Scenario-based energy simulation of tree planting strategies to reduce the heating and cooling demand of buildings under 2050 climate conditions

Adhisye Rahmawati[1], Weixiao Gao[2,3], Camilo León Sánchez[3], Giorgio Agugiaro[3]

[1] Master in Geomatics, Delft University of Technology, Delft, The Netherlands
adhisyerahmawati@gmail.com
[2] Department of Geo-information Science and Remote Sensing, Wageningen University & Research, Wageningen, The Netherlands
weixiao.gao@wur.nl
[3] 3D Geoinformation Group, Department of Urbanism, Faculty of Architecture and Built Environment,
Delft University of Technology, Delft, The Netherlands
{c.a.leonsanchez,g.agugiaro}@tudelft.nl

Keywords: Urban Building Energy Modelling, CityGML, SimStadt, Vegetation, Climate Scenarios, Heating and Cooling Demand

Abstract

Urban areas account for a large share of global energy use and emissions and face increasing climate- and heat-related challenges. These conditions drive the development of district-scale strategies such as Positive Energy Districts. Urban Building Energy Modelling (UBEM) enables the systematic assessment of urban energy performance, but vegetation effects are often neglected or require complex model coupling. This paper presents an approach to integrate simplified 3D tree geometries into a CityGML-based UBEM framework using the energy simulation software SimStadt. Experiments are conducted in two neighbourhoods in Rotterdam, The Netherlands, using current and future climate datasets. Results show that cooling demand increases under future climate conditions, while heating demand decreases. Moreover, trees reduce cooling demand but introduce heating penalties due to winter shading, with a limited net energy effect and a seasonal imbalance between cooling and heating demand.

1. Introduction

Urban areas face immense challenges with respect to energy management, environmental sustainability, and adaptation to climate change. Rapid population growth and intensification of urban heat islands drive up energy demands, particularly in the built environment (IEA, 2021). In 2010, the building sector represented roughly 32% of global final energy demand and 30% of CO_2 emissions related to energy, driven primarily by the need to heat and cool spaces (Ürge Vorsatz et al., 2015). In Europe, space heating accounts for 62.5% of household energy use (eurostat, 2025). However, space cooling demand is rising rapidly as climate change drives higher global temperatures and more frequent, severe heatwaves (Elnagar et al., 2023).

These circumstances have led to the development of district-scale strategies, such as Positive Energy Districts (PEDs), which require analytical methods to evaluate building performance under evolving environmental conditions and mutual interactions, rather than as standalone entities (IEA, 2021; Smart Cities Marketplace, 2021). Recent work has demonstrated the relevance of data-driven urban energy simulations for assessing PED potential in real-world contexts such as Rotterdam (Gao et al., 2025).

Urban Building Energy Modelling (UBEM) serves as one of the technical foundations for these evaluations (Reinhart and Cerezo Davila, 2016). By simulating energy production and consumption across multiple structures using building geometry, construction data, and climate input, UBEM allows for a systematic assessment of urban performance (García-López et al., 2024).

Bottom-up, simulation-based UBEM approaches are especially valuable because they use engineering principles, thermodynamic calculations, and standard building archetypes to analyse the impacts of different design choices and environmental conditions. While bottom-up physics-based UBEM is effective to simulate heating and cooling demand, most applications overlook environmental factors such as vegetation. Current efforts to include trees as nature-based solutions to reduce urban stress heat often rely on complex tool coupling or have limited spatial scales, rarely accounting for long-term climate projections.

A preliminary study was conducted to identify the strengths and weaknesses of current physics-based UBEM platforms regarding vegetation modelling. The findings, summarised in table 1, highlight the technical gaps that this research aims to fill.

Table 1 indicates that SimStadt provides a suitable basis to extend UBEM workflows and include vegetation at the city scale. Its ISO 13790 heat-balance approach offers the computational efficiency required for large-scale simulations, while the native CityGML integration enables direct use of spatial datasets representing trees and canopy geometry. However, the main limitation of SimStadt’s workflow is the representation of vegetation, for simulation purposes, as simple buildings. As a result, trees are treated as static obstructions to solar radiation rather than thermally dynamic vegetation elements that are characterised by evapotranspiration, wind flow, or seasonal canopy dynamics. While this representation ensures consistent treatment of shading across the model domain, it may introduce artefacts in the radiative balance, as these objects are treated as opaque surfaces rather than porous or reflective canopies.

As a workaround to these limitations, this research develops and applies a simulation-based workflow to evaluate how

Table 1. Strengths and weaknesses of selected physics-based UBEM tools for vegetation

Tool	Strengths	Weaknesses
CityBES	Mature web platform; EnergyPlus-based detail; good documentation; supports Energy ADE	No native vegetation module; vegetation typically via custom shading objects or external coupling; heavier setup for microclimate effects
URBANopt	Modular pipelines; HPC support for scale; EnergyPlus/ OpenStudio ecosystem	Vegetation requires external processing or custom measures; workflow complexity increases for city-wide runs with vegetation
SimStadt	ISO 13790 heat-balance model scales to city; native CityGML ingestion and Energy ADE interoperability; workflow modularity for batch analyses	Vegetation represented as building-like objects; limited direct representation of evapotranspiration and wind effects without coupling
TEASER/ OpenIDEAS	Python/Modelica openness; archetype flexibility; useful for prototyping	Weaker native GIS workflows at very large scale; vegetation/microclimate needs external models or custom code

urban tree-planting strategies can influence building heating and cooling demands under current and projected 2050 climate conditions. Vegetation effects are embedded directly into a single modelling environment, removing the need for external microclimate coupling. Based on these findings and our scope, this study adopts SimStadt (Bao et al., 2022; Weiler et al., 2022) as the energy building simulation tool in this research.

2. Methodology

This research uses a scenario-based simulation approach to address the main research question: How can tree-planting scenarios, as nature-based solutions, be integrated into neighbourhood-scale, simulation-based UBEM to evaluate their effectiveness in reducing heating and cooling demand under projected 2050 climate conditions? Since existing district-wide UBEM tools provide only limited ways to represent vegetation, the study adopts a workflow that combines simplified vegetation modelling with climate scenario adjustments. The framework follows a five-stage process: (i) scenario development, (ii) simulation tool and data requirements identification, (iii) modelling simplifications and assumptions, (iv) model configuration, (v) simulation execution, post-processing, analysis, and visualisation.

2.1 Scenario Development

The purpose of this step is to provide a robust comparison framework for six distinct scenarios that avoid overlapping influences. The scope is to isolate the impact of vegetation from other factors, such as refurbishment, or energy systems. Therefore, we focus our analyses on the influence of trees on the energy performance of buildings after climate conditions change.

These scenarios, illustrated in figure 1, are defined as follows:

- Reference Scenarios (S0 and S3): These are the "No Tree" control scenarios. S0 simulates the built environment under present-day climate conditions with absolutely no vegetation, while S3 does the same under projected 2050 climate conditions. These serve as baselines to isolate the pure effect of climate change on building energy performance.

- Baseline Vegetation Scenarios (S1 and S4): These scenarios represent the environment with "Existing Trees". S1 models the current building stock alongside the district's currently existing urban tree inventory and the current climate conditions. S4 projects this same setting into the 2050 climate, representing the baseline future state if no new greening initiatives are undertaken.

- Enhanced Greening Scenarios (S2 and S5): These scenarios simulate "Existing and Proposed Trees". S2 evaluates the impact of adding newly proposed tree planting locations to the current environment under present-day climate conditions. S5 tests this enhanced tree canopy under the 2050 climate conditions, which is crucial to evaluate whether planting strategies can successfully mitigate future cooling demands.

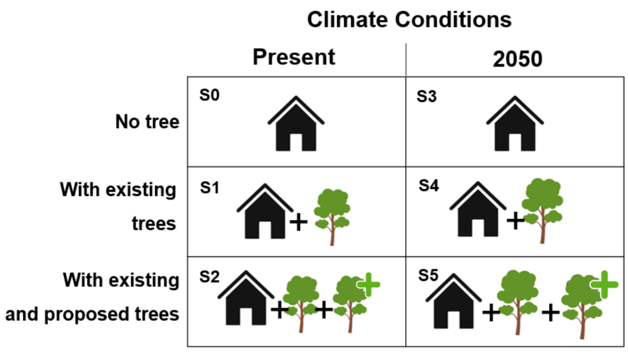

Figure 1. Overview of the six designed scenarios combining three vegetation settings with two climate conditions (Rahmawati, 2025)

2.2 Simulation Tool and Data Requirements Identification

All spatial data, including buildings and vegetation, must be formatted as CityGML geometries (OGC, 2012). SimStadt offers several energy-related workflows. For this research, we used the "Heat Demand Analysis" workflow, which processes geometric, usage, and climatic data to compute energy balances. We prepare monthly typical meteorological year (TMY3) files for the current and projected 2050 data, including global horizontal irradiance and ambient temperatures.

For the radiation modelling, we have chosen the Simplified Radiosity Algorithm (SRA) Perez with tiling to calculate direct, diffuse, and reflected radiation, as it actively computes shading from vegetation geometries. However, this algorithm adds complexity to the computation, as it requires dividing the study area into tiles to handle the large number of buildings. Furthermore, there is no clear documentation when it comes to this feature, and we chose the tile size based on trial-and-error testing.

2.3 Modelling Simplifications and Assumptions

The basic geometries for this research are derived from the municipality of Rotterdam’s existing urban forestry dataset, provided as a CityGML dataset. To reduce the computational demand of SRA in SimStadt, the high-detail surface geometries were simplified into CityGML LoD1 cylindrical volumes using FME. To do so, we replace the crown of trees with the smallest cylinder that covers it. This geometry is less simplified than a 3D bounding box but it provides a better representation of trees. This conversion is essential to prevent computational overload while still capturing the necessary vertical tree profile for shading analysis. Figure 2 illustrates this process.

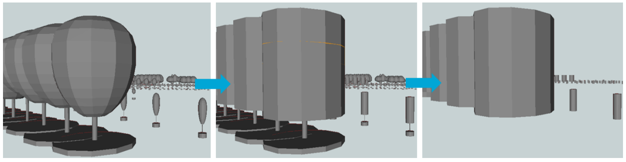

Figure 2. Simplification of tree geometries: original models, overlap, and simplified cylindrical representations.

Furthermore, due to SimStadt limitations regarding non-building geometries, these cylinders were computationally “disguised” as residential buildings. To do so, we assigned a generic construction year and the usage code 1010. Therefore, these geometries are not neglected by the Physics Preprocessor step within the ”Heat Demand Analysis” workflow.

We account for biological growth and seasonal phenology by applying mathematical scaling factors to the cylindrical geometries. To simulate seasonal leaf loss in deciduous species, the cylinder diameter D_c is adjusted based on empirical Leaf Area Index (LAI). Summer values remained at D_c, while winter diameters are reduced to $0.64 \times D_c$ to reduce the shading density of leafless canopies. However, it only differentiates between deciduous and evergreen trees and does not account for species-specific canopy characteristics, gradual seasonal transitions or interannual variability.

To project the urban canopy to 2050, existing geometries were expanded using a linear growth rate. However, to maintain biological and urban realism, these expansions were capped at a maximum increase of +2 meters in diameter and +2.5 meters in height, reflecting both natural growth limits and standard urban maintenance practices.

2.4 Model Configuration

This is the data preparation stage, where the 3D models that are used for the simulations are built. For buildings, the CityGML LoD2 geometries were processed to repair their geometry using automated processes in CityDoctor2 (Betz et al., 2026). Then, we used FME workbenches to add missing semantic information extracted from other data sources, such as the building’s year of construction or its usage (among others). These data are fundamental for SimStadt physics processors to work.

For trees, the process can be split into two main branches. The first corresponds to the existing trees and is already explained in section 2.3. The second one corresponds to the proposed planting locations; the main reason for proposing this is the municipality of Rotterdam’s need to find nature-based solutions to mitigate the impact of climate change and reduce electricity use on its already congested electrical networks.

We developed a GIS-based workflow to identify suitable locations for new trees. Furthermore, we consider the 3-30-300 rule (Konijnendijk, 2023). This rule provides a clear framework for integrating greenery into urban planning. Each resident should see at least three trees from their home or workplace, neighbourhoods should achieve 30% tree canopy cover, and every home should be within 300 m of a public green space. However, that is not the only criterion considered in the workflow, as existing infrastructure shall not be ignored. Among the elements included in our multicriteria analysis are land-use features, underground infrastructure, roads and lanes (pedestrian, cycling, vehicular), buildings, bridges, water surfaces, utility networks, existing trees, and city furniture such as lamps, posts, service boxes, masts, and poles. Figure 3 illustrates the workflow. Further details are provided on page 35 of (Rahmawati, 2025).

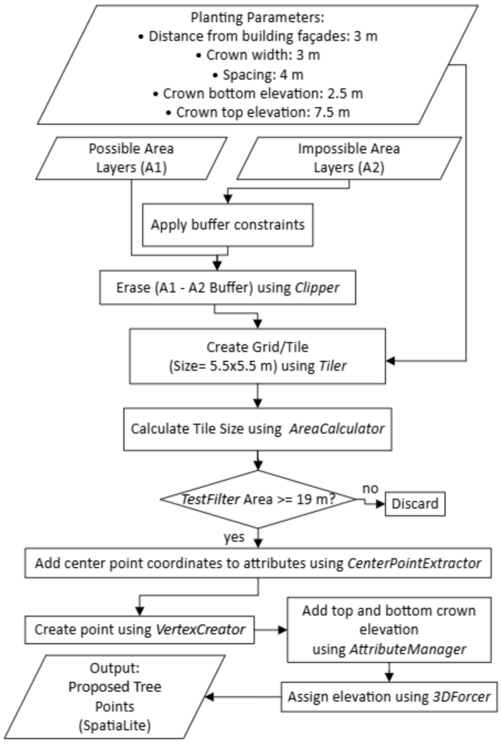

Figure 3. Workflow for tree planting point generation (Rahmawati, 2025)

The criteria can be summarised in the following points:

- Land-Use Selection: Suitable areas include vegetated parts, recreation zones (parks, playgrounds), and low-intensity circulation zones (pedestrian paths, parking)
- Distance constraints: Planting points are generated with a 3m distance from building facades and 4m spacing between trees
- Suitable areas are populated with evenly spaced points to represent future tree locations

2.5 Simulation Execution, Post-Processing, Analysis, and Visualisation

After preparing input datasets for each scenario and season, simulations were conducted to estimate building-level heating and cooling demand under both current and future climate conditions. Following the execution of SimStadt models, the raw monthly simulation outputs were processed. The post-processing workflow begins by loading the summer and winter simulation results separately. For the summer dataset, only values corresponding to May-October were retained, while November-April values were used for the winter dataset. For the yearly values, we use the “specific space heating/cooling demand” attribute from the simulation results to compare values across building sizes; it is a normalised value with units of $kWh/(m^2 \cdot a)$. The processed results were then linked to the building polygon dataset, and further aggregation was performed by neighbourhood and month. This neighbourhood-level aggregation was used to assess how climate change alone is expected to influence energy demand.

Figure 4 illustrates the next steps taken for analysing the impact of additional tree planting on building heating and cooling demand under both current and future climate conditions. Scenarios with only existing trees were compared with those including both existing and proposed trees to isolate vegetation effects. For each climate condition, absolute and relative differences in energy demand were calculated, and spatial patterns were visualised using colour-coded maps. The contribution of each proposed tree is evaluated by comparing energy demand in scenarios with and without that tree.

Trees that reduced heating or cooling demand were classified as having a positive impact, while those with no change or higher demand were classified as having no or a negative impact. The final output was a tree impact map, showing the spatial distribution of trees with positive, neutral, and negative effects on building heating and cooling demand.

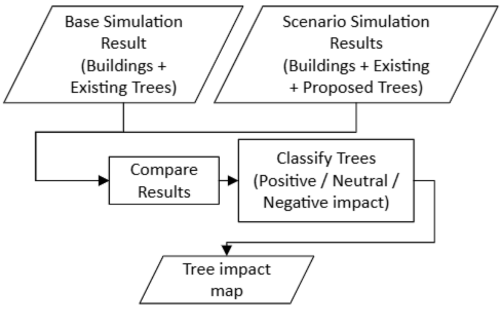

Figure 4. Flowchart for analysis and visualisation of the simulation output (Rahmawati, 2025)

3. Results and Analysis

The methodology is applied to the Afrikaanderwijk and Kop van Zuid neighbourhoods in the Feijenoord district of Rotterdam, The Netherlands. We chose this area because it is a known densely populated district that suffers from lack of green spaces - which affects liveability during extreme summer heat events. Located below sea level, the district is highly vulnerable to climate changes, making it a priority for long-term urban-resilience planning.

We have used several datasets to generate the input data models for each scenario. The resulting models provide the basic parameters for the simulation workflow (SimStadt’s Heat Demand Analysis). However, these input datasets pose significant integration challenges. The structural baseline is derived from the Rotterdam 3D City Model, available via the municipality’s open data portal (Gemeente Rotterdam, 2026). The Rotterdam 3D City Model is a CityGML LoD2 dataset that contains semantic and geometric data. To ensure the compatibility with SimStadt, Dutch building functions were mapped to equivalent German ALKIS codes and missing attributes were enriched.

Environmental conditions were established using two datasets: current data from the DigiTwins4PEDs[1] project (TMY3 format, 1991-2019) and projected 2050 data from the Royal Netherlands Meteorological Institute based on KNMI’23 (KNMI, 2023). A key challenge involved manually transforming the 2050 projections into the specific TMY3 monthly format required by SimStadt to generate consistent hourly synthetic profiles for dynamic energy calculations. An overview of the used data and their preparation steps is summarised in table 2.

Table 2. Overview of input datasets and preprocessing.

Dataset	Description	Preprocessing
Buildings	LoD1/LoD2 geometries with usage type and construction year	Error correction and attribute enrichment
Vegetation	Locations of existing and proposed planting sites	Conversion to CityGML; seasonal variation
Weather data	Monthly global horizontal irradiance and ambient temperature (TMY3)	Formatting for SimStadt compatibility
Urban context	District boundaries and land-use data	Coordinate system harmonisation

The data resulting from the simulations were post-processed using in-house Python scripts. Since we generate winter and summer input models separately, the data were processed to consolidate values across the different seasons, i.e. consisting of May-to-October data from the summer simulations and November-to-April data from the winter simulations. The processed data for each scenario were stored in a 3DCityDB schema that supported the Energy ADE 3.0 data model (Agugiaro and Padsala, 2025).

Building-level results were stored as Energy Resource elements associated with the buildings and the building parts. The neighbourhoods were modelled as EnergyADE 3.0 UrbanFunctionArea CityObjects, and the aggregated simulation results were stored as Energy Resource elements. Figure 5 shows the value of the annual space heating demand for Afrikaanderwijk in the exported CityGML file.

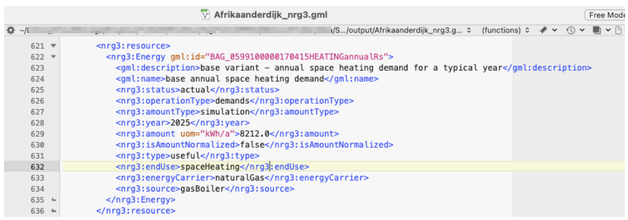

Figure 5. Excerpt of Afrikaanderwijk CityGML + Energy ADE v3 exported file.

[1] https://digitwins4peds.eu/

The first analysis of the simulation output corresponds to scenario S0. We identified several extreme energy demand values that are most likely irrealistic. An example is presented in figure 6 and shows a mixed-use building (industrial and residential). However, this is a typical case when the internal subdivision or the multiple building usages cannot be represented in LoD2. The energy demand calculation is a direct result of how SimStadt handles complex geometries. When the exact number of storeys is missing from the input data, SimStadt estimates it by dividing the building's maximum height (in meters) by 3m, then multiplying by the total building footprint. Because this building has a massive footprint but only a small tower portion that reaches its maximum height, SimStadt overestimated the total internal floor area, leading to an artificially high specific cooling demand. This is an inherent limitation of the SimStadt framework, which simplifies shading, infiltration, and local microclimates. However, the presence of these absolute errors does not affect the main conclusions of this research, as the core analyses do not rely on absolute energy values. Instead, these focus on the relative percentage difference between scenarios (e.g., comparing a building surrounded by trees to the same building without trees).

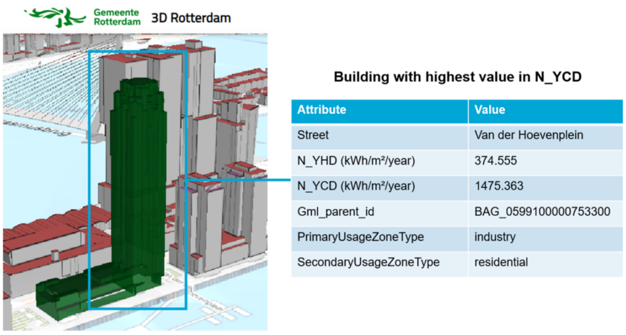

Figure 6. Building with the highest simulated cooling demand value in Kop van Zuid neighbourhood

Tables 3 and 4 show that cooling demand in 2050 is consistently higher than in 2023 across both neighbourhoods. Peak demand occurs in July and August for both areas, with Kop van Zuid requiring significantly higher absolute energy, reaching nearly 3,900 MWh in July 2050 compared to 2,800 MWh in Afrikaanderwijk.

Table 3. Comparison of total monthly cooling demand for Afrikaanderwijk in 2023 and 2050 (in MWh).

Month	2023 (MWh)	2050 (MWh)	Increase (%)
January	12.31	15.34	24.67
February	16.11	17.95	11.40
March	47.88	54.46	13.74
April	172.43	233.56	35.45
May	625.45	823.64	31.69
June	1,327.70	1,631.19	22.86
July	1,986.23	2,789.31	40.43
August	1,675.74	2,548.53	52.08
September	556.07	821.03	47.65
October	115.72	168.10	45.26
November	28.09	37.76	34.43
December	13.42	16.79	25.08

Table 4. Comparison of total monthly cooling demand for Kop van Zuid in 2023 and 2050 (in MWh).

Month	2023 (MWh)	2050 (MWh)	Increase (%)
January	16.33	20.64	26.45
February	24.28	27.62	13.77
March	83.66	98.32	17.53
April	305.32	414.98	35.92
May	1,040.39	1,341.00	28.89
June	2,058.47	2,460.36	19.52
July	2,983.80	3,911.17	31.08
August	2,665.63	3,712.26	39.26
September	1,107.00	1,547.94	39.83
October	268.68	402.71	49.88
November	46.22	69.93	51.29
December	16.95	22.15	30.69

In terms of relative growth, Afrikaanderwijk experiences the most substantial summer increases, particularly in August, where demand is projected to rise by 52.08%. Conversely, Kop van Zuid exhibits its most significant relative rises during the autumn months, with increases of 49.88% in October and 51.29% in November. The results also show persistent cooling demand during the colder months (September-April), which is higher than what is typically expected in the Netherlands. This may be attributed to SimStadt's building modelling parameters, such as the inclusion of internal heat gains from occupants and appliances, solar gains on sunny days, and fixed temperature set-points that trigger cooling whenever limits are exceeded. Furthermore, specific building types such as offices or shops may require year-round cooling. These factors likely explain why the model predicts higher cooling demand outside the summer months than would normally occur in reality.

Figure 7 shows the comparison of the monthly increase in the cooling demand between the two neighbourhoods. Afrikaanderwijk presents its highest peaks during the core summer months, with a maximum increase of 52.08% in August. In contrast, Kop van Zuid demonstrates a more pronounced growth during the transition into autumn, with the highest relative increases occurring in October (49.88%) and November (51.2%). This suggests that while the intensity of summer heat has a profound impact on the older urban fabric of Afrikaanderwijk, the modern architectural profile of Kop van Zuid may be increasingly susceptible to cooling requirements during the shoulder seasons under 2050 climate projections.

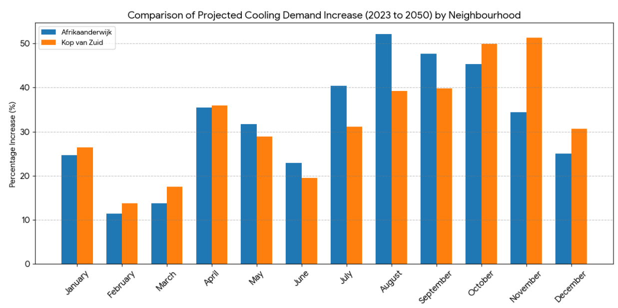

Figure 7. Comparison of monthly cooling-demand increase between neighbourhoods.

To isolate the effects of climate change, we first present the energy simulation results using baseline scenarios (S0 and S3), which exclude trees and therefore indicate the climate-only impact on district energy performance.

3.1 Climate Change Projections (2023–2050)

Climate forecasts from the Royal Netherlands Meteorological Institute (KNMI) indicate a significant increase in average temperatures by 2050. Based on annual projections, cooling demand is expected to surge by 39.2% in Afrikaanderwijk and 32.1% in Kop van Zuid. Unexpectedly the simulation shows increased cooling demand during traditionally colder months (September-April). However, this behaviour might be attributed to high internal heat gains, significant solar radiation on sunny days, and fixed indoor temperature set-points that trigger cooling even when outdoor temperatures are moderate. Annual values per neighbourhood are presented in table 5.

Table 5. Annual energy demand values by neighbourhood (baseline climate-only comparison) in MWh/a.

Scenario	Cooling (MWh/a)	Heating (MWh/a)	Total (MWh/a)
	Afrikaanderwijk		
2023	6,577	29,524	36,102
2050	9,157	25,962	35,120
Change	2,580	-3,562	-982
% Change	39.23%	-12.07%	-2.72%
	Kop van Zuid		
2023	10,616	20,593	31,210
2050	14,029	17,918	31,947
Change	3,412	-2,675	736
% Change	32.14%	-12.99%	2.36%

Conversely, heating demand is projected to decline by 2050. Both neighbourhoods show an annual reduction of the heating demand of approximately 12% to 13% respectively. Most of the significant drops occur during spring and autumn seasons, where milder temperatures reduce the space heating demand. The combination of these opposing trends results in a low net change in the annual energy demand. In the case of Kop van Zuid, there is an increase of 2.4%, while Afrikaanderwijk shows a decrease of 2.7%. Comparing the monthly simulation results between the two neighbourhoods indicates distinct spatial and seasonal disparities. Cooling demand universally peaks in July and August for both locations. However, Afrikaanderwijk is projected to experience its most severe demand surges directly during these peak summer months. In contrast, Kop van Zuid shows more pronounced relative increases in October and November.

3.2 Mitigation Through Vegetation

The application of the workflow shown in figure 3 results in the identification of 11.8 hectares of plantable space in Kop van Zuid (45% of its total land area) and 21.8 hectares in Afrikaanderwijk (35.5% of its land area). From these suitable zones, the simulation generated precise coordinates for 374 proposed new trees in Kop van Zuid and 1,405 in Afrikaanderwijk. The simulation outputs resulting by the addition of trees (both existing and proposed planting scenarios) are shown in tables 6 and 7.

Table 6. Aggregated energy demand values per neighbourhood under current climate conditions (in MWh/a).

Scenario	Cooling (MWh/a)	Heating (MWh/a)	Total (MWh/a)
	Afrikaanderwijk		
Existing trees	6,207	29,857	36,064
Existing + proposed trees	6,019	30,053	36,072
Change	-187	195	7
% Change	-3.03%	0.66%	0.02%
	Kop van Zuid		
Existing trees	10,561	20,613	31,174
Existing + proposed trees	10,429	20,728	31,157
Change	-132	115	-16
% Change	-1.25%	0.56%	-0.05%

Table 7. Aggregated energy demand values per neighbourhood under 2050 climate conditions (in MWh/a).

Scenario	Cooling (MWh/a)	Heating (MWh/a)	Total (MWh/a)
	Afrikaanderwijk		
Existing trees	8,574	26,339	34,913
Existing + proposed trees	7,717	26,869	34,587
Change	-856	530	-325
% Change	-9.99%	2.01%	-0.93%
	Kop van Zuid		
Existing trees	13,943	17,942	31,885
Existing + proposed trees	13,711	18,060	31,771
Change	-231	117	-113
% Change	-1.66%	0.66%	-0.36%

From the analysis of the simulation results, the addition of deciduous trees reduces neighbourhood-wide cooling demand by 3-10%. However, these benefits are partially offset by winter shading, which introduces heating penalties of up to 2%. Consequently, net annual energy changes at the neighbourhood scale are modest, ranging from -0.9% to -0.4%. Under current climate conditions (S1 vs S2), introducing proposed trees creates a clear seasonal trade-off. The new foliage successfully intercepts summer solar radiation, lowering cooling demands by 3.03% in Afrikaanderwijk and 1.25% in Kop van Zuid. However, this same canopy blocks beneficial low-angle sunlight during the winter, increasing heating demand by 0.66% and 0.56%, respectively. Because the cooling savings and heating penalties offset each other, the net impact on total annual energy demand is negligible (+0.02% in Afrikaanderwijk, -0.05% in Kop van Zuid). Under the 2050 climate scenarios (S4 vs S5), the cooling benefits of the new trees increase. In Afrikaanderwijk, cooling demand drops by nearly 10% (up from 3% in 2023), although heating demand increases 2.01%. In Kop van Zuid, cooling reductions reach 1.66%, with heating increasing by 0.66%. The overall net energy change is a slight reduction for both (Afrikaanderwijk: -0.93%, Kop van Zuid: -0.36%). The spatial distribution of the influence of trees in the study areas are shown in figures 8 and 9.

Visual analysis of the simulation output reveals that effects are highly heterogeneous and depend on the spatial context. Kop

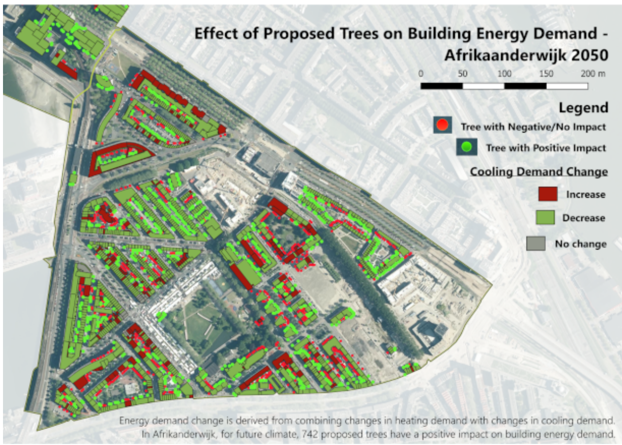

Figure 8. Effect of proposed tree planting on heating + cooling demand in Afrikaanderwijk (Rahmawati, 2025)

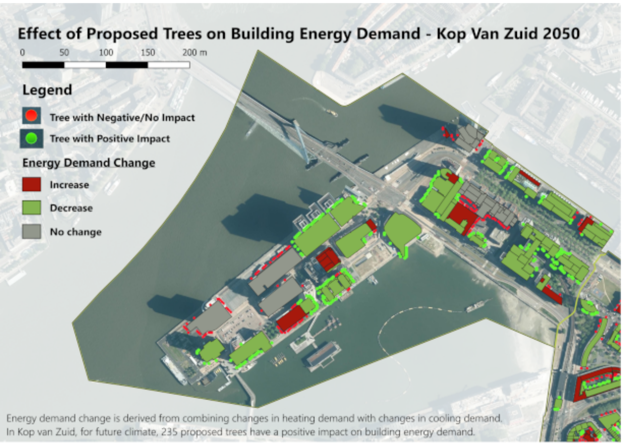

Figure 9. Effect of proposed tree planting on heating + cooling demand in Kop van Zuid (Rahmawati, 2025)

van Zuid is a neighbourhood with a high density of high-rise buildings and wide spaces between them, while Afrikaanderwijk is a consolidated, typical Dutch neighbourhood. In compact areas, trees may block critical winter solar gains, while, in open areas, they consistently reduce peak summer loads. Orientation and façade exposure are the primary factors affecting this balance. Under current conditions, 173 proposed trees in Kop van Zuid and 945 in Afrikaanderwijk reduce the total annual energy demand in the neighbourhoods.

4. Discussion

Although future warming amplifies the cooling benefits of trees, the trade-off with winter heating penalties remains a critical factor. The 30-30-300 guideline is a useful benchmark, but it is not sufficient on its own to achieve PED objectives. Currently, Kop van Zuid has a canopy coverage of just 4.3%, and Afrikaanderwijk 9.1%, meaning that both fall short of the target. Although the spatial analyses showed that planting enough trees to reach 30% is physically possible, the simulation results serve as a strong warning against doing so without further reasoning. The aggregated results in tables 6 and 7 show that maximising canopy cover solely to meet a 30% metric will result in severe winter heating penalties for specific buildings, particularly those with poor solar orientation. The simulation results show that:

- The share of trees leading to net energy savings actually decreases in some locations under future climate conditions.
- Higher canopy cover does not automatically lead to proportional improvements in energy.
- In some cases, meeting a canopy target could lead to neutral or even negative energy outcomes if trees are placed where they block essential winter sun, as in the case of compact and heating-dependent buildings.

Therefore, a planting strategy should transition from being based on quantity (i.e. total cover) to performance (i.e. strategic placement) to ensure that greening contributes effectively to PED goals.

Data and Modelling Limitations

The 3D City Model of Rotterdam only includes public trees. Private trees are excluded under data protection regulations, meaning areas such as private gardens and courtyards are significantly under-represented in the current simulation. This is visually evident in figure 10, the white line delimitates a section within the building block where trees are not modelled.

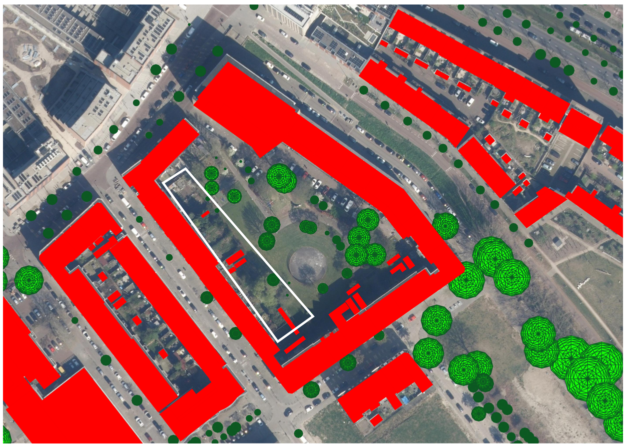

Figure 10. Trees and buildings modelled in Afrikaanderwijk

Furthermore, the simulations do not account for future building refurbishments. Improved insulation or passive heating strategies could reduce winter heating demand, potentially mitigating the negative shading impacts identified in this study. Tree planting offers co-benefits—such as air quality and biodiversity—that are not captured by energy metrics but should be weighed in final planning decisions. Finally, the results presented in this research must still be interpreted critically and taken *cum grano salis* due to the simplifications and assumptions needed as a result of lack of more detailed information.

5. Conclusions

The integration of 3D tree representations directly into a single CityGML-based Urban Building Energy Modelling (UBEM) framework is both computationally viable and analytically robust. Representing trees as LoD1 volumes enables capturing seasonal shading impacts without the overhead of coupling to external microclimate software. Although highly detailed geometries remain impractical for district-scale simulations, this simplified representation balances computational efficiency with the requirement to simulate vertical structure and solar obstruction.

However, this approach entails specific tradeoffs. Treating trees as opaque and static volumes neglects the porous architecture of natural canopies, spatial heterogeneity, and species-specific leaf-area dynamics. Furthermore, as static obstructions, these models do not account for complex hygrothermal processes, such as evapotranspiration, or aerodynamic effects, such as wind sheltering.

Although the net annual energy change across a district remains relatively small, this masks a growing seasonal imbalance. Adding deciduous trees successfully reduces summer cooling demands by up to 10% under 2050 conditions, as their canopies shade building surfaces, limiting heat gain. However, these same shading blocks beneficial low-angle sunlight during the colder months, creating a "heating penalty".

To maximise energy efficiency benefits, planners must use site-specific, orientation-aware planting strategies. Trees should be prioritised in locations where their shading delivers a definitive net energy benefit. In compact and dense districts, adding trees can sometimes block the already limited winter solar gains, worsening heating needs.

6. Acknowledgements

The work presented in this paper has been developed within the European project DigiTwins4PEDs (Utilisation of urban digital twins to co-create flexible positive energy systems for districts). The project is funded by the European Commission under the Horizon Europe Partnership scheme (Funding Indicator: 03EN3081A). The DUT Call 2022 also contributes to the Urban Transition Mission of Mission Innovation as part of the MICall 2022 initiative.

References

Agugiaro, G., Padsala, R., 2025. A proposal to update and enhance the CityGML Energy Application Domain Extension. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, Tokyo, Japan.

Bao, K., Kalisch, L., Santhanavanich, T., Thrän, D., Schröter, B., 2022. A bottom-up GIS-based method for simulation of ground-mounted PV potentials at regional scale. *Energy Reports*, 8, 5053–5066.

Betz, M., Riegel, L., Coors, V., 2026. CityDoctor / CityDoctor2 · GitLab.

Elnagar, E., Gendebien, S., Georges, E., Berardi, U., Doutreloup, S., Lemort, V., 2023. Framework to assess climate change impact on heating and cooling energy demands in building stock: A case study of Belgium in 2050 and 2100. *Energy and Buildings*, 298, 113547.

eurostat, 2025. Energy consumption in households.

Gao, W., Agugiaro, G., León-Sánchez, C., 2025. Data-Driven Energy Simulations To Evaluate Positive Energy District Potential In Rotterdam. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, X-4/W7-2025, 25–32. https://isprs-annals.copernicus.org/articles/X-4-W7-2025/25/2025/.

García-López, J., Sendra, J. J., Domínguez-Amarillo, S., 2024. Validating 'GIS-UBEM'—A Residential Open Data-Driven Urban Building Energy Model. *Sustainability*, 16(6), 2599.

Gemeente Rotterdam, 2026. Rotterdam 3D Downloads.

IEA, 2021. World Energy Outlook 2021. Technical report, International Energy Agency. Published: Retrieved January 15, 2024, from https://www.iea.org/reports/world-energy-outlook-2021.

KNMI, 2023. KNMI'23-klimaatscenario's.

Konijnendijk, C. C., 2023. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. *Journal of Forestry Research*, 34(3), 821–830.

OGC, 2012. OGC City Geography Markup Language (CityGML) Encoding Standard. ISSN:18632246.

Rahmawati, A., 2025. Scenario-based energy simulation: Modelling tree planting strategy to reduce heating and cooling demand under 2050 climate conditions. Master's thesis, Delft University of Technology, Delft, Netherlands.

Reinhart, C. F., Cerezo Davila, C., 2016. Urban building energy modeling - A review of a nascent field. *Building and Environment*, 97, 196–202.

Smart Cities Marketplace, 2021. Positive Energy Districts: Fact Sheet.

Weiler, V., Lust, D., Brennenstuhl, M., Brassel, K.-H., Duminil, E., Eicker, U., 2022. Automatic dimensioning of energy system components for building cluster simulation. *Applied Energy*, 313, 118651.

Ürge Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., Petrichenko, K., 2015. Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews*, 41, 85–98.