represented floor area. Extrapolating from labelled structures assumes, implicitly or explicitly, that the unknown use distribution can be approximated from observed archetype shares. This assumption may fail if the excluded population contains systematically smaller houses, industrial structures, mixed-use properties or other functions underrepresented in the classified data. A more defensible whole-inventory estimate would report several alternative allocations and show how much total heating demand changes under each one.

Geometry introduces another source of uncertainty. The 3.0 m storey-height rule may work reasonably for common building types while misclassifying atypical structures. Because energy totals are calculated through intensity multiplied by area, any error in storey count propagates directly into the stock calculation even if the simulated intensity is unchanged. Median archetype geometry likewise suppresses differences in wall-to-floor ratio, roof exposure, and window area. An improved workflow could compare sampled building heights and floor counts with field or cadastral records, then quantify uncertainty by archetype. Such a probabilistic evaluation was not part of the reported analysis, and no numerical confidence interval is claimed.

Operational assumptions may be equally influential. Heating setpoints, infiltration, ventilation, and annual schedules interact with envelope performance rather than affecting demand independently. A fixed leakage rate does not capture wind exposure, pressure effects, or occupancy-related window opening. School terms, hospital activity patterns, hotel occupancy, and household water use may also depart from standard profiles. When these data are unavailable, a transparent range of assumptions is preferable to a single unqualified city total. The current manuscript does not claim to have measured the distribution of these variables, and its scenario comparisons should be interpreted accordingly.

4.3 Validation, calibration and recommended next steps

Validation and calibration should be distinguished in any subsequent extension. Validation asks whether a model can reproduce observations that were not used to set its parameters. Calibration adjusts selected inputs to improve consistency with appropriate observations within plausible parameter bounds. The existing yearbook comparison is a useful first check but is not sufficient for either a detailed calibration or an independent predictive test. Its reference value describes a different reporting system and potentially different building coverage. No arbitrary numerical correction is imposed solely to eliminate this discrepancy.

A practical future process would begin by harmonising the observation and simulation boundaries. For district heating, researchers would need to establish which buildings are connected, whether the reference reports plant output, heat sold or heat delivered at the building, and which distribution losses are included. Metered demand would ideally be matched to the same year and spatial subset as the simulation, or normalised to account for weather and occupancy differences. Where utility records are available by building type or district, they could reveal whether errors are concentrated in certain categories. Without this reconciliation, lowering U-values or increasing infiltration to reach the yearbook intensity would risk compensating for a boundary mismatch with physically inappropriate parameters.

Once consistent measurements are assembled, parameters such as infiltration, envelope U-values, schedules and selected ventilation rates could be varied within defensible engineering ranges. The calibration objective should be defined separately for heat and electricity, and model evaluation should include both aggregate and category-level performance. A portion of observations should be held back from parameter tuning to provide a genuine validation test. Sensitivity analysis could then identify which variables most strongly affect each archetype's output and where improved field surveys would be valuable. These are methodological recommendations, not procedures performed in the reported 28 simulations.

The same principle applies to uncertainty communication. Instead of quoting an extrapolated value as a uniquely determined municipal total, a future study might report scenario bands reflecting uncertain building types, floor counts and operation. For heat recovery, a realistic expanded study should represent ventilation equipment electricity, frost management and part-load performance. This would permit a comparison of net delivered energy and, eventually, economic or emission consequences. The existing results justify further examination of such measures but do not contain enough information to calculate those additional outcomes.

4.4 Relationship to earlier research and transferability

The approach shares with prior UBEM research the use of archetype engineering models as an interface between urban data and dynamic simulation [1, 3]. It also follows the broader direction of automated model creation demonstrated by GIS-integrated tools such as CityBES [4]. Its distinctive emphasis is the combination of a small locally parameterised library, explicit mixed-use separation, and a severe cold high-altitude case. Compared with more detailed urban modelling systems, the compact representation reduces parameter demands and makes assumptions easier to inspect. The trade-off is that building-specific variation, neighborhood shading and actual equipment diversity are not resolved at the same level of detail.

Transfer to another Chinese city would require more than changing geographic coordinates. A new application would need climate-appropriate weather information, a correctly classified building inventory, and local construction and operation parameters. The effectiveness of archetypes should also be re-examined when land-use patterns or the prevalence of mixed occupancies differ. A library that is adequate for screening in one setting may not reproduce another city's energy

composition, especially where cooling systems or fuel mixes dominate. Thus, transferability lies primarily in the modular procedure, not in unrestricted reuse of the numerical intensities reported for Xining.

For planning, the current results support two complementary priorities. One is improved data coverage: resolving the unknown building types would reduce uncertainty in the absolute scale of demand. The other is targeted analysis of high-ventilation public uses, where the idealised heat-recovery case indicates substantial heating potential. Neither priority should be mistaken for a final cost-benefit ranking. Decisions about specific projects would still require building audits, practical equipment specifications and an accounting of local supply systems. The workflow is most valuable as a transparent first layer on which these higher-resolution investigations can be built.

5. Conclusion

This study reformulates a GIS-based urban energy assessment for central Xining into a clearly bounded archetype workflow. Fifteen representative building models were implemented through a JSON-to-Ruby/OpenStudio procedure and analysed with EnergyPlus. Across the reported configurations, 28 executions completed without fatal errors. A usable functional classification was available for 20,342 of the 60,304 mapped footprints, representing 64.4% of the inventory's reported floor area. The incompleteness of the remaining stock is therefore as important to the interpretation of city totals as the performance of the simulation software.

For the classified stock, the original simulations give annual amounts of 3.79 TWh for space heating, 3.96 TWh for electricity, and 0.65 TWh for gas used in domestic hot water. Energy intensity differs markedly by building function, with ventilation-intensive schools and restaurants exhibiting particularly large heating requirements. Under the specified 60% sensible heat-recovery scenario for public functions, modeled heating demand falls to 3.02 TWh, a 20.3% reduction. The results identify a potential efficiency strategy but do not incorporate the electricity and operational costs of a real heat-recovery installation.

The residential floor-area comparison differs from the yearbook by 5.8%, whereas the corresponding heating-intensity indicators do not share an identical accounting boundary. Recalculation makes these comparisons numerically consistent, but it does not convert them into calibration evidence. Future work should strengthen use classification, verify geometric inputs, collect boundary-compatible metered data, and assess uncertainty and equipment-level performance. With those qualifications, the proposed workflow offers a transferable method for preliminary urban heating analysis and for prioritising the data improvements needed before city-wide predictions are treated as operational estimates.

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