Energy and Indoor Environment Quality Performance Predictions for Multi-residential Projects in Four European Climates

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Abstract. This article presents the research on dynamic performance models developed for six multi-residential demonstration projects as a part of the syn.ikia Horizon 2020 project in four European climate zones: mediterranean, marine, continental, and sub-arctic.

The main aim of these models is to evaluate buildings' performance based on final design inputs, focusing on energy, environmental impact, and indoor environmental quality characterised by a set of key performance indicators.

The dynamic performance models of the syn.ikia demonstrations were based on detailed multi-zone modelling methods and well-established and validated building performance tools such as TRNSYS, IDA-ICE, and DesignBuilder.

The simulated performance results demonstrate that in all new-build demonstration projects, the final design scenario enables the achievement of the main syn.ikia project targets related to a positive energy balance, operational net-zero GHG emission, and high thermal comfort. This accomplishment is attributed to implementing thermally efficient and airtight building envelopes, efficient HVAC systems, and on-site renewable energy systems. In the case of the two retrofit demonstration projects, the positive energy and net-zero emission targets were not achieved, which is related to the combination of the limited renewable energy generation potential and higher energy demand. The comparison of the simulated performance results with the available annual monitoring data in the Dutch demonstration project indicates good accuracy of the developed building performance model and confirms the achievement of the main syn.ikia project goals related to the positive energy balance and net-zero GHG emission operation. The highest performance gap is observed for energy consumption related to the domestic hot water and space heating, whereas there is a neglectable difference for the renewable energy generation from on-site PV system.

U. Berardi (Ed.): IABP 2024, LNCE 554, pp. 457–470, 2025.
https://doi.org/10.1007/978-981-97-8313-7_64

Keywords: Sustainable plus energy neighbourhoods · plus energy buildings · building performance simulations

1 Introduction

1.1 Sustainable Plus Energy Buildings (PEBs) and Neighbourhoods (SPENs)

The built environment significantly impacts the economy, quality of life and climate. Over the whole life cycle, the real estate sector accounts for around 35% of global energy use and 40% of the GHG emissions [1]. With 75% of the EU population living in urban areas [2] and a rising focus on both new and existing buildings to achieve full decarbonization in the short term [3], there is a significant opportunity and need for wide market implementation of sustainable positive energy buildings (PEBs) and neighbourhoods (SPEN). A positive energy building can be defined as an "energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption and energy flexibility rate over the one year" [4]. The switch from the single building scale towards a more holistic, sustainable plus energy neighbourhood (SPEN) based approach enables multiple synergies to enhance the decarbonisation of the built environment more efficiently and collectively.

1.2 syn.ikia: Demonstration Project of the Sustainable Plus Energy Neighbourhoods in Europe

To increase SPEN implementation in Europe, the main goal of the syn.ikia, as an EU-funded research and innovation project, is to develop and demonstrate the functionality of sustainable neighbourhoods with surplus renewable energy in four different climatic zones, contexts and markets in Europe. The syn.ikia definition of SPEN [4] follows a principle similar to PEBs but with expanded boundaries to the neighbourhood scale, including local energy storage and supply units. Throughout the project, syn.ikia will develop, construct, and test six real-life SPENs (Fig. 1). Table A1(Annex section), presents the key design data for the multi-family residential demonstration projects in Spain, Netherlands, Austria and Norway. The composition of syn.ikia demonstration project types combines new construction (Demo I-III and VI) and retrofit (Demo IV-V). Additionally, the scale of the projects ranges from the single-building focus (Demo I-II) and building group (Demo III,V,VI) up to the entire neighbourhood scale (Demo III). The main performance goals to be achieved by demonstration projects in syn.ikia are related to i) over 100% non-renewable primary energy savings, ii) 100% operational GHG emission reduction, iii) 90% renewable energy generation triggered when compared to the nearly zero-energy buildings (nZEB) level. The main three design principles of syn.ika SPENs relate to optimising and integrating: i) energy efficiency in buildings, ii) flexibility for energy consumption within neighbourhoods, and iii) regional/local supply of renewable energy.

Fig. 1. Visualisation of the six syn.ikia demonstration projects

1.3 Role of Dynamic Building Performance Simulations in the Design Process of SPEN and PEB

Building performance simulation (BPS) is an essential design tool that assesses the implications of various building design choices, construction methods, and occupant behaviour patterns. By employing models, engineers and designers can explore a range of scenarios related to a building's energy usage and environmental impact, drawing from diverse sets of model inputs. In the collaborative design process, energy simulation is a crucial linking tool and method, delivering forecasts on how the building will perform regarding energy consumption, indoor air quality, operational GHG emissions, and costs. Furthermore, the significance of energy modelling extends to the integrated design process, where it plays a central role in providing critical data for the design team. In the syn.ikia project, the developed dynamic performance models described in this article were the primary tools used for the design optimisation and prediction of energy, environment and indoor environment quality performance.

2 Methodology

2.1 Energy and Indoor Environmental Quality Key Performance Indicators (KPIs)

Evaluating Sustainable Positive Energy Neighborhoods (SPENs) in syn.ikia relies on a comprehensive methodology framework developed inside the project [10]. This framework introduces a range of key performance indicators (KPIs) grouped into five main categories: i) energy and environmental, ii) economic, iii) indoor environmental quality

(IEQ), iv) social, and v) smartness and flexibility. Table 1 provides a detailed description of the energy, environmental, and IEQ KPIs. Assessing syn.ikia demonstration project design performance based on described KPIs was a primary objective in developed dynamic performance models, described in the section below. In the framework of syn.ikia, energy uses are assessed, including HVAC, DHW, and lighting needs. The energy balance assessment does not consider plug loads, appliances, and electrical vehicle consumption. This approach is in line with the Energy Performance of the Building Directive (EPBD) [11], which is the main construction standard in the European Union.

Table 1. Energy and Indoor Environmental Quality Key Performance Indicators (KPIs) defined in syn.ikia methodology framework

KPI category	Subcategory	KPI	Description
Energy and Environmental	Overall performance	Non-renewable primary energy balance	A single indicator (kWh/m^{2}a) based on the sum of all delivered and exported energy for all energy carriers, with corresponding non-renewable primary energy weighting factors
		Renewable energy ratio	Share (%) of the energy from renewable energy sources in total energy use, calculated in terms of the primary energy and accounting for all renewable energy sources
	Matching factors	Grid delivered factor	Share (%) of the energy delivered from the grid and the total energy used by the system over a time period
		Load cover factor/ Self-Generation	Share (%) of the energy produced on-site and directly used and the total electric energy use
		Supply cover factor/ Self-Consumption	Share (%) of the energy produced on-site and directly used and the total on-site produced energy

(*continued*)

Table 1. (*continued*)

KPI category	Subcategory	KPI	Description
	Grid interaction factors	Net energy/power	Amount of the energy/power (kWh/kW) delivered and exported from/to the grid
		Peak delivered/ exported power	Maximum value (kW) of the delivered and exported energy from/to the grid
	Environmental balance	Total greenhouse gas emissions	A single indicator ($kgCO_{2eq}/m^2a$) is based on the sum of all delivered and exported energy for all energy carriers, with corresponding GHG emission factors
Indoor Environmental Quality	Indoor Air Quality	Carbon dioxide (CO2)	The percentage of the occupancy time that CO_2 concentrations (ppm) fall into four IAQ categories (IEQ I-IV) according to EN ISO 16798–1-2019 [12]
	Thermal Comfort	PMV/PPD	Calculations are in line with ISO 7730 [13] and ASHRAE Standard 55 [14]. Percentage of the occupancy time that PMV/PPD indicators fall into four thermal comfort categories (IEQ I-IV) according to EN ISO 16798–1-2019
		Operative Temperature	Percentage of time that indoor operative temperatures (°C) are out of the ranges specified in the thermal comfort categories (IEQ I-IV) of EN 167989–1-2019

2.2 Dynamic Performance Models of Demonstration Projects

Table 2 summarises the simulation tool (software), timestep, and general methodology approach for developing dynamic performance models of the syn.ikia demonstration projects. The dynamic performance models of the syn.ikia demonstrations were mainly based on detailed multi-zone modelling methods and well-established and validated building performance tools TRNSYS [15], IDA-ICE [16], and DesignBuilder [17]. In most performance models, the energy system modelling was based on the simplified approach using the fixed efficiency approach. In all demos, the main goal of the developed performance models was to optimise design inputs and estimate the energy and IEQ KPIs based on the final building design. The simulation inputs and consequential performance results in dynamic performance models were based on the design specifications specified in Table A1 (Annex section), which are the final design scenarios.

Table 2. Overview of the developed dynamic performance models of syn.ikia demonstration projects

Demonstration project	Simulation Software	Simulation timestep [min]	Objective and simulation methodology overview
Demo 1 Mediterranean, Barcelona	TRNSYS 18 and Archelios (PV generation)	3	Detailed multi-zone building performance model with detailed energy system modelling based on the standard library components and self-created models
Demo 2 Marine, Uden	TRNSYS 18	15	Detailed multi-zone building performance model with simplified energy system modelling based on fixed efficiency values
Demo3 Continental, GNICE	Design builder 7.0.2	15	Simplified neighbourhood energy modelling with the detailed reference multi-zone building performance model with simplified energy system modelling based on fixed efficiency values

(*continued*)

Table 2. (*continued*)

Demonstration project	Simulation Software	Simulation timestep [min]	Objective and simulation methodology overview
Demo 4 Continental, WirInHouser	IDA ICE 4.8	60	Simplified neighbourhood energy modelling with the detailed reference multi-zone building performance model with simplified energy system modelling based on fixed efficiency values
Demo 5 Continental, Straße70–72	Design builder 7.0.2	15	
Demo 6 Subarctic, Fredrikstad	IDA ICE 4.8 and PVsyst	60	Simplified building performance model (apartment-based scale) with simplified energy system model [18]

3 Results and Discussion

3.1 Overall Energy Performance: Delivered, Generated Energy and Non-primary Energy Balance

The simulation results related to the delivered, generated, and non-primary energy balance of the six demonstration projects are presented in Fig. 2. Values of annual total delivered energy vary between 16 kWh/m^{2}a in Spanish Demo I up to 76 kWh/m^{2}a in the case of the Austrian Demo V, whose energy performance significantly stands from other demo results. This difference can be explained by the fact that the heating system in this demo is dominantly based on the biomass boiler, whose thermal efficiency is severely lower than in other demos, which are based on the heat pump system. In each of the residential demonstration projects, the delivered energy for space heating and domestic hot water is the dominant source of energy consumption. Simulated annual energy generation from the on-site PV system is higher than the total delivered energy in all new-build demonstration projects (Demo I-III and VI), meaning that these projects fulfil the positive energy-building ambition (PEB). However, this PEB ambition is not achieved in the case of the building retrofits (Demo IV-V), which is related to the combination of the limited renewable energy generation potential and higher energy demand. Similarly, the negative value of the annual non-renewable primary energy balance is achieved for only all new build demonstration projects.

3.2 Energy Key Performance Indicators: Renewable Energy Ratio, Matching Factors and Environmental Balance

Based on the simulated results (Table 3), the renewable energy ratio (RER) indicator is more than 100% in the case of Demos I-IV, meaning that the whole primary energy

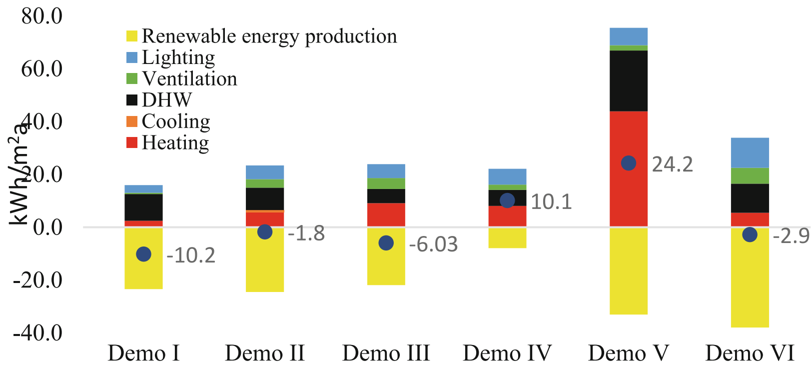

Fig. 2. Simulated final energy consumption, renewable energy generation and non-renewable energy balance in the syn.ikia demonstration projects

demand of demonstration projects is entirely covered by energy from renewable energy sources, including aero-, geo-, and hydrothermal energy (lower source of the heat pump system) beside wind, solar, hydro, biomass as renewable energies. Generally, the RER is getting higher in the demonstration buildings with the lower energy demand, the higher share of renewable energy sources in the thermal energy budget, and the higher on-site renewable energy generation, the surplus of which is fed into the local grid. It is worth mentioning that the calculation of the RER indicator inside the syn.ika framework follows the "symmetric weighting approach", meaning that the compensation credit is given to the surplus of the generated renewable electricity exported to the grid. This is why the RER values in demos are above 100%. The available simulation results indicated that for the fully electrified demonstration projects (Demo I – Demo II) the load cover (self-generation) factor is around 30% (Table 3), meaning that on an annual basis, the relatively low ratio of the total electric consumption comes from the on-site PV system. Similarly, in these demonstration buildings, the supply-cover (self-consumption) ratio is in the range of 24% (Demo I) to 33% (Demo II), indicating that the dominant share of the generated on-site renewable electricity is exported to the grid. The low values of these indicators can be explained by the significant imbalance between renewable energy generation and electricity demand, mainly during the summer season, where renewable energy generation is the highest and the total electricity demand is the lowest (no heating demand). The Norwegian project (Demo VI) is characterised by a higher load and supply cover ratio than the other demos, which is related to the better balance between electricity generation and consumption. Similarly to the annual non-primary energy balance values, the negative value of the environmental balance is achieved in Demos 1–3 and 6, meaning that on an annual basis, these demonstration projects can be defined as zero-emission buildings according to the EPBD.

Table 3. Overview of the developed dynamic performance models of syn.ikia demonstration projects

Energy and environmental KPI	Demo 1	Demo 2	Demo 3	Demo 4	Demo 5	Demo 6
Overall performance						
Renewable energy ratio [%]	124	106	101	101	53	88
Matching factors						
Grid purchase factor [%]	71	67	-	-	-	22
Load cover factor [%]	29	32	-	-	-	78
Supply cover factor [%]	24	33	27	-	-	68
Environmental balance [$kgCO_{eq}/m^2a$]	-1.87	-0.43	-2.85	-	-	-0.65

3.3 Indoor Environmental Quality (IEQ) Indicators: PMV/PPD and Operative Temperature

The simulated annual category levels of indoor environmental quality performance of representative apartments according to EN16798–1-2019 and based on the PMV/PPD and operative temperature key performance indicator are presented in Figs. 3–4 below. The available results for two KPIs indicate high thermal comfort levels, mainly corresponding to the first and second indoor environmental quality categories (IEQ1–2). The simulated results demonstrate that positive energy ambition is achieved in Demos I-III and VI, together with a high thermal comfort level.

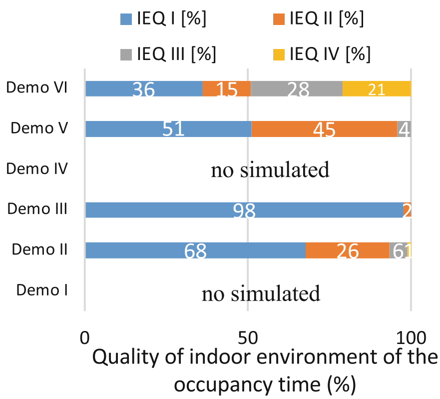

Fig. 3. Simulated results of PMV/PPD KPI in syn.ika demonstration projects.

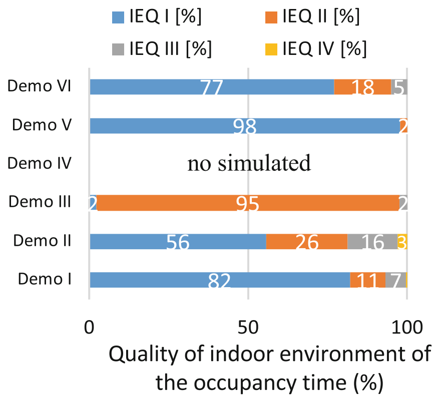

Fig. 4. Simulated results of Operative Temperature KPI in syn.ika demonstration projects.

3.4 Performance Gap: Energy and Environmental KPIs in Demo II, Uden, Netherlands

The comparison of the simulated and measured annual values related to the Energy and Environmental KPIs in the marine climate demonstration project in Uden, Netherlands (Demo 2) is presented in Table 4 below. At the moment of this article's development, only energy monitoring data from Demo 2 is available, and it was based on a monitoring system with a data resolution of 15 min gathered between 01.09.2022 and 01.09.2023. Calculation and analysis of Energy and Environmental KPIs based on measured values confirms that the annual operation of the demonstration project fulfils the main syn.ika project goals: i) positive energy-building ambition, where per annual basis renewable energy generation is higher than total energy consumption, ii) negative non-primary energy balance, and iii) net-zero GHG emission ambition. The comparison indicates that the total difference between measured and simulated energy consumption is around 8%. The highest mismatch between simulation and monitored results can be observed for space heating and domestic hot water, with the difference being as high as 50%. A perfect match between renewable energy generation prediction and real measured value is present.

Table 4. Comparison between simulated and monitored (measured) indicators of energy and environmental KPIs in syn.ika demonstration project in Uden, Netherlands

Indicator	Simulated value	Monitored value
Space Heating [kWh/m2a]	5.7	8.3
Space cooling [kWh/m2a]	0.8	1.2
DHW [kWh/m2a]	8.5	4.8
Ventilation [kWh/m2a]	3.2	2

(*continued*)

Table 4. (*continued*)

Indicator	Simulated value	Monitored value
Lighting [kWh/m2a]	5.2	5.2
Total [kWh/m2a]	23.4	21.5
PV generation [kWh/m2a]	24.5	23.9
Non-renewable primary energy [kWh/m2a]	-1.8	-6.4
Renewable energy ratio [%]	106	91
Load cover factor [%]	32	30
Supply cover factor [%]	33	19
Grid purchase factor [%]	67	70
GHG emissions [kgCO2eq/m2a]	-0.43	-3.7

4 Conclusions

Within this article, dynamic building performance models of the six syn.ikia demonstration projects based on the final design inputs of the building's envelope, layout, systems, and renewable energy generation were presented and evaluated following the assessment framework based on the key performance indicators of energy, environment, and indoor environmental quality. The simulated performance results demonstrate that in all new-build demonstration projects, the final design achieves the main syn.ikia project targets related to positive energy balance, net-zero GHG emission, and high thermal comfort. This accomplishment is attributed to implementing thermally efficient and air-tight building envelopes, efficient HVAC systems, and on-site renewable energy systems. In the case of the two retrofit demonstration projects, the positive energy and net-zero emission targets are not achieved, which is related to the combination of the limited renewable energy generation potential and higher energy demand. The comparison of the simulated performance results with the available annual monitoring data in the Dutch demonstration project indicates good accuracy of the developed building performance model and confirms the achievement of the main syn.ika project goals related to the positive energy balance and net-zero GHG emission operation. Future research inside the syn.ikia project will evaluate all demonstration projects' holistic performance based on energy, environmental and indoor environmental quality monitored data coupled with the economic and social data. Additionally, the performance gap between results from the dynamic performance models and monitoring data will be investigated to develop recommendations for future energy buildings and neighbourhood projects.

Acknowledgments. The work presented is a part of the syn.ikia research project. This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N 869918.

Annex

Table A1 Overview of the key design parameters of the six syn.ikia demonstration projects (demos)

	Demo 1	Demo 2	Demo 3	Demo 4	Demo 5	Demo 6
Name and location of the project	Santa Coloma de Gramenet, Barcelona, Spain	Loopkantstraat, Uden, Netherlands	Gnice, Salzburg, Austria	WirInHouser, Salzburg, Austria	Straße70–72, Salzburg, Austria	Verket Panorama, Fredrikstad, Norway
Climate data	Mediterranean HDD: 1438 h CDD: 75 h	Marine HDD: 2814 h CDD: 20 h	Continental HDD: 3211 h CDD: 2 h			Subarctic HDD: 4112 h CDD: 2 h
Building envelope U-values walls U-values glazing U-values roof U-values floor Air leakage (n50)* Glass-to-wall ratio	0.26 W/m^2K 1.10 W/m^2K 0.33 W/m^2K 0.46 W/m^2K 0.4 h^{-1} 38%	0.16 W/m^2K 1.0 W/m^2K 0.12 W/m^2K 0.19 W/m^2K 0.3 h^{-1} 37%	0.13 W/m^2K 0.80 W/m^2K 0.10 W/m^2K 0.18 W/m^2K 0.6 h^{-1} 35%	0.09 W/m^2K 0.71 W/m^2K 0.09 W/m^2K 0.20 W/m^2K 0.6 h^{-1} 30%	0.14 W/m^2K 1.6 W/m^2K 0.19 W/m^2K 0.20 W/m^2K 0.6 h^{-1} 32%	0.10 W/m^2K 0.85 W/m^2K 0.08 W/m^2K 0.13 W/m^2K 0.6 h^{-1} 22%
Construction type	New construction	New construction	New construction	Retrofit and extension	Retrofit	New construction
Neighbourhood layout No. of building units No. of housing units No. of floors Conditioned floor area	1 building 38 dwellings 7 floors 2 154 m^2	1 building 39 dwellings 3 floors 2 335 m^2	19 buildings 251 dwellings 2–4 floors 20 952 m^2	3 buildings 99 dwellings 4–6 floors 8 107 m^2	2 buildings 24 dwellings 3 floors 1 474 m^2	2 buildings 88 dwellings 6 floors 4002 m^2
Heating/Cooling system **Ventilation system**	Air-to-Water HP w. 4 pipes	Ground-Source HP	Ground-Source HP	Ground-Source HP, Sewage and exhaust air HP, biomass boiler	Biomass plant and solar thermal system	Ground-Source HP and District Heating
	Radiators (35/30) No cooling	Floor heating (40/35) Floor cooling	Floor heating (40/35), Natural ventilation cooling	Radiators (40/35), Natural ventilation cooling	Radiators (60/40), Natural ventilation cooling	Floor heating (40/35) No cooling

(*continued*)

Table A1 (*continued*)

	Demo 1	Demo 2	Demo 3	Demo 4	Demo 5	Demo 6
	Natural Cross Ventilation	Mechanical Exhaust Ventilation	Natural Cross Ventilation	Mechanical Exhaust Ventilation	Mechanical Exhaust Ventilation	Balanced Ventilation w. heat Recovery
SCOP* heating / cooling / DHW	4.98 / - / 2.96	5.7 / 50 / 3.6	3.9 / - / 3.0	4.0 / - / 3.0	0.8/ - / 0.7	4.0 / - / 4.0
Heating setpoint	21/ 17 °C day/ night	20/ 21/ 19 °C day/ evening/ night	20/ 18 °C setpoint/ setback	22/ 18 °C setpoint/ setback	22/ 18 °C setpoint/ setback	21/ 19 °C setpoint/ setback
Cooling setpoint	n/a	23 °C	n/a	n/a	n/a	n/a
Photovoltaic system	39.1 kWp	60.5 kWp	505 kWp	85kW	65kW	107 kWp

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