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Optimal design of net zero energy buildings under different climates

Fatima Harkouss

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$$e^{i\pi} + 1 = 0$$

THÈSE DE DOCTORAT

Conception optimale de bâtiments à énergie nette nulle sous différents climats

Fatima Harkouss

Laboratoire Jean-Alexandre Dieudonné

**Présentée en vue de l'obtention
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et de l'université Libanaise

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Conception optimale de bâtiments à énergie nette nulle sous différents climats

Résumé:

La conception des bâtiments à consommation énergétique nette zéro (BCENN) a été introduite pour limiter la consommation d'énergie et les émissions polluantes dans les bâtiments. En général, il est admis qu'il y a trois étapes principales pour atteindre la performance du BCENN: d'abord l'utilisation de stratégies passives, puis de technologies économes en énergie, et enfin de systèmes de production d'énergie renouvelable (ER). L'optimisation des bâtiments est une méthode prometteuse pour évaluer les choix de conception de BCENN. Le défi dans la conception de BCENN est de trouver la meilleure combinaison de stratégies de conception qui feront face aux problèmes de performance énergétique d'un bâtiment particulier. Cette thèse présente une méthodologie pour l'optimisation multicritères basée sur la simulation des BCENN. La méthodologie est caractérisée principalement par quatre étapes: la simulation du bâtiment, le processus d'optimisation, l'aide à la décision multicritère (ADM) et une analyse de sensibilité pour évaluer la robustesse de la solution optimale. La méthodologie est appliquée à l'étude de l'optimisation de la conception des BCENN dans différentes études de cas, prises dans des zones climatiques diverses. La méthodologie proposée est un outil utile pour améliorer la conception des BCENN et faciliter la prise de décision dans les premières phases de la conception des bâtiments. L'amélioration des bâtiments en matière d'efficacité énergétique nécessite une optimisation des paramètres passifs. Une étude complète sur la conception passive optimale pour les bâtiments résidentiels est présentée. Vingt-cinq climats différents sont simulés dans le but de produire les meilleures pratiques pour réduire les charges énergétiques du bâtiment (pour le refroidissement et le chauffage) et son coût global sur son cycle de vie (hors déconstruction du bâtiment). Le confort thermique adaptatif des occupants est également amélioré en mettant en œuvre les stratégies de refroidissement passif appropriées telles que les dispositifs d'occultation et la ventilation naturelle. Les mesures passives optimales s'avèrent efficaces elles conduisent à une diminution de demande énergétique, du coût globale sur le cycle de vie, et de la surchauffe.

Les caractéristiques des systèmes de conditionnement de l'air et de production d'énergie mis en œuvre dans les BCENN doivent être sélectionnées avec soin pour garantir l'objectif de performance prévu. Dans cette thèse, six ensembles de systèmes énergétiques sont comparés et optimisés, pour la conception de BCENN dans des climats représentatifs choisis, à savoir Indore (besoin de froid dominant), Tromso (besoin de chaud dominant) et Beijing (climat mixte). La

performance des BCENN y est évaluée en fonction du coût global sur le cycle de vie, du temps de retour sur investissement, du coût actualisé de l'énergie, des émissions de CO₂, du bilan énergétique, de l'indice d'autosuffisance énergétique et enfin, de l'indice d'interaction au réseau électrique. Des recommandations pour chaque région sont fournies.

Mots-clés: BCENN, optimisation, climat, mesures passives, confort adaptatif, énergie renouvelable, interaction au réseau, environnement, économie

Optimal design of net zero energy buildings under different climates

Abstract:

The conception of net zero energy buildings (NZEB) has been introduced to limit energy consumption, global warming potentials, and pollution emissions in buildings. In general, it is traditionally agreed that there are three main steps to reach the NZEB performance, starting through the use of passive strategies, energy efficient technologies, and then renewable energy (RE) generation systems. Building optimization approaches are promising techniques to evaluate NZEB design choices. The challenge in NZEB design is to find the best combination of design strategies that will enhance the energy performance of a particular building. The aim of this thesis is to develop an understanding of NZEBs design concepts. Besides, it aims to assist NZEB designers to select the suitable design options of passive and RE systems based on a systemic evaluation in different climates. This thesis presents a methodology for the simulation-based multi-criteria optimization of NZEBs. Its main features include four steps: building energy simulation, optimization process, multi-criteria decision making (MCDM) and testing solution's robustness. The methodology is applied to investigate the cost-effectiveness potential for optimizing the design of NZEBs in different case studies taken as diverse climatic zones. The proposed methodology is a useful tool to enhance NZEBs design and to facilitate decision making in early phases of building design. The high potential of buildings towards energy efficiency has drawn special attention to the passive design parameters. A comprehensive study on optimal passive design for residential buildings is presented. Twenty five different climates are simulated with the aim to suggest best practices to reduce building energy demands (for cooling and heating) in addition to the life cycle cost (LCC). The occupants' adaptive thermal comfort is also improved by implementing the appropriate passive cooling strategies such as blinds and natural ventilation. The integrated optimal passive measures have demonstrated its competency since it leads to a significant energy demand, LCC, and overheating-period decrease. The configurations and capacities of the implemented RE systems in NZEBs must be appropriately selected to ensure the intended performance objective. In the thesis, investigation, optimization and comparison of six RE solution sets for designing NZEBs is carried out in three typical climates: Indore (cooling dominant), Tromso (heating dominant) and Beijing (mixed climate). The performance of NZEB is evaluated in terms of a combined performance comprised of building energy consumption, LCC,

payback period, levelized cost of energy, CO₂eq emissions, load matching index, and grid interaction index. Recommendations for each region are provided.

Keywords: Net zero energy building, optimization, climate, passive measures, adaptive comfort, renewable energy, grid stress, environment, economy

**TO MY MOTHER,
TO MY FAMILY**

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Nomenclature

A	area (m ²)
A_w	Windows area (m ²)
ASHP	Air source heat pump
AHU	Air handling unit
ASHPWH	Air source heat pump water heater
ASHRAE	American society of heating, refrigerating, and air-conditioning engineers
AIA	American institute of architects
ACH	Air change per hour
AHU	Air handling unit
ASHHP	Air source hybrid heat pump
AWHP	Air to water heat pump
A_{PV}	Area of the photovoltaic array, m ²
A_{HX}	Area of the heat exchanger, m ²
AC	Alternating current
AC	Air Conditioner
AHP	Analytical Hierarchy Process
ADM	Aide à la décision multicritère
ANN	Artificial Neural Network
BIPV	Building integrated photovoltaic
BIPV-T	Building integrated photovoltaic thermal
BIM	Building information modeling
BCENN	Bâtiment à consommation énergétique nette nulle
BDG	Biodiesel generator
COP	Coefficient of performance
CHP	Cogeneration or combined heat and power
CO ₂ eq	Carbone dioxide equivalent
C	Cooling
C	Concordance index
C	Cost, \$
CI	Consistency index
CDD	Cooling Degree Days
CCHP	Combined cool heat and power
CH ₄	Methane
CHP	Combined heat and power
C_p	Water specific heat, kJ/kg.K
D	Discordance index
DWHR	Drain water heat recovery
DOE	Department of energy
DPBP	Discounted payback period

DHW	Domestic hot water
DMOPSO	Dynamic multi objective particle swarm optimization algorithm
DC	Direct current
DM	Decision maker
DG	Diesel generator
D	Depth of borehole, m
DB	Drain back
EAHE	Earth to air heat exchanger
ERV	Energy recovery ventilation
ECM	Electronically computed motors
Ext.	External
EH	Electric heater
E	East
EER	Energy efficiency ratio
EPBD	EU directive on energy performance of buildings
EAC	Electrical AC unit
EP	Energy performance
Ex	Experimental
ECBC	Energy Conservation in Building Codes
EUI _a	Actual Annual Energy Use Index
EUI _r	Reference Annual Energy Use Index
EUL LA	End use loads for lighting and appliances (kWh/y)
Ex	Experimental
EC	Electrochromic
EC	Annual Energy Cost (\$)
EP	Expanded polystyrene
ELECTRE	Elimination and Choice Expressing the Reality
ETSC	Evacuated tube solar collectors
$E_{building}$	Total energy consumption, kWh/y.m ²
η_{pump}	Overall pump efficiency
F	Façade
FH	Floor heating
FFH	Fossil fuel heater
F1, F _n	Fitness values
FCU	Fan coil unit
FO	Fuel oil
FC	Floor cooling
FPSC, FP	Flat plate solar collectors
f_{load}	Load matching index
$f_{grid,year}$	Grid interaction index
GB	Gas boiler

GHG	Greenhouse gas
GSHP	Ground source heat pump
GS	Geothermal system
GPS	Generalized pattern search algorithm
GA	Genetic algorithm
GRG	Generalized Reduced Gradient Algorithm
GPSPSOCHJ	Generalized Particle Swarm Optimization with Hook Jeeves algorithm
GPS	Generalized Pattern Search algorithm
<i>g</i> -value	Solar energy transmittance
GWP	Global warming potential
<i>g</i> (<i>m</i>)	Monthly renewable energy generation, kWh
HP	Heat pump
HPWH	Heat pump water heater
HR	Heat recovery
HRV	Heat recovery ventilation
H	Heating
HVAC	Heating, ventilation and air conditioning
HERS	Home Energy Rating System
HR	Heat recovery
H	Windows height (m)
HX	Heat exchanger
HDD	Heating Degree Days
IESNA	Illuminating engineering society of north America
IEA	International energy agency
ICT	Information and communication technologies
IC	Initial cost (\$)
Loc	Location
LCC	Life cycle cost
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy, \$/kWh
LiBr	Lithium bromide
<i>l</i> (<i>m</i>)	Monthly load, kWh
LCIA	Life Cycle Impact Assessment
LPD	Long-term Percentage of Dissatisfied
Mtoe	Mega tons of oil equivalent
MPC	Model predictive control
MENA	Middle East and North Africa
MOPSO	Multi objective particle swarm optimization
MOGA	Multi-objective genetic algorithm
MILP	Mixed Integer Linear Programming
MOO	Multi-objective optimization

MCDM	Multi-criterion decision-making
MOABC	Multi-Objective Artificial Bee Colony
MOBO	Multi-Objective Building Optimization tool
\dot{m}	Hot water mass flow rate, kg/h
N ₂ O	Nitrous oxide emissions
NGCB	Natural gas condensing boiler
NREL	National Renewable Energy Laboratory
N	North
N	Life period (year)
N	Population size
NED	Net Energy Deficit
NG	Natural gas
NZEB	Net zero energy building
NZEOb	Net zero emission building
NPEB	Net positive energy building
NC	Night cooling
NPC	Net present cost
NED	Net energy deficit (kWh)
NSGA	Non-dominated sorting genetic algorithm
nMEUL	Normalized Modified End Use Loads (kWh/y)
NREL	National Renewable Energy Laboratory
NZExB	Net Zero Exergy Building
NZE	Net zero energy
NPV	Net present value
NV	Natural ventilation
N _{ETSC}	Number of evacuated tube solar collectors
N _{FPSC}	Number of flat plate solar collectors
OPP	On-site Power Production (kWh/y)
OPOBEM	Optimization of an Office Building envelope Energy performance and configuration Model
Off	Office
O	Orientation
OMO	Optimisation multi objectifs
O&M	Operation and maintenance costs, (\$)
PV	Photovoltaic
P_{WWHP}	Cooling capacity of water to water heat pump, RT
P_{BDG}	Capacity of biodiesel generator, kW
P_{ASHP}	Cooling capacity of air source heat pump, RT
P_{pump}	Pump rated power, kW
P_B	Natural gas condensing boiler capacity, kW
P_{CT}	Cooling tower nominal cooling capacity, RT

P_{WT}	Wind turbine rated power, kW
PNEB	Positive-net energy building
PE	Primary energy
PL	Predominant load
PCM	Phase change material
PV	Photovoltaic
PV/T	Photovoltaic-thermal
PMV	Predicted mean votes
PBP	Payback period (Year)
PPD	Predicted Percentage of Dissatisfied
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
Pt	Parent population
Q _{cool}	Cooling demand (kWh/y.m ²)
Q _{heat}	Heating demand (kWh/y.m ²)
Q _{DHW}	Domestic hot water load, kW
Q _t	Child descendant population
Q _{abc}	Absorption chiller rated capacity, kW
Q _e	Electric chiller rated capacity, kW
RHP	Reversible heat pump
Ref	Reference
REC	Renewable energy credits
RE	Renewable energy
REHVA	Federation of European heating, ventilation and air-conditioning associations
RER	Renewable energy ratio
Rad	Radiator
R	Roof
REUL LA	Reference end use loads for lighting and appliances (kWh/y)
RC	Reinforced concrete
R _t	Initial population
RT	Refrigerant tons
rd	Annual discount rate (%)
r	Objective functions number
SD	Shading devices
SP	Set point
SCNH	Swedish center for zero-energy buildings
SEER	Seasonal energy efficiency ratio
SC	Solar collector
S	South
S	Simulation
SS	Solution set
STD	Standard deviation

SF	Solar fraction [%]
SS	Sequential research
SDHW	Solar domestic hot water
SCOP	Seasonal coefficient of performance
SHC	Solar heating and cooling
SDHW	Solar domestic hot water
SSPP	Strategic Sustainability Performance Plan
STPV	Semi-transparent photovoltaic
SPF	Spray Polyurethane Foam
S	Credibility index
SS	Sequential research
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TSA	Tabu Search Algorithm
T_i	Indoor operative temperature (°K)
T_{rm}	Exponentially weighted running mean of outdoor dry-bulb air temperature (°K)
ΔT	Mean temperature difference between inside and outside (°K)
T_{supply}	Temperature of supplied hot water, °C
T_{tap}	Tap water temperature, °C
T_{mean1}	Daily average outdoor air temperature on the same day, °C
T_{mean2}	Average outdoor air temperature for the past seven days, °C
TEU	Total energy use (kWh/y)
TPES	Total primary energy supply
TRNSYS	Transient system simulation program
TWh	Tera watt hour
TC	Thermochromic
T_{or}	Temperature operation range °C
T_w	Temperature of water supply, °C
T_a	Monthly mean air temperature, °C
TCF	Temperature correction factor
TIC	Technologies de l'information et de la communication
tCO ₂ eq	Tons of CO ₂ eq
U-value	Thermal transmittance, W/m ² .K
UK	United kingdom
USGBC	U.S. green building council
UNDP	United Nations Development Program
USPW (N, rd)	Uniform Series Present Worth factor (years)
VAV	Variable air volume
VT	Ventilation tower
VTC	Vacuum tube collector
VR	Ventilation rate
V	Ventilation

V	Room volume (m ³)
V_w	Mean wind speed (m/s)
V_{tank}	Storage tank volume, L
WWR	Window to wall ratio
W	West
WT	Wind turbine
WWHP	Water to eater heat pump
WSM	Weighted sum method
WPM	Weighted product method
ZEB	Zero energy building
ZEH	Zero energy home
ZEL	Zero energy level
ZEPI	Zero Energy Performance Index

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Introduction

A l'échelle mondiale, la charge énergétique des bâtiments continuera à augmenter dans les prochaines décennies. Les bâtiments (résidentiels, commerciaux et publics) ont consommé environ 30% de l'approvisionnement total en énergie primaire du monde en 2015 [1]. Si aucune mesure n'est prise pour améliorer l'efficacité énergétique dans les bâtiments, les besoins en énergie devraient augmenter de 50% d'ici à 2050 [2]. Fin de 2015, les bâtiments représentaient environ 49% de la consommation mondiale d'électricité, le secteur résidentiel représentant 27% de la consommation totale d'électricité et se classant au deuxième rang mondial des consommateurs d'électricité [1]. En général, les bâtiments sont aussi responsables d'environ 21% des émissions mondiales de CO₂eq, avec environ 15% pour le secteur résidentiel [1]. Par conséquent, la consommation d'énergie du secteur résidentiel joue un rôle important dans l'augmentation des émissions mondiales de CO₂eq et l'accélération du changement climatique.

Une nouvelle approche a émergé pour limiter la consommation d'énergie et les émissions polluantes dans les bâtiments : les bâtiments à consommation énergétique nette nulle (BCENN). De nombreuses recherches dans le monde tentent de trouver une définition générale pour le BCENN afin de faciliter leur application. Une revue de la littérature a montré qu'il n'y a pas de définition commune. Chacun définit le BCENN en fonction de ses besoins, intérêts et objectifs à atteindre.

L'optimisation multi objectifs (OMO) est une technique efficace pour évaluer, concevoir et obtenir la solution optimale pour une application spécifique. Les résultats d'OMO sont des ensembles de solutions non dominées appelées solutions optimales de Pareto, représentées par un front de Pareto [3][4]. Une fois le front de Pareto obtenu, vient l'importance d'un processus additionnel d'aide à la décision multicritère (ADM), pour sélectionner la solution optimale finale parmi toutes les solutions disponibles [5]. Des chercheurs du monde entier étudient l'applicabilité des méthodologies d'optimisation aux bâtiments, afin d'améliorer leur performance énergétique. La recherche d'une conception passive optimale pour chaque climat est un moyen essentiel d'aider les concepteurs à rendre les bâtiments énergétiquement efficaces, en particulier pour les bâtiments résidentiels. Les configurations et les capacités des systèmes d'énergie renouvelable (ER) mis en œuvre dans les BCENN doivent également être judicieusement sélectionnées pour garantir l'objectif de performance prévu. Les critères d'évaluation suggérés pour l'évaluation de la performance des BCENN sont divers et répondent à une variété de besoins.

Cette thèse est structurée comme suit:

Le chapitre 1 fait une revue complète des définitions des BCENN à ce jour. Il s'en suit une présentation des études de cas typiques sous différents climats présents dans la littérature. Différentes méthodologies d'optimisation pour les bâtiments sont ensuite passées en revue. La technique d'optimisation, la fonction objective, les variables d'optimisation et les contraintes sont présentés. Les systèmes d'ER électriques et thermiques les plus couramment utilisées dans différentes zones climatiques sont également résumés. Un organigramme détaillé pour la conception de BCENN en trois étapes est suggéré.

Le chapitre 2 présente une méthodologie d'ADM pour l'optimisation des performances des BCENN. Le but de la méthode proposée est d'obtenir la meilleure solution de conception à partir d'un ensemble de solutions du front de Pareto, une solution qui reflète les préférences de décideur. La méthodologie de simulation proposée est composée de quatre étapes: simulation du bâtiment à l'aide d'un logiciel d'énergétique, optimisation, ADM et enfin, étude de sensibilité pour tester la robustesse du résultat optimal. En outre, elle est appliquée à un BCENN résidentiel typique dans différentes zones climatiques au Liban et en France. Enfin, un ensemble de recommandations est présenté afin d'améliorer la conception des performances des BCENN.

Le chapitre 3 mène une étude systématique pour trouver la conception passive optimale d'un bâtiment résidentiel. Vingt-cinq climats différents de la classification de Köppen Geiger sont simulés dans le but de produire les meilleures pratiques pour minimiser la demande énergétique du bâtiment (refroidissement et chauffage) ainsi que le coût du cycle de vie. Le confort thermique adaptatif des occupants est également inspecté dans le but d'obtenir des solutions de conception passives acceptables pour l'occupant.

Le chapitre 4 vise à aider les concepteurs de BCENN à choisir les options de conception appropriées en fonction d'une évaluation systématique. Il optimise et évalue six ensembles de solutions de conditionnement de l'air et d'ER pour passer d'un bâtiment à basse consommation énergétique (chapitre précédent), à un BCENN dans trois régions représentative des climats à besoin de refroidissement dominant, à besoin de chauffage dominant et mixte. Les ensembles de solutions étudiés sont des systèmes de production d'énergie fréquemment mis en œuvre dans la littérature. La performance des BCENN est évaluée en termes de performance combinée, composée d'indicateurs économiques (coût sur le cycle de vie, coût actualisé de l'énergie, délai de retour sur investissement), environnementaux (émissions en CO₂eq), énergétiques (indice

d'autosuffisance énergétique, indice de réponse à la demande énergétique), et d'indicateur liés au réseau (indice d'interaction au réseau).

Introduction

Globally, buildings' energy load is estimated to keep increasing in the next decades. Buildings (residential, commercial and public) have consumed around 30% of worlds' total primary energy supply (TPES) in 2015 [1]. If no action is taken to develop energy efficiency in buildings, energy need is predicted to augment by 50% in 2050 [2]. By the end of 2015, buildings represented about 49% of the world's electricity consumption, where the residential sector represents 27% of the total electrical usage and is ranked as the second-largest electricity consumer worldwide [1]. In general, buildings emit about 21% of global CO₂eq emissions, and the residential sector, in particular, emits around 15% of universal CO₂eq emissions [1]. Therefore, residential sector's energy consumption plays an important role in increasing global CO₂eq emissions and climate change.

Nowadays, a new approach is suggested to limit energy consumption and pollution emissions in buildings; Net zero energy buildings (NZEBs). Many studies in the world are trying to find a particular definition for NZEB in order to facilitate their application, by easily specifying and finding their target. There is no common definition. Each one defines NZEB depending on his/her needs, interests, and goals to achieve.

Multi-objective optimization (MOO) is an effective technique to evaluate, design and to get the optimal solution for a specific intention. MOO results are sets of non-dominated solutions called Pareto optimal solutions represented as a Pareto frontier [3][4]. Once the Pareto frontier is obtained, here comes the importance of the multi-criterion decision-making (MCDM) process in order to select the final optimal solution among all available possibilities [5]. Researchers worldwide are investigating the applicability of building optimization methodologies in order to enhance buildings' energy performance. Adopting one optimal passive design recommendation for each climate is a fundamental way to help the buildings to become energy efficient, especially for residential buildings. The configurations and capacities of the implemented renewable energy (RE) systems in NZEBs must be appropriately selected to guarantee the intended performance objective. The inspected evaluation criteria suggested for NZEBs' performance assessment are diverse and addresses a variety of needs.

This thesis is structured as follows:

Chapter 1 gives a comprehensive review of NZEB definitions that exist up-to-date, to the best of the authors' knowledge. Followed by, a presentation of typical case studies in different

climates studied in the literature. Different optimization applications are reviewed, where the optimization techniques, objective functions, optimization variables, and constraints are presented. The most commonly used electric and thermal RE in different climatic zones are summarized. A detailed flowchart for three-stage of NZEB design is suggested.

Chapter 2 presents a MCDM methodology for NZEB performance optimization. The aim of the proposed method is to get the best design solution from a set of Pareto-front solutions, a solution which reflects the decision maker preferences. The suggested simulation-based methodology is composed of four steps: building energy simulation, optimization, MCDM and finally a sensitivity study to test the robustness of the optimal result. Besides, it is applied to a prototypical residential NZEB in different climatic zones in Lebanon and France. Finally, a set of recommendations is outlined in order to improve the performance design of NZEBs.

Chapter 3 conducts a comprehensive investigation on the optimal passive design for a case study residential building. Twenty-five different climates from Köppen Geiger classification are simulated with the aim to produce best practices to minimize building energy demands (cooling and heating) in addition to the life cycle cost (LCC). The occupants' adaptive thermal comfort is also inspected aiming at getting more practical and detailed passive design solutions.

Chapter 4 aims to assist NZEB designers to select the suitable RE solution sets based on a systemic evaluation. It optimizes and evaluates six RE solution sets to go from low energy building to NZEB in one representative city of cooling dominant, heating dominant and mixed climates. The investigated solution sets include the frequently implemented or considered energy production systems in the literature. The performance of NZEB is evaluated in terms of combined performance comprised of economic indicators: LCC, levelized cost of energy (LCOE), and simple payback period, environment indicator: CO₂eq emissions, energy balance and self-sufficiency indicator: load matching index in addition to grid stress indicator: grid interaction index.

Chapitre 1: Bâtiments à consommation énergétique nette nulle : Revue des définitions et approches d'optimisation en fonction des climats.

Résumé en Français

Le concept des bâtiments à consommation énergétique nette nulle (BCENN) a été introduit pour limiter la consommation d'énergie et les émissions polluantes dans les bâtiments. Depuis 2006, le nombre des publications et des projets traitant ce sujet sont en constante augmentation. Cependant, il demeure difficile de trouver une définition globale de BCENN regroupant tous les concepts. Des nombreuses organisations et chercheurs ont présenté leur définition permettant de classer les BCENN. La classification de BCENN est basée sur les options de production d'énergie renouvelable (ER), le processus de mesure de l'énergie, la localisation des sources d'ER et les bilans, qu'ils soient énergétiques ou exergetiques. Une des définitions les plus courantes est qu'un BCENN est un bâtiment avec des demandes énergétiques significativement basses, qui sont assurées à la fois par les ressources de réseau public et d'ER du site. De plus, la balance annuelle entre les deux sources d'énergie est au moins égal à zéro ou en faveur des ER du site.

En général, il est convenu qu'il y a trois étapes principales pour atteindre la performance BCENN : d'abord l'utilisation des stratégies passives, puis l'utilisation de technologies économes en énergie et enfin, le recours à des systèmes de génération d'ER. Ces trois étapes traditionnelles peuvent s'accompagner de l'intégration intelligente de technologies énergétiques avancées telles que le photovoltaïque-thermique, le photovoltaïque intégré au bâtiment, les fenêtres avec vitrage photovoltaïque semi-transparent, les technologies de contrôle de l'éclairage naturel, les fenêtres avec vitrage électrochrome et thermochrome, les dispositifs d'ombrage contrôlés et les systèmes de stockage thermique intégrés au bâtiment [6].

Un état de l'art montre que l'essentiel des études sur les BCENN visent à économiser l'énergie, réduire la facture d'électricité, assurer l'indépendance énergétique, réduire les émissions polluantes et assurer le confort des occupants. Certaines études s'intéressent également à l'esthétique en combinant des technologies modernes pour atteindre une haute performance énergétique et améliorer la durabilité.

Le recours à des méthodes d'optimisation est une voie prometteuse pour évaluer les choix de conception des BCENN. L'optimisation d'une fonction objective liée à l'énergie et/ou

l'environnement et/ou l'économie est faite pour choisir la solution optimale permettant d'atteindre la consommation énergétique nette nulle.

Ce chapitre commence par présenter les défis énergétiques et de pollution auxquels le monde est confronté. En outre, il montre, au mieux à la connaissance de l'auteur, les définitions existantes pour le BCENN et les études de cas correspondantes dans huit zones climatiques différentes (climat continental humide, subtropical humide, méditerranéen, continental modéré, océanique, tropical, aride, chaud). Le chapitre relève également l'importance de traiter chaque climat séparément car même au sein d'un même pays, deux ou plusieurs climats coexistent généralement. Les inconvénients des BCENN sont également présentés. Différents problèmes d'optimisation sont également examinés dans la dernière section. Finalement, trois organigrammes sont proposés pour résumer l'état de l'art sur les BCENN. L'un présente les étapes de conception de ces bâtiments, le second, les différentes procédures d'optimisation tandis que le dernier permet de catégoriser les BCENN.

Ce chapitre est basé sur l'article de revue:

Fatima Harkouss, Farouk Fardoun, Pascal Henry Biwole. Optimization Approaches and Climates investigations in NZEB-A Review, Building Simulation journal, in press, 2018.

Chapter 1: Optimization Approaches and Climates Investigations in NZEB - A Review

Abstract

The conception of net zero energy buildings (NZEB) has been introduced to limit energy consumption and pollution emissions in buildings. Classification of NZEB is based on renewable-energy (RE) supply options, energy measurement process, RE-sources location, and balances whether are energetic or exergetic. In general, it is traditionally agreed that there are three main steps to reach the NZEB performance, starting through the use of passive strategies, energy efficient technologies, and then RE generation systems. Then, these three steps could be accompanied with the smart integration of advanced efficient energy technologies. A state of the art shows that the main ZEB studies are related to: energy savings, reduce electric bills, energy independence, pollution reduction, and occupants comfort, in addition, others are more interested in the aesthetic aspect by combining modern technologies with innovations to achieve high energy and sustainability performance. Building optimization is a promising technique to evaluate NZEB design choices; it has been adopted to choose the perfect solution to reach the zero energy performance through the optimization of an objective function related to energy (thermal loads, RE generation, energy savings) and/or environment (CO₂ emissions) and/or economy (Life-cycle cost (LCC), Net-present value (NPV), investment cost). This chapter starts by presenting the global energetic and pollution challenges the world faces. Moreover, it shows, to the best to the author's knowledge, the existing NZEB definitions and the corresponding case studies investigated in 8 different climatic zones (Humid continental, humid subtropical, Mediterranean, moderate continental, marine west coast, tropical, semi-arid and hot), the chapter also focus on the importance to treat each climate separately. Even in the same country, two or more climates may co-exist. NZEBs drawbacks are also presented. Furthermore, different optimization problems are reviewed in the last section. Building energy optimization methods are employed to obtain the ideal solution for specific objective functions which are either related to energy, and/or environment and/or economy. Optimization variables are distributed between passive and/or RE generation systems. Finally, a table summarizing the most commonly used electric and thermal RE applications which yield to the zero energy balance in each climate, as well as three flowcharts are presented to summarize the whole three-stage procedure, to reach NZEB, starting from

building designing, passing through the optimization procedure, and lastly categorizing the zero energy balance.

Keywords: Net zero energy building; climatic zones; optimization; renewable energy.

1. Introduction

Economic growth and social development nowadays push governments to focus on providing population with necessary energy requirements. Concerns about energy security arise from increasing energy demand, rising oil prices, and doubts from oil and fossil fuel depletion. Currently, the concept of energy security includes challenges to provide secure, unabated, reasonably priced, and sustainable energy sources for electricity supplies and other energetic applications, taking into consideration reducing greenhouse gases emissions and exploiting renewable energy (RE) resources [7].

Globally, buildings’ energy load is estimated to keep increasing in the next decades. Buildings (residential, commercial and public) have consumed around 30% of worlds’ total primary energy supply (TPES) in 2015 [1]. As Figure 1. 1 shows, TPES final consumption in buildings has grown from 2776.48 Mtoe in 2011 to 2806.88 Mtoe in 2015, and it is predicted to reach 4400 Mtoe by 2050 [1,8]. The residential sector represents approximately 73% of TPES final consumption in buildings, and is ranked as the third-largest main energy consumer worldwide (21.85% of world’s TPES) after industrial and transportation sectors (Figure 1. 2). If no action is taken to develop energy efficiency in buildings, energy need is predicted to augment by 50% in 2050 [2].

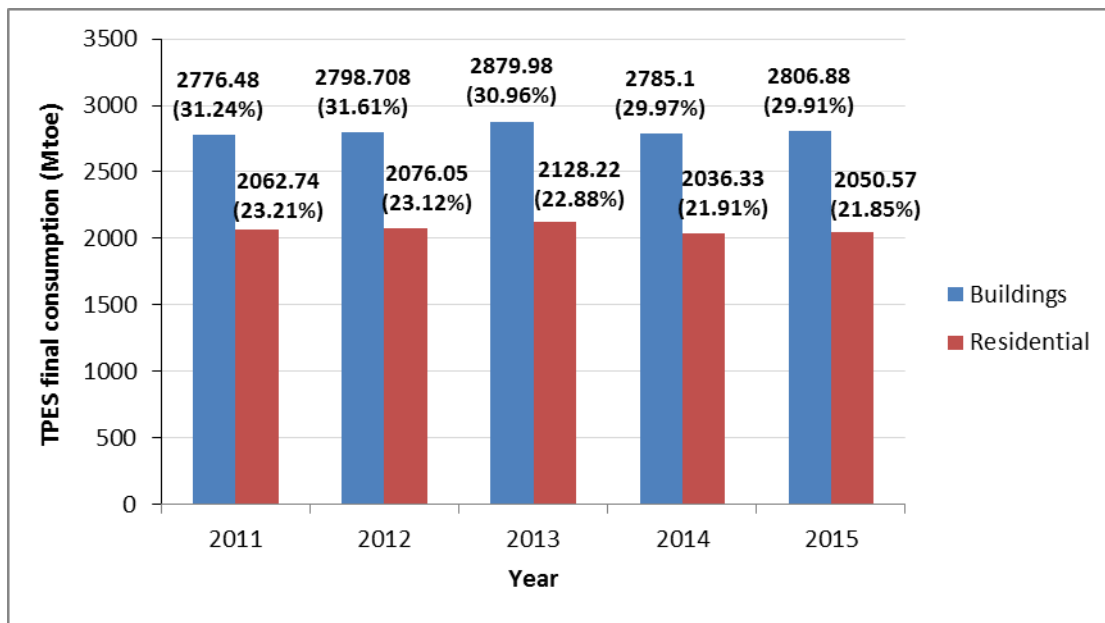


Figure 1. 1 World’s building sector TPES final consumptions between 2011 and 2015 (Data source: [1])

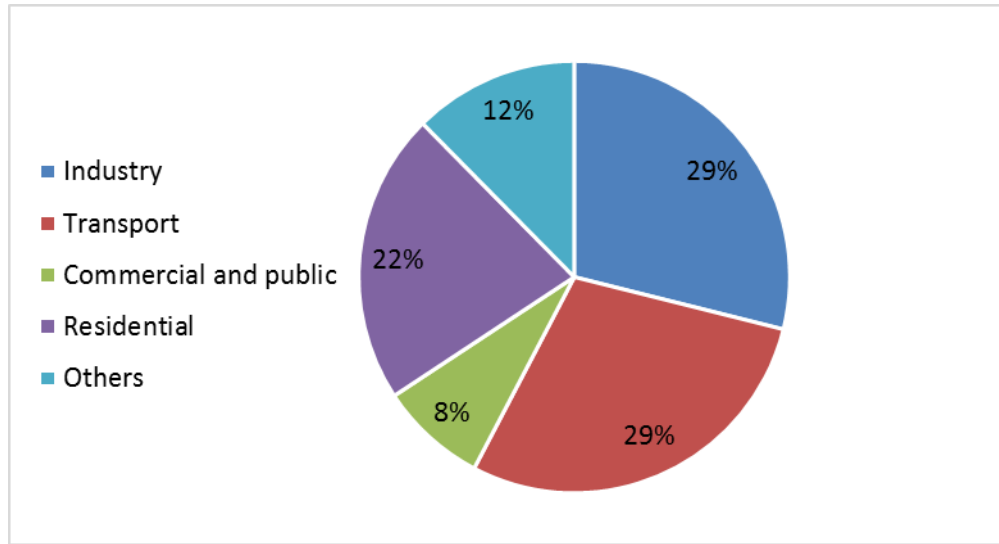


Figure 1. 2 Shares by sectors of world's TPES (2015) (Data source: [1])

By the end of 2015, buildings represented about 49.29% (9957.86 TWh) of the world's electricity consumption, where the residential sector represents 27% (5465.7 TWh) of the total electrical usage, and is ranked as the second-largest electricity consumer worldwide (Figure 1. 3, Figure 1. 4). Comparing these values to those of 2011, the electric consumption in buildings sector is increased by 8.13% [1].

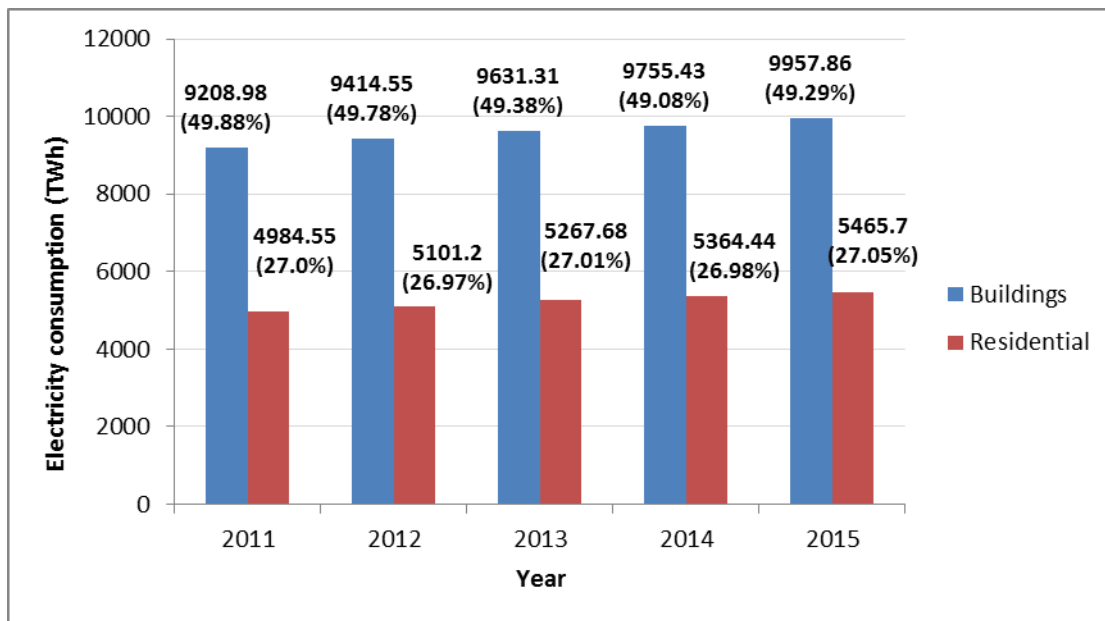


Figure 1. 3 World's building sector electricity consumption between 2011 and 2015 (Data source: [1])

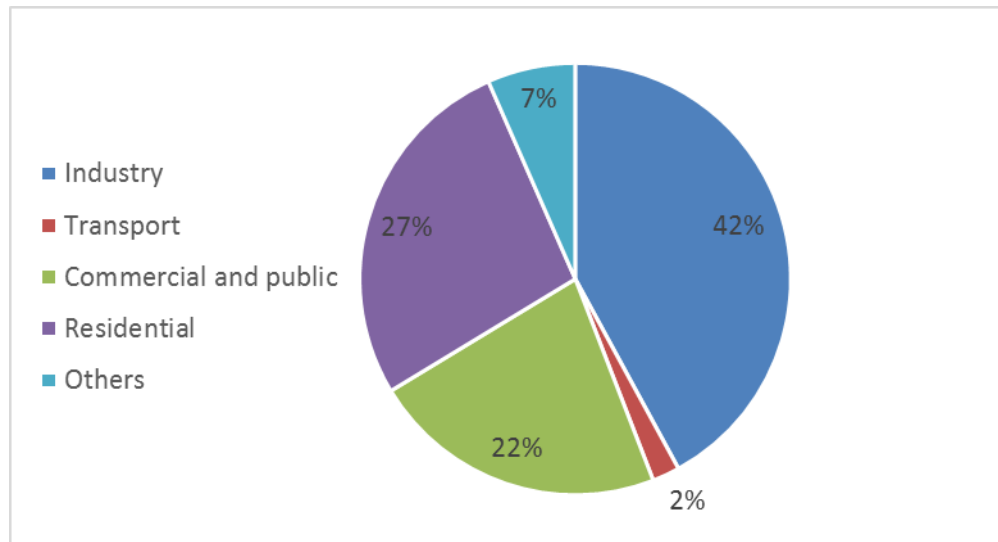


Figure 1. 4 Shares by sectors of World's Electricity Consumption (2015) (Data source: [1])

The greenhouse gases emissions due to climate changes are becoming more and more obvious to scientists. Figure 1. 5 shows that during 2015, CO₂eq emissions from building sector are estimated to be about 6680.37 MtCO₂eq, which illustrates a raise when compared to the emissions of the year 2011 (6635.78 MtCO₂eq). In general, buildings emit about 21% of global CO₂eq emissions, and the residential sector in particular emits around 15% of universal CO₂eq emissions [1]. Therefore, residential sector's energy consumption plays an important role on increasing global CO₂eq emissions and climate change. Furthermore, climate change affects solar radiation, wind speed and direction, precipitation, temperature, and humidity, which in turn influence electricity demand for cooling and heating loads in buildings. Hence, the relationship between building energy consumption and climate change is reciprocal. An investigation in Europe shows that climate alteration will lead to an increase in winter's humidity by 15% in 2020 and 25% in 2050. Another investigation shows that London's cooling degree-days had augmented by 20% and 60% in 1995 and 2005 respectively when compared to 1976, and will be increased by 200% in 2080 [8].

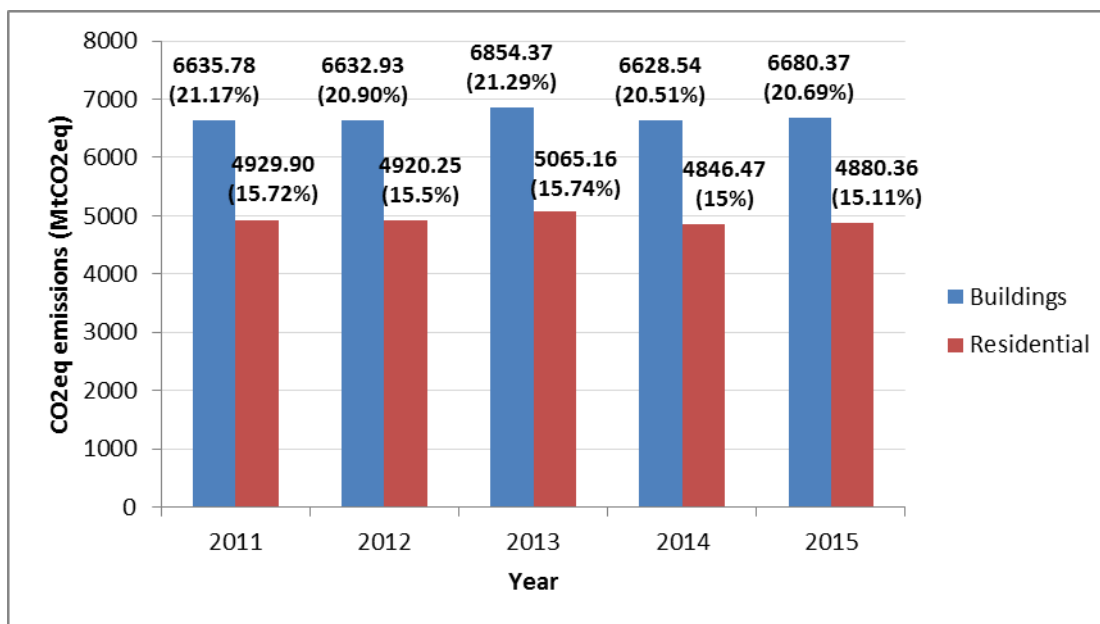


Figure 1. 5 World buildings and residences CO₂eq emissions between 2011 and 2015 (Data source: [1])

Medical progress, public health amelioration, personal hygiene, food availability, and development in agriculture, industry, and transport sectors are reasons of the growth in population. The world’s population size has increased from 6.99 billion in 2011 to 7.33 billion in 2015 (increase of 4.8%) [1]. It is expected that the population will keep growing to reach 8.5 billion in 2030 [9]. Increase of population means an increase of energy consumptions which exert more demands on energy resources and making them rare.

The world energy consumption is also affected by urbanization rates. The urbanization rate is predicted to attain 56% by 2020 [8].

Nowadays, a new approach is suggested to limit energy consumption and pollution emissions in buildings (since buildings have a real potential to ameliorate energy efficiency); NZEBs. In this work, a comprehensive review on NZEB definitions that exist up-to-date, to the best of the authors’ knowledge, is carried out. Followed by, a presentation of typical case studies in different climates studied in literature. Different optimization applications are reviewed, where the optimization technique, objective function, optimization variables, and constraints are presented. The most commonly used electric and thermal RE in different climatic zones are summarized. A detailed flowchart for three-stage of NZEB design is suggested.

2. NZEB definitions

Many researches in the world are trying to find a particular definition for NZEB in order to facilitate their application by easily specifying and finding their target. There are in excess of 70 low or zero energy/carbon building definition and standards around the world [10]. This section presents the most known international NZEB definitions. There is no common definition; each one defines NZEB depending on his needs, interests, and goals to achieve. In general, it is agreed that the three traditional essential steps to achieve the NZEB performance are as presented in Figure 1. 6: the utilization of passive design strategies, energy efficient technologies and RE generation systems [11][12].

Moreover, these three traditional steps could be accompanied with the smart integration of advanced efficient energy technologies such as photovoltaic-thermal (PV/T), building-integrated PV (BIPV), windows with semi-transparent PV (STPV) glazing, daylighting control technologies, including electrochromic (EC) and thermochromic (TC) windows coatings, controlled shading devices and building integrated thermal storage (BITES) [6].

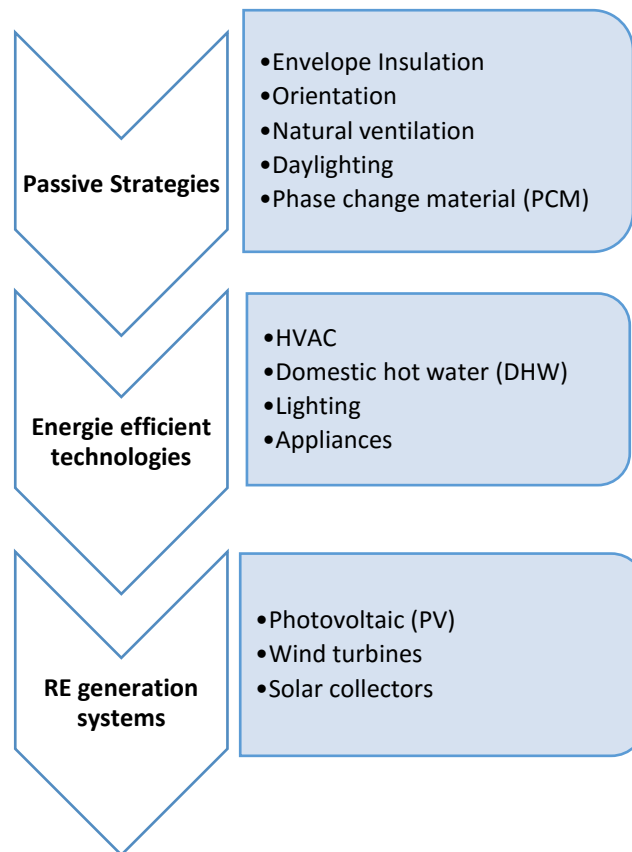


Figure 1. 6 Traditional three steps to achieve NZEB

2.1. General definition

A ZEB is a building with significantly small energy demands and the balance of energy demands can be provided by RE systems [13]. ZEB can be divided in two types: grid-connected and off-grid (stand-alone). NZEB is a ZEB connected to the utility grid (electricity grid, district hot water, or other central energy distribution system) to balance its energy needs. NZEB might employ utility's energy when the on-site RE generation doesn't meet its needs. However, it has to return back to the grid the equivalent of the energy drawn as a RE form in a yearly basis, in order to maintain the zero energy status of the building. Once the on-site energy production surpasses the building's needs, the additional energy is transferred to the utility grid, or stored in the building for later use during non-favorable weather conditions. The off-grid ZEB is a grid-independent building that requires supplemental on-site generation potentials combined with important energy storage technologies. In addition to RE, it usually imports fossil energy sources for backup generators, cooking, domestic hot water and space heating to cover the energy demands. Some buildings (hospitals, laboratories, grocery stores) have high energy needs, so they tend to utilize off-site supply options to reach NZEB position [14].

A NZEB can be classified as high-quality when it exploits the passive strategies and energy efficient technologies to the maximum extents, and then utilizes the available RE resources within the building footprint.

Weather conditions influence the RE resources. During winter, summer or abnormal seasons, solar and wind energies may highly fluctuate. Hence, a building may not achieve a NZE situation each year, so it may fall into near NZEB. The NZEB position must be followed-up each year by means of necessary metering systems [14].

2.2. International organizations adopted definition

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the one way to decide if a building can be considered NZEB is to consider the energy crossing the building's boundary. For source, emission and cost NZEB definitions to be considered, conversion coefficients for the metric of benefits are needed. However, these coefficients are difficult to obtain. ASHRAE in agreement with the American Institute of Architects (AIA), the U.S. Green Building Council (USGBC), and the Illuminating Engineering Society of North America (IESNA) adopted the Net zero site energy to define NZEB. This

definition corresponds to a building that produces as much RE as its annual consumption when measured at the site. NZEBs can switch energy with the utility grid as long as the net energy balance is zero on an annual basis [15]. Moreover, The Federation of European Heating, Ventilation and Air-conditioning Associations (REHVA) defines a NZEB as grid-connected energy-efficient building that equilibrates its total annual energy demands by on-site energy production and related feed-in green credits [16]. On the contrary of an independent building and to highlight the balance concept, the term “Net” has been presented. So, it is possible to classify buildings as NZEBs, nearly NZEBs or Net plus energy buildings. Knowing that, in independent buildings, the “net” term does not exist, since there is no connection with the grid. The European Directive on Energy Performance of Buildings (EPBD) defines “nearly zero-energy building” as a building with high energy performance. The almost nil or slight quantity of energy required in the building must be ensured to the maximum extent by RE resources whether located on-site or nearby [17]. The U.S. department of energy (DOE) defines NZEB, residential or commercial, as a building with reduced needs for energy through efficiency gains (60 to 70 percent lower than conventional practice), with the balance of energy demands supplied by RE technologies. In the residential sector, the US DOE called NZEB as a net zero energy home (NZEH). A net-zero energy home produces annually, with on-site RE sources, as much energy as it consumes. The home must offer an accepted level of service and comfort. Purchased fuel will be transformed to an electrical equivalent at a conversion efficiency of 40%. Co-generation with purchased fuel is not involved [18]. Lausten, in an IEA information paper (2008) [19], defines ZEB as a building that does not utilize fossil fuels and obtains all its energy needs from RE resources such as solar energy. According to Lausten there are several ways to classify ZEBs:

- 1. Zero Net Energy Buildings:** they are yearly neutral buildings; the energy exported from the building to the supply grid is equal to that imported from the grid. This type of buildings does not use fossil fuels for any energy needs.
- 2. Zero Stand Alone Buildings:** these buildings do not need to be connected to the utility grid. They may use it just as backup. They are self-independent, they generate the required energy to cover their energy needs, and are capable to store the generated energy for night-time or wintertime employ.

3. **Plus Energy Buildings/Net Positive Energy Buildings (NPEB):** these buildings transfer to the supply grid more energy than they yearly import from it, as they generate much more RE than they need.
4. **Zero Carbon Buildings:** these buildings use energy resources that do not contribute to CO₂ emissions. They are carbon neutral or positive, which means that they generate sufficient free-CO₂ energy to cover their yearly energy needs.

2.3. RE supply option hierarchy

Torcellini et al. (2006) developed a hierarchy which classifies NZEBs based on RE supply options that a building can employ (Table 1. 1) [13].

- 1- **Option 0:** it tends to lower building's energy demands through energy efficient technologies and demand-side RE systems. The demand-side RE systems correspond to the passive use of RE sources, for example: the solar day-lighting, passive solar heating, passive cooling, wind catching.
- 2- **Option 1:** it is an on-site supply option. It tends to exploit RE sources available within building's footprint. Generated RE is directly connected to building's energy distribution systems (electricity, hot water), which reduces transmission and distribution losses. The footprint energy collection area is assured to provide long-term production over building's lifetime; accordingly it is not necessary to displace/disassemble these systems due to future development plans of adjacent lands.
- 3- **Option 2:** it is an on-site supply option. It tends to exploit RE resources available at the boundary of building's site, but not mounted on the building's roof itself or within its footprint.
- 4- **Option 3:** it is an off-site supply option. It tends to bring to site off-site renewable resources in order to generate electricity on-site, these resources must be available within the building lifetime .This option is less preferable than options 1 and 2, because of the Carbon traces related to the production and transportation of renewable resources to the site.
- 5- **Option 4:** it is an off-site supply option. It consists to purchase installed RE sources. Building owner negotiates with Power Company in order to build off-site wind turbine and solar PV because of better off-site solar and wind resources. The building might own a part of the hardware and obtain credits for the power. The building would also pay an amount

to the utility to transport this energy. It is the worst classification; in general, it does not reduce the energy consumption.

Table 1. 1 NZEB RE supply option hierarchy (Data source: [13])

Option 0	→ Building envelope improvement, efficient energy measures & demand-side RE technologies	→ Insulation, efficient equipment, lighting, passive solar heating, day-lighting, solar ventilation air pre-heaters, natural ventilation, evaporative cooling.
Option 1	→ RE within building footprint	→ Thermal solar collectors, PV located on building's roof or façade, building-mounted wind turbines.
Option 2	→ RE at boundary of building's site, not mounted on building nor within building footprint	→ Parking lot PV, ground-mounted thermal solar systems, tower-based wind turbines, on-site solar-driven chiller.
Option 3	→ RE from off-site to produce electricity on-site	→ Wood pellets, biodiesel, waste, and vegetable oil imported to the site, combined heat and power (CHP) systems, to produce electricity and heat.
Option 4	→ Purchase installed off-site certified RE source	→ PV panels installed off-site, utility-based wind turbines, RECs (e.g. Green credits certified by Green-E (2009)).

2.4. Classification based on energy measurements methods

Torcellini et al. (2006) classified NZEB into four categories based on energy measurements process, in order to clarify the concept of NZEB [13]. Each category can be used to achieve a certain owner's project target. And, there is no category better than the other. Every category exploits the grid for net usage and has various appropriate RE resources.

1- Net-zero site energy: a building that yearly generates from RE at least as much as it consumes.

- **Advantages:** easy to achieve, can be directly measured, easy to understand by the building society, no outside fluctuations (e.g. fuel prices, availability) could affect the performance of the building.

- **Disadvantages:** needs additional electrical exports from solar energy to offset natural gas use. Doesn't equate energy values of fuel kinds, does not take into consideration the non-energy distinctions between fuel kinds (supply availability, pollution). It doesn't necessary achieve energy price savings. If peak loads and utility bills are not controlled, the energy charges may not be minimized.

2- Net-zero source energy: a building that yearly generates at least as much RE as it consumes including the energy used to transport grid-energy to the building.

Imported and exported energies are multiplied by the appropriate site-to-source conversion coefficients (coefficients that depend on the utility's energy source type) in order to determine building's source energy. Noting that, in this category it is not necessary to produce more electricity than in the Net-zero site energy building category. This depends on site-to-source energy factors, for example 1 unit of on-site generated electricity exported to grid can offset 3.37 units of site natural gas use.

- **Advantages:** able to equate energetic value of fuel kinds used at the site. Better model for influence on national energy system. More realistic ZEB to attain.
- **Disadvantages:** does not take into consideration the non-energy discrepancies between fuel kinds (supply availability, pollution). Does not necessary achieve energy cost savings. The national site-to-source energy factors do not take into consideration regional electricity generation diversities and hourly modifications in the heat rate of power plants or how utilities transmit generation facilities for peak loading.

3- Net-zero energy costs: in this category, the yearly net paid bills between the building using RE and the utility should be at least zero or in favor of the building.

- **Advantages:** easy to execute and measure with utility bills. Market forces will result in an acceptable balance between different fuel kinds based on fuel availability. Allows for demand-responsive control.
- **Disadvantages:** may not reflect the demand impact for the national grid. Since additional PV generation can be more beneficial for decreasing demand with on-site storing than exporting to the grid. Requires net-metering agreements such that exported electricity can offset energy and non-energy charges. Highly Variable energy rates make it difficult to track over time periods.

4- Net-Zero Emissions: the building generates or buys sufficient emission-free RE to compensate emissions formed from annual building energy consumption. To determine building's emissions, Greenhouse gas (GHG) and CO_{2eq} emissions multipliers for each energy source must be calculated.

- **Advantages:** better model for green power. Takes into consideration the non-energy discrepancies between fuel kinds (pollution, greenhouse gases).
- **Disadvantages:** difficulties in determining precise emission multipliers.

2.5. Classification based on ranking RE sources

Pless et al. (2009) classified ZEB according to RE sources position with respect to the building. This categorization system is based on the fact that the building must mainly use all passive and energy-efficient strategies (building envelope improvement, efficient equipment, lighting), then exploit RE technologies that exist within the building footprint (on building's roof, integrated within building walls). After that, if needed, the building may use the on-site RE strategies to cover its demands. Furthermore, if the building had exploited all cost effective passive and energy-efficient strategies and it needs more energy, then, off-site resources might be employed. In the building ranking system, generating RE within a building's footprint rank higher than importing off-site renewable to generate energy on-site, even though both are considered as renewable energies [14][20].

- 1- **NZEB-A:** they are buildings with a well-improved envelope and energy efficient systems. Their energy needs are offset using RE technologies available within the building footprint.
- 2- **NZEB-B:** if the methods described in a NZEB-A can't cover buildings' energy needs, buildings might employ on-site RE technologies.
- 3- **NZEB-C:** if both footprint and on-site RE technologies are not sufficient to cover the building energy needs, then off-site renewable sources can be imported.
- 4- **NZEB-D:** if all above mentioned RE technologies are exploited to the maximum extent without covering the needed energy, so the building may purchase certified RE such as utility-based wind and RECs from certified sources.

2.6. Definition based on imported/exported energy balance

Sartori et al. [21], presented the essential elements in defining NZEB, the relationship between these elements and an operating mechanism of NZEB evaluation. As Figure 1. 7 shows, the essentials are: building system boundary, energy grids and weighting system. Inside the building system boundary, the building consumes its on-site generated RE and delivered energy from the grid (electricity, natural gas, hot water) and exports the extra generated RE back to the grid. Depending on the designer objectives, different weighting systems are selected to estimate the net energy obtained by the building. Then, weighted imports and exports are compared to verify whether or not the net zero balance is attained (Eq. 1. 1, Eq. 1. 2 and Eq. 1. 3).

$$\text{import} = \sum_i \text{delivered_energy}_{(i)} \times \text{weight}_{(i)} \quad \text{where } i = \text{energy carriers} \quad \text{Eq. 1. 1}$$

$$\text{export} = \sum_i \text{exported_energy}_{(i)} \times \text{weight}_{(i)} \quad \text{Eq. 1. 2}$$

$$\text{Net ZEB: } |\text{export}| - |\text{import}| \geq 0 \quad \text{Eq. 1. 3}$$

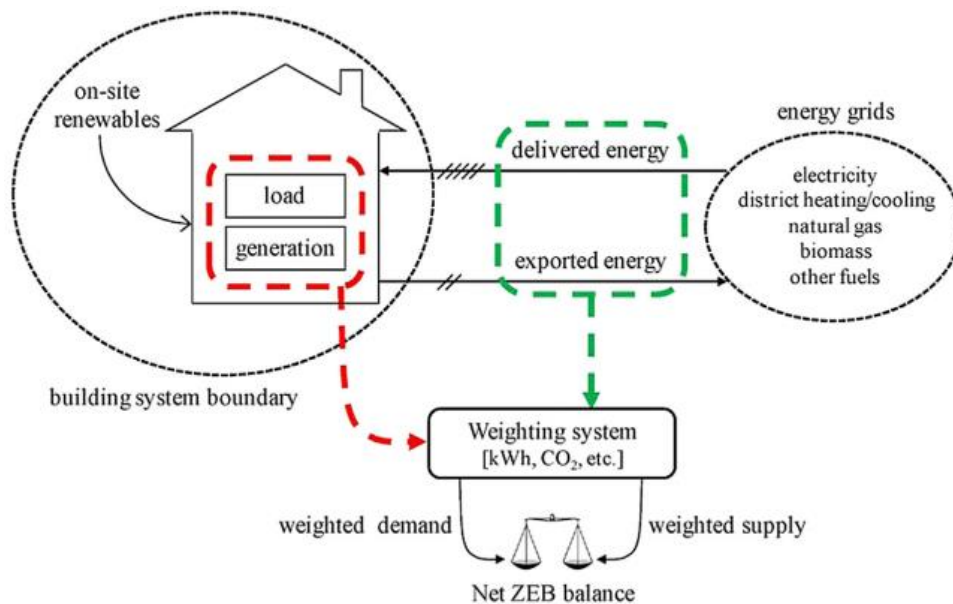


Figure 1. 7 Basic elements in definition of NZEB [21]

2.7. Net Zero Exergy Building (NZExB)

Kilkis presented the case of a NZEB which uses heat and electric energy from district energy systems [22][23][24]. Although the building is energetically balanced (imported and exported heat and electric power through building's boundary are equalized), it is not balancing the exergy of heat it uses. Even though imported and exported heats have the same quantity and quality, but are not at the same temperature: the received heat is at higher temperature than the exported one.

The impact of this NZEB on the environment remains risky since the negative exergy balance has to be achieved by the district at a cost of additional fuel expenses and dangerous emissions.

Hence, Kilkis offers a recent definition for the concept of NZEB. He introduced the Net-Zero Exergy Building (NZExB), which is a building with an annual zero exergy transfer balance across the building-district boundary, corresponding to all energy transfers (electricity and heat) occurring in a specific period of time.

According to Kilkis, focusing on the exergetic balance instead of the energetic one permit to rate the quantity of building’s carbon releases, and consequently to estimate the building's harm effects on the environment. Furthermore, allowing to completely detect the size of the problem and suggest solutions [22][23].

A summary of the above mentioned definitions of ZEBs is presented in Table 1.2.

Table 1.2 Summary of NZEB definitions

Criterion Reference	CO ₂ eq	Balance (Demand-RE)	On-site generation	Building footprint generation	Off-site generation	Buy RE	Building tightness	Cost
General		•	•	•	•		•	
RE supply option hierarchy			•	•	•	•	•	
Classification based on energy measurements method	•		•					•
Classification based on ranking RE sources			•	•	•	•	•	
ASHRAE		•	•					
REHVA		•	•				•	
EPBD			•	•			•	
US-DOE		•	•	•			•	
IEA	•	•	•					

From the above it can be observed that there is no common definition for NZEBs. The definition depends completely on the purpose intended by the designer. All definitions agree on the fact that the NZEB must be a low energy building. Then, in terms of net balance NZEBs, might be energetically, economically, environmentally, or exergetically balanced. Furthermore, the RE generation systems might be implemented on building’s footprint, on-site, or off-site. The most adopted definition is the following: a NZEB is a building with significantly small energy demands which are assured by both sources: the grid and RE systems. The annual net balance between both energy sources is at least zero or in favor of the RE.

3. State of the Art

The concept of NZEBs has gained large awareness during the last years. It is seen as the future objective for the design of buildings. Different organization and governments started to put deadlines to achieve this approach gradually. The U.S. DOE has established an ambitious target to create the technology and knowledge base for cost-effective NZEBs by 2025 [25]. In parallel, research communities in the European Union begin to develop efficient building projects which rely on RE resources to achieve ZEB. The EPBD sets the target of ‘nearly net zero energy buildings’ for all the recent buildings from 2020 [17]. Researchers through the task 40/ Annex 52 ‘‘Towards net zero energy solar buildings’’ from the solar heating and cooling program (SHC) of the IEA, are studying nearly/net zero energy buildings, to develop an international common understanding framework definition in addition to computer based tools, reliable solutions and industrial plans [26]. Within the task, ‘‘IEA SHC Task 40 – ECBCS Annex 52’’, an excel tool was created to evaluate NZEBs. It allows the calculation of building energy balance, operating cost and the load match index for predefined chosen ZEB definition [27]. Also, they analyzed and evaluated the concept and performance of about 360 international NZEBs and has presented them in a Google maps view [28]. The main target requirements of NZEB in some selected European countries, are presented in Table 1.3 [29]. Li et al. in their review [30], focused on the importance of NZEBs in enhancing future sustainable development strategies. They also focused on the necessity of ameliorating the studies on the following sustainable subjects: LCC and environmental impacts analysis, climate change, and social policies. Liu et al. [31], suggested a building information modeling (BIM) which is based on building design optimization method which helps designers to improve buildings’ sustainability. In addition, NREL developed a strategic sustainability performance plan (SSPP) for NZEBs which includes the following requirements: Sustainable Building Design, sustainable building operations, sustainable procurements and sustainability performance reporting [32].

Table 1.3 NZEB requirements in some selected European countries (Data source: [29])

Country	Year of enforcement		NZEB definition for new buildings		NZEB definition for existing buildings	
	Public	Non Public	Maximum primary energy [kWh/m ² y]		Maximum primary energy [kWh/m ² y]	
			Residential buildings	Non-residential buildings	Residential buildings	Non-residential buildings
Austria	2019	2021	160	170 (from 2021)	200	250 (from 2021)
Belgium Brussels	2015	2015	45	90 [a]	54	108 [a]
Bulgaria	2019	2021	30-50	40-60	30-50	40-60
Cyprus	2019	2021	100	125	100	125
Denmark	2019	2021	20	25	20	25
France	2011	2013	40-65 [a, b]	70-110 [a,b]	80 [b]	60% PE [a]
Germany	2019	2021	40% PE [c]	Under development	55% PE [c]	Under development
Hungary	2019	2021	50-72 [a]	60-115 [a]	Under development	
Latvia	2019	2021	95	95	95	95
Malta	2019	2021	40	60	Not defined	
Poland	2019	2021	60 [a]	75 [a]	Not defined	
Slovenia	2019	2021	45-50 [a]	70	70-90 [a]	100
Sweden	2019	2021	30-75 [a, b]	30-105 [a, b]	Not defined	

[a] Depending on the reference building, [b] Depending on the location, [c] Maximum primary energy consumption defined as a percentage of the primary energy (PE) consumption of a reference building.

Researchers addressed many subjects in ZEB domain. For example: Marszal et al. presented a literature review on existing definition and energy calculation methodologies of ZEBs [33]. Garde et al. [34] presented an analysis of solution sets for passive, energy efficient and RE systems by type of thermal demand from 30 NZEBs cases in the world, as shown in Figure 1. 8. They noted that 100% of buildings use PV to generate electricity, and 100% of NZEBs in cooling dominated and mixed climates rely on solar shading devices. The advanced envelope and optimized building form play an important role in cooling dominated climates as they account for 100%. Kurnitski et al. reported the energy performance and design strategies of some NZE office buildings (Table 1. 4) [35]. Panao et al. found an optimal cost effective solution for the house design in the Mediterranean climate: Thermal insulation thickness from 40 to 60 mm and double glazing of 6/16/6 mm [36]. Pikas et al. [37][38] found energy efficient and cost optimal fenestration design for low energy building in Estonia: small window to wall ratio (WWR), triple glazing with argon filling, and 20cm insulation for walls. Deng et al. presented a summary on definition and energy

efficient measures of NZEB. they also reviewed the commonly used research methodologies, tools and performance evaluation indicators for NZEBs [39]. Baglivo et al. noted that in warm climates, external walls superficial mass is important to achieve the greatest building performance. They performed an analysis to find high energetic efficiency external walls for ZEB through the combination of various commercial materials [40]. Szalay et al. presented a methodology for setting nearly ZEB PE requirements based on a large building sample [41]. Liu et al. recommended the use of solar thermos-electric cooling technologies in ZEBs (active building envelope technology which consists of integrating thermoelectric and PV modules within the building envelope, thermoelectric energy recovery systems, and solar thermoelectric air conditioners). They noticed that these technologies reduce building energy demands, increase energy efficiency and decrease fossil energy use [42]. Al-Ajmi et al. demonstrated the possibility to achieve NZEB for an existing building in Kuwait, through energy efficiency measures and implementation of solar energy systems [43]. Good et al. compared the use of solar thermal, PV and photovoltaic thermal systems (PV-T) to achieve the NZE balance for a Norwegian residential building. They found that the building with only PV modules is the closest to reach a ZE balance (balance between imported and locally generated exported RE). In addition, they noticed that PV-T system could give an increased output compared to solar thermal collectors alone [44]. Hirvonen et al. introduced the concept of zero energy level of buildings (ZEL) which can be employed as a policy tool for RE support schemes [45]. Congedo et al. presented the application of the comparative methodological framework reported in the EPBD to identify cost-optimal design solutions for a NZE office located in warm climate [46]. Krarti et al. evaluated the most economic energy efficiency measures (orientation, window location, window size, glazing type, wall and roof insulation levels, lighting fixtures, set points, and efficiency of heating and cooling systems) and PV system sizes that should be used to achieve a NZEB for a typical residential building located in different locations of the Middle East and North Africa (MENA) region. They noticed that the energy consumption in residential buildings can be cost-effectively reduced from 32% up to 60% through optimal designs compared to existing design practices [47]. Goggins et al. presented the lifecycle environmental and economic analysis of nearly ZEBs in Ireland, taking into account the previous, current and future energy performance regulations [48]. Lopes et al. addressed the load matching improvements in NZEBs [49]. Williams et al. reviewed the most important 35 global low/ZEB standards. Percentages of the main parameters of these standards are shown in Figure 1. 9. For

example, 76% of the 35 standards are based on low energy concept. Furthermore, they focused on the urgent need for an international standard and a common definition of ZEBs that should ignore carbon emissions in favor of energy and not comprise embodied energy or any lifetime issues which must be left to national standards [10]. Good et al. evaluated the effect of PV system design on greenhouse gas emission balance in a net zero emission building [50]. Brinks et al. developed a concept for cost-optimal nearly ZEBs for the industrial steel building sector. The concept is based on parametric studies simulating more than 1800 different variations in a building model [51]. Sotehi et al. studied the possibility of obtaining a NZEB and simultaneously producing freshwater via a solar still by using a hybrid PV/T water solar collector [52]. Ndiaye [53] investigated and compared various building shape alternatives suitable in the design of NZE office buildings. Attia et al. examined the use of building performance simulation tools as a method of informing the design decision of NZEBs [54]. Carpino et al. assessed the influence of housing occupancy patterns on the definition of residential nearly ZEB in Italian climatic conditions [55]. Li et al. [56] proposed an informed decision making framework for NZEB design based on an automated energy simulation approach. Choudhary et al. presented an incremental stage for supporting the design and construction process of an experimental solar house driven by the overarching goal to obtain NZE performance [57].

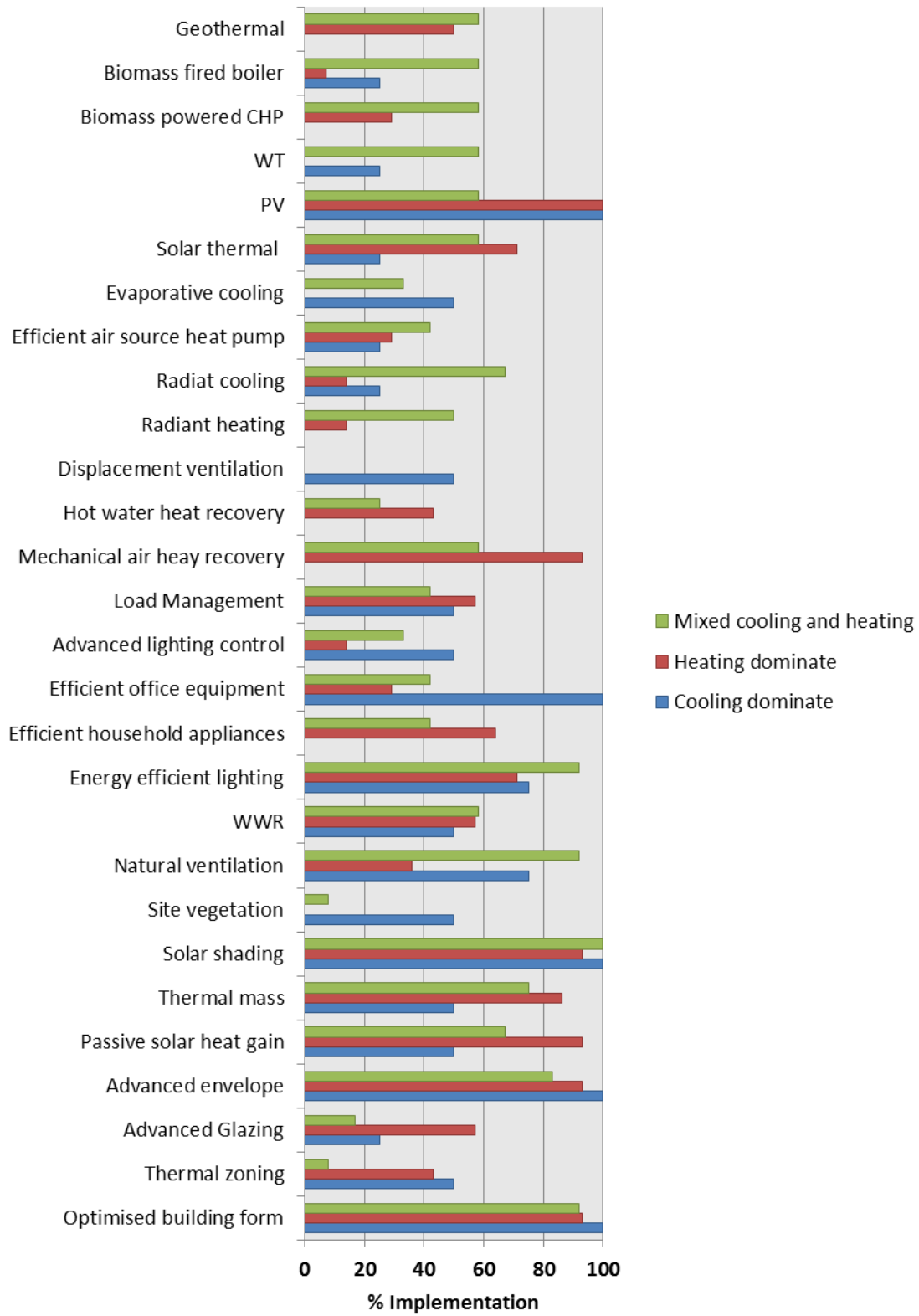


Figure 1. 8 Percentage of implementing passive, energy efficient and RE systems by type of thermal demand in 30 NZEB case studies (Data source: [34])

Table 1. 4 Energy performance of some NZE Office buildings across Europe [35]

Project/Country	Area	Delivered and exported energy (kWh/m ² .y)	Total primary energy use (kWh/m ² .y)
Elithis Tower/France	Gross	12	57
Ympäristötalo/Finland	Net	73	85
IUCN Headquarter/Switzerland	Net	33	66
TNT Green Office/Holland	Net	137	72

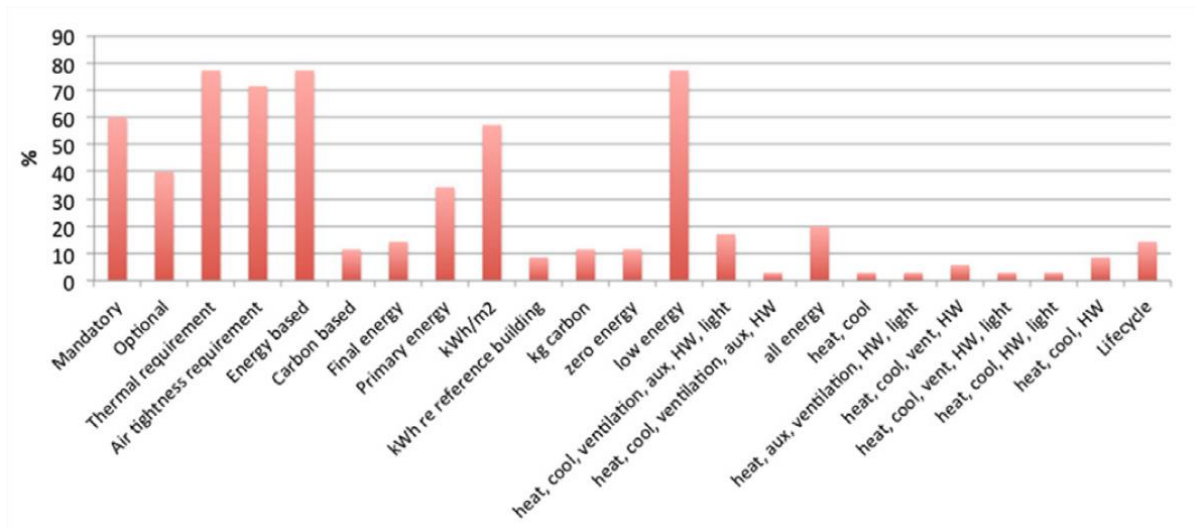


Figure 1. 9 Percentage of main parameters in the 35 most important global low/ZEB standards (Data source: [10])

Advancements in passive strategies, energy efficient technologies, besides RE generation systems for building applications are under continuous investigation and improvement. Shukla et al. [58–60] reviewed the design development of building integrated photovoltaic (BIPV) technologies. Indeed, BIPV is one of the powerful and useful power generation systems for achieving the ever increasing demand of NZEBs. Inoue et al. [61] reported advanced technologies and mechanisms for appropriate control of heat and light through windows, to ensure satisfactory thermal and lighting levels. Dussault et al. [62] investigated the influence of using smart windows on reducing energy consumption while improving thermal and visual comfort. Goia [63] searched for the optimal WWR in different European climates for an office building, in order to reduce the annual energy consumption. Tsikaloudaki et al. [64] evaluated the cooling energy performance of windows, for office buildings, with respect to their geometrical, thermos-physical and optical characteristics, in addition to their shading provisions. The investigation of phase change materials (PCM) as passive strategy for cooling applications in buildings is similarly inspected by many researchers [65–70].

Many research works have investigated the drawbacks in NZEBs. The main NZEB drawbacks include [71][72][73]:

- High initial investment costs.
- Lack of qualified expertise designers to build NZEBs.
- Possible severe decrease in RE costs may reduce investments in energy efficiency.
- Definitions of NZEBs are still not absolute, which is a disadvantage in setting the design targets.
- Challenge to recuperate high initial expenses on resale of NZEB, but new energy rating systems are being introduced gradually.
- NZEB by definition do not mandate a minimum heating and cooling performance level. Therefore, permitting oversized RE systems to cover energy needs.
- NZEB may not decrease the required power plant capacity. Since, the building may demand energy at the time when peak demand for the grid occurs.
- Solar energy capture using the building envelope is efficient in locations unobstructed from the sun (No physical limitations: shades or wooden surroundings).

The state of the art shows that the main concern of researchers when designing NZEBs is to achieve energy savings, energy independence, pollution reduction, to reduce electricity bills and to ensure occupants comfort. In addition, other researchers are more interested in the aesthetic aspect by combining modern technologies with innovations to achieve high energy and sustainability performance in buildings. Whatever is the designer interest, to ameliorate building's design is to find those solutions which increase benefits of NZEBs, whereas simultaneously overcome some of NZEBs drawbacks. It is noticed that most research works are related to achieving NZEB performance in new buildings while more highlights must be emphasized on existing buildings. In addition, there are very few studies taking into account maintenance of NZEBs, which should be further investigated.

4. Indices for NZEBs

In this section, performance indices that are used to evaluate buildings energy performance and efficiency are presented. Besides, these indices are employed to evaluate how far buildings deviate from NZE balance.

4.1. Zero Energy Performance Index (zEPI)

It is a measuring scale for the energy performance of a building [74][75], Figure 1. 10. It defines the energy objectives of the current building to match a typical low energy consumption building in the same location climate. It is calculated according to Eq. 1. 4. A zEPI score of ‘0’ corresponds to a NZEB, whereas a score of ‘100’ represents a building constructed under energy consumption benchmark as of the year 2000.

$$zEPI = 100 \times \frac{EUI_a}{EUI_r} \tag{Eq. 1. 4}$$

Where, EUI_a (kWh/y.m²) is the actual annual energy use index for the building and building site. It is the sum of all utility bills (gas, electricity imported (+) or exported (-)) divided by building’s floor area. EUI_r (kWh/y.m²) is the reference annual energy use index for building’s use and occupancy. It is derived from the commercial building energy consumption survey (CBECS) tables.

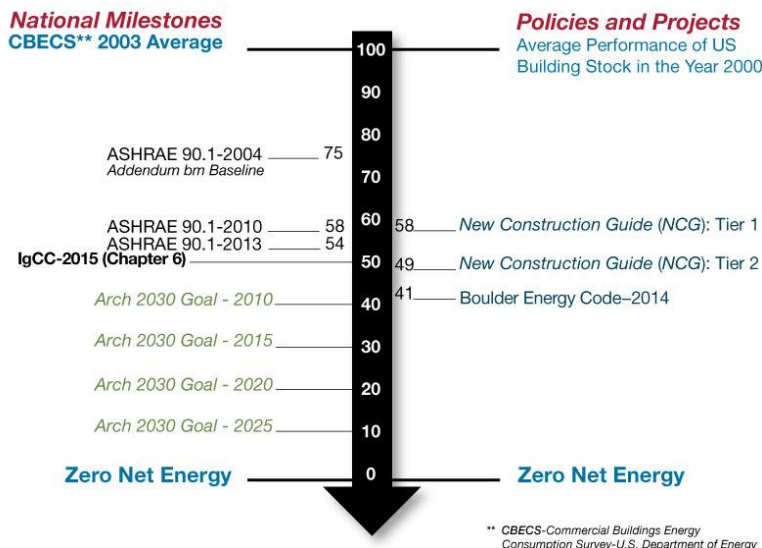


Figure 1. 10 zEPI Scale to zero net energy [75]

4.2. Home Energy Rating System (HERS)

It is a measure of home's energy efficiency [76], Figure 1. 11. It is determined using Eq. 1. 5, Eq. 1. 6, Eq. 1. 7 and Eq. 1. 8 [77].

$$HERS\ Index = PEfrac \times \left(\frac{TnML}{TRL} \right) \times 100 \quad Eq. 1. 5$$

Where:

$$PEfrac = \frac{(TEU - OPP)}{TEU} \quad Eq. 1. 6$$

$$TnML\ (kWh/y) = nMEUL\ HEAT + nMEUL\ COOL + nMEUL\ DHW + EUL\ LA \quad Eq. 1. 7$$

$$TRL\ (kWh/y) = REUL\ HEAT + REUL\ COOL + REUL\ DHW + REUL\ LA \quad Eq. 1. 8$$

TEU (kWh/y) = Total energy use of the Rated Home.

OPP (kWh/y) = On-site Power Production.

nMEUL (kWh/y)= normalized Modified End Use Loads as computed using accredited simulation tools.

EUL LA (kWh/y) = Rated Home end use loads for lighting and appliances.

REUL LA (kWh/y) = Reference Home end use loads for lighting and appliances.

A score index of 100 is adopted in the scale as a reference value. The lower index number corresponds to more energy efficient home. For example, with reference to a standard new home, a home with a HERS index score of 80 is 20% more energy efficient. While, a home with an index of 120 is 20% less energy efficient. According to the US DOE regulations, the HERS index should not exceed 130 and 100 for a typical resale home and new built home (under 2004 International Energy Conservation Code) respectively [76].

ENERGY STAR certificate [78] is delivered to new homes that are designed and built under standards well above most currently existing homes. It corresponds to homes with a HERS index score of maximum 85 and of 70 according to DOE.

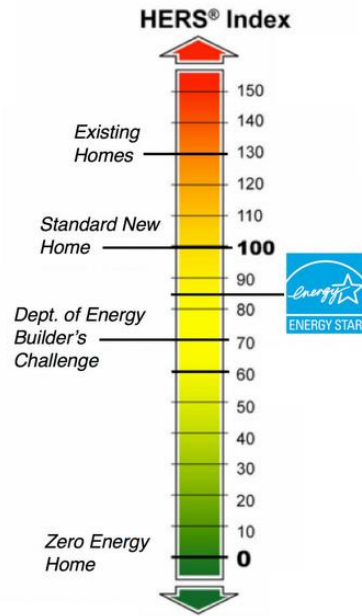


Figure 1. 11 HERS Scale to zero energy home [78]

Compared to zEPI, HERS-type scale is independent of climate, building type, or operating hours. However, for the zEPI rating, climate and operating hours for the designed building should match those of the baseline building [74].

4.3. Energy Efficiency Rating

EFR is a measure of the overall efficiency of a home [79], Figure 1. 12. The higher the rating corresponds to more energy efficient home. The rating measures both energy and carbon emission efficiencies of the home using a scale from 'A' to 'G'. Where, 'A' and 'G' ratings correspond to most and least efficient homes respectively.

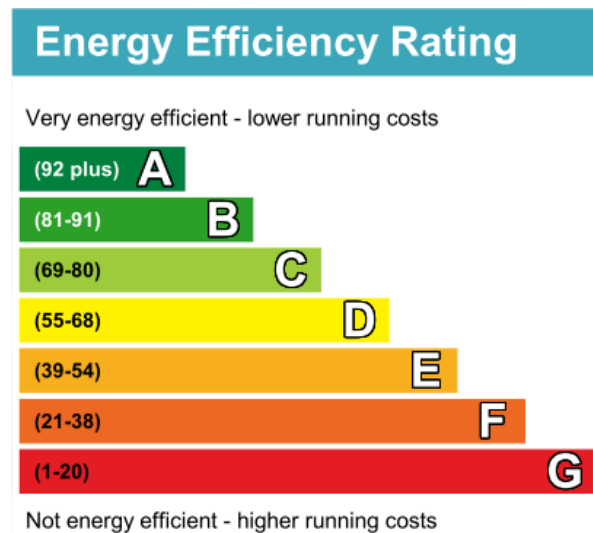


Figure 1. 12 Energy Efficiency Rating [79]

5. Investigated case studies and models simulations in different climatic zones

5.1. Introduction

Many studies, real case studies and models simulation, have been conducted in various regions in the world to investigate the feasibility of achieving ZEB in these regions. Table 1. 5 summarizes 26 case studies over the last ten years in addition to the exploited RE to achieve the zero energy balance. Table 1. 5 classifies the researches between real case studies and buildings' simulations. In addition, it includes the general data of the investigated cases: type of building (residential, office), type of study (experimental or numerical simulation and which software is used), location, climate, predominant loads, area, cooling and heating set points, the employed renewable electric and thermal systems, summary of the electric balance for each case, and the adopted energy efficient systems to cover heating, ventilation and air conditioning (HVAC) and domestic hot water (DHW) loads. In all cases, the studied designs' envelope is optimized to the maximum extent (construction material type, insulation thickness, orientation).

From the listed studies: Biao et al. simulated R-2000 home, energy-efficient home that include high levels of insulation, important air quality and environmental friendly measures, located in Montreal. The near zero net energy balance is achieved using PV arrays to produce electricity and a ground source heat pump (GSHP) for air cooling, floor heating and domestic water preheating [80]. Norton et al. at the National Renewable Energy Laboratory (NREL) presented the design of

Habitat for Humanity of Metro Denver zero energy home. The zero energy balance is achieved by a combination of efficient design (energy star appliances, compact fluorescent lighting, envelope insulation and tightness) and RE systems. Where DHW demands are covered by a solar domestic hot water (SDHW) system combined with auxiliary natural gas heater. Space heating is covered by electric and natural gas heaters. While electric power is generate through a solar PV system [81]. Wang et al. considered the case of a house in the UK. They optimized different façade parameters including U-Value of external walls, WWR, and house orientation in order to minimize the cooling and heating loads. Then, they examined the feasibility of zero energy house design. An optimization procedure is carried out for the mass flow rate and collector area of the SDHW system [82]. Denget al. simulated two different case studies in two special climates: humid (Shanghai) and dry (Madrid). The first case, for both locations, is a building that uses passive strategies such as ventilation tower and solar chimney, besides mechanical ventilation air handling unit (AHU) with heat recovery (HR). Cooling and heating loads are covered using a reversible water source heat pump connected to a radiant floor; a PV-T system combined with ceiling phase change materials (PCM) also offers some of the required cooling loads through night radiative cooling. The employed solar PV array system is integrated in the facade's walls. However, in the second case for both locations, a hybrid heat pump connected to a fan coil units and to a floor heating system for cooling and heating purposes respectively [83]. Fong et al. simulated a village house in Hong Kong. The net zero energy balance is achieved using a PV array, building integrated PV (BIPV) and roof wind turbines to produce electricity. They studied the net zero energy performance under different energy saving strategies related to human behavior [84]. Berggren et al. studied an office building situated in Sweden. They examined the possibility to attain the ZEB requirements according to the Swedish Centre for Zero-energy buildings (SCNH). The NZEB balance is reached using a GSHP for heating and cooling [85]. Causone et al. considered the case of a house in Italy. Energy simulations are carried out to optimize the house design, then, the house is equipped with accurate control system for energy monitoring. The Zero energy balance is achieved using an earth-to-air heat exchanger (EAHE) for ventilation [86]. Wiberget al. investigated the feasibility to achieve a Net Zero Emission Building (NZEOb) in Norway, by balancing CO₂eq embodied and operational emissions with those covered by on-site renewable energies [87]. Tsalikis et al. optimized SDHW (collector area, storage capacity, and solar loop heat exchanger area) and PV (Installed capacity kW_p) systems in four different locations in Greece in

order to obtain a nearly NZEB. The chosen combination leads to the highest net present value of investment (NPV) and to the lowest discounted payback period (DPBP) [88]. Cellura et al. presented different energy balance methods to define ZEB. They examined a case study in Italy; the Leaf house, which benefits from GSHP and SDHW systems to cover its cooling, heating and DHW demands. PV systems located on house roof and walls to generate electricity [89].

The main results of these case studies and buildings' simulations are represented in the next section.

5.2. Discussion

From the above case studies and buildings' simulation, it can be noticed that there are eight major climates investigated: humid continental, humid subtropical, Mediterranean, moderate continental, marine west coast, tropical, semi-arid and hot climates. In this part, it is intended to investigate the maximum variation between extreme reached values of yearly electricity consumption per m^2 for certain climates.

For humid continental climate, where heating load predominates, it is found that the electricity consumption ranges from 24 kWh/y.m^2 [90] to 87 kWh/y.m^2 [80], even though all studies have adopted RE systems but with different strategies. Moreover, it is noticed that the generated electricity from the BIPV-T system could cover up to 61% of the required electric load [90]. Besides, when the GSHP is employed [80], the electric demand is decreased by 44%, while the used PV system covers 100% of the required electricity.

Concerning humid subtropical climate, where both cooling and heating loads are present, the electric consumption ranges from 26 kWh/y.m^2 [91] to 154 kWh/y.m^2 [84]. In [91], the house has a HERS index of 29. It uses energy star appliances, efficient lightings in addition to the implemented RE plans. The other case [84], covers 22% of its demands from PV located on roof, 53% of its demands from BIPV and 10% from wind turbines.

In Mediterranean climate, where both cooling and heating loads exist, it is noted that the electricity consumption ranges from 31 kWh/y.m^2 [88] to 86 kWh/y.m^2 [83] for the RE plans adopted in each case. However, the generated electricity in [88] and [83] are 51 and 119.6 kWh/y.m^2 respectively using PV systems.

Therefore, it could be noticed that relatively low yearly electric consumption per m² could be achieved depending on the adopted steps to reach the NZEB performance. Table 1. 6 summarizes the most common used electric and thermal renewable systems in different climates.

Table 1. 5 Case studies and buildings' simulations general data, energy efficient systems adopted to cover HVAC and DHW loads, renewable electric and thermal systems and summary of the electrical balance

Reference	Location (Climate, Predominant load: H:heating, C: cooling) Area (m ²) Set point (°C) (Mode)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(Number of modules, Slope , Location/Orientation, Area (m²), Power (kW)) WT(Quantity, Location, Height (m), Power (kW)) • <u>Thermal RE</u> SC(Type, Slope, Orientation, Area (m²), Storage tank volume (m³), Mode) GS(Number of boreholes, Borehole length, Pipe type, Pipe diameter (m), Mode) • <u>Heating</u> • <u>Cooling</u> • <u>DHW</u> • <u>Ventilation</u> 	Electric balance	
			Demand (kWh/y.m ²)	Generated electricity (kWh/y.m ²)
Buildings' simulations				
[82] S(Energy Plus +TRNSYS)	Cardiff/Uk (Marine west coast, H) - 24(C) 18(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(8,50,R/S,10.08,1.32) WT(2,-,15,5) • <u>Thermal RE</u> SC(FP,50,S,5,0.3,DHW) • <u>Heating</u>: ASHP/FH • <u>DHW</u>:SDHW • <u>Ventilation</u>: NV 	-	-
[80] S(TRSNYS +IISIBAT)	Montreal (Humid continental, H) 156 25(C) 20(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(70,45,R/S,85.4,9.8) • <u>Thermal RE</u> GS(1,100,U-tube,2.5,"H,C,DHW") • <u>Heating</u>: GSHP/FH • <u>Cooling</u>: GSHP • <u>DHW</u>:GSHP/EH 	86.85	87.53
[84] S(TRNSYS)	Hong Kong (Humid subtropical, C) 196.5 25.5(C)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,22, R/S,50,-) PV(-,-,F°N,S,E,W", "44.25,30,66,76.5",-) WT(4,R,-,-) • <u>Thermal RE</u> SC(-,22,S,6,-,DHW) • <u>Cooling</u>: Window type coolers 	153.82	130.61

		<ul style="list-style-type: none"> • <u>DHW:SDHW/EH</u> 		
[87] S(SIMIEN)	Oslo/Norway (Humid continental, H) 160 -	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,"10,5",R/"S,N",-,-) <ul style="list-style-type: none"> • <u>Thermal RE</u> SC(VTC,90,S,8.32,0.6,"DHW,H")	70	71
[88] S(TEE-KENAK)	(a): Florina/Greece (Humid subtropical/H) (b): Thessaloniki/Greece (Humid subtropical/H) (c): Athens/Greece (Hot Mediterranean / dry-summer subtropical/C) (d): Heraklion/Greece (Hot Mediterranean / dry-summer subtropical/C) 120 20(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,30,-/-,-,3) <ul style="list-style-type: none"> • <u>Thermal RE</u> SC _a (FP,-,-,24,1,"DHW,H") SC _b (FP,-,-,16,0.75,"DHW,H") SC _c (FP,-,-,12,0.75,"DHW,H") SC _d (FP,-,-,12,0.75,"DHW,H") <ul style="list-style-type: none"> • <u>Heating: SDHW/FFH</u> (NG or FO: b, c; FO: a, d)/FH • <u>Cooling: EAC</u> • <u>DHW:SDHW/FFH</u> 	31.25	(a): 38.55 (d): 51.4
[92] S(DIALUX+TRNSYS)	Quaregnon/Belgium (Marine west coast, H) 740 25(C) 20(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(35,-,-,-,1.26,10.59) <ul style="list-style-type: none"> • <u>Heating: ASHP</u> • <u>DHW:ASHP</u> • <u>Ventilation: HRV</u> 	9.8	10.24
[93] S(Energy Plus)	South Europe (Mediterranean, C/H) 110 25,28(C) 16,18,20 (H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,35,R/S,11,1.6) <ul style="list-style-type: none"> • <u>Thermal RE</u> SC(-,50,S,4,0.3,"H,DHW") <ul style="list-style-type: none"> • <u>Heating: SDHW/HP/EH</u> • <u>Cooling: HP/FCU</u> • <u>DHW:SDHW/HP</u> 	-	-
[94] S(Homer)	Newfoundland (Humid continental ,H) 157.93 21(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> WT(1,Site,2.74,10) <ul style="list-style-type: none"> • <u>Heating: Electric</u> • <u>DHW: Electric</u> 	134.43	137.81 to 204
[95] S(DIALux)	Tehran (Semi-arid) 78	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(28,-,-,-,35.28,6.16) <ul style="list-style-type: none"> • <u>Thermal RE</u> 	52.62	147.98

			<ul style="list-style-type: none"> SC(FP,30,-, 16,-,"DHW,C,H") SC(VTC,30,-,9,-,"DHW,C,H") • <u>Heating</u>: SC/Absorption chiller • <u>Cooling</u>: SC/Absorption Chiller • <u>DHW</u>:SDHW 		
[96] S(Energy Plus)	Kragujevac/Serbia (Moderate continental, H) 131 -		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV₁(-,45,-/S,14.5,-) PV₂(-,45,-/S,29,-) PV₃(-,45,-/S,45.6,-) • <u>Thermal RE</u> GS(-,76.2,U-tube,2.67,H) • <u>Heating</u>: GSHP/FH • <u>DHW</u>:EH 	32.86	15.9 32.97 50.88
[97] S(IDA ICE)	Sydney (Humid subtropical) 200 23.8(C) 21.1(H)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,-/,-,-,2.4) • <u>Heating</u>: Electric • <u>Cooling</u>: EAC • <u>Ventilation</u>: NV(4 ACH) Heat exchange system 	17.15	17.15
[98] S(TRNSYS, GenOpt)	Beirut/Lebanon (Mediterranean, C/H) 101 24(C) 20(H)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(21,33,R/S,34.48,-) • <u>Thermal RE</u> SC(FP,33,S,2.09,0.25,"DHW") • <u>Heating</u>: ASHP • <u>Cooling</u>: ASHP • <u>DHW</u>:SDHW/EH 	80.24	78.43
[99] S(Energy Plus, ZEBO)	Cairo/Egypt (Hot/C)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,-,10,-) • <u>Cooling</u>: EAC • <u>DHW</u>:GB • <u>Ventilation</u>: HRV 	-	-
Case studies					
[81] S(BEOpt +DOE2 +TRNSYS) &Ex	Wheat Ridge/Colorado (Humid Continental, H) 118.91 20(H)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,-/,-,-,4) • <u>Thermal RE</u> SC(DB,27,-,8.91,0.75,DHW) • <u>Heating</u>: NGH/EH • <u>DHW</u>:SDHW/NGWH 	35.5	45.3

			<ul style="list-style-type: none"> • <u>Ventilation</u>: ERV+ECM 		
			<ul style="list-style-type: none"> • <u>Electrical RE</u> 		
			PV(-,-,R/-,66,12.5)		
			PV(-,-,F/"E,W",-,-)		
			<ul style="list-style-type: none"> • <u>Thermal RE</u> 		
			SC(VTC,-,-,6.6,0.3,DHW)		
			SC(PVT,-,-,38,-,C)	75.1	152
[83]	Shanghai				
S(Energy Plus	(Humid subtropical, C/H)				
+TRNSYS)	56				
	-				
			<ul style="list-style-type: none"> • <u>Heating</u>: RHP/FH • <u>Cooling</u>: a-RHP/FC b-PVT/PCM ceiling • <u>DHW</u>:SDHW/EH • <u>Ventilation</u>: VT/AHU+HR 		
			<ul style="list-style-type: none"> • <u>Electrical RE</u> 		
			PV(-,-,R/-,66,12.5)		
			PV(-,-,F/"E,W",-,-)		
			<ul style="list-style-type: none"> • <u>Thermal RE</u> 		
			SC(VTC,-,-,6.6, 0.3,DHW)		
			SC(PVT,-,-,38,-,C)	68.4	203.8
[83]	Madrid				
S(Energy Plus	(Mediterranean-continental, C/H)				
+TRNSYS)	56				
	-				
			<ul style="list-style-type: none"> • <u>Heating</u>: RHP/FH • <u>Cooling</u>: a-RHP/FC b-PVT/PCM ceiling • <u>DHW</u>:SDHW/EH • <u>Ventilation</u>: VT/AHU+HR 		
			<ul style="list-style-type: none"> • <u>Electrical RE</u> 		
			PV(-,-,R/-,64,-)		
			<ul style="list-style-type: none"> • <u>Thermal RE</u> 		
			SC(VTC,-,-,30,0.5,"H,C,DHW")	89.5	94.1
[83]	Shanghai				
S(Energy Plus	(Humid subtropical, C/H)				
+TRNSYS)	93				
	-				
			<ul style="list-style-type: none"> • <u>Heating</u>: ASHHP/FH • <u>Cooling</u>: ASHHP/FCU • <u>DHW</u>:SDHW • <u>Ventilation</u>: HRV 		
			<ul style="list-style-type: none"> • <u>Electrical RE</u> 		
			PV(-,-, R/-,64,-)		
			<ul style="list-style-type: none"> • <u>Thermal RE</u> 		
			SC(VTC,-,-,30,0.5,"H,C,DHW")	85.7	119.6
[83]	Madrid				
S(Energy Plus	(Mediterranean-continental, C/H)				
+TRNSYS)	93				
	-				
			<ul style="list-style-type: none"> • <u>Heating</u>: ASHHP/FH • <u>Cooling</u>: ASHHP/FCU • <u>DHW</u>:SDHW 		

			<ul style="list-style-type: none"> • <u>Ventilation:</u> HRV 		
[86] S(Energy Plus)	Mascalucia /Italy (Mediterranean, C) 144 -		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(20,22,R/S,32.6,6) <ul style="list-style-type: none"> • <u>Thermal RE</u> GS(3,10,round duct,14.2,V) <ul style="list-style-type: none"> • <u>Heating:</u> RHP • <u>Cooling:</u> RHP • <u>DHW:</u> Solar thermal/HP • <u>Ventilation:</u> EAHE 	50.36	52.63
[85] S(IDA ICA 4.5 Beta) & Ex	South of Sweden (Marine west coast) 23(C) 21(H)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,-/S,450,67.5) <ul style="list-style-type: none"> • <u>Thermal RE</u> GS(-,-,-,-,"C,H") <ul style="list-style-type: none"> • <u>Heating:</u> GSHP+ Variable speed compressor: • <u>Cooling:</u> Boreholes free cooling GSHP +Variable speed compressor • <u>Ventilation:</u> VAV 	-	-
[89] S(TRNSYS) & Ex	Marche/Italy (Mediterranean, C/H) 481.76 27(C) 20(H)		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,18, R/S,150,20) <ul style="list-style-type: none"> • <u>Thermal RE</u> SC(-,-,-,-,1,"H,DHW") <ul style="list-style-type: none"> • <u>Heating:</u>(GSHP(integrated with PV)-SDHW-GB)/FH • <u>Cooling:</u> GSHP/FC, AHU, NC: Open windows (10ACH) • <u>DHW:</u>(GSHP(integrated with PV)-SDHW-GB) • <u>Ventilation:</u> AHU 	39.48	67.37
[100] S(EGUSA) & Ex	Callaway/Florida (Humid subtropical) 127.37 -		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(18,-,R/S,-,3.6) <ul style="list-style-type: none"> • <u>Thermal RE</u> GS (-,-,-,-,"C,H,DHW") <ul style="list-style-type: none"> • <u>Heating:</u> GSHP • <u>Cooling:</u> GSHP • <u>DHW:</u>EH/GSHP super heater 	44	38.09
[91] S(EGUSA) & Ex	Gainesville/Florida		<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,R/W,-,4.2)	21.86	22

[102] Ex	Gaithersburg (Humid subtropical, C/H) 387 25(C) 20(H)	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(32,18.4,R/S,-,10.24) • <u>Thermal RE</u> SC(FP,18.4,S,4.4,0.303,"DHW,H") • <u>Heating</u> SDHW/WWHP/EH/HP water heater • <u>Cooling: ASHP</u> • <u>DHW:SDHW/WWHP/EH/HP water heater</u> • <u>Ventilation: HRV</u> 	33.69	34.94
[103] S(Energy Plus, Sketchup)	La Reunion/France (Hot, C) 625	<ul style="list-style-type: none"> • <u>Electrical RE</u> PV(-,-,R/-,350,49) • <u>Cooling: EAC</u> • <u>Ventilation: NV</u> 	31	78

Table 1. 6 Most commonly used electric and thermal RE applications in different climates

Climate	Electrical RE		Thermal RE		Application/System
	PV	Wind	SC	GS	
Humid continental	•		•		GSHP/FH, SDHW/ASHPWH/FH, SDHW/ASHPWH/R, SDHW/ASHPWH/EH
Humid subtropical	•		•		SDHW/HP/FH, SDHW/EH
Mediterranean	•		•	•	GSHP/FH, SDHW/HP/FH, SDHW/HP/EH, GSHP/FCU
Moderate continental	•			•	GSHP/FH
Marine west coast	•		•	•	ASHP/FH,SDHW,ASHP,GSHP/Compressor
Semi-arid	•		•		Solar assisted absorption chiller, SDHW
Hot	•		•		EAC

6. Optimization in NZEB designs

6.1. Introduction

Building optimization is an effective technique to evaluate design choices (building envelop, internal set points conditions, type and size of installed renewable systems) and to get the perfect solution for a specific purpose (economy, environment, energy, and exergy) expressed as objective functions (minimize greenhouse gases emissions, minimize energy consumption, minimize capital cost, maximize energy and exergy efficiencies) under several constraints (thermal comfort, area availability) [6]. NZEB investigations and projects have been worldwide promoted.

6.2. Building optimization state of the art

In Table 1. 7 recent studies on NZEBs design optimization are summarized. Nguyen et al. (2013) reviewed the application of simulation-based optimization methods on building performance analysis. They presented bibliographic study on simulation software, optimization tools, effectiveness of optimization techniques and tendencies in optimization studies. The review mentions that further studies must be oriented towards improving the effectiveness of research techniques and estimation methods for large-scale building optimization problems; plus reducing time and effort for such activities [104]. Sharafiet al. optimized the size of hybrid RE system for an apartment in Canada. The generated RE is also employed to recharge plug-in electric vehicle for transportation, in order to decrease the petrol use [105]. Lu et al. reviewed the design and control of nearly/NZEB. The comprehensive review includes effect of climate and site, design optimization methods, sensitivities analysis of robust design and control of generation and energy storage systems for shifting the peak load and other parameters [106]. Sun et al. and Zhang et al. suggested a multi-criterion system design optimization method for NZEBs under uncertainties [107][108]. Almeida et al. presented a method for cost-effective energy and carbon emission optimization of a building under restoration [109]. Delgarm et al. introduced a powerful, time saving and useful approach to find the optimal solution for multi-objective optimization problem of building energy consumption. The approach facilitates decision making in early phases of a building design optimization problem [5]. Ascione et al. suggested an original multi-stage and multi-objective optimization methodology, based on the EPSD recast, to retrofit a hospital building [110]. Stadler et al. presented a multi-objective optimization technique to design building thermal and electric systems in regard of thermo-economic performance indicators to suit consumer and

grid operator interests [111]. Lin et al. developed the optimization of an office Building envelope energy performance and configuration model (OPOBEM). They applied the OPOBEM to a real office building to minimize the construction budget under the energy conservation regulations of green buildings [112]. Lindberg et al. investigated the cost-optimal solutions for energy system design in NZEBs and the consequent grid impacts through a Mixed Integer Linear Programming (MILP) optimization model [113]. Hamdy et al. compared the performance, in term of six performance indicators (normalized inversed generational, generational distance, diversity metric, number of solutions on the Pareto-optimal set, execution time, contribution of best solutions to best Pareto-front), of seven frequently used multi-objective optimization algorithms in optimizing NZEBs. The optimization results show that the two-phase optimization with a genetic algorithm method (PR-GA: Preparation phase and optimization by genetic algorithm) is the best to obtain the closest optimal solution set with an acceptable diversity. They also found that the minimum necessary number of estimations to stabilize optimization results of building energy model is 1400-1800 [114]. Cho et al. introduced a recent bi-directional methodical building design approach in order to optimize building thermal demand and energy consumption [115].

From the above represented studies, it can be noticed that objective functions are related either to energy (thermal loads, RE generation, energy savings) and/or environment (CO₂eq emissions) and/or economy (LCC, NPV, investment cost). Optimization variables are distributed between passive (WWR, U-values, orientation) and/or RE generation systems (SC area, storage tanks capacities, PV area, RE systems configuration). A variety of optimization methods and software's are adopted according to the case-study and simulation.

Table 1. 7 Summary of recent studies on design optimization of NZEBs

Ref	Objective functions	Design/Operating variables	Constraints	Optimization method/Software
[82]	1-Minimize cooling/heating loads 2-Maximize SC efficiency 3-Maximize solar fractional energy saving	1-U values external wall 2-WWR 3-Building orientation 4-SC area 5-SC mass flow rate	-	-/Energy Plus & TRNSYS
[84]	1-Minimize total electricity demand 2-Minimize Net energy deficit (NED) 3-Maximize total renewable generated electricity	1-Energy saving strategy 2-Nominal efficiency PV & BIPV 3-Building orientation	NED ≤ 0	-/TRNSYS
[88]	1-Maximize total solar coverage 2-Maximize NPV 3-Minimize DPBP	1-SC area 2-Storage tank capacity 3-Solar loop heat exchanger area 4-PV system capacity	Energy savings = electricity produced – electricity covered + electricity from/to the grid ≥ 0	f-chart method/-
[92]	1-Minimize PMV 2-Minimize Cooling/heating loads 3-Minimize Cost (insulation, installation, glazing, & windows frame)	1-Walls level of insulation 2-Windows width, U & G values 3-Windows frame U value 4-Heat recovery ventilator efficiency	PMV ≤ 0.5 Heating loads ≤ 15 kWh/m ²	Generalized pattern search algorithm (GPS)/GenOpt
[97]	1-Minimize life cycle cost (LCC) 2-Minimize Cooling/Heating loads	1-U values of insulation (Walls & Ceiling) 2-Window type 3-Wall thermal mass thickness 4-Mechanical ventilation rate	Annual space energy requirements ≤ 5Mj/m ²	Multivariate optimization/IDA ICE
[107]	Maximize overall performance score (initial cost score, thermal comfort score and grid stress score)	1-Air conditioning system size 2-PV panels total area 3-Wind turbines number	(PV+ Wind turbines) energy supply = Building annual energy demand	-/TRNSYS
[5]	Minimize annual total building energy demand	1-Building orientation 2-Window length 3-Window height 4-Glazing solar transmittance 5-Glazing visible transmittance 6-Glazing conductivity 7-Wall thermal absorptance 8-Wall solar absorptance 9-Wall visible absorptance	-	Multi objective particle swarm optimization (MOPSO)/ MATLAB + Energy Plus

		10-Wall conductivity 11-Overhang tilt angle 12-Overhang depth		
[116]	Minimize total Net present cost (NPC)	1-SC installed capacity 2-PV installed capacity 3-Heat pump installed capacity	1-Decoupling of SC system 2-Maximal area of PV+SC 3- Heat pump's compressor capacity 4-Avoid over sizing the supply system 5-Heat and energy balance	Linear programming/-
[117]	1-Minimize deviation from the various demands (electrical, thermal, domestic water) 2-Minimize energy taken from the net 3-Maximize energy in storage system	1-Energy provided from RE sources (wind turbines, PV) and grid for heating and electric supply 2-Energy provided from RE sources to storage system	1-Energy sent to network < Energy produced 2-Energy in storage system ≤ storage system size 3-Produced energy from biomass + flat collector plant ≤ Available potential	Model Predictive Control (MPC)/-
[118]	1-Minimize initial system cost 2-Minimize CO ₂ emissions 3-Minimize cost effectiveness 4-Maximize net present value	1-SC number, area 2-Thermal capacity of GSHP 3-Power capacity of PV system	1-Capacity of PV modules 2-Number of SC 3-Area of (PV modules +SC) 4-Thermal capacity of GSHP	Generalized Reduced Gradient Algorithm (GRG)/-
[119]	Minimize total NPC	Electricity generation system configuration	-	-/HOMER
[120]	1-Minimize total NPC 2-Minimize CO ₂ emissions	-	-	Calculation based/-
[121]	Energy management	-	-	-
[122][123]	1-Minimize total NPC 2-Minimize CO ₂ emission 3-Minimize energy consumption	1-Configuration of electricity generation, heating and cooling systems	1-Upper value of energy output from PV and SC 2-The heat pump can operate for both heating and cooling but not at the same time	Calculation Energy hub concept/-
[124]	Minimize CO ₂ emission	2-Capacity & operational load factor of electric turbo refrigerator 3-Capacity of cooling/heating heat pump 4-Capacity & operational load factor of hot water heat pump	Avoid frequent ON/OFF operation	Genetic Algorithm/-
[125]	1-Minimize energy cost 2-Minimize CO ₂ emission	Energy system model scenario	-	-/ RET Screen International
[126]	1-Minimize total NPC 2-Maximize RE usage	1-RE power system configuration 2-PV array rated capacity	-	-

	3-Minimize CO ₂ emission	3-WT number, rated capacity, Generator capacity 4-Storage battery quantity 5-Inverter & Rectifier capacities 6-House area		
[127]	1-Minimize total NPC 2-Minimize CO ₂ emission	1-CHP capacity 2-PV array area 3-Battery storage capacity 4-SC area 5-Heat storage tank capacity 6-Waste water storage tank capacity	1-Battery cannot be charged and discharged at the same time 2-Converter cannot simultaneously convert power from DC to AC and vice versa 3-Avoid start-up and shut-down cycles of CHP 4-Coolingthe heat storage tank	Mixed-integer linear programming (MILP)/ MATLAB/Simulink
[128]	1-Minimize operation cost 2-Maximize energy saving 3-Minimize CO ₂ emission	Trigeneration system configuration	-	-
[129]	1-Minimize summer thermal discomfort 2-Minimize winter thermal discomfort 3-Minimize visual discomfort	1-U values (Floor, Roof & Walls) 2-Windows(U value, g value and visible transmittance at normal incidence) 3-Control strategy of shading devices 4-Windows opened area %	Air change rate $\geq 0.6h^{-1}$	Non-dominated sorting genetic algorithm (NSGA-II)/ Energy plus+GenOpt
[105]	1-Minimize total NPC 2-Maximize RE ratio (RER) 3-Minimize CO ₂ emission	1-Size of PV panels 2-Size of the wind turbine 3-Size of the solar collectors 4-Size of the heat storage tanks 5-Size of heat pump 6-Biomass boiler rated capacity 7-PV panels rated power	1-Amount of hot water demand and heating load that should be provided by boiler and heat pump 2-Amount of cooling load that should be provided by heat pump and refrigerator 3-Total energy supplied by HP should not exceed its rated capacity 4-Amount of excess energy that must be sold to grid 5-Available area for installing PV panels and SC on building's roof	Dynamic multi objective particle swarm optimization algorithm (DMOPSO)/-
[130]	1-Minimize discounted investment 2-Minimize operational costs	1-Sizing of heat storage tank 2-Installed capacity of heat pumps, pellets boiler, gas boiler and the micro CHP unit. 3-Heat generated from heating technologies.	1-Building heat demand has to be met. 2-Buiding electricity demand must be met 3-Avoid import and export of electricity within the same hour. 4-Zero emission 5-Zero primary energy constraint 6-Heat or electricity generated cannot surpass the installed capacity.	Mixed-integer linear deterministic optimization Model/-

[131]	1-Maximize solar radiation gain 2-Maximize space efficiency 3-Minimize shape coefficient	Building shape (control-point coordinates of curve and surface)	1-West side area of building is a parking lot 2-South side area of building is an outdoor playground	Multi-objective genetic algorithm (MOGA)/ Rhinoceros, Grasshopper
[132]	1-Minimize operational energy use 2-Minimize life cycle environmental impact	1-South WWR 2-Wall's thermal resistance 3-Insulation material 4-Window type 5-Window frame material	-	eQuest, Life Cycle Assessment (LCA) methodology and Athena IE, Artificial neural network (ANN) NSGA-II Multi-objective Optimization by Genetic Algorithm (GA)/-
[133]	1-Minimize envelope construction cost 2-Minimize building energy demand 3-Maximize window opening rate	1-Number of windows 2-Window length 3-Window width 4-Window glass material 5-Wall material 6-Glass curtain material 7-Roof material 8-Sunshade type 9-Sunshade board size	1-Total window width \leq Floor width 2-Original design window opening rate \leq Window opening rate	NSGA-II /-
[134]	1-Minimize power demand 2-Maximize overall comfort	1-Temperature 2-Relative humidity 3-CO ₂ concentration 4-Illumination level	1-78 °F \leq Temperature \leq 67°F 2-40% \leq Relative humidity \leq 60% 3-750 lux \leq CO ₂ concentration \leq 880 lux 4-400 ppm \leq Illumination level \leq 850 ppm	MOGA/ MATLAB
[135]	1-Minimize primary energy consumption 2-Minimize initial investment cost	1-Type of solar collectors 2-Size of solar collectors 3-Type of PV panels 4-Size of PV panels 5-Generation system for space Heating 6-Generation system for DHW 7-Generation system for space cooling	1-Minimum integration of the primary energy demanded for the production of DHW, cooling and heating 2-Minimum size of the PV system	Genetic algorithm /Energy Plus, MATLAB,
[136]	Minimize LCC	1-U-value of floor 2-U-values of walls 3-U-value of roof 4-Area of windows 5-ggl value (window solar gain coefficient multiplied by 0.75) 6-Power of cooling system	1-Power of cooling system sufficient for the most adverse day of summer 2-Components of building envelope should have acceptable lower and upper limits of u values 3-The overall average u value of building should be lower than what is required by standard	Simulated annealing and genetic algorithm /MATLAB

		<p>7-Power of heating system 8-Seasonal coefficient of performance of the heating system (SCOP) 9-Seasonal coefficient of performance of the cooling system (SEER) 10-Heating energy needs 11-Smaller and larger dimensions of each timber element of the timber frame</p>	<p>4-Total area of building windows should ensure sufficient natural illumination and ventilation 3-The Power of PV for the most adverse day of winter is ensured.</p>	
[137]	<p>1-Minimize total cost 2-Minimize carbon dioxide emissions 3-Minimize grid interaction index</p>	<p>1-PV area 2-Wind turbine power 3-Bio-dieselgenerator power</p>	Zero energy balance between building and grid	GA NSGA-II /TRNSYS, MATLAB,
[138]	Minimize cooling and heating energy consumption	<p>1-Window area 2-Glass solar factor 3-Cardinal directions</p>	-	GPSPSOCCHJ /IDA ICE, Energy 4.5 and GenOpt
[139]	<p>1-Minimize overall investment cost for the building retrofit 2-Maximize energy savings 3-Minimize discomfort hours</p>	<p>1-External walls insulation materials 2-Roof insulation materials; 3-Windows type 4-Solar collector type</p>	Constraints on introduced binary variables related to optimization variables.	-/TRNSYS, GenOpt, MATLAB
[140]	<p>1-Minimize LCC 2-Minimize annual energy cost</p>	<p>1-Azimuth 2-Aspect ratio of the building bounding rectangle 3-Building shape 4-Foundation insulation type 5-Wall insulation 6-Roof insulation 7-Window type 8-WWR 9-Thermal mass 10-Shading devices 11-Heating set point 12-Cooling set point 13-HVAC system efficiency 14-HVAC system type</p>	Budget constraint	GA, PSO, Sequential research (SS)/ DOE-2
[141]	<p>1-Minimize LCC 2-Minimize the life time utility cost</p>	<p>1-Building shape 2-Azimuth</p>	Constraints on the geometric parameters	GA, PSO /DOE-2, MATLAB

3-Minimize the energy use

- 3-Aspect ratio
 - 4-Wall construction
 - 5-Ceiling insulation
 - 6-Thermal mass
 - 7-Infiltration
 - 8-Foundation insulation
 - 9-Window area
 - 10-Glazing type
 - 11-Relative compactness
-

7. Summary

The flowcharts represented in Figure 1. 13, Figure 1. 14 and Figure 1. 15 summarize the three stages of designing, optimizing and categorizing a NZEB with reference to the above state of the art. The first stage starts, as shown in Figure 1. 13, with specifying the dominated load according to the meteorological data of the investigated region. Then, passive parameters, energy efficient and RE systems are implemented successively. Furthermore, in the second stage, Figure 1. 14, the design parameters are optimized through a specified algorithm in order to find the best combination which ensure the objectives of the designer. Finally, the third stage consists to categorize the ZEB according to the balance type and grid connectivity, Figure 1. 15.

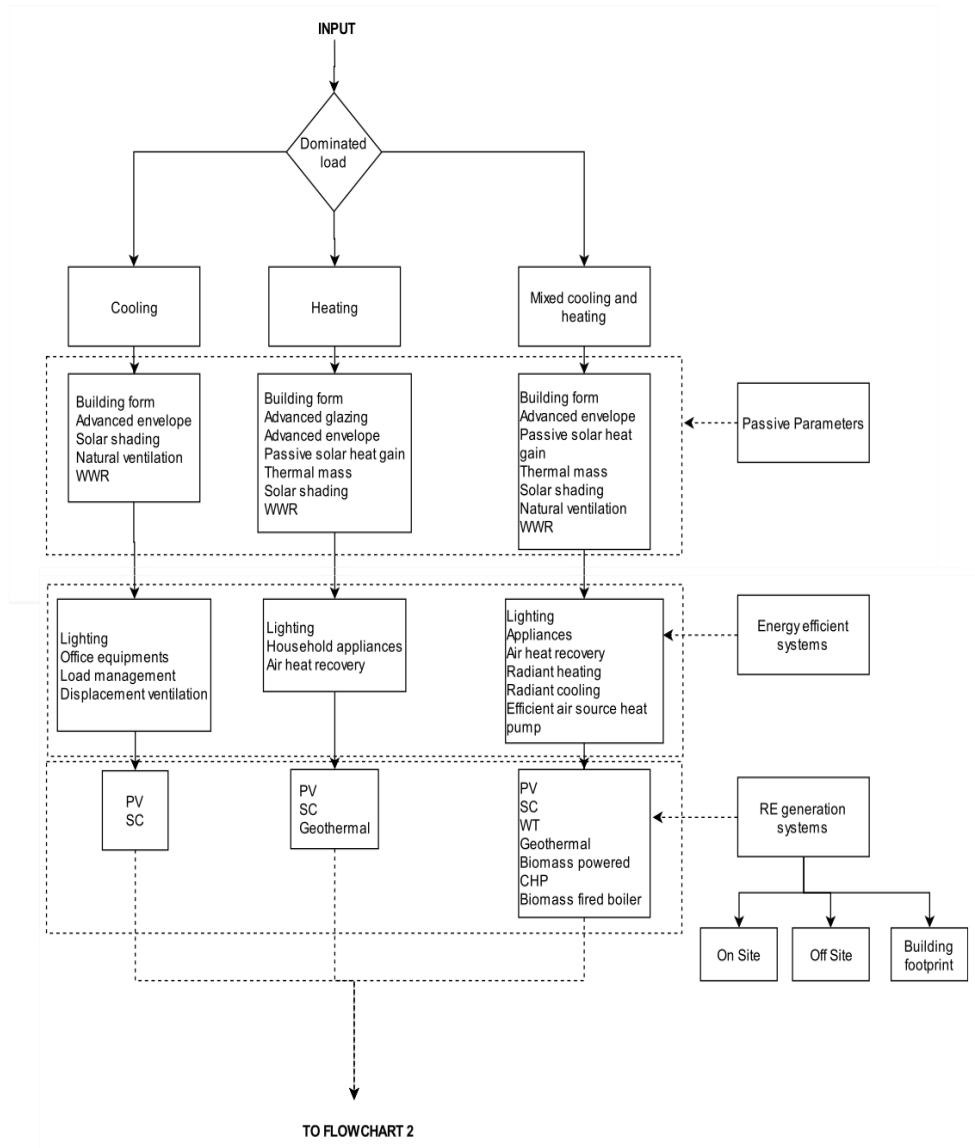


Figure 1. 13 Flowchart of the first-stage in designing ZEBs

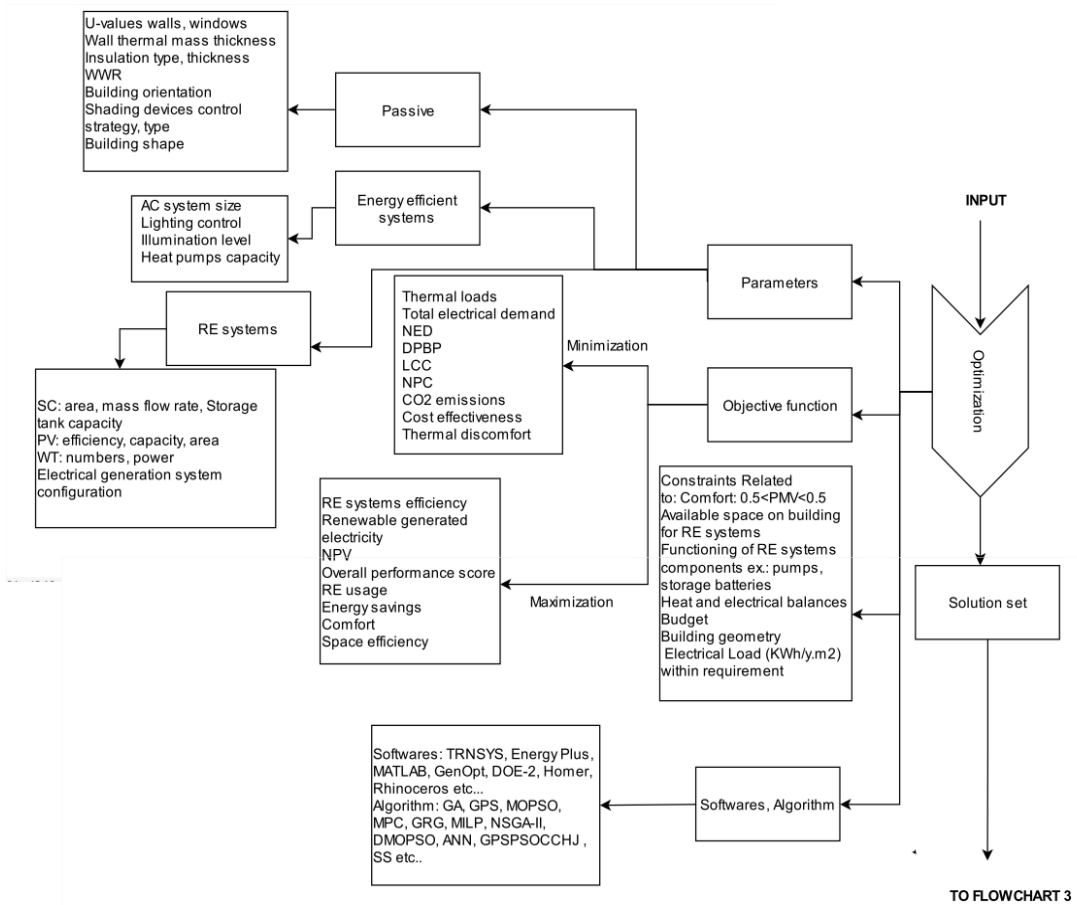


Figure 1. 14 Flowchart of optimization procedure in the second-stage

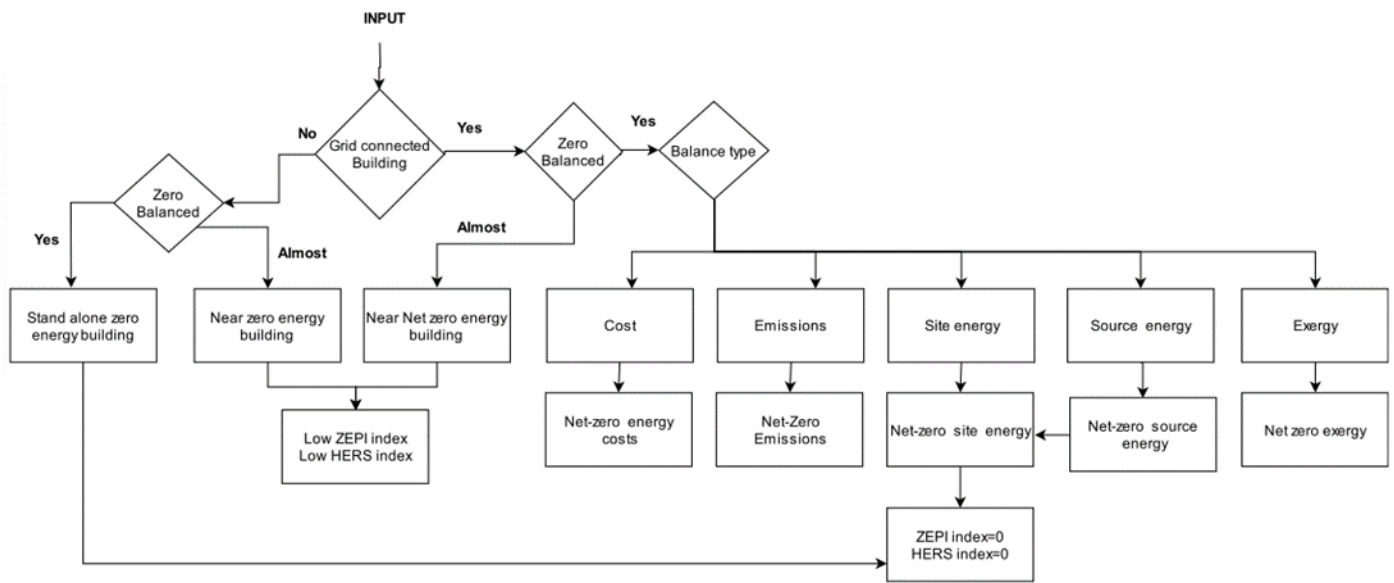


Figure 1. 15 Flowchart of the third-stage to categorize the ZEBs

8. Conclusion

A comprehensive review on definitions, concepts, rating indices, drawbacks, typical case studies and buildings' simulations according to climate, optimization methods, software's employed for design and assessment of NZEB is carried out in this chapter. The most commonly used electric and thermal RE applications in different climates are presented. Three detailed flowcharts representing the three stages of designing, optimizing, and categorizing of a NZEB are suggested.

The world is challenging global energetic and pollution problems. NZEB concept is introduced to limit these problems and since 2006 the amount of publications and projects treating this topic has increased promptly. However, a global definition of NZEB regrouping all these concepts is still missing. The NREL, ASHRAE, REHVA, EPBD, US DOE, IEA and many other organizations and researchers presented their definitions trying to classify NZEBs. One of the most common definitions: a NZEB is a building with considerably low energy demands which are assured by both: the grid and site RE resources in an annual balance that is at least zero or in favorite of the RE. The reduction of energy demand is critical in the design of NZEB. Initially the building envelope must be improved. Where, orientation, insulation, shading devices, passive strategies, infiltration, and ventilation rates are main factors that have to be taken into account in designing any NZEB. Next, the building must use energy efficient systems: appliances and lightings. Then, the electric and thermal productions from renewable resources in order to balance the grid drawn uses are considered.

About typical 30 detailed case-studies and buildings' simulations were found in 8 different climatic zones (humid continental, humid subtropical, Mediterranean, moderate continental, moderate continental, marine west coast, tropical, semi-arid and hot). In each case, the NZEB balance is achieved using a chosen RE system: PV or Wind turbines to generate electric energy, solar collectors or geothermal system to generate thermal energy for domestic, heating, and cooling purposes. By comparing these case studies, the common point of similarity found is that the majority of cases relay on PV systems to generate electricity. Humid continental, humid subtropical and semi-arid relay on solar collectors to generate heat. Moderate continental relays on geothermal systems. Mediterranean and marine west coast climates relay on both solar collectors and geothermal systems to produce thermal energy. Also, it is noticed that even in

relatively small countries, different climates may co-exist and accordingly must be treated separately.

There are numerous strategies available to design NZEBs. Scientists now are emphasizing on which part they have to focus on in each climate: passive, energy efficient measures, or RE generation system? And here comes the importance of building energy optimization.

Building energy-optimization methods are employed to obtain the ideal solution for specific objective functions which are either related to energy (thermal loads, RE generation, energy savings) and/or environment (CO₂eq emissions) and/or economy (LCC, NPV, investment cost). Optimization variables are distributed between passive (WWR, U-values, orientation), and/or RE generation systems (SC area, storage tanks capacities, PV area, RE systems configuration). In literature, some drawbacks of NZEBs can be found. These drawbacks must be considered and solved in order to achieve sustainable future. It is noticed that most papers are related to achieving NZEB performance in new buildings. There are rare studies taking into account maintenance of NZEBs in addition to the integration of advanced efficient energy technologies which should be further investigated. Finally, three consecutive flowcharts representing the three stages of designing, optimizing and categorizing a NZEB are represented.

Chapitre 2: Méthodologie d'optimisation multicritères pour les bâtiments à consommation énergétique nette nulle

Résumé en Français

Il est convenu que les méthodes de conception classiques pour les BCENN peuvent facilement conduire à des systèmes d'ER surdimensionnés ou à un confort thermique inacceptable, même si le bilan énergétique nul est atteint. Le défi dans la conception de BCENN est de trouver la meilleure combinaison de conception passive, d'efficacité des systèmes, et d'intégration d'ER qui répondrait aux problèmes de performance énergétique d'un bâtiment particulier.

Ce chapitre présente une méthodologie d'ADM pour l'optimisation des performances des BCENN. Le but de la méthode proposée est d'obtenir la meilleure solution de conception à partir d'un ensemble de solutions du front de Pareto, une solution qui reflète les préférences du décideur. La méthodologie de simulation proposée est composée de quatre étapes: simulation du bâtiment sur TRNSYS, optimisation sur MOBO, ADM et enfin une étude de sensibilité pour tester la robustesse du résultat optimal. Cette méthodologie est appliquée à un BCENN résidentiel type dans différentes zones climatiques au Liban et en France. Tout d'abord, la conception du bâtiment de base, son enveloppe et ses systèmes, ainsi que les résultats de la simulation énergétique sont décrits. Ensuite, une large gamme de paramètres de conception et d'exploitation sont optimisés, notamment le niveau d'isolation des murs et de la toiture, le type de vitrage, la proportion de surfaces vitrées sur les façades est et ouest, les températures de consigne de refroidissement et de chauffage, les panneaux solaires photovoltaïques et thermiques, afin de minimiser les bilans énergétiques et le coût sur le cycle de vie. Enfin, afin d'obtenir une solution unique, la technique ADM est utilisée.

La méthodologie d'optimisation proposée est un outil utile pour améliorer la conception des BCENN et faciliter la prise de décision dans les premières phases de la conception des bâtiments. La stabilité et la robustesse de la solution optimisée est réalisée grâce à une analyse de sensibilité, pour assurer son indépendance vis-à-vis des préférences du décideur.

Les résultats de l'analyse indiquent clairement que, indépendamment du climat, pour concevoir un BCENN résidentiel, il est essentiel de minimiser la charge thermique de l'espace grâce à des stratégies passives qui sont assurées par une enveloppe de bâtiment à haute performance thermique. Les demandes d'énergie restantes (thermique, eau chaude, éclairage et

appareils électroménagers) doivent être couvertes au maximum, par des sources d'ER. De plus, dans tous les climats, il faut mettre davantage l'accent sur le contrôle des températures de consigne de la climatisation et du chauffage, en tenant compte du confort des occupants. Les approches de confort adaptatif sont des méthodes prometteuses pour réduire le temps mis par les systèmes de refroidissement, de chauffage et de ventilation pour atteindre la consigne.

Pour décider où investir, le décideur doit d'abord organiser les priorités: soit économiser de l'argent directement pendant les investissements initiaux du projet, soit attendre 10 à 20 ans avant de commencer à faire des profits. Il est important de mentionner que la caractéristique de conception optimale de chaque pays dépend des coûts des services publics et des coûts de mise en œuvre des mesures d'efficacité énergétique.

Ce chapitre est basé sur l'article de revue:

Fatima Harkouss, Farouk Fardoun, Pascal Henry Biwole. Multi-objective optimization methodology for net zero energy buildings, 2018, Journal of Building Engineering 16: 57-71

Chapter 2: Multi-Objective Optimization Methodology for Net Zero Energy Buildings

Fatima Harkouss, Farouk Fardoun, Pascal Henry Biwole, 2018, Building Engineering 16: 57-71

Abstract

The challenge in Net Zero Energy Building (NZEB) design is to find the best combination of design strategies that will face the energy performance problems of a particular building. This chapter presents a methodology for the simulation-based multi-criteria optimization of NZEBs. Its main features include four steps: building simulation, optimization process, multi-criteria decision making (MCDM) and testing solution's robustness. The methodology is applied to investigate the cost-effectiveness potential for optimizing the design of NZEBs in different case studies taken as diverse climatic zones in Lebanon and France. The investigated design parameters include: external walls and roof insulation thickness, windows glazing type, cooling and heating set points, and window to wall ratio. Furthermore, the inspected RE systems include: solar domestic hot water (SDHW) and photovoltaic (PV) array. The proposed methodology is a useful tool to enhance NZEBs design and to facilitate decision making in early phases of building design. Specifically, the non-dominated sorting genetic algorithm (NSGA-II) is chosen in order to minimize thermal, electrical demands and life cycle cost (LCC) while reaching the net zero energy balance; thus getting the Pareto-front. A ranking decision making technique Elimination and Choice Expressing the Reality (ELECTRE III) is applied to the Pareto-front so as to obtain one optimal solution.

Keywords: Net Zero Energy Building, Optimization, Decision making, Climate, Passive measures, Life cycle cost, Renewable energy systems

1. Introduction

Economic growth and social development nowadays push governments to focus on providing population with necessary energy requirements. Concerns about energy security arise from increasing energy demand, rising oil prices, and doubts from oil and fossil fuel depletion. Currently, the concept of energy security includes challenges to provide secure, unabated, reasonably priced, and sustainable energy sources for electricity supplies and other energetic applications. While taking into consideration reducing greenhouse gases emissions and exploiting renewable energy resources.

Globally, buildings' energy demand is estimated to keep increasing in the next decades. Buildings (residential, commercial and public) have consumed around 30.6% of worlds' total primary energy supply (TPES) in 2014. The residential sector represents approximately 66.5% of TPES final consumption in buildings, and is ranked as the third-largest main energy consumer in the world (22.7% of world TPES) after industrial and transportation sectors [1]. If no action is taken to develop energy efficiency in buildings' sector, energy demand is expected to augment by 50% in 2050 [2]. By the end of 2014, buildings represented about 49% of the world's electricity consumption, where the residential sector accounts for 27% of the total electrical use, and is ranked as the second-largest electricity consumer in the world [1].

Nowadays, a new approach is suggested to limit energy consumption and pollution emissions in buildings (since buildings have a real potential to ameliorate energy efficiency), Net Zero Energy Building (NZEB). Many researches in the world are trying to find a particular definition for NZEB in order to facilitate their application, by easily specifying and finding their target. There is no common definition. Each one defines NZEB depending on his/her needs, interests, and goals to achieve. The adopted definition in this study is the following: a Zero Energy Building (ZEB) is a building with significantly low energy demands and the balance of energy needs can be supplied by renewable energy (RE) systems. A NZEB is a ZEB connected to the utility grid (electricity grid, district hot water, or other central energy distribution system) to offset its energy needs. NZEBs might employ utility's energy when the on-site RE generation doesn't meet its needs. However, it has to return back to the grid the equivalent of the energy drawn as a RE form in a yearly basis, in order to maintain the zero energy status of the building. Once the on-site energy production surpasses the building's needs, the surplus energy is exported to the utility grid, or stored in the building for later use during non-favorable weather conditions [13,14]. Innovative

concepts, reviews, calculation methodologies and feasibility of achieving NZEBs have been inspected deeply all over the world. Figure 2. 1 represents the essential elements in defining NZEB in this study according to Sartori et al. scheme [16].

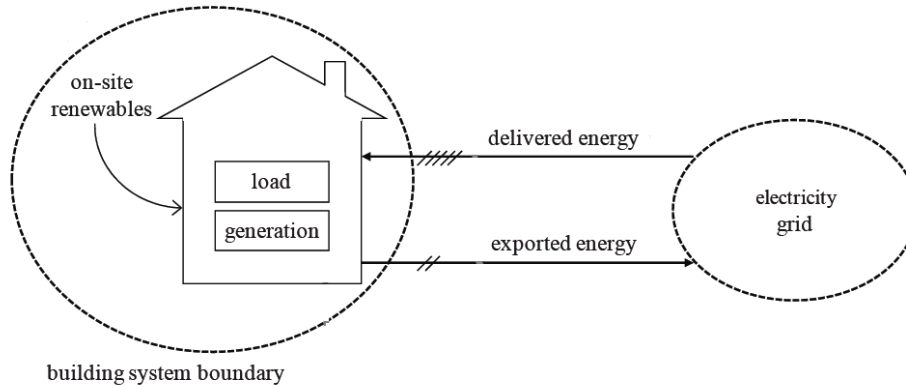


Figure 2. 1 Basic elements in definition of NZEB [16]

Besides, building optimization is an effective technique to evaluate design choices (building envelop, internal set points conditions, energy efficient appliance and lights, and type and size of installed renewable systems) and to get the perfect solution for a specific intention (i.e. economy, environment, energy, or exergy) expressed as objective functions (minimize greenhouse gases emissions, minimize energy consumption, minimize capital cost, maximize energy and exergy efficiencies) under several constraints (thermal comfort, area availability, investment costs limits, thermal regulations in benchmarks) [6]. Multi-objective optimization (MOO) is the optimization of conflicting objective functions that require to be satisfied simultaneously [142]. MOO results are sets of non-dominated solutions called Pareto optimal solutions represented as a Pareto frontier [3][4]. The Pareto frontier is a curve in case of two dimensional problems (bi-objective optimization) and a surface in case of three dimensional problems. Each point of the Pareto frontier is a possible best solution. An extensive variety of researches are reported to evaluate the impact of optimization application on improving buildings zero energy performance, and the implementation and testing of recent MOO algorithms and techniques [5,6,12,35,38,40,46,51,97,98,104,106–108,113,114,116,117,124,129,132,133,135,137–139,141,143–163].

Once the Pareto frontier is obtained, here comes the importance of the multi-criterion decision-making (MCDM) process in order to select the final optimal solution among all available possibilities [5]. MCDM is a well-established research technique with a comprehensive

combination of solution concepts and methodologies. It has been extensively used to evaluate sustainable energy solutions in buildings domain. Noting that the decision regarding the use of NZEB measures is complex, MCDM can efficiently review the problem in accordance with the significance of different criteria and the preferences of the decision maker (DM) (for an overview see, for example, [164–175]). MCDM approaches can be classified into [176–178]:

a) Aggregation methods: They are based on the principle that a disadvantage on a particular objective function might be compensated by outperforming with respect to another objective function, which creates a weakness in case of multi-dimensional MCDM problems. In addition, these methods masks the extreme non-comparable situations (actions with very strong differences, such that it is not reasonable to compare them). Among aggregation methods, there are:

Weighted sum method (WSM)

Weighted product method (WPM)

Analytical Hierarchy Process (AHP)

b) Outranking methods: They are based on concordance and discordance tests. Among outranking methods, there are:

Choice problematics, select the ideal variant from all feasible variants (e.g. ELECTRE I, ELECTRE IV, and ELECTRE IS).

Sorting problematics, assign variants to predefined real or fictive categories which serve as reference (e.g. ELECTRE TRI).

Ranking problematics, rank variants from the best to the worst (e.g. ELECTRE II, ELECTRE III, ELECTRE IV, and PROMETHEE)

Description problematics, understand the problem through actions, criteria and performances.

This chapter presents a MCDM methodology for NZEB performance optimization. The aim of the proposed method is to get the best design solution from a set of Pareto-front solutions, a solution which reflects the DM preferences. The suggested simulation-based methodology is composed of four steps: building simulation, optimization, MCDM and finally a sensitivity study to test the

robustness of the optimal result. Besides, it is applied to a prototypical residential NZEB in different climatic zones in Lebanon and France. First, the base case design conditions, RE systems, and simulation results are described. Then, a wide range of design and operating measures is optimized, including wall and roof insulation levels, windows glazing type, WWR in eastern and western facades, cooling and heating set points, photovoltaic (PV) and solar collector (SC) systems sizing. Besides, in order to obtain a unique solution, a MCDM technique is employed. Finally, a set of recommendations is outlined in order to improve the performance design of NZEBs.

2. Methodology

This section presents a methodology for NZEBs multi-objective optimization. The methodology consists of several sequential steps as presented in Figure 2. 2, and are described below.

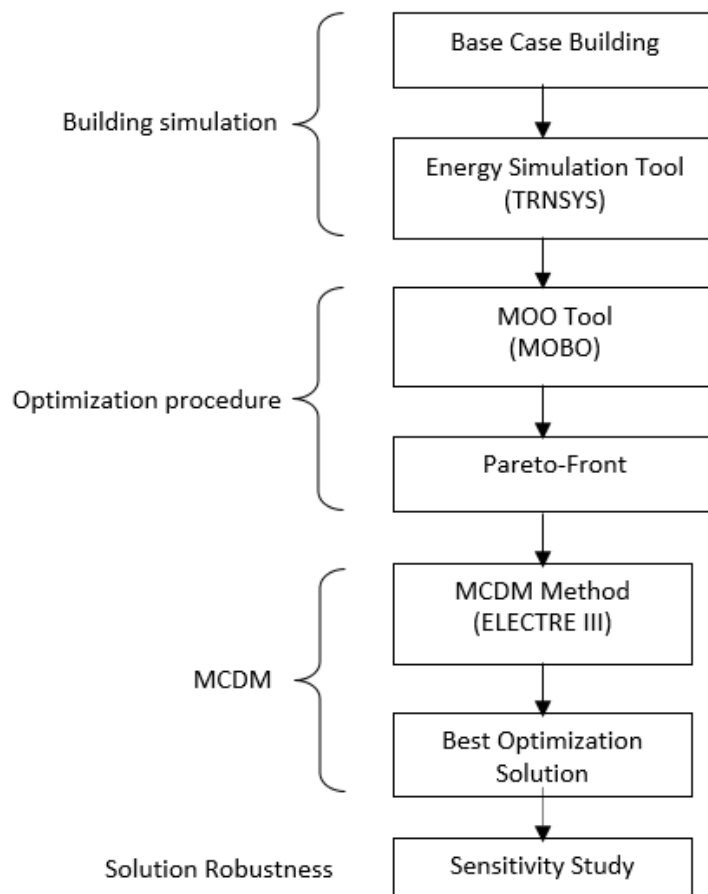


Figure 2. 2 Methodology to optimize NZEBs

2.1. Base case building simulation

The first step is to constitute the building to be optimized including but not limited to: building construction materials, climatic zone, orientations, different internal gains, occupancy schedule, operating conditions, energy efficient systems, integrated RE systems, implementation and operating costs. After that, buildings different loads, i.e. electrical, thermal, together with energy balances and economic sight represented by the life cycle cost (LCC) are simulated using TRNSYS simulation tool. Figure 2. 3 summarizes the first step of the methodology.

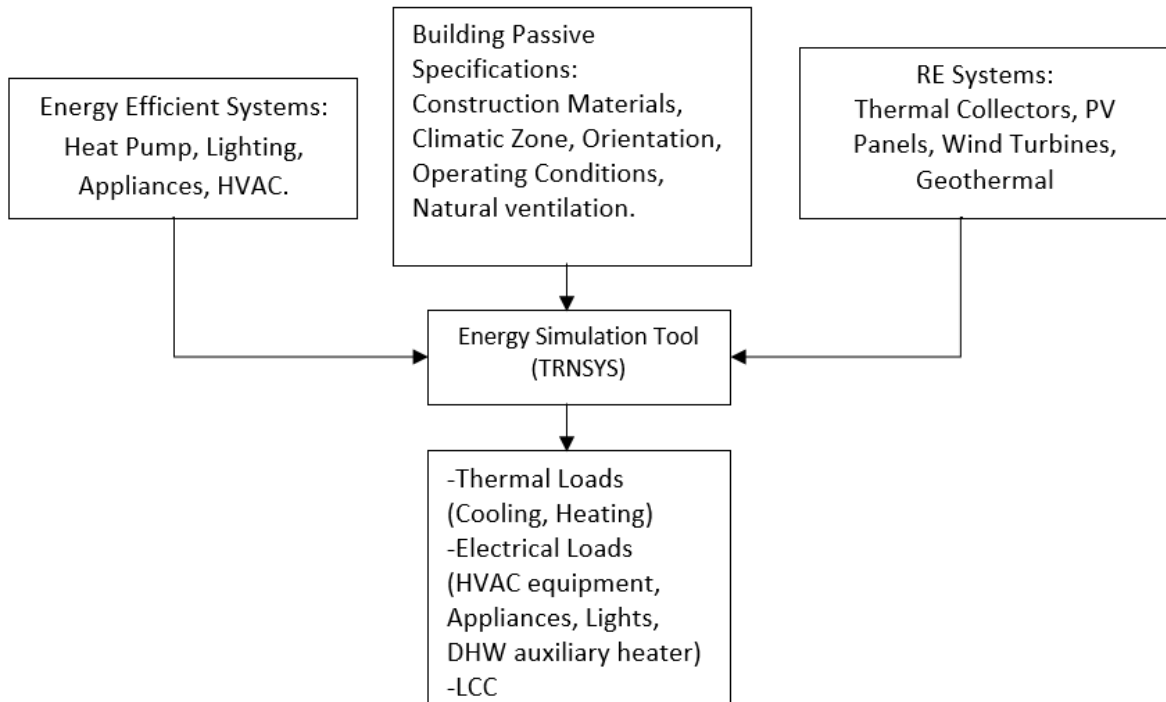


Figure 2. 3 Methodology’s first step: Building simulation

2.2. Optimization problem formulation procedure

Then after, the MOO problem is formulated (design variables, objective function and constraints) and run through an optimization tool after choosing the adequate optimization algorithm in order to obtain the Pareto-front.

a) Optimization tool

In this study, the optimization is conducted using TRNSYS coupled with MOBO, a Multi-Objective Building Optimization tool introduced by Palonen et al. (2013) [179]. It is a generic freeware tool capable of handling single and MOO problems, with continuous and discrete variables and constraint functions. It has a library of different types of algorithms (evolutionary,

deterministic, hybrid, exhaustive and random). Several advantages that characterize MOBO from other optimization tools include the following: open source, parallel computing, generic for Building Performance Simulation programs, multiple algorithms, graphical user interface, cost function flexibility, parameters flexibility, algorithmic extensibility and independent of computer operating system [104]. On the building optimization point of view, MOBO shows promising capabilities and may become the major optimization engine in coming years, as mentioned by Nguyen et al. (2014) [104].

b) Optimization algorithm

The non-dominated sorting genetic algorithm (NSGA-II), developed by Deb et al. [180], is one of the most popular and reliable MOO algorithms that can be used in building's optimization as stated by Evins [181]. Nassif et al. [182] found that the NSGA-II performs better than the NSGA, both in terms of distance to the true Pareto front and spread of optimal points, in resolving the design of simple variable air volume (VAV) systems. Brownlee et al. [183] found that the NSGA II is very effective, both in terms of the size of hyper volume and the spread of optimal points, in solving a multi-objective problem related to windows location. For an overview on the application of NSGA II, see for example [4,114,129,133,142,180,184–191].

Its main process includes population generation, population fitness evaluation, population ranking according to crowding distance (measure of how close an individual is to its neighbors, a large average crowding distance indicates a high degree of diversity), elitist selection, bimodal crossover, and mutation [133] [142]. Furthermore, its special features consist of adopting fast non-dominated sorting and crowded distance estimation approaches and simple crowded comparison operator [192] [190]. Due to these features, both convergence and spreading of the population are guaranteed [133]. Moreover, It has a computational complexity of order $r \times N^2$ (where r is the objective functions number and N is the population size) [192]. Figure 2. 4 summarizes the second step of the methodology.

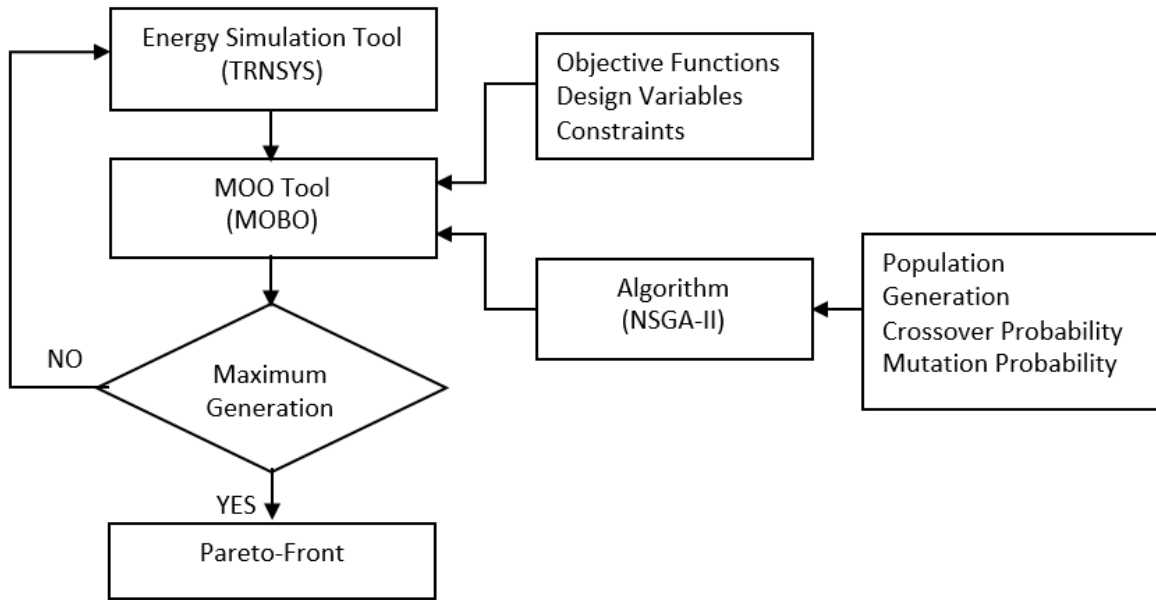


Figure 2. 4 Methodology’s second step: Optimization procedure

2.3. Multi-criterion decision-making process

ELECTRE III (Elimination and Choice Expressing the Reality) MCDM technique, developed by Roy [193], reflects the DM's priorities. It is used when a set of solutions must be classified according to a group of conflicting objective functions. It compares solutions using the binary outranking relationship that is based upon a concordance/discordance principle, to create a hierarchical ranking. [194][195]. For each considered objective function, the DM is involved to provide his/her preferences by choosing the following associated thresholds: indifference, preference, and veto, and by assigning relative weights to each of the objectives [196]. Furthermore, ELECTRE III is graphically presented on (x-y plan) through an ascending (y-axis, selection starts with the worst to the best solution) and descending (x-axis, selection starts with the best to the worst solution) distillation procedures. Indeed, the main peculiarities of ELECTRE III include: direct interaction of DM in decision process, non-compensation which means that a very bad score in one objective function is not compensated by good scores in the other one, ability to deal with inaccurate and uncertain data, ability of the DM to analyze both quantitative and qualitative criteria at different degrees of ambiguity [195][197]. In fact, many authors use this ranking method in numerous domains to solve MCDM problems [165,178,194–202].

Furthermore, the Analytical Hierarchy Process (AHP), created by Saaty [203], is adopted in this work to assign weights to each objective function. Those weights are implemented later in ELECTRE-III ranking method. The hierarchy of the decision problem is constructed through the definition of its overall objective, evaluation criteria, and the variables. On each level of the hierarchy, the DM assigns a relative weight to every objective function. Weights represent relative strength of the compared function against another one and it is expressed as a number from 1 to 9, see Table 2. 1. All weights have a compensatory character. Considering a pair of objectives, the value set to the less important function is the inverse of the value set to the more important one. When the preferential information is defined, the AHP algorithm investigates the consistency level of all matrices of relative weights on each level of hierarchy. Through the calculation of a consistency index (CI) one can measure how consistent is the preferential information given by the DM. If the value of CI is close to 0, the preferential information given by the DM is considered to be perfect. The acceptable level of CI is below 0.1 [178].

Table 2. 1 Numerical scale for criteria comparative judgment (Data source: [203])

Value	Significance
1	Equal importance
3	Moderate importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

Figure 2. 5 summarizes the third step of the methodology.

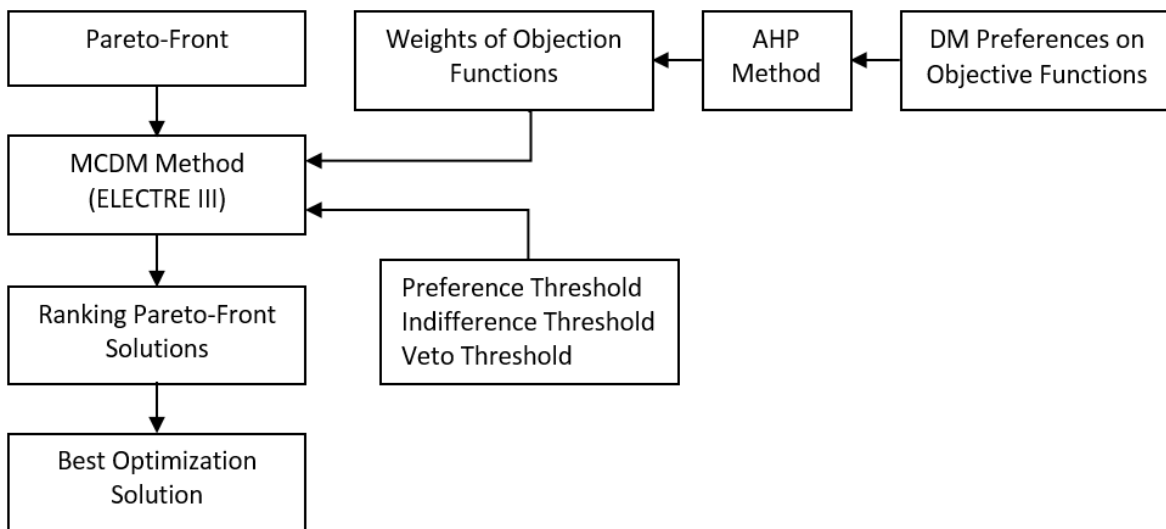


Figure 2. 5 Methodology's third step: MCDM

2.4. Sensitivity study

Moreover, to check the robustness of results, a sensitivity analysis of the best optimization solution on different DM preferences (Objective functions weights, and thresholds) is conducted, with the aim of understanding to which extent DM preferences' change can alter the optimal result. Many recent researches included and focused on the importance of this step in order to stabilize the final solution [165–167,171]. Figure 2. 6 summarizes the last step of the methodology.

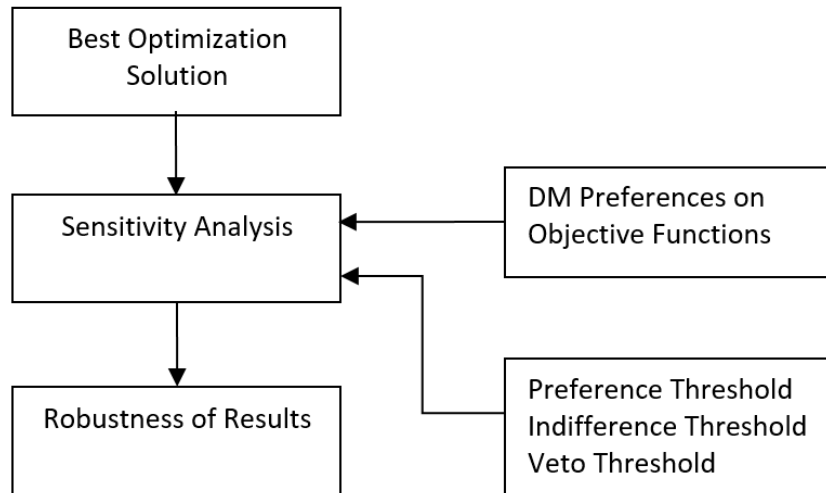


Figure 2. 6 Methodology's fourth step: Sensitivity analysis

3. Implementation of the methodology

The methodology is applied to a residential NZEB in different climates in Lebanon and France, in order to improve the building energetic and economic performance and to investigate the influence of climates differences on the zero energy balance.

3.1. Base case studies in different climatic zones

Different climatic zones are investigated in Lebanon and France to evaluate the dependence of improving building zero energy performance on the climatic zone.

a) Lebanon

Lebanon is situated on the eastern coast of the Mediterranean Sea. It is characterized by mild rainy winters and hot dry summers. Lebanese climate is Alpine in mountains and Mediterranean in Bekaa and along the coast. In 2005, Lebanon was divided into four climatic zones as shown on (Figure 2. 7) [204]. Figure 2. 8 represents the monthly average dry bulb temperature for the chosen investigated regions in each of the four zones according to the data

from meteorological stations [204], Beirut (Zone 1), Qartaba (Zone 2), Zahle (Zone 3) and Cedars (Zone 4).

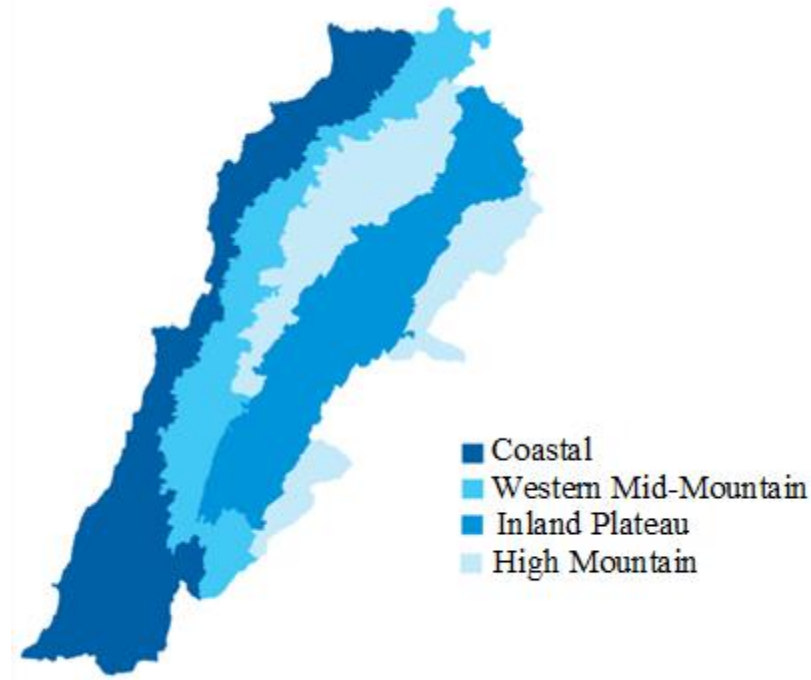


Figure 2. 7 Lebanon climatic zones [204]

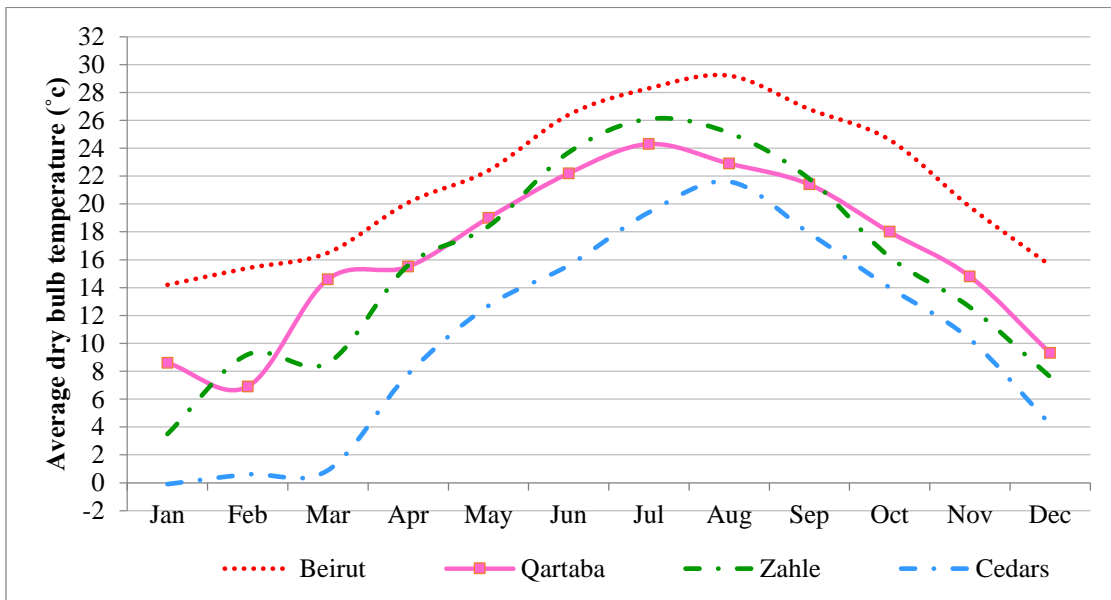


Figure 2. 8 Monthly average dry bulb temperature for chosen regions in Lebanese climatic zones (Data source: [204])

b) France

The territory of metropolitan France is relatively large, so that it includes different climates. West of France has strictly oceanic climate, which converts to semi-oceanic in the internal western zone. This predominantly oceanic climate changes to continental slightly towards the east and in the intra-mountain basins. Because of the mountainous edges which isolate it somewhat from the rest of the territory, the south-east experiences a Mediterranean climate. Moreover, the mountain climate, exists mainly in the Alps. Figure 2. 9 represents French climatic zones distribution [205]. Nice (Mediterranean climate), La Rochelle (oceanic climate), Embrun (inland mountain climate), Nancy (cold continental climate) and Limoges (Semi-oceanic climate) are chosen as representatives of the French climatic zones in this study. Figure 2. 10 represents the monthly average dry bulb temperature for the chosen investigated regions in each of the climates according to the data from meteorological stations [206].

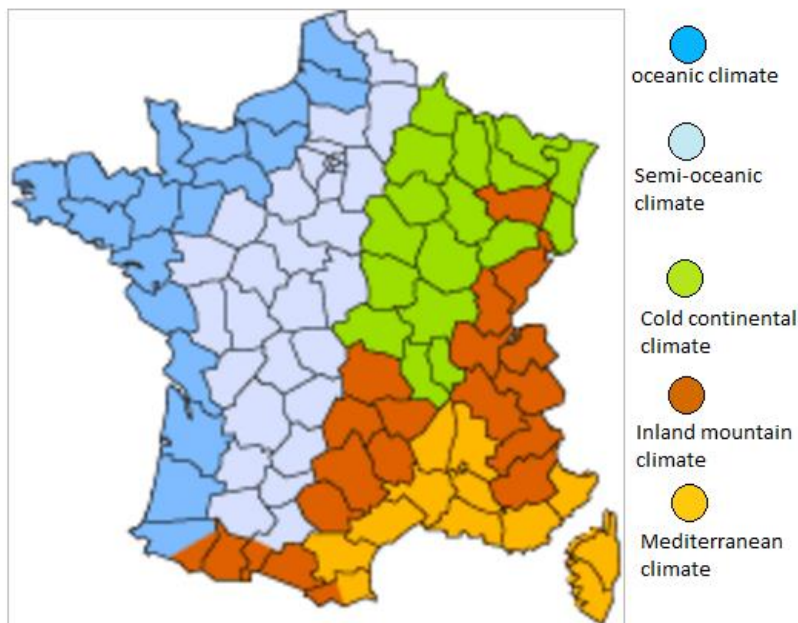


Figure 2. 9 France climatic zones [205]

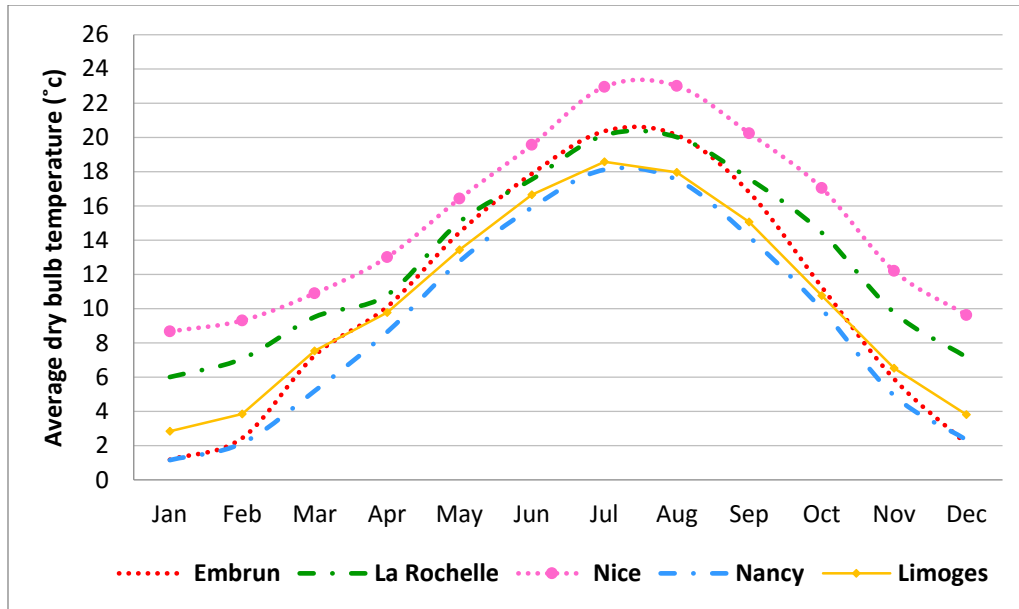


Figure 2. 10 Monthly average dry bulb temperature for chosen regions in French climatic zones (Data Source: [206])

3.2. Building simulation

3.2.1. Buildings' specifications

Table 2. 2 describes the investigated building in each region. Each floor is 205 m², consisting of two apartments noted: A & B, housing a family of four respectively. Building shape, dimensions, orientation, and openings are presented in the plan view of Figure 2. 11, as well as construction properties are summarized in Table 2. 3. Note that the defined walls, roof, and floor structures are generic serving as the base case.

Table 2. 2 Investigated building in each region

Country	Lebanon				France				
Region	Beirut	Qartaba	Zahle	Cedars	Embrun	La Rochelle	Nice	Nancy	Limoges
Number of Floors	10	4	6	3	3	3	3	3	3
Underground parking	Y	N	Y	N	N	N	N	N	N
Elevator	Y	N	Y	N	N	N	N	N	N

Y: Yes, N: No

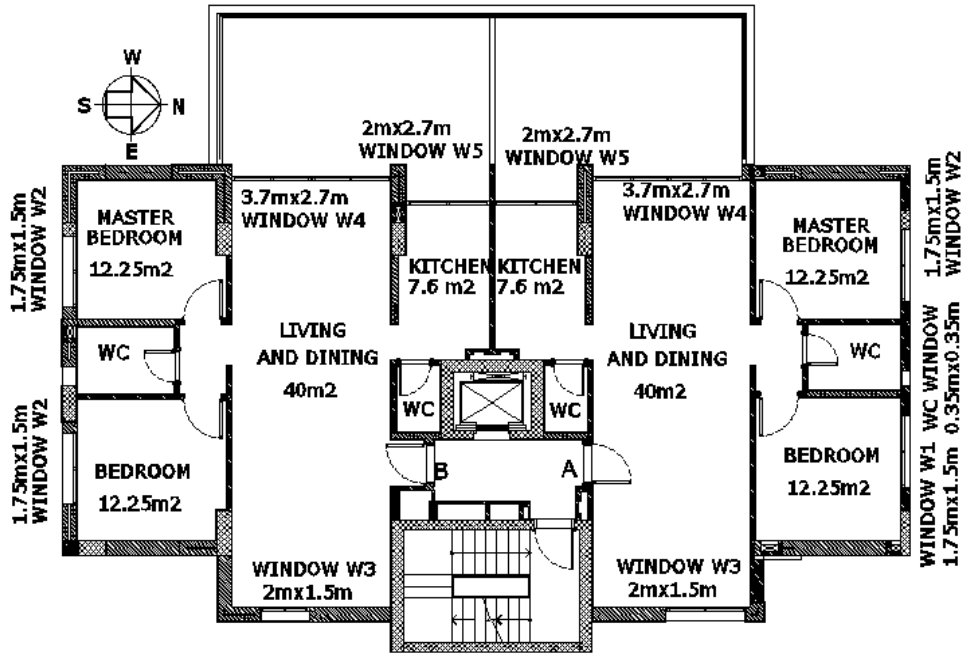


Figure 2. 11 Plan view of building’s typical floors (with two apartments A and B)

Table 2. 3 Building construction materials (Properties: Data source [207])

Components	Layers (Out to in)
External walls (0.467 W/m ² K)	2 cm Cement plaster 15 cm Concrete (2240 Kg/m ³) 5 cm Expanded polystyrene 10 cm Concrete (2240 Kg/m ³) 2 cm Cement plaster
Internal walls (3.306 W/m ² K)	2 cm Cement plaster 10 cm Concrete (2240 Kg/m ³) 2 cm Cement plaster
Partition floor (2.65 W/m ² K)	0.8 cm Marble tile 0.3 cm Lime-mortar 0.5 cm Sand-gravel 30 cm Reinforced concrete (2500 Kg/m ³) 2 cm Cement plaster
Roof (1.247 W/m ² K)	0.5 cm Asphalt roll 1 cm Expanded polystyrene 15 cm Reinforced concrete (2500 Kg/m ³) 2 cm Cement plaster
Basement walls (2.97 W/m ² K)	25 cm Reinforced concrete 2 cm Cement plaster
Windows (1.4 W/m ² K)	Argon double glazing (4/16/4) with aluminum frame, g=0.589
Ground (2.861 W/m ² K)	0.8 cm Marble tile 0.3 cm Lime-mortar 0.5 cm Sand-gravel 30 cm Reinforced concrete (2500 Kg/m ³)

Eastern and western windows are shaded with opaque roller blinds. Furthermore, cooling and heating loads are covered by air source heat pumps, characterized by a coefficient of performance (COP) equal to 2.9 and 3.1 for cooling and heating modes respectively. Only in Cedars, Embrun, La Rochelle, Nancy and Limoges, heating loads are covered by a natural gas condensing boiler (Efficiency=98.3%) due to the high heating demand in these regions. Systems set points in bedrooms, living rooms and kitchens (cooling only in kitchen) are set respectively at 24 °C for cooling and 20 °C for heating during occupied hours. During unoccupied hours, both cooling and heating systems are turned off. The desired relative humidity is set at 50 %. The building is considered as tight, so the infiltration rate is equal to 0.38 ACH [207]. The adopted electric appliances in each apartment include a computer, TV, washing machine, dish washer, refrigerator, electrical oven, kitchen extraction hood, and toilet exhaust fans. Lights are fluorescent type. The technical areas comprise necessary equipment for each building operation, including pumps, domestic water treatment plant, elevator, basement ventilation exhaust and fresh air fans.

3.2.2. Building renewable energy systems

In order to cover domestic hot water demands, a flat plate direct active SDHW system with auxiliary electric heater inside the tank, located on the house roof, is chosen. Building electrical demands are covered through a PV system.

a) Solar domestic hot water system characteristics

The Solar domestic hot water system (SDHW) is composed of fifteen solar collectors connected in series of total area equal to 31.35 m², note that the required collectors’ number in each region will be optimized in a later stage. Collectors are south oriented, their slope is approximately equal to the local latitude of each region. A summary of the considered system characteristics is presented in Table 2. 4.

Table 2. 4 SDHW system characteristics (Data source: [208])

Characteristics	Value	Characteristics	Value
Collector area, m²	2.09	Collector flow rate, Kg/hr	70
Storage tank area, m³	2.271	Intercept efficiency	0.79
Hot water set point, °C	60	Efficiency slope, W/m².K	3.48
Hot water supply temperature, °C	45	Efficiency curvature, W/m²K²	0.0056

The dead band, which is the temperature difference between inlet and outlet of the tank, is set to 5 °C. When this condition is satisfied, the circulating pump will turn on. On the other hand, when

the difference becomes lower than 2 °C, the pump will turn off. The controller monitors the temperature of the water at the top of the tank. In order to ensure that it does not get too hot, the controller has a high temperature cut-off of 90 °C. If this temperature is reached during operation, the pump will stop to avoid the water in the domestic tank from boiling.

b) Photovoltaic system characteristics

In order to generate electricity, a PV array composed of monocrystalline silicon modules is used. The array is south oriented and sloped at the region local latitude. The technical characteristics of each module are presented in Table 2. 5. The area of the PV array (m2) is calculated based on Eq. 2. 1 [209].

Table 2. 5 Parameters of PV module (Data source:[210])

Panel characteristics	Value	Panel characteristics	Value
Short circuit current, A	9.32	Open circuit voltage, V	45.92
Current at maximum power, A	8.85	Number of cells in series	72
Voltage at maximum power, V	37.38	Panel area, m ²	1.94
Temperature coefficient of open circuit voltage, V/K	-0.318	Module efficiency, %	17
Temperature coefficient of short circuit current, A/K	0.042	Nominal output, Wp	295.3

$$PV\ area = \frac{E_L}{G_{av} \times \eta_{PV} \times TCF \times \eta_{Inv}} \tag{Eq. 2. 1}$$

Where,

- E_L Daily electrical load (kWh/day)
- G_{av} Average irradiation available per day (kWh/m².day)
- η_{PV} PV efficiency
- TCF Temperature correction factor
- η_{Inv} Inverter efficiency

It is assumed that the temperature correction factor (TCF) is equal to 80% due to 15–20% loss in efficiency as a result of increasing cell temperature to about 60 °C [211]. The used direct current (DC) to alternating current (AC) electricity converter has an efficiency of 97% [212]. The peak PV power is calculated using Eq. 2. 2.

$$PV\ Peak\ power = PV\ area \times PSI \times \eta_{PV} \tag{Eq. 2. 2}$$

Where PSI stands for the Peak Solar Irradiance (W/m²).

After applying Eq. 2. 1 and Eq. 2. 2, then taking into account that the array series/parallel configuration can be adjusted according to the required DC bus voltage and current respectively

[213], results are presented in Table 2. 6. The building exploits the utility power grid for storage, delivering energy to the grid when the photovoltaic (PV) system produces more energy than the building uses and draws from the grid when the PV system produces less energy than the building needs. This approach eliminates the need for battery storage and reduces the energy loss, cost, complexity, and maintenance of the solar electric system [81].

Table 2. 6 PV array size for different regions

Region	Beirut	Qartaba	Zahle	Cedars	Embrun	Nice	Nancy	La Rochelle	Limoge
Number modules series	15	15	15	15	15	15	15	15	15
Number modules parallel	38	10	23	6	6	9	10	9	9

3.2.3. Life cycle cost (LCC)

The LCC analysis method is an economic evaluation of projects cost effectiveness. It is a suitable method to compare and rank different options for a certain project. Besides, LCC is the most commonly confidential method to evaluate financial benefits of energy conservation projects over their lifetime [47] [214]. The LCC is given by Eq. 2. 3 and Eq. 2. 4:

$$LCC = IC + USPW (N, rd) \times EC \tag{Eq. 2. 3}$$

$$USPW (N, rd) = \frac{1 - (1 + rd)^{-N}}{rd} \tag{Eq. 2. 4}$$

Where,

- LCC* Life cycle cost (\$)
- IC* Initial cost for implementing design and operating features for building envelope and HVAC system (\$)
- USPW (N, rd)* Uniform series present worth factor which converts future recurrent expenses to present costs (year)
- rd* Annual discount rate (%)
- N* Life period (year)
- EC* Annual energy cost required to maintain building indoor comfort for the selected design and operating features (\$)

For the present economic analysis, the life time is set to be N = 20 years and the discount rate is assumed to be rd= 5%. Thus, USPW (20, 5%) = 12.46 years. The annual maintenance costs are generally assumed to be as a percentage of the initial cost of each system [136]. The maintenance,

building dismantling and material recycling costs are not considered in the economic analysis of this study.

3.2.4. Base case simulation results

Buildings different demands are simulated using TRNSYS software. Hence, results obtained after simulating models of different zones, are shown in Table 2. 7. The obtained buildings total annual electrical loads range from 61.53 kWh/y.m² to 86.53 kWh/y.m² for Zahle and Nice respectively. Heating loads vary between 0.06 kWh/y.m² for Beirut to 137.43 kWh/y.m² for Nancy. Owing to temperature difference in these two regions. The lowest exterior air temperature attained in Beirut during heating season is 14°C, which is the highest temperature attained in Nancy for the same times, Figure 2. 8 and Figure 2. 10. Besides, cooling demands range from 10.45 kWh/y.m² to 189.67 kWh/y.m² for Embrun and Beirut respectively. It is also obvious that the percentage of latent demand is higher than sensible for La Rochelle, Nice and Nancy. Which means that in order to decrease thermal demands for cooling and heating in these regions, it is more beneficial to work on the latent rather than the sensible part. Figure 2. 12, Figure 2. 13 and Figure 2. 14 represent the monthly distribution of building’s electrical, heating and cooling loads in each region.

Table 2. 7 Yearly electrical and thermal loads per zone

	Electric (kWh/y.m²)	Heating (kWh/y.m²)	Cooling (kWh/y.m²)	Cooling sensible (kWh/y.m²)	% Cooling sensible	Cooling latent (kWh/y.m²)	% Cooling latent
Beirut	83.2	0.06	189.6	111.1	58.5	78.5	41.4
Qartaba	71.7	47.1	35.9	30.6	85.2	5.3	14.7
Zahle	61.5	44.0	44.0	40.6	92.3	3.3	7.6
Cedars	61.5	89.6	14.4	10.5	72.7	3.9	27.2
Embrun	64.0	107.5	10.4	6.9	66.1	3.5	33.8
La Rochelle	77.7	67.5	60.0	7.1	11.8	33.9	88.1
Nice	86.5	34.6	65.7	18.1	27.6	47.5	72.3
Nancy	71.8	137.4	35.9	2.0	5.6	33.9	94.4
Limoges	72.5	111.3	39.4	3.3	8.4	36.1	91.6

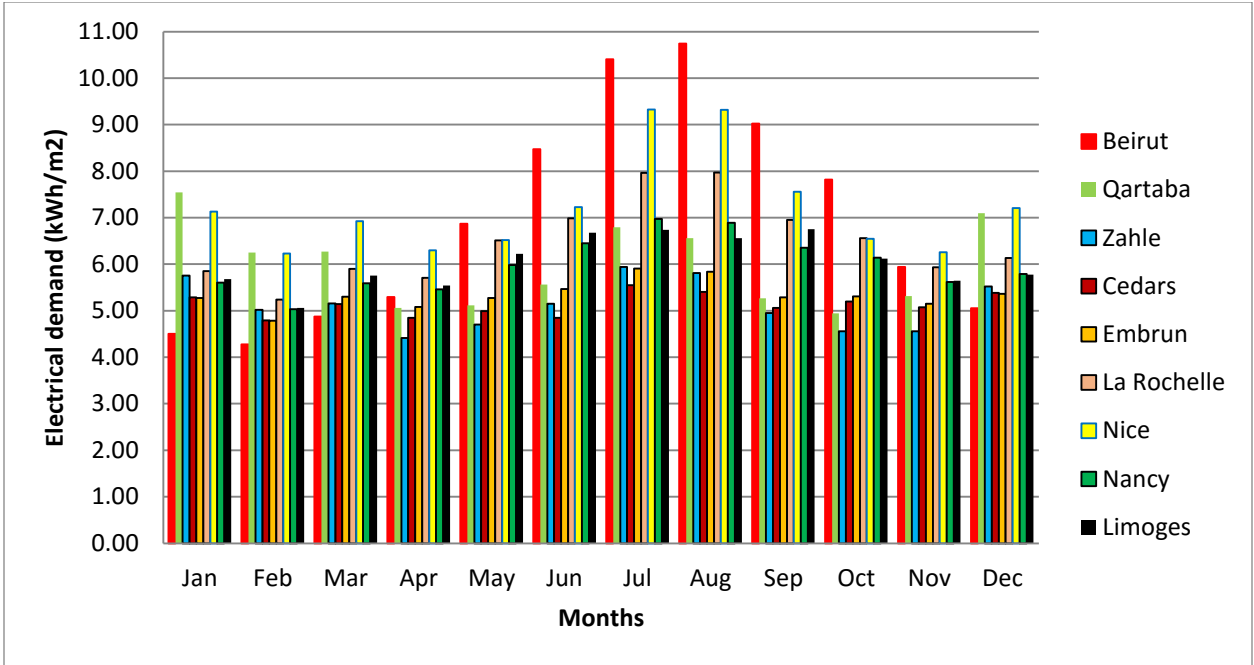


Figure 2. 12 Monthly electrical load in each zone (kWh/m²)

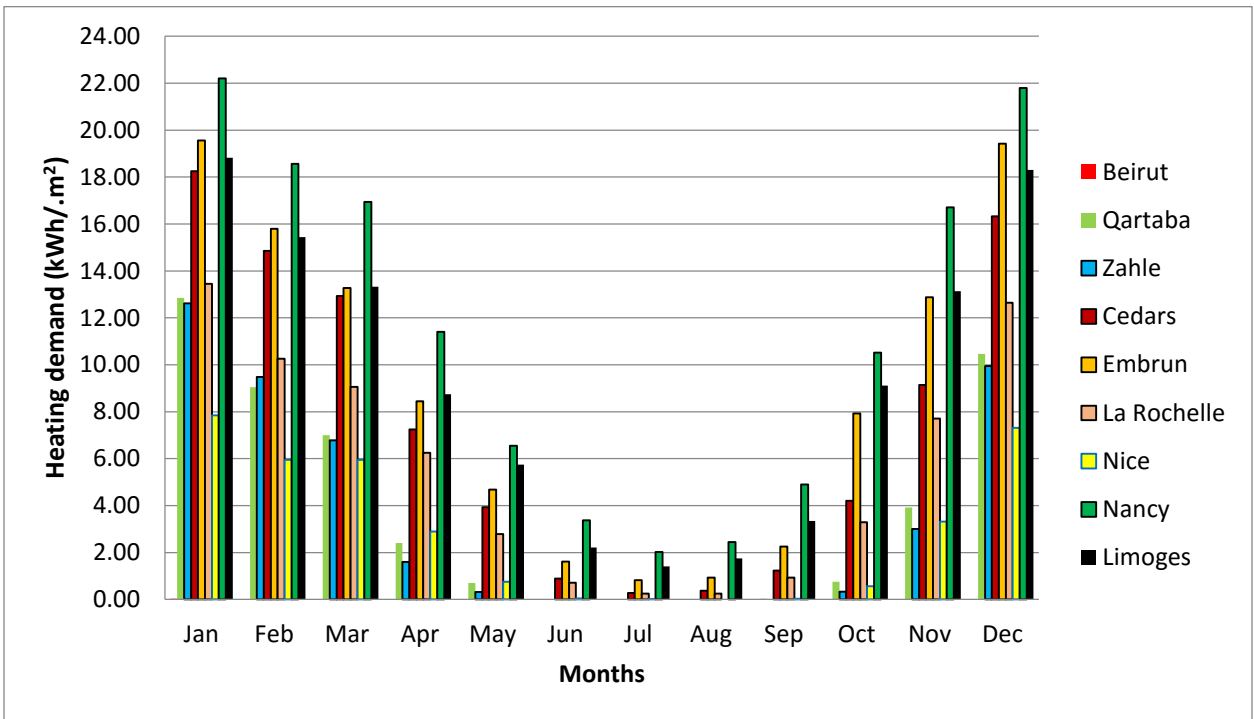


Figure 2. 13 Monthly space heating thermal load (kWh/m² of heated area) per zone

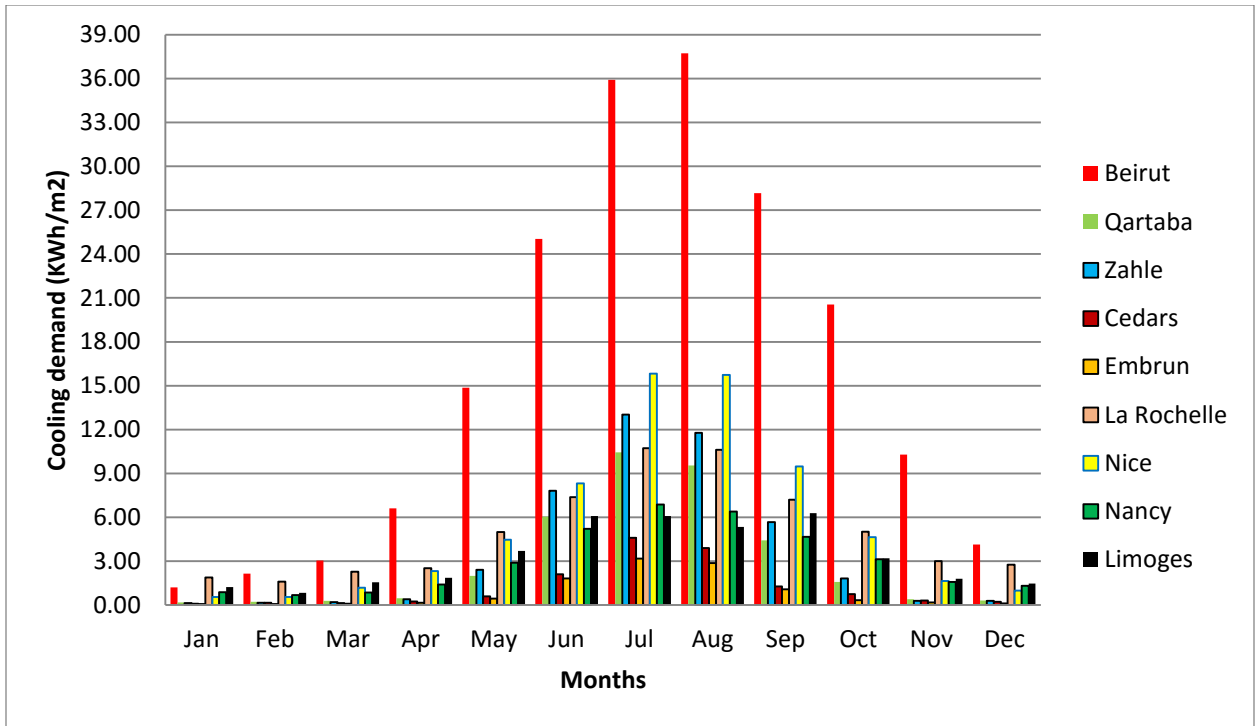


Figure 2. 14 Monthly space cooling thermal load (kWh/m² of cooled area) per zone

After integrating the analytically sized PV system in different models, the annual electric balances in different regions, i.e. consumption, generation, and electric flows are summarized in Table 2. 8. Besides, Table 2. 9 presents the LCC (1000\$) and LCC (\$/m²) to simplify the analysis. The LCC ranges from 145.1 \$/m² for Zahle to 373.7 \$/m² for Nancy. It can be noticed that over 40% of building loads are covered by PV system in Beirut, Zahle and Cedars. All models attained the zero energy balance but with a high amount of “Exports” which represent a loss in terms of PV capital costs. It is better to find the just necessary required size to decrease the stresses on the grid during high production seasons. . Besides, the load matching can be enhanced in two methods: the first is called demand site management (DSM), by regulating the demand to the generation, and the second is by regulating the generation to the needs [215].

Table 2. 8 Summary of electrical balances in different regions

Description	Beirut	Qartaba	Zahle	Cedars	Embrun	Nice	Nancy	La Rochelle	Limoges
PV system output (Before inverter), MWh	378.7	98.3	234.2	61.5	54.6	75.4	58.8	67.8	62.7
Supplied from PV to the building, MWh	116.1	23.0	61.2	15.2	15.3	20.6	16.3	18.5	17.0
Supplied from PV to the grid, MWh	251.2	72.3	165.9	44.4	37.6	52.4	40.7	47.2	43.7
Inverter losses (3%), MWh	11.3	2.9	7.0	1.8	1.6	2.2	1.7	2.0	1.8
Total building load, MWh	271.5	58.8	150.2	37.8	39.3	53.2	44.2	47.8	44.5
Supplied from Grid to the building, MWh	155.4	35.8	88.9	22.6	24.0	32.5	27.8	29.2	27.5
Exports “Load-generated by PV”, MWh	-95.8	-36.5	-77.0	-21.8	-13.6	-19.9	-12.9	-18.0	-16.2
% covered by PV	42.7	39.1	40.7	40.2	38.8	38.8	36.9	38.8	38.2

Table 2. 9 LCC for each region

Region	LCC (in 1000\$)	LCC (in \$/m ²)
Beirut	569.2	174.5
Qartaba	186.1	227.0
Zahle	354.3	145.1
Cedars	181.1	294.6
Embrun	169.3	275.2
La Rochelle	184.3	299.6
Nice	164.5	267.5
Nancy	229.8	373.7
Limoges	204.1	332.0

3.3. Optimization procedure

3.3.1. Formulation of the optimization problem

The optimization problem is formulated as follows:

a) Objective functions

In general, the electrical consumption is given by Eq. 2. 5.

Electrical consumption = consumption of (cooling+ heating + appliances+ lighting+ SDHW) Eq. 2. 6

However, electric consumption from cooling and heating can be minimized by minimizing the thermal loads for cooling and heating. Furthermore, the implemented appliances are energy start and lights are florescent type, designed in a way to maintain visual comfort and at the same time to save electricity. Thus, minimizing electrical consumption is minimizing the consumption from the SDHW system, i.e. (auxiliary electric heater + circulating pump).

Hence, in this study there are four objective functions to be minimized:

f1=min (“Auxiliary electric heater + Pump” consumptions)

f2=min (Thermal demands for cooling and heating)

f3=min (Exports)

f4=min (LCC)

b) Design variables

Table 2. 10 provides the list of building envelope and RE systems decision variables and their possible values considered in the optimization analysis. Furthermore, the implementation costs of different design options are shown in Table 2. 11.

Table 2. 10 Description and different options of decision variables used in the optimization problem

Variable	Units	Type	Values	Step	Description
a	cm	Discrete	{1,3,5,7,10}	-	External walls insulation thickness
b	cm	Discrete	{1,3,5,7,10}	-	Roof insulation thickness
d	W/m ² .K	Discrete	{0.86, 1.4}	-	Type of double glazing: Krypton or Argon g: U-value
e	°C	Discrete	24, 25, 26	-	Cooling set point
f	°C	Discrete	19, 20	-	Heating set point
g	-	Continuous	1 to 20	1	Number of solar collectors in series. Total area
h	Kg/h	Continuous	50 to 120	5	SDHW system flow rate, on the data sheet the recommended flow rate is 60 L/h to 120 L/h
i	-	Continuous	1 to 20	1	Number of solar panels in series
j	-	Continuous	1 to 40	1	Number of solar panels in parallel
w1	m	Continuous	1 to 2	0.25	Width of windows of bedroom (East)
w2	m	Continuous	1 to 2	0.25	Width of windows of master bedroom (West)
w3	m	Continuous	1 to 3	0.25	Width of windows of Living and dining (East)
w4	m	Continuous	1 to 3.7	0.25	Width of windows of Living and dining (West)
w5	m	Continuous	1 to 2	0.25	Width of windows of Kitchen (West)

Table 2. 11 Implementation costs of different options used for the optimization analysis (Data source: [116], [47], [216], [217], [218] [219], [220], [221])

Specification	Options	Cost
Wall insulation, Roof insulation	EP	2.6 \$/m2/cm
Glazing type for windows	Double glazing Argon (4/16/4, 1.4W/m2.K)	110 \$/m2
	Double glazing Krypton (4/16/4, 0.86W/m2.K)	180 \$/m2
Air conditioning	-	780 \$/Ton
		221.78 \$/kW
		0.22178 \$/W
Boiler	Condensing gas boiler (Efficiency=98.3%)	1900\$/Unit
SDHW	SC, circulating pump, connections and accessories	800 \$/unit
PV	PV panel, connections and accessories	2.16 \$/Wdc
		2160 \$/kWdc
Electricity*/Lebanon	-	0.086 \$/kWh
Electricity/France	-	0.172 \$/kWh
Natural gas/France	-	0.078\$/kWh

*Average prices for residential buildings estimated based on 500 kWh of consumption

c) Constraints

In order to guarantee occupant’s thermal comfort, limitations on the average predicted mean vote (PMV) for each apartment are adopted as constraints for the optimization problem. Typically a value of $|PMV| \leq 0.5$ is considered as acceptable values for thermal comfort according to Fanger’s scale. The average PMV for each apartment is given by the following equation [92]:

$$PMV = \sum_{i=1}^N C_i (PMV)_i$$

Where,

N: Number of rooms under investigation (Kitchen, living room, bedrooms)

i: Counter for the number of rooms

C_i: Weight coefficient for the part of the time that the family spends in the ith room during one year. The part of the time that family spends in a room is the ratio of the time that the family spends in that room to the total time the family spends in the entire apartment.

(PMV)_i: The PMV of the ith room, output of the TRNSYS software.

For the investigated building the PMV for each apartment is given by the following:

$$PMV = C_{Living} PMV_{Living} + C_{Kitchen} PMV_{Kitchen} + C_{Bedroom} PMV_{Bedroom} + C_{Master\ bedroom} PMV_{Master\ bedroom}$$

Where, C_{Living} = 0.45, C_{Kitchen} = 0.2, C_{Bedroom} = 0.175 and C_{Master bedroom} = 0.175.

d) Genetic algorithm parameters

The parameters' setting of the NSGA-II used in this study are listed in Table 2. 12. These parameters are selected based on the preliminary researches to get the best compromise between the Pareto-front accuracy and the optimization computational time [142]. The evolution of population will stop once the maximum number of generation is reached. The maximum number of iterations calculated by the NSGA-II is equal to the generation number \times population size, 1000 iterations in this case.

Table 2. 12 Input parameters' setting of NSGA-II

Parameter	Value
Population size	40
Generation number	25
Crossover probability, %	70
Mutation probability, %	2

3.3.2. Optimization results

The MOO results are usually graphically represented. However, in the present work the four-objective optimization generates a four-dimensional (4D) problem space. When projecting the 4D-Pareto-front on a bi-dimensional (2D) graph, points belonging to the front may (incorrectly) appear to be dominated variants, Figure 2. 15 shows the case of Beirut. Differences between the minimal attained value for each objective function and the base case are represented in Table 2. 13. For each region, it is noticed that electrical consumption variation of SDHW system (i.e. f1 function) ranges from 5.84% for Nancy to 31.41% for Qartaba. Thermal load reduction (i.e. f2 function) varies between 8.66% for Beirut to 39.04% for Nancy. While, life cycle cost (i.e. f4 function) decrease varies between 4.6% for Embrun to 39.56 % for Qartaba. The objective is to decrease these three functions without affecting the zero balance (i.e. function f3) which must be negative. For French cities it is clear that the variation of SDHW system electrical consumption is less than 10%. Similarly, for Beirut concerning thermal load, then for Embrun and La Rochelle concerning LCC. However, in these cases, whatever value taken by these objective functions, the MOO result is favorable for all.

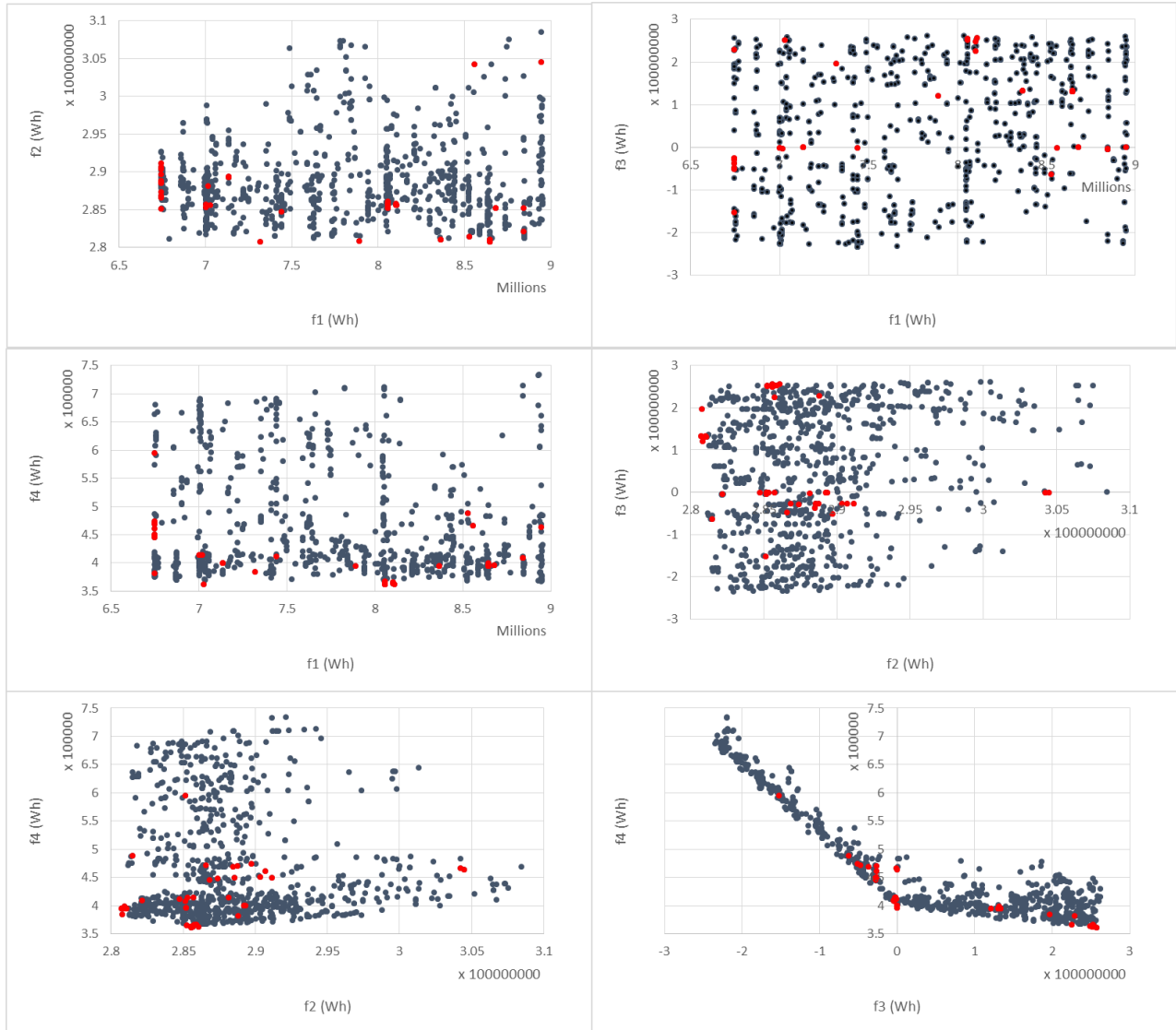


Figure 2. 15 Bi-dimensional projections of the analyzed 4D-problem space for Beirut (Blue: Building variants, Red: Pareto-front)

Table 2. 13 Differences between the best attained value for each objective function and the base case

		f1 (MWh)	f2 (MWh)	f3 (MWh)	f4 (1000\$)
Beirut	Best case of each objective function alone	6.7	280.7	-152.4	361.7
	Base case value	8.5	307.3	-95.7	569.2
	% difference	21.1	8.6	59.1	36.4
Qartaba	Best case of each objective function alone	3.8	35.6	-403.4	112.5
	Base case value	5.5	50.0	-36.5	186.1
	% difference	31.4	28.7	1005.2	39.5
Zahle	Best case of each objective function alone	5.7	61.2	-316.4	221.4
	Base case value	7.4	80.3	-77.0	354.3
	% difference	22.5	23.7	310.8	37.5
Cedars	Best case of each objective function alone	3.4	29.8	-472.1	96.5
	Base case value	4.8	45.1	-21.8	181.1
	% difference	28.1	34.0	2063.6	46.7
Embrun	Best case of each objective function alone	6.4	32.5	-428.8	162.2
	Base case value	6.9	50.9	-13.5	169.3
	% difference	8.0	36.0	3055.9	4.1
La Rochelle	Best case of each objective function alone	6.6	43.0	-341.3	171.5
	Base case value	7.0	57.9	-18.0	184.3
	% difference	6.9	25.6	1794.1	6.9
Nice	Best case of each objective function alone	6.1	36.3	-291.2	100.1
	Base case value	6.8	46.6	-19.9	164.5
	% difference	9.1	22.0	1361.3	39.1
Nancy	Best case of each objective function alone	7.0	53.9	-240.3	191.5
	Base case value	7.5	76.0	-12.9	229.8
	% difference	5.8	39.0	1761.8	16.6
Limoges	Best case of each objective function alone	6.8	47.3	-315.2	176.9
	Base case value	7.3	66.6	-16.2	204.1
	% difference	6.4	29.0	1843.4	13.3

3.4. MCDM and Sensitivity Analysis

This research employs the ELECTRE III method in order to classify the Pareto-front solutions and to choose the most adequate one for each region. Indifference, preference and veto thresholds of ELECTRE III are assigned according to the preference of the DM. In this study, the thresholds are calculated relative to the average value of each objective function derived from the Pareto-front, Table 2. 14.

Table 2. 14 ELECTRE III method thresholds

Threshold	Percentage relative to objective function average
Indifference	5%
Preference	10%
Veto	30%

The relative weight of each objective function is assigned using the AHP method. In order to analyze the stability of the ranking of the optimized solution from the DM point of view, six different cases are chosen. The first case assumes that the four objective functions are with the same importance. The second and third cases give more importance to f2, f3 and f4 than f1 but with different consistency levels, Table 2. 15 shows weights values for each case and the attained consistency index.

Table 2. 15 Relative weight of each objective function and the consistency index for each case

	f1	f2	f3	f4	CI
Case 1	0.25	0.25	0.25	0.25	0
Case 2	0.07	0.29	0.41	0.21	0.048
Case 3	0.21	0.29	0.25	0.23	0.06
Case 4	0.11	0.31	0.37	0.19	0.07
Case 5	0.16	0.27	0.15	0.40	0.09
Case 6	0.20	0.39	0.28	0.11	0.1

After getting the set of best solutions using ELECTRE III ranking for each weighting factors, we chose for each town the frequent solution, a solution which is not affected by the change in DM preferences, and we represented them in Table 2. 16 all together with the difference between the ideal case and the base case. It is noticed that the zero balance is attained in all regions but with different design values. Moreover, the thermal energy consumption can be decreased up to 6.7%–

33.1% through optimal designs compared to the base case, then the SDHW electric consumption and LCC reductions are up to 26.7% and 31.0% respectively.

Table 2. 16 Differences between the best solution by ELECTRE III and the base case

		f1 (MWh)	f2 (MWh)	f3 (MWh)	f4 (1000\$)
Beirut	Best solution	6.7	286.5	-47.2	471.1
	Base case value	8.5	307.3	-95.7	569.2
	% difference	21.1	6.7	-50.6	17.2
Qartaba	Best solution	4.0	40.4	-0.7	139.4
	Base case value	5.5	50.0	-36.5	186.1
	% difference	26.7	19.1	-97.8	25.0
Zahle	Best solution	6.3	61.2	-51.0	317.0
	Base case value	7.4	80.3	-77.0	354.3
	% difference	14.6	23.7	-33.7	10.5
Cedars	Best solution	3.9	30.1	-0.3	124.8
	Base case value	4.8	45.1	-21.8	181.1
	% difference	17.9	33.1	-98.4	31.0
Embrun	Best solution	6.7	34.1	-27.1	197.9
	Base case value	6.9	50.9	-13.5	169.3
	% difference	3.5	32.9	-49.9	14.4
La Rochelle	Best solution	6.8	43.7	-17.9	195.6
	Base case value	7.0	57.9	-18.0	184.3
	% difference	3.3	24.5	-0.2	6.1
Nice	Best solution	6.2	37.9	-13.9	176.0
	Base case value	6.8	46.6	-19.9	164.5
	% difference	8.8	18.6	-30	6.9
Nancy	Best solution	7.3	55.0	-8.2	220.7
	Base case value	7.5	76.0	-12.9	229.8
	% difference	2.6	27.5	-35.9	3.9
Limoges	Best solution	7.0	48.4	-13.5	205.9
	Base case value	7.3	66.6	-16.2	204.1
	% difference	3.2	27.2	-16.6	0.8

Table 2. 17 lists NZEBs parameters consequent of the decision making phase for all regions representing an extensive range of climatic conditions. The results clearly indicate that there is a significant potential to improve the energy performance of residential buildings in different climates by using proven passive strategies.

Table 2. 17 Summary of the optimal building design options in each region

Region	Base case	Beirut	Qartaba	Zahle	Cedars	Embrun	La Rochelle	Nice	Nancy	Limoges
Climate	-	Mediterranean	Western mid mountain	Inland plateau	High mountain	Inland mountain	Oceanic	Mediterranean	Cold continental	Semi-Oceanic
External walls insulation thickness (cm)	5	3	5	10	10	7	10	7	10	10
Roof insulation thickness (cm)	1	5	5	10	10	10	7	7	10	7
Windows U-value (W/m ² .K)	1.4	1.4	1.4	1.4	0.86	0.86	1.4	1.4	1.4	1.4
Cooling set point (°C)	24	26	25	26	25	25	25	25	24	25
Heating set point (°C)	20	19	19	19	19	19	19	19	19	19
Number of solar collectors in series	15	8	13	10	8	16	13	19	15	18
Circulating pump flow rate (Kg/h)	70	120	120	110	115	95	100	120	105	95
Number of PV (Base case)	-	570	150	345	90	90	135	135	150	135
Number of PV (Optimal case)	-	468	119	273	72	108	144	120	133	126
Eastern WWR (%)	23.4	20.3	25	17.1	21.8	17.1	17.1	21.8	25	14.0
Western WWR (%)	59.4	27.4	52.2	22.7	35.1	32.9	29.9	47.7	39.6	40.8

The building envelope level of insulation is found to vary depending on the climate. However, the optimal design options for exterior walls and roof insulation consist of high insulation level. Therefore, 1cm roof insulation thickness is not sufficient to protect the building from external weather conditions in all climates. Besides, in Beirut, where cooling load dominates, wall insulation is decreased up to 3cm. This is because there is a certain limit of wall insulation after which the heat will accumulate in the building and won't escape during cool nights for example, causing a higher cooling load.

In all climates, it is cost-effective and energy efficient to decrease heating set point further and to increase cooling set point. The occupants comfort is not affected in this study since the PMV is imposed as a constraint in the optimization problem.

Furthermore, it is noticed that U value of windows remains equal to $1.4 \text{ W/m}^2\cdot\text{K}$ for all regions except for Cedars and Embrun where heating demand dominates. Lowering U value will lead to lower thermal flows from outside, and thus decreasing heating demand.

For Beirut, where cooling load dominates, it is profitable to decrease the eastern WWR up to 20% and the western WWR to 27%. Although, in heating dominated climates as Nancy, and Limoges the ratio in western orientation, 39.6% and 40.8% respectively, is more than that of cooling dominated climates, in order to collect necessary heat from the sun for heating purposes. While, for Cedars and Embrun, because of the investment in windows insulation, so the sufficient WWR is less than that of Nancy and Limoges.

The total optimal number of PV to attain the zero balance is decreased in all regions except in Embrun and La Rochelle. In the current work, the number of PV panel is optimized by considering it as a discrete variable between 1 and 800 panels. However, optimization and thus selection of the PV system can be carried out by selecting the just necessary number of PV to attain the zero balance, without giving importance to generating more electricity than needed. It is worth mentioning that the LCC is the amount to pay during the life cycle of 20 years, but we won't ignore that the extra amount of electricity produced which is represented by the function f_3 , will be sold to the utility at the rate the government imposes.

4. Conclusions

It is agreed that the conventional design methods for ZEBs can easily lead to oversized RE systems or unacceptable performance of different design conditions, even though the zero energy balance is attained. The challenge in ZEB design is to find the best combination of passive, energy efficient and RE systems design strategies that would face the energy performance problems of a particular building.

In this chapter, a multi-criteria decision-making methodology for NZEB design optimization is introduced to enhance its energetic and economic performance.

The methodology is applied through the combination of energy simulation and optimization programs (TRNSYS and MOBO) coupled with a ranking decision-making technique (ELECTRE III). The objective is to evaluate the most cost-effective passive strategies and RE system sizes that should be implemented to achieve a NZE-design for a typical residential building located in various climatic zones. In the optimization analysis, a wide range of design and operating measures are considered including wall and roof insulation levels, windows glazing type, WWR at eastern and western facades, cooling and heating set points, PV and SDWH systems sizing.

The proposed optimization methodology is a powerful and useful tool to enhance NZEBs design and to facilitate decision-making in early phases of building design. The stability and robustness of the optimized solution, to ensure its independence of the DM preferences, is carried out through a sensitivity analysis.

The optimum design parameters and their corresponding objective functions shows that the annual thermal loads decrease in a range from 6.7% for Beirut to 33.1 % for Cedars, compared to the base case in different climates. Meanwhile the SDHW auxiliary electric resistance and circulating pump electricity decrease ranges from 2.6% for Nancy to 26.7% for Qartaba. Furthermore, the LCC decrease ranges from 0.8% for Limoges to 31.0% for Cedars.

The results of the analysis clearly indicates that, regardless of the climate, for designing a residential NZEB, it is essential to minimize space thermal load through passive strategies which is ensured by a building envelope with high thermal performance. Moreover, the remaining energy demands (thermal, hot water, lighting, and appliances) are covered to the maximum extent, by RE sources.

Furthermore, in all climates more emphasis should be placed on air conditioning set points control, taking into account the occupants comfort. The adaptive comfort approaches are promising methods to reduce the required times for cooling, heating, and ventilation.

In order to decide where to invest, the decision maker must at first organize the priorities: whether to save money directly during the project initial investments or to wait for 10-20 years to start getting profits. It is important to mention that the optimal design feature of each country depends on the utility costs and the implementation costs of energy efficient measures.

Chapitre 3: Optimisation des paramètres passifs des bâtiments à basse consommation dans différents climats

Résumé en français

Le potentiel élevé des bâtiments vis-à-vis de l'efficacité énergétique a attiré l'attention des ingénieurs et des chercheurs sur les paramètres de conception et les stratégies passives.

L'objectif de ce chapitre est d'étudier de manière approfondie la conception passive optimale pour un modèle de bâtiment résidentiel. Ainsi, une optimisation des paramètres passifs est réalisée sous vingt-cinq climats différents de la classification de Köppen-Geiger. Les climats sont classés en trois catégories en fonction de la charge thermique dominante (chauffage dominant, refroidissement dominant, climat mixte) dans le but de simplifier la recherche d'une solution optimale recommandée pour chaque catégorie. La méthodologie mise en place est composée de quatre étapes: simulation du bâtiment, optimisation, ADM, étude de sensibilité pour tester la robustesse du résultat optimal, et enfin intégration des stratégies passives pour assurer le confort adaptatif des occupants.

La solution optimale d'enveloppe désirée est celle qui minimise en même temps les charges de refroidissement et / ou de chauffage et le coût sur le cycle de vie du bâtiment. Premièrement, les conditions de conception du cas de base, y compris le plan du bâtiment, les températures de consignes, les différentes villes représentatives pour chaque climat et les résultats de la simulation sont décrits. Ensuite, un large intervalle des mesures de conception passive est optimisé pour chaque climat, y compris les niveaux d'isolation des murs et du toit, le type de vitrage des fenêtres, et la proportion de surfaces vitrées sur chaque façade. Le confort thermique adaptatif des occupants est également amélioré en intégrant des mesures passives telles que les dispositifs d'occultation et la ventilation naturelle.

La solution passive optimale du bâtiment étudié indique la possibilité d'améliorer jusqu'à 54%, 87% et 52% les demandes de refroidissement, les demandes de chauffage et le coût global respectivement, par rapport à la configuration d'origine. De plus, les stratégies passives intégrées ont démontré leurs compétences puisqu'elles entraînent une importante diminution de la surchauffe.

Enfin, un ensemble de recommandations spécifiques à chaque climat est présenté, afin d'améliorer les performances énergétiques et de confort des bâtiments résidentiels.

Ce chapitre est basé sur l'article de revue:

Fatima Harkouss, Farouk Fardoun, Pascal Henry Biwole. Passive design optimization of low energy buildings in different climates, submitted to Energy Journal, 2018

Chapter 3: Passive design optimization of low energy buildings in different climates

Abstract

Worldwide, the residential buildings are consuming a considerable amount of energy. The high potential of buildings towards energy efficiency has drawn special attention to the passive design parameters. A comprehensive study on optimal passive design for residential buildings is presented in this chapter. Twenty five different climates are simulated with the aim to produce best practices to reduce building energy demands (for cooling and heating) in addition to the life cycle cost (LCC). The occupants' adaptive thermal comfort is also improved by implementing the appropriate passive cooling strategies such as blinds and natural ventilation. In this respect, the implemented methodology is composed of four phases: building energy simulation, optimization, Multi-criteria Decision Making (MCDM), sensitivity study, and finally an adaptive comfort analysis. Optimal passive solution of the studied building, indicates the potential to save up to 54%, 87% and 52% of the cooling demands (Q_{cool}), heating demands (Q_{heat}) and LCC respectively with respect to the initial configuration. Additionally, the integrated passive cooling strategies have demonstrated its competency since it leads to a significant overheating decrease.

Keywords: Building envelope, Passive cooling strategies, Optimization, Decision making, Climate, Life cycle cost, Adaptive thermal comfort.

1. Introduction

Buildings (residential, commercial and public) have consumed more than 30% of worlds' total primary energy supply (TPES) since 2014. The residential sector accounts for more than 65% TPES consumption in buildings [1]. Under these circumstances, it is critical to ameliorating the buildings' energy efficiency, since the energy demand is predicted to increase by 50% in 2050 when compared to 2013 [2].

The high potential of buildings towards energy efficiency has drawn special attention to the passive design parameters i.e. building envelope characteristics and passive strategies namely natural ventilation, shading devices, overhangs, and daylighting.

Researchers worldwide are investigating the applicability of building optimization methodologies in order to enhance buildings' energy performance. The investigated methodologies are aimed to facilitate the finding of a unique optimal solution which satisfies both sides: the designer-architecture, and benchmarks regulations. Adopting one optimal passive design recommendation for each climate is a fundamental way to help the buildings to become energy efficient, especially for residential buildings. Even though the optimal passive design solution is related to many factors such as the local climate, building utilization, topography and landscape design.

It is worth mentioning the following definitions used in this study: passive parameters are variables related to building envelope such as: type of walls, roof, ground, windows, WWR, and building shape. Passive strategies are scenarios implemented during the building operation such as blinds, overhangs, and natural ventilation with the aim to reduce thermal and lighting demands, while ensuring thermal comfort.

An overview of recently investigated optimization problems in the literature [5,31,40,47,82,84,92,97,98,106,107,109,110,112,115,126,129,131–133,136,138–142,146–148,151,156,157,188,222–232] is represented in Table 3. 1. The summary includes the most examined passive parameters/strategies. The objective functions under investigation are divided into five categories: Economy, energy, environment, comfort, and others. Besides, the adopted optimization algorithms and Multi-criteria Decision Making (MCDM) techniques are stated. Finally, most used sensitivity analysis or uncertainty quantification methods are reviewed. They are used with the aim to test the robustness of optimal solution on different conditions related to algorithms setting parameters, design/fabrication errors, decision maker (DM) preferences, and energy costs.

Table 3. 1 Overview of the largely optimized passive parameters including the optimization characteristics (Data source: [5,31,40,47,82,84,92,97,98,106,107,109,110,112,115,126,129,131–133,136,138–142,146–148,151,156,157,188,222–232])

Investigated parameters	Objective functions
<p>U-value: walls, roof, floor, windows frame, and glazing. Wall thermal, solar, and visible absorptance. Wall emissivity. WWR. Number of windows. G-value of glazing. Glazing solar and visible transmittance. Windows opened area % (Natural ventilation). Overhang tilt angle and depth. Sunshade type. External and internal shading systems. Control strategy of shading devices. Building shape. Relative compactness. Aspect ratio. Ceiling height. Building orientation. House area. Air tightness/ Infiltration rate. Convection coefficients. Vegetation.</p>	<p><u>Economy:</u> Minimize: Life cycle cost (LCC), overall investment cost, lifetime utility cost, building operation cost. Maximize Net present value (NPV). <u>Energy:</u> Minimize: Total electricity load, lighting energy consumption. Net energy deficit (NED). <u>Environment:</u></p>
<p>Constraints</p>	<p>Minimize: life cycle environmental impact, Life cycle impact assessment (LCIA), life cycle carbon emissions.</p>
<p>NED \leq 0. Heating loads \leq 15 kWh/m². Annual space energy requirements \leq 5 Mj/m². Air change rate \geq 0.6 ACH. Area availability. Total window width \leq Floor width. Windows' area must guarantee adequate natural illumination and ventilation. Acceptable ranges of envelope components' U-values. Budget constraint. Constraints on design variables. Maximum discomfort hours fixed at 200 h up to 350 h. PMV \leq 0.5-0.7. Construction budget. Life cycle cost budget.</p>	<p><u>Comfort:</u> Minimize: Predicted mean votes (PMV), summer thermal discomfort, winter thermal discomfort, visual discomfort, seasonal long-term discomfort indices (=Long-term Percentage of Dissatisfied (LPD) in summer and winter), Predicted Percentage of Dissatisfied (PPD). <u>Others:</u> Minimize: shape coefficient. Maximize: window opening rate, thermal admittance, solar radiation gain, space efficiency.</p>
<p>Algorithms</p>	
<p>Generalized pattern search algorithm (GPS), Multivariate optimization, Multi objective particle swarm optimization (MOPSO), Non-dominated sorting genetic algorithm (NSGA-II), Multi-objective genetic algorithm (MOGA), Life Cycle Assessment (LCA) methodology, Artificial neural network (ANN), Generalized particle swarm optimization with Hook Jeeves algorithm (GPSOCCHJ), Sequential research (SS), Genetic Algorithm (GA), Tabu search algorithm (TSA), Multi-objective artificial bee colony (MOABC).</p>	
<p>MCDM/Sensitivity analysis-Uncertainty quantification</p>	
<p><u>Decision making:</u> Weighted sum method (WSM), Weighted product method (WPM), Decision making: Technique for order of preference by similarity to ideal solution (TOPSIS), Analytical Hierarchical Process (AHP), ELimination and Choice Expressing REality (ELECTRE) methods, Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) methods.</p>	<p><u>Sensitivity analysis-Uncertainty quantification:</u> Impact of: energy prices, discount rates, CO₂ emissions prices, climate, utility rates, operating points (heating and cooling set-points). Sensitivity of algorithms parameters. Objective function weights. DM preferences thresholds. Uncertainties in design variables according to probabilistic distributions.</p>

This chapter follows the MCDM methodology for buildings energy performance optimization introduced by the previous chapter. The aim of the chosen method is to identify the best design solution from a set of Pareto-front solutions, a solution which reflects the DM preferences. The implemented simulation-based methodology is composed of four steps: building energy simulation, optimization, MCDM and finally a sensitivity study to test the robustness of the optimal result.

According to the European standard EN 15251: “An energy declaration without a declaration related to the indoor environment makes no sense. Therefore, there is a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings” [233]. These criteria are related to the occupants’ thermal comfort [99,229,234–241].

The objective of the present chapter is to comprehensively investigate the optimal passive design for a case study residential building. Twenty-five different climates from Köppen Geiger classification are simulated with the aim to produce best practices to minimize building energy demands (cooling and heating) in addition to the LCC. The occupants’ adaptive thermal comfort is also inspected aiming at getting more practical and detailed passive design solutions.

So, an additional step is added to the adopted methodology, which is the introduction of adequate passive cooling strategies (natural ventilation, shading devices) that ensure to the maximum extent the occupant’s adaptive comfort in the optimal model.

At first, the base case design conditions including building model, operating points, different representative cities for each climate and the corresponding simulation results are described. Then, a wide range of passive design measures is optimized for each climate, including wall and roof insulation levels, windows glazing type, WWR at each facade. Besides, in order to obtain a robust unique solution, a MCDM technique and sensitivity analysis are employed. Then, the impact of implementing shading devices and natural ventilation on the optimal building’s energy consumption in different climates is investigated by comparing the overheating hours’ percentage. Finally, a set of general recommendations is outlined in order to improve the energy and comfort performances of residential buildings depending on the climate.

2. Base case building and investigated climates

2.1. Building model and design conditions

The base case model is a generic residential building composed of three typical floors. Each floor is 205 m² divided into two apartments noted A and B, as shown in Figure 3. 1. Building's net area (excluding balconies, bathrooms, lobbies and non-conditioned spaces) is 432.6 m².

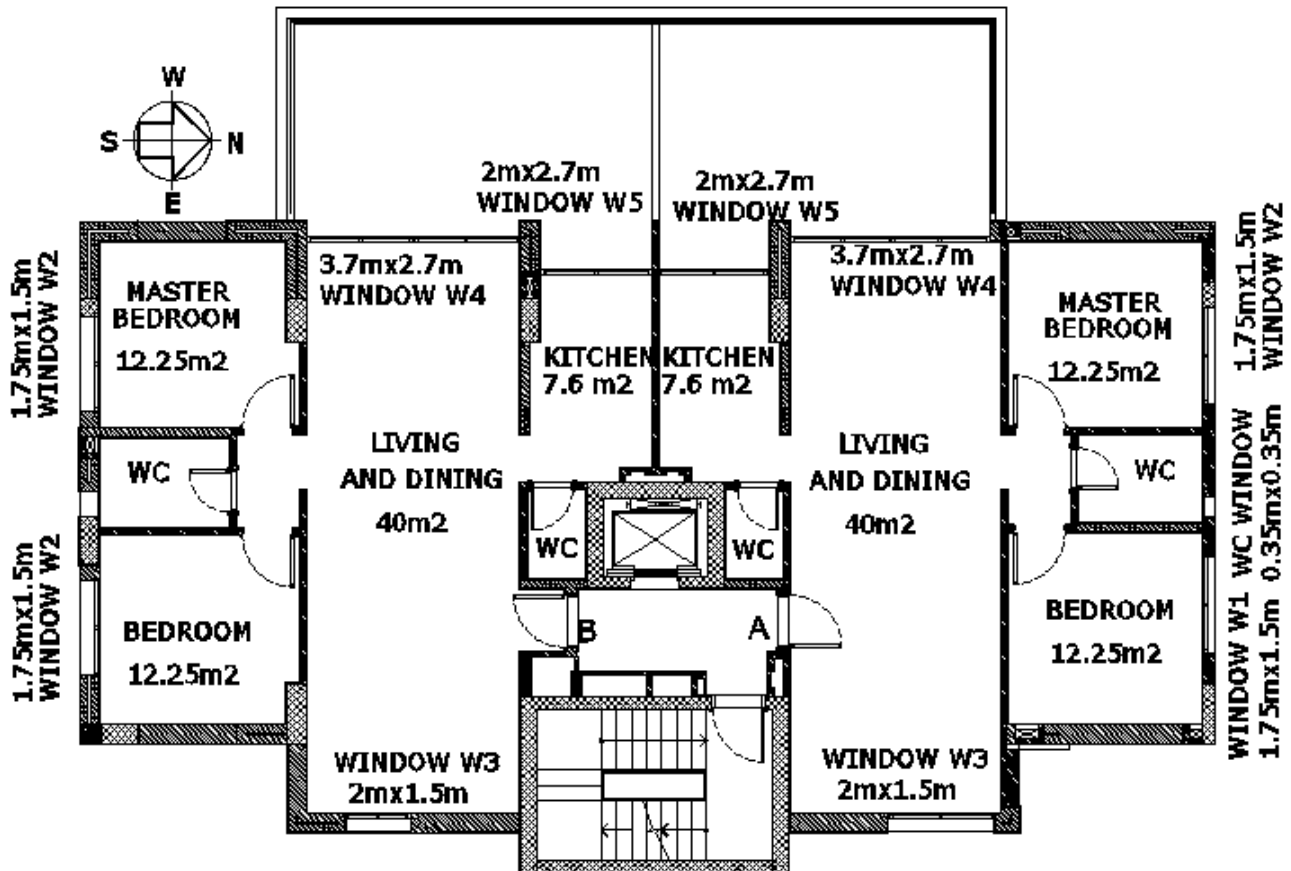


Figure 3. 1 Typical floor plan of the base case building

The thermo-physical characteristics of building's envelope are represented in Table 3. 2. WWR at Northern, Southern, Eastern and Western façades are 22%, 22%, 25% and 84% respectively. Windows use insulating double glazing with Argon 4/16/4, having a U-value of 1.4 W/m².K and a g-value of 0.6, without shading devices, overhangs nor blinds.

Table 3. 2 Thermo-physical characteristics of building's envelope (Properties: data source [207])

Building envelope	Components	Thickness	Thermal Conductivity	Density	Specific Heat
Overall U-Value	(From inside to outside)	(cm)	(W/m.K)	(kg/m ³)	(J/kg·K)
External Wall 0.46 W/m ² .K	Plaster	2	0.72	1860	840
	Concrete masonry unit	10	1.3	2240	800
	Extruded Polystyrene	5	0.029	29	1210
	Concrete masonry unit	15	1.3	2240	800
	Plaster	2	0.72	1860	840
Internal Wall 3.30 W/m ² .K	Plaster	2	0.72	1860	840
	Concrete masonry unit	10	1.3	2240	800
	Plaster	2	0.72	1860	840
Internal Floor 2.65 W/m ² .K	Marble	0.8	3.5	2800	1000
	Lime mortar	0.3	0.87	1800	1000
	Sand gravel	0.5	0.7	1800	1000
	Reinforced concrete	30	1.8	2500	840
	Plaster	2	0.72	1860	840
Ground 2.60 W/m ² .K	Marble	0.8	3.5	2800	1000
	Lime mortar	0.3	0.87	1800	1000
	Sand gravel	0.5	0.7	1800	1000
	Waterproofing	-	-	-	-
	Extruded Polystyrene	0	0.029	29	1210
	Reinforced concrete	30	1.8	2500	840
	Plaster	2	0.72	1860	840
Roof 1.58 W/m ² .K	Reinforced concrete	15	1.8	2500	840
	Extruded Polystyrene	1	0.029	29	1210
	Waterproofing	-	-	-	-
	Asphalt roll	0.5	0.75	1100	1510
	Plaster	2	0.72	1860	840

Each apartment is housing a family of four persons, the adopted occupants' schedule of presence in living and dining room, kitchen and bedrooms is represented in Figure 3. 2.

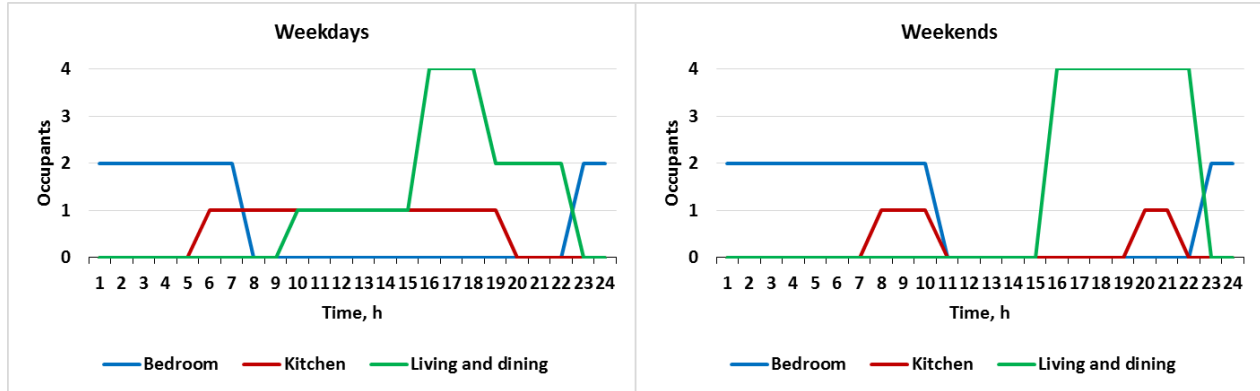


Figure 3. 2 Occupants’ schedule of presence in living and dining, kitchen and bedrooms

The infiltration rate for a single-family home at low leakage level is 0.4 ACH at 4 Pa according to EN 15242 [2]. The adopted unoccupied hour ventilation rate in this model is 0.075 L/s.m². During occupied hours the minimum specified ventilation air change rate, for new residential buildings with a normal level of expectation, is 0.42 L/s.m² assuming continuous operation and complete mixing of air [2].

The lighting illuminance level for residential buildings is chosen based on recommendations of EN 12464-1 [242]. An illuminance level of 100 lux is chosen for bedrooms and 200 lux for kitchens and dining rooms. Fluorescent lighting fixtures with a luminous efficiency of 60 lm/W are implemented corresponding to occupants’ schedule of presence. The adopted electric appliances in each apartment include a computer, TV in living rooms, washing machine, refrigerator, electric oven, extraction hood in kitchens, and toilet exhaust fans. The hourly appliances electrical consumption is given in Figure 3. 3 [207,243].

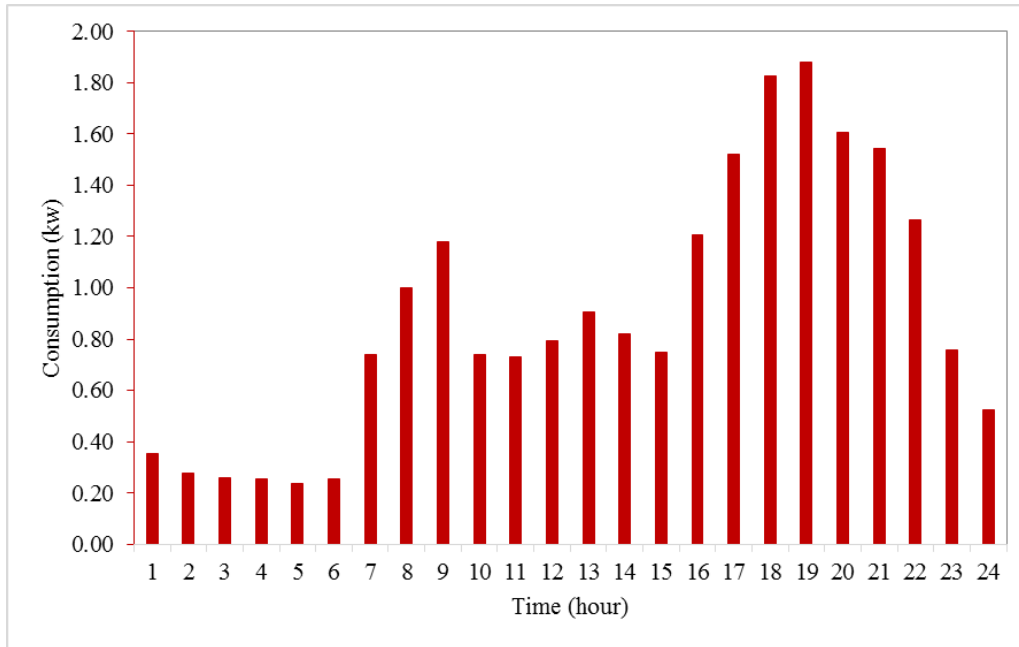


Figure 3. 3 Hourly appliances consumption (kW) (Data source: [207,243])

Based on the type of building, a consistent interval for indoor operative temperature (T_i) is recommended by EN 15251 [233] in order to appropriately dimension cooling and heating systems. For recent residential building, the recommended T_i in living space under the metabolic rate of 1.2 met are as follows: T_i ($^{\circ}\text{C}$) = 20-25 $^{\circ}\text{C}$ for heating (Clothing \sim 1 clo) and T_i ($^{\circ}\text{C}$) = 23-26 $^{\circ}\text{C}$ for cooling (Clothing \sim 0.5 clo). The settings for sizing cooling and heating systems are respectively the upper and lower values of the comfort range, i.e. 26 $^{\circ}\text{C}$ and 20 $^{\circ}\text{C}$ according to occupants' schedule of presence. In this study an air source heat pump of COP = 2.9 and gas boiler of 98.3% efficiency are used as cooling and heating systems. Commonly, humidification or dehumidification is desired only in distinctive buildings like industries, health care facilities, museums etc. [233]. So, humidification and dehumidification are turned off in this model.

2.2. Investigated climates

In this work, the Köppen-Geiger climates classification is adopted [244]; Figure 3. 4. This classification divides the world into five main climatic zones based on the average annual precipitation, the average monthly precipitation, and the mean monthly temperature. The zones are A: equatorial, B: arid, C: warm temperate, D: snow, and E: polar. The level of precipitation is defined as W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, and m: monsoonal. Besides, the temperature is provided as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, and F: polar frost. In the current study, one city of each dominant climatic zone is selected. Table 3. 1 presents the twenty-five selected cities’ geographical information in addition to cooling degree days (CDD) and heating degree days (HDD). The CDD 10°C and HDD 18°C are computed using TRNSYS software. The degree days are the sum (on a yearly basis) of the temperature difference between the average daily outdoor temperature and a base temperature which is the indoor temperature that a cooling/heating system should compensate to satisfy the comfort requirements.

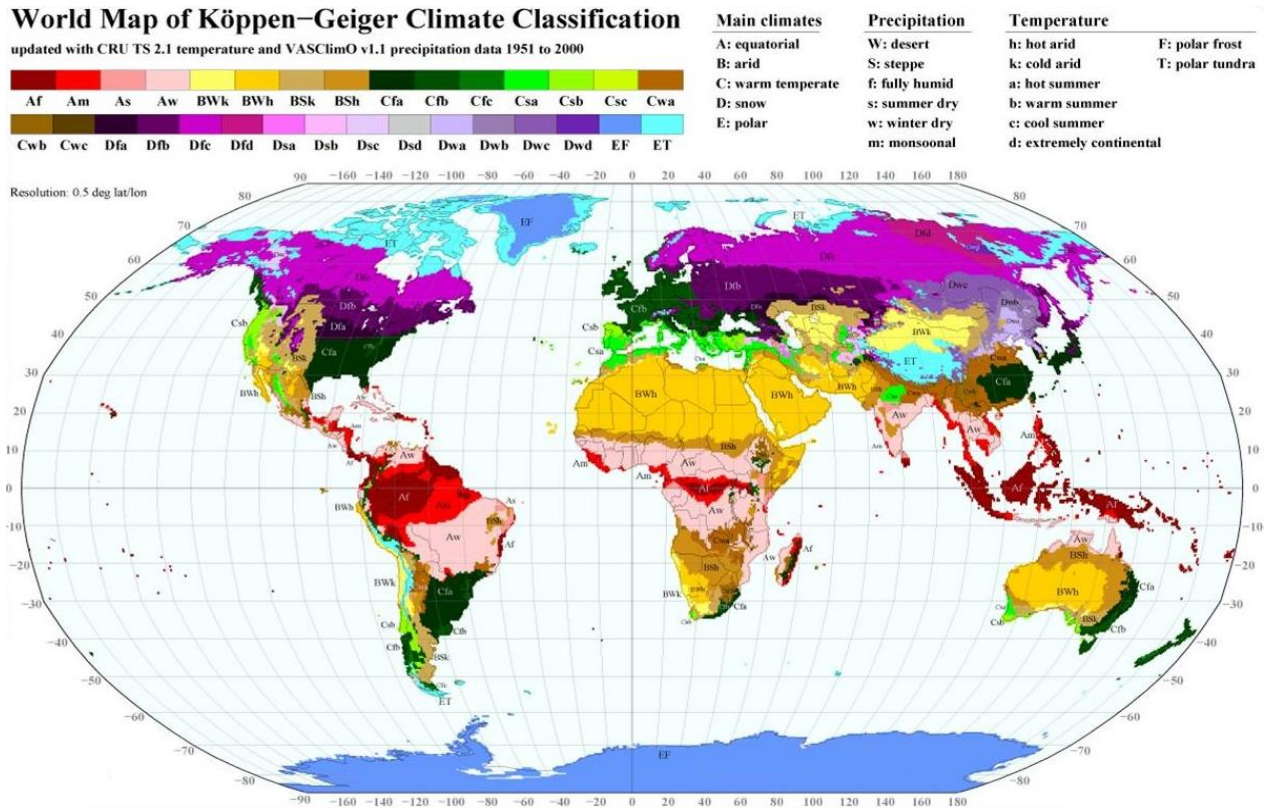


Figure 3. 4 World Map of Köppen–Geiger climate classification [244]

Table 3. 3 Selected cities and climate characteristics (Data source: [244,245])

Climatic Zone	City	Altitude (m)	Longitude, Latitude	CDD base 10°C	HDD base 18°C
Af	Singapore	16	104.00°E, 1.03°N	6058	0
Am	Douala (Cameroon)	5	9.70°E, 4.00°N	6037	0
As	Indore (India)	567	75.80°E, 22.70°N	5400	54
Aw	Caracas (Venezuela)	43	66.98°W, 10.60°N	5819	0
BSh	Dakar (Senegal)	20	17.47°W, 14.73°N	5242	0
BSk	Baku (Azerbaijan)	5	49.85°E, 40.38°N	2262	2091
BWh	Abu Dhabi (UAE)	27	54.65°E, 24.43°N	6068	28
BWk	Esfahan (Iran)	1590	51.67°E, 32.62°N	2826	1895
Cfa	Milan (Italy)	103	9.28°E, 45.43°N	1528	2651
Cfb	Nancy (France)	212	6.20° E, 48.70° N	907	3228
Csa	Sacramento (USA)	8	121.5° W, 38.5° N	2349	1467
Csb	Ankara (Turkey)	902	32.88°E, 39.95°N	1607	2735
Csc	Cedars (Lebanon)	1832	36.03°E, 34.25°N	1539	2605
Cwa	New Delhi (India)	212	77.20°E, 28.58°N	5454	230
Cwb	Kunming (China)	16	102.70°E, 25.00°N	1814	202
Dfa	Sapporo (Japan)	17	141.33°E, 43.05°N	1183	3808
Dfb	Montreal (Canada)	133	73.62°W, 45.50°N	1126	4507
Dfc	Tromso (Norway)	102	18.95°E, 69.65°N	120	5525
Dfd	Kotelny Island (Russia)	11	137.90°E, 76.00°N	0	12073
Dsa	Hakkari (Turkey)	1720	43.77°E, 37.57°N	1663	3425
Dsb	Dras (India)	3100	75.76°E, 34.43°N	620	5921
Dwa	Beijing (China)	55	116.28°E, 39.93°N	2125	3046
Dwb	Khabarovsk (Russia)	87	135.17°E, 8.52°N	1021	6126
Dwc	Chita (Russia)	671	113.33°E, 52.02°N	576	7593
ET	Barentsburg (Norway)	75	14.22°E, 78.07°N	0	8517

3. Simulation of the base case model

The building annual energy consumptions, costs, and comfort are simulated using TRNSYS software, according to the above-mentioned design conditions. In order to evaluate the building model cost-effectiveness, LCC is adopted. LCC is the most frequent method to estimate financial benefits of energy conservation projects over their lifetime [47,214]. The LCC is given by:

$$LCC (\$) = IC + USPW (N, rd) \times EC \tag{Eq. 3. 1}$$

$$USPW (N, rd) = \frac{1 - (1 + rd)^{-N}}{rd} \tag{Eq. 3. 2}$$

where, IC stands for the initial cost of implementing design and operating conditions for building envelope in addition to heating, ventilation and air conditioning (HVAC) system (\$), USPW (N, rd) is the uniform series present worth factor (it converts future recurrent expenses to present costs) (years), Rd is the annual discount rate (%), N stands for the life period (year), and EC is the annual energy cost essential to maintain building’s indoor comfort for the selected design and operating conditions (\$).

Herein, the life period and discount rate are set to 30 years and 5% respectively [140]. The implementation costs of different design options are represented in Table 3. 4. Figure 3. 5 represents the average energy costs of electricity and gas in each of the investigated cities. It is worth mentioning that the implementation costs of various materials are just indicative due to the potential change of prices in the market.

Table 3. 4 Implementation costs of base case design options (Data source:[47,116,216])

Specification	Options	Cost
Wall insulation, Roof insulation, Ground insulation	Expanded polystyrene	2.6 \$/m ² /cm
Glazing type for windows (U-value W/m ² .K,g-value)	Double glazing with Argon, 4/16/4 (1.4, 0.58)	110 \$/m ²
Air conditioning	-	221.78 \$/kW
Boiler	Condensing gas boiler (Efficiency=98.3%)	1900 \$/Unit

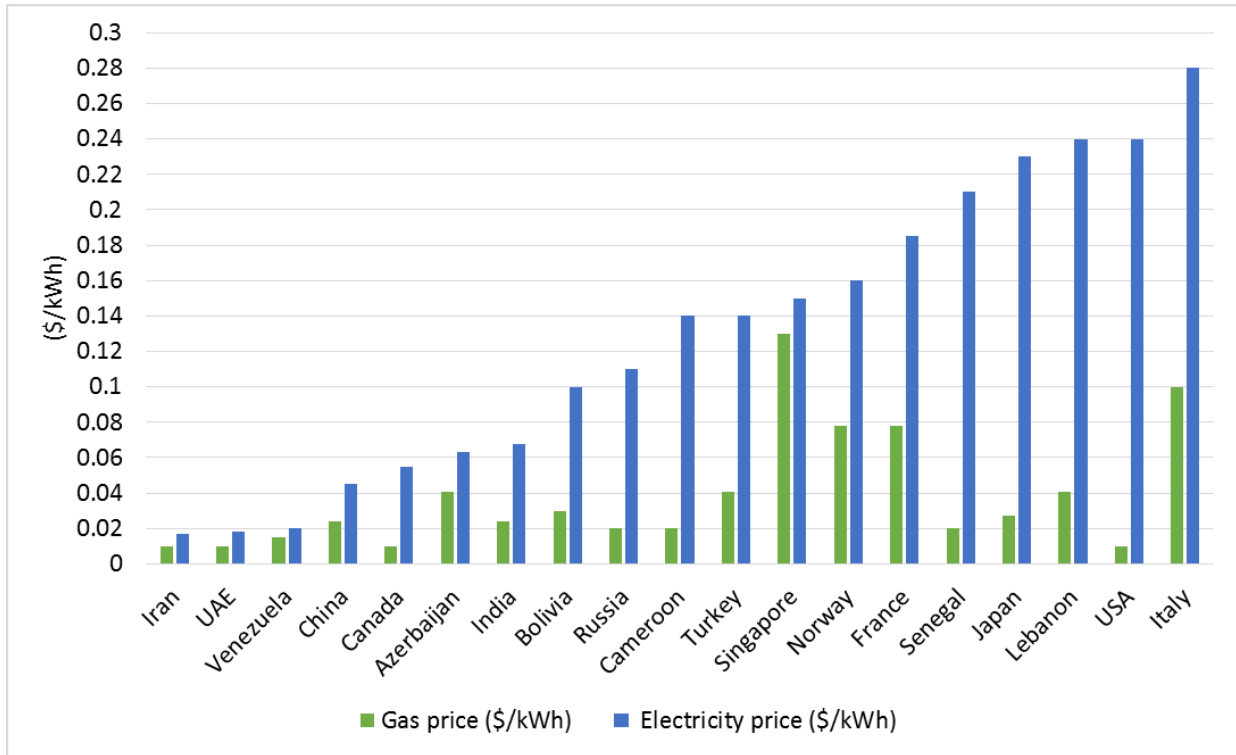


Figure 3. 5 Average energy costs (electricity and gas) in each of the investigated cities (Data source: [220,246–258])

The simulation phase steps through TRNSYS simulation tool are represented in Figure 3. 6.

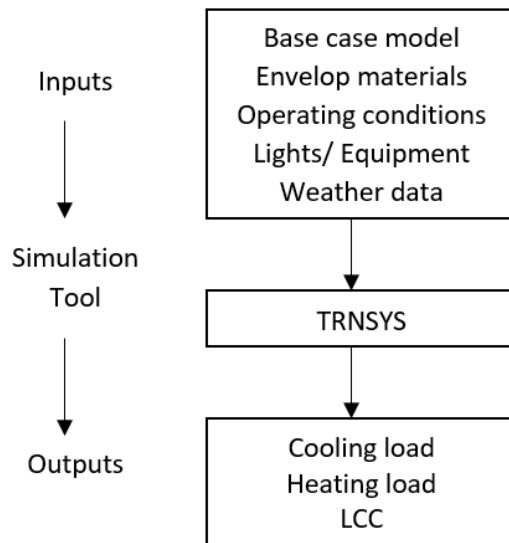


Figure 3. 6 Simulation phase steps to evaluate thermal loads and LCC

Figure 3. 7 represents the annual cooling loads (Q_{cool}), heating loads (Q_{heat}) and 30-years LCC of the base case building in each of the investigated climates.

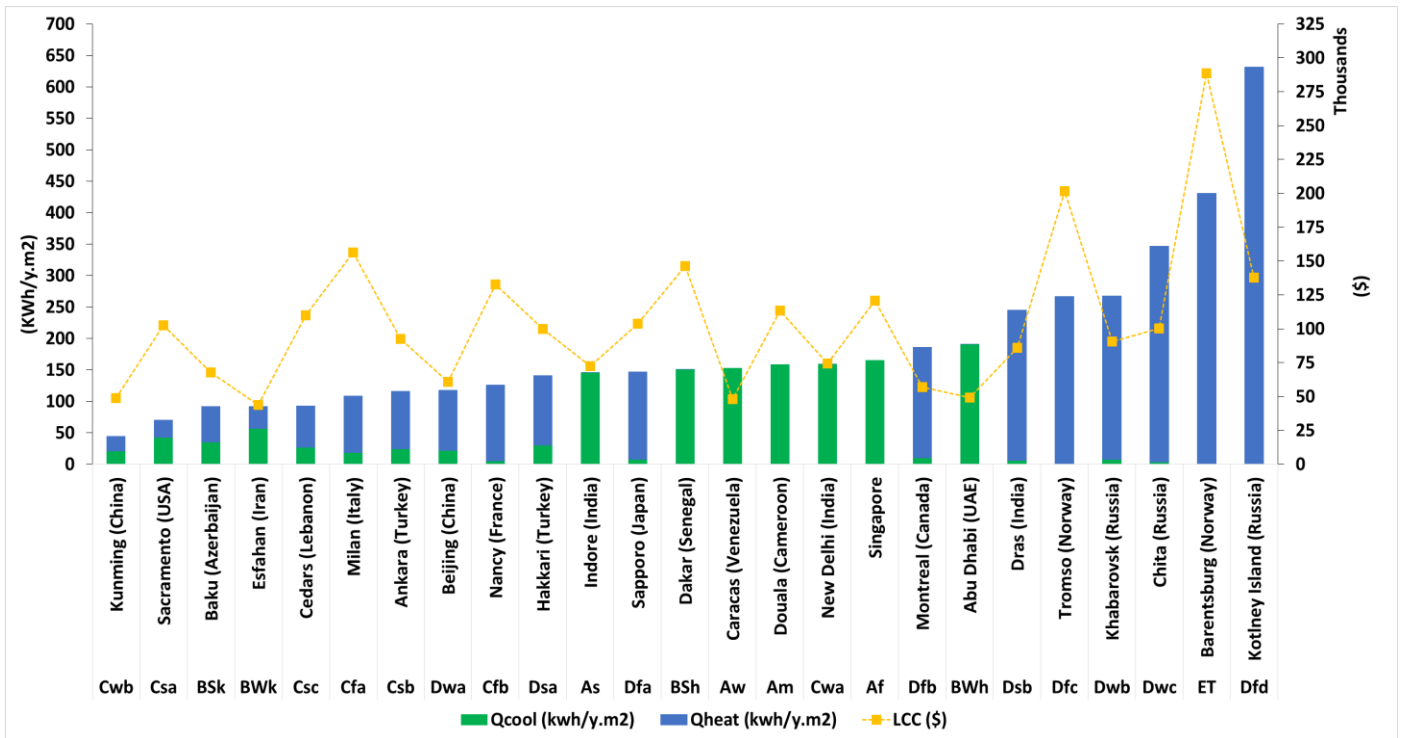


Figure 3. 7 Evaluated Qcool (kWh/y.m²), Qheat (kWh/y.m²) and 30-years LCC (\$) for each of the investigated climates

Generally from Figure 3. 7 and Table 3. 3, it can be noticed that the cooling load ranges from less than 10 kWh/y.m² in climates where the CDD 10°C < 1200: Tromso, Barentsburg, Kotlney Island, Khabarovsk, Chita, Dras, Nancy, Sapporo, and Montreal, to more than 100 kWh/y.m² in climates where CDD 10°C > 3500: Indore, Dakar, Caracas, Douala, New Delhi, Singapore and Abu Dhabi. Conversely, the heating loads varies from less than 10 kWh/y.m² in climates where HDD 18°C < 250: Indore, Dakar, Caracas, Douala, New Delhi, Singapore and Abu Dhabi, to more than 100 kWh/y.m² in climates where HDD 18°C > 3250: Hakkarti, Nancy, Sapporo, Montreal, Dras, Tromso, Barentsburg, Kotlney Island, Khabarovsk, and Chita.

It is clear from Figure 3. 5 and Figure 3. 7 that the LCC mainly depends on two conditions: thermal loads and energy prices in each region. The LCC ranges from less than 50000 \$ in Kunming (low thermal loads and energy prices), Esfahan (low thermal loads and energy prices), Caracas (low energy prices) and Abu Dhabi (low energy prices), up to triple, to more than 150000 \$ in Milan (high energy prices), Tromso and Barentsburg in Norway (high thermal loads and relatively high gas prices). Even though the thermal load in Milan is the half when compared to other cities such

as Dras, Khabarovsk, Chita and Kotelny Island, the LCC is so much higher due to the high gas cost in Italy (0.1 \$/kWh).

Hence, the importance of building multi-objective optimization (MOO) is in taking into account all factors including energy prices and envelope construction materials prices, to ameliorate the base case building energy, economic and comfort performances in each of the investigated climates.

From the above, three categories of cities might be derived as shown in Table 3. 5. The categories rely on the dominating presence of cooling and/or heating loads in each climate. Category 1 is dominated by heating loads with cooling loads less than 10 kWh/y.m². Conversely, category 2 is dominated by cooling loads with heating loads less than 10 kWh/y.m². Furthermore, category 3 corresponds to mixed climates where both cooling and heating loads coexist. Each category will be examined separately in order to simplify the finding of one optimal solution related to the dominant load. Noting that when comparing the above categorization with ASHRAE climates classification [259], categories 1, 2 and 3 refer to ASHRAE thermal zones 6 to 8, 0 to 2 and 3 to 5 respectively.

Table 3. 5 Categorization of investigated climatic zones

Category 1 Heating dominant	Category 2 Cooling dominant	Category 3 Mixed climate
Nancy (Cfb)	Indore (As)	Baku (BSk)
Sapporo (Dfa)	Caracas (Aw)	Esfahan (BWk)
Montreal (Dfb)	Douala (Am)	Milan (Cfa)
Tromso (Dfc)	Singapore (Af)	Sacramento (Csa)
Kotlney Island (Dfd)	Dakar (BSh)	Ankara (Csb)
Khabarovsk (Dwb)	Abu Dhabi (BWh)	Cedars (Csc)
Chita (Dwc)	New Delhi (Cwa)	Hakkari (Dsa)
Dras (Dsb)		Beijing (Dwa)
Barentsburg (ET)		Kunming (Cwb)

4. Optimization phase

In this study, the optimization is carried out using TRNSYS coupled with MOBO, a Multi-Objective Building Optimization tool developed by Palonen et al. [179]. On the building optimization judgment, MOBO shows promising competences and might become the main optimization engine in coming years, as mentioned by Nguyen et al. [104]. The building simulation and optimization phase steps are summarized in Figure 3. 8.

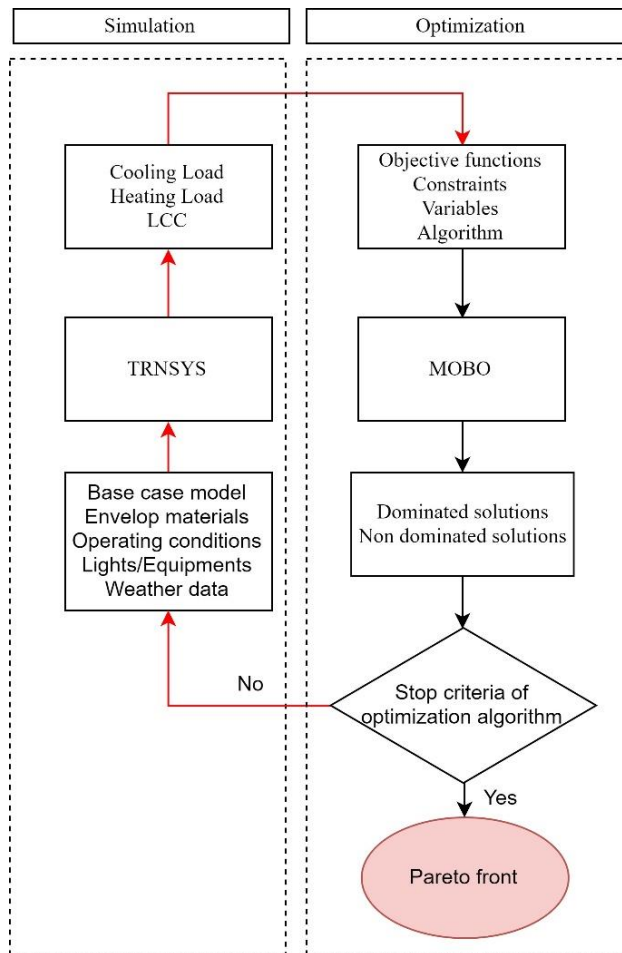


Figure 3. 8 Building simulation and optimization phase steps

4.1.Objective functions

The adopted objective functions in this optimization problem are to minimize building heating load, cooling load, and LCC. Hence, the optimization problem can be summarized as follows:

$$\left\{ \begin{array}{l} \text{Min (Qheat)} \\ \text{Min (Qcool)} \\ \text{Min (LCC)} \end{array} \right\} \quad \text{Eq. 3. 3}$$

4.2. Decision variables

The purpose of this research work is to obtain the optimal passive design solution for the considered residential building model in different climates. From the literature review [5,31,40,47,82,84,92,97,106,107,109,110,112,115,126,129,131–133,136,138–142,146–148,151,156,157,188,222–230], the most suitable design variables to investigate in this work, including their different values, are shown in Table 3. 6. Furthermore, the implementation costs of different investigated materials are represented in Table 3. 4 and Table 3. 7.

Table 3. 6 Description and different options of decision variables used in the optimization problem

Variable	Value 1	Value 2	Value 3	Value 4	Value 5
External walls U-value (W/m2.K)	0.2	0.3	0.4	0.5	0.6
Roof U-value (W/m2.K)	0.2	0.3	0.4	0.5	0.6
Ground U-value (W/m2.K)	0.2	0.3	0.4	0.5	0.6
WWR at each façade: N, S, E and W (%)	10	30	50	70	90
Glazing Type at each façade: N, S, E and W (U-value W/m2.K,g-value)	Double glazing with Krypton (0.86, 0.59)	Double glazing with Argon, low-e (1.26, 0.39)	Double glazing with Argon (1.4, 0.58)	Double glazing (2.83, 0.75)	Single glazing (5.68,0.85)

Table 3. 7 Implementation costs of different glazing options used for the optimization analysis (Data source:[47,116,216,220,248,250–256])

Specification	Options	Cost
Glazing type for windows (U-value W/m2.K,g-value)	Double glazing with Krypton, 4/16/4 (0.86, 0.59)	145 \$/m ²
	Double glazing with Argon, low-e 6/16/6 (1.26, 0.39)	120 \$/m ²
	Double glazing with Argon, 4/16/4 (1.4, 0.58)	110 \$/m ²
	Double glazing, 4/16/4 (2.83, 0.75)	66 \$/m ²
	Single glazing (5.68,0.85)	45 \$/m ²

4.3.Optimization algorithm

The NSGA-II, developed by Deb et al. [180], is a MOO algorithm that can be used in building’s optimization [181]. The NSGA-II performs greater than the NSGA in terms of distance to the true Pareto front, size of hyper-volume and spread of optimal points [182,183]. Further overview on the application of NSGA II, could be found in literature [4,114,129,133,142,180,184–191]. NSGA-II main process includes population generation, fitness evaluation, and ranking according to crowding distance (estimation of how near an individual is to its neighbors, a large crowding

distance reveals a high degree of diversity), elitist selection, bimodal crossover, and mutation [133,142].

The input setting parameters of the NSGA-II adopted in this work is listed in Table 3. 8. These parameters are selected based on the preliminary researches to get the best compromise between the Pareto-front accuracy and the optimization computational time [142].

Table 3. 8 Input setting parameters of NSGA-II

Parameter	Value
Population size	40
Generation number	25
Crossover probability, %	70
Mutation probability, %	2

4.4.Optimization results

In MOO, there is not a practical solution that minimizes/maximizes all objective functions simultaneously. Consequently, more emphasis is paid to Pareto optimal solutions which are not dominated by any other solutions and cannot be upgraded with respect to any objective without worsening at least one objective.

The Figures from 9 to 13 illustrate the projection of Pareto fronts in Qcool, Qheat, and LCC plans. Generally, it could be noticed that the scattering of each of the projections for each category is almost parallel in all cities. Even though some scatters are shifted with respect to each other due to particular climates specifications and energy prices.

Figure 3. 9 and Figure 3. 10 illustrate the projection of categories 1 and 2 Pareto fronts in Qheat, LCC, and Qcool, LCC spaces. It is clear that the dispersion of Pareto points is similar in some regions and different in other ones. For example, the Pareto front in Barentsburg is reduced to very close points, which means that there is a unique solution which minimizes both objectives, Qheat and LCC, at the same time. The same case is found in Caracas, Douala, and Singapore.

The conflict between the three objective functions for all cities of category 3, where both heating and cooling loads exist, is projected on *Qcool*, *Qheat* and *LCC* plans in order to simplify the analysis; Figure 3. 11, Figure 3. 12, and Figure 3. 13. It is obvious from Figure 3. 11 that cooling and heating loads are mostly inversely proportional, except in Beijing and Esfahan where the dispersion of Pareto front points seems to be random. The randomness distribution form of the Pareto front in some scatters is due to the projection in the 2D-space. Some points may appear to be dominated while in fact, they are not. Furthermore, it is noticed that the cooling load and the

LCC are almost directly proportional as revealed in Figure 3. 12. Contrariwise, the heating load and the LCC are inversely proportional as shown in Figure 3. 13. This is because electricity is more expensive than gas in all cities and because of the inverse relationship between cooling and heating loads.

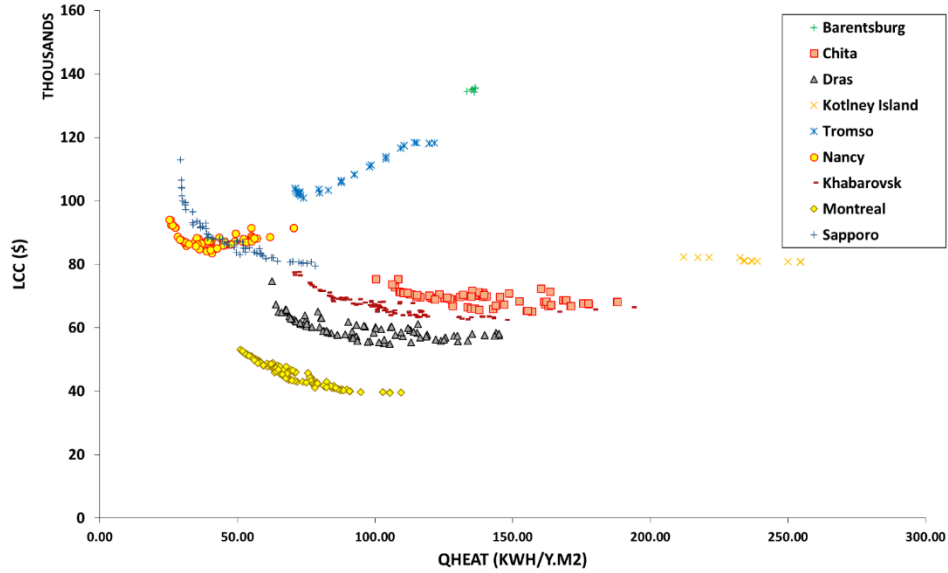


Figure 3. 9 Projection of “Category 1” Pareto front in (Qheat, LCC) 2D-space

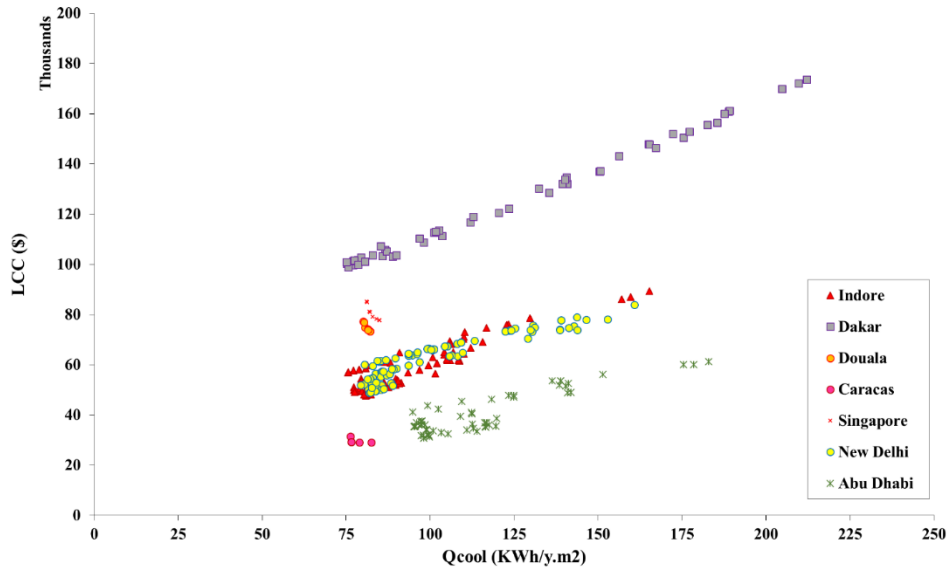


Figure 3. 10 Projection of “Category 2” Pareto front in (Qcool, LCC) 2D-space

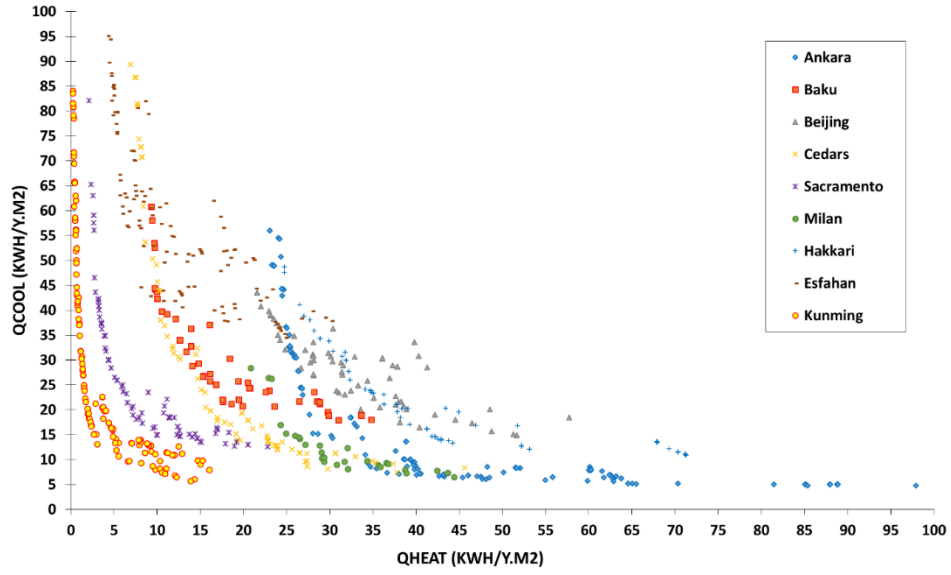


Figure 3. 11 Projection of “Category 3” Pareto front in (Qheat, Qcool) 2D-space

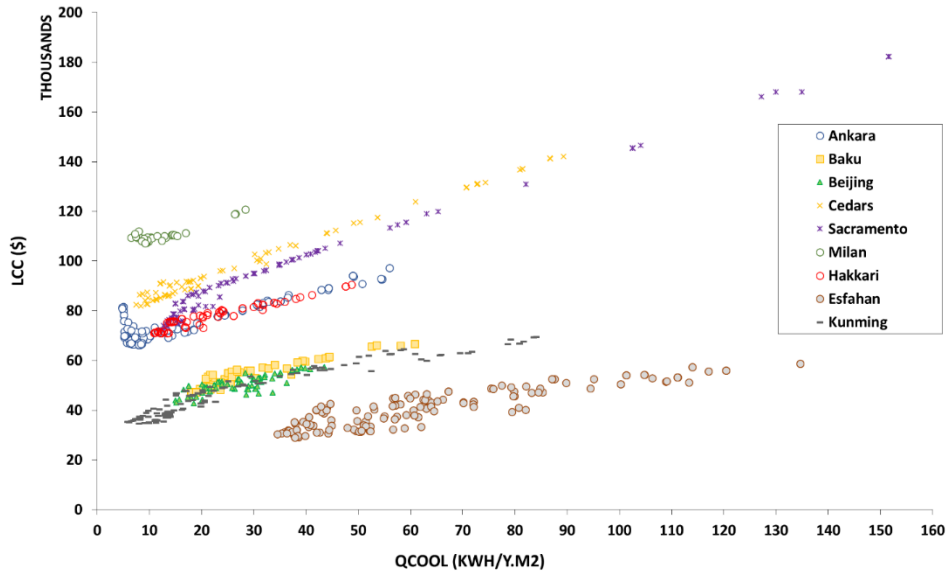


Figure 3. 12 Projection of “Category 3” Pareto front in (Qcool, LCC) 2D-space

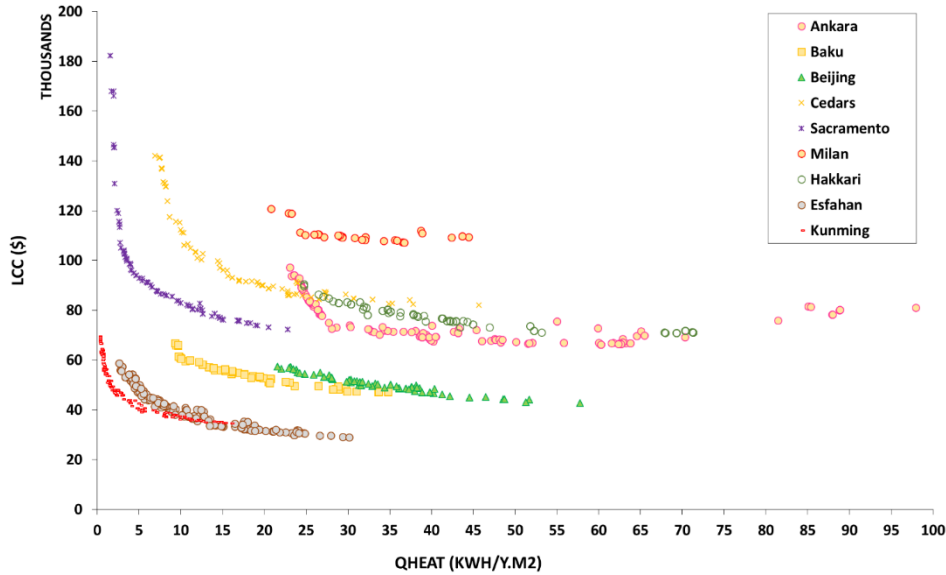


Figure 3. 13 Projection of “Category 3” Pareto front in (Qheat, LCC) 2D-space

5. Optimal solution selection using multi-criteria decision making (MCDM)

Although the Pareto front is found, the ultimate solution of the MOO problem involves the explicit integration of the DM preferences over the different objective functions. In this work, it is decided to use ELECTRE III outranking method [194,260]. The extensive employment of this method in the literature [165,178,194–198,200–202,261,262] against other MCDM techniques, made it the best option to implement in the MCDM phase. Starting with the sets of Pareto front obtained for each category, results of the MOO problem, indifference, preference and veto thresholds of each set are calculated accordingly as 5%, 10%, and 30% with respect to the average of each objective function. On the other hand, the objective functions weights are calculated by means of the AHP method developed by Saaty [178,203].

5.1. Sensitivity analysis

Since the final result might be heavily influenced by the weights assigned to each objective function, it is useful to perform a sensitivity analysis to identify how the final optimal solution would have changed if the weights would have been different. This is a key phase of the process and, generally, no eventual decision should be taken without performing sensitivity analysis. So as to evaluate the robustness of the optimized solution ranking from the DM point of view, seven different cases are chosen. Table 3. 9 represents the relative weights for each case of objective functions’ importance level.

Table 3. 9 Relative weight of each objective function for different DM preferences

Cases	Importance level	Weights		
		Qheat	Qcool	LCC
Case 1	Qheat~Qcool~LCC	0.33	0.33	0.33
Case 2	Qheat > (Qcool, LCC) Qcool~LCC	0.60	0.20	0.20
Case 3	Qcool > (Qheat, LCC) Qheat~LCC	0.20	0.60	0.20
Case 4	LCC > (Qheat, Qcool) Qheat~Qcool	0.20	0.20	0.60
Case 5	Qheat~Qcool (Qheat, Qcool)> LCC	0.43	0.43	0.14
Case 6	Qheat~LCC (Qheat, LCC)> Qcool	0.43	0.14	0.43
Case 7	Qcool~LCC (Qcool, LCC)> Qheat	0.14	0.43	0.43

After applying ELECTRE III on each of the found Pareto fronts for different cities and for different cases of objective functions' weights, the frequent best-ranked solutions are derived. Figure 3. 14 represents the case of Singapore-category 2. S6, S7, and S8 in the figure correspond to the 6th, 7th and 8th Pareto front points.

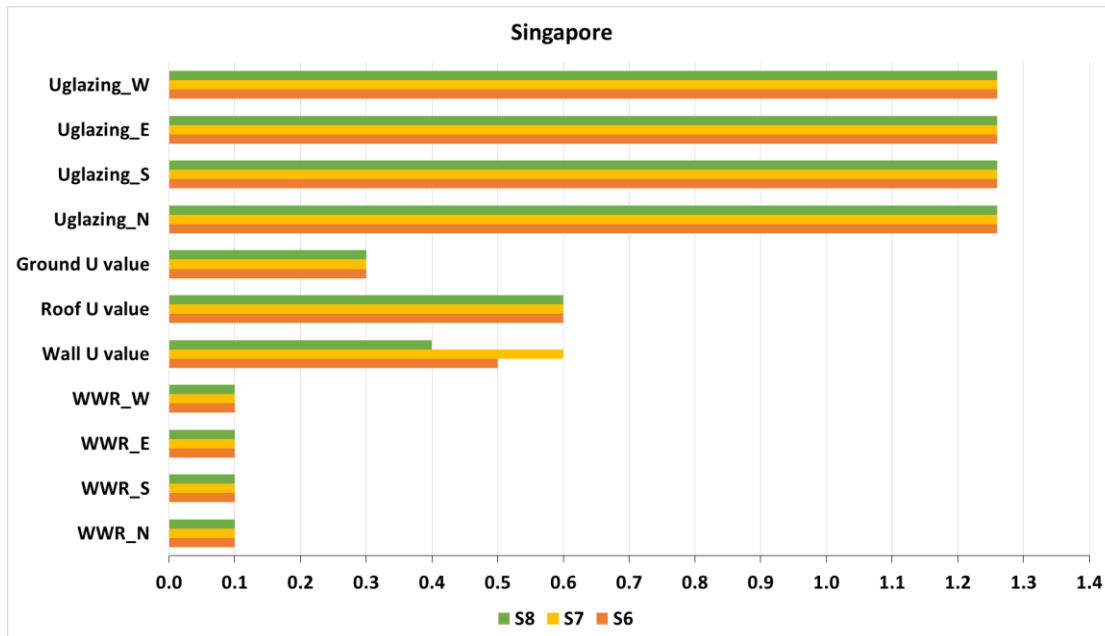


Figure 3. 14 Frequent solutions after ELECTRE III application for Singapore-Category 2

As it could be seen, the sensitivity analysis approves the results since the ranking of the Pareto optimal points does not change significantly in most cities. For example, in Chita, Nancy, Sapporo, Barentsburg and New Delhi the obtained ranking of the optimal point is the same no matter the DM preferences. The sensitivity analysis phase steps are summarized in Figure 3. 15.

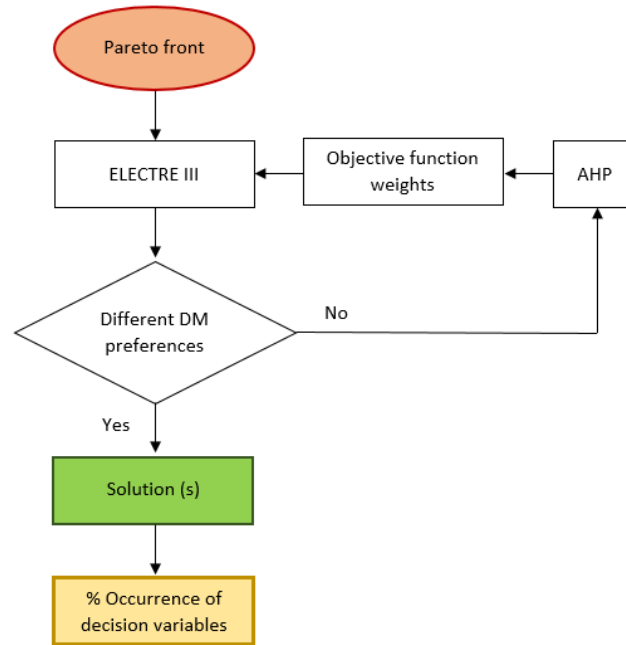


Figure 3. 15 Sensitivity analysis phase steps

Afterward, the percentage of times at which each decision variable has occurred in the final solutions is derived for each category. The decision variables with the highest percentage of occurrence are selected to be the optimal solutions representative for each category (Table 3. 10). This choice is justified to simplify the finding of only one recommended ultimate solution. Next, the decision variables of Table 3. 10 are implemented in the model for different cities and their impact on each objective function, relative to the base case, is examined (Table 3. 11).

Table 3. 10 Optimal decision variables with the highest percentage of occurrence

Category	WWR (%)				U-Value (W/m ² .K)			Ug (W/m ² .K)			
	North	South	East	West	Wall	Roof	Ground	North	South	East	West
1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	1.26	1.26	1.26	1.26
2	0.1	0.1	0.1	0.1	0.6	0.6	0.5	1.26	1.26	1.26	1.26
3	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.86	0.86	1.26	1.26

Table 3. 11 Summary of building energy and LCC savings

Region	Qcool (kWh/y.m ²)		Qheat (kWh/y.m ²)		LCC (1000\$)	
	Optimal case	% savings	Optimal case	% savings	Optimal case	% savings
Category 1						
Kotelny Island	0.00	-	221.61	65%	86.25	37%
Barentsburg	0.00	-	141.54	67%	139.67	52%
Tromso	0.01	98%	76.11	71%	105.20	48%
Chita	2.01	39%	118.83	65%	73.22	27%
Nancy	4.05	20%	32.06	74%	88.45	33%
Dras	2.70	51%	80.93	66%	62.81	27%
Sapporo	7.30	-3%	43.70	69%	89.61	14%
Khabarovsk	6.63	11%	90.82	65%	70.84	22%
Montreal	7.91	20%	58.44	67%	52.30	8%
Category 2						
Dakar	68.61	54%	0.00	-	93.88	36%
Indore	74.65	49%	0.00	-	48.48	33%
New Delhi	87.51	45%	2.76	-92%	50.61	32%
Singapore	89.87	46%	0.00	-	81.52	32%
Abu Dhabi	99.60	48%	0.00	-	32.25	34%
Caracas	81.22	47%	0.00	-	31.62	34%
Douala	87.15	45%	0.00	-	77.04	32%
Category 3						
Milan	13.77	23%	24.91	73%	111.96	28%
Beijing	20.45	5%	32.59	66%	52.89	13%
Sacramento	23.72	44%	5.33	81%	93.03	9%
Ankara	16.92	29%	22.89	75%	73.76	20%
Cedars	14.82	44%	18.73	72%	92.70	16%
Hakkari	18.65	37%	36.71	67%	78.14	22%
Baku	24.69	29%	15.35	73%	56.53	16%
Esfahan	37.48	33%	9.87	73%	43.09	1%
Kunming	13.21	36%	3.22	87%	47.14	3%

5.2.Discussion on optimal solutions

It is commonly agreed that the passive design requirements vary with the climates. In severe cold climates where the heating is the main load, category 1, the temperature inside the building is typically greater than the outside. Consequently, heat is dissipated through the building envelope. Thus, it is effective to restrict the heat loss through a high level of insulation. Hence, it makes sense the selection of low U-value 0.2 W/m².K for building walls, roof, and ground and

1.26 W/m².K for windows. On the other hand, the selection of the correct WWR is essential. The WWR is limited to 10% at each façade, because even the highest performing glazing, triple glazing with $U_g = 0.86$ W/m².K for example, has a much higher U-value than a typical wall ($U < 0.6$ W/m².k).

In hot climates, category 2, it is not necessary to resort to high levels of insulation in walls, roof, and ground. As shown in Table 3. 10, the acceptable U-values of walls, roof and ground are in the range of 0.6 W/m².K, 0.6 W/m².K and 0.5 W/m².K respectively. This is because the insulated envelope restrains the dissipation of the internal heat gains to the exterior ambient at off-peak temperatures. Thus, the heat will be stored in the building which contributes to an increase of the cooling loads. So, the thermal insulation of building envelope in hot climates has a restrictive role. On the other hand, a low WWR and low emissivity double glazing (U-value of glazing (U_g) = 1.26 W/m².K) are required to ensure the limitation of heat transmitted through windows from outside. For category 3, where both cooling and heating loads coexist, it could be noticed that walls and roof must be well insulated (U-Value = 0.2 W/m².K). Inversely, the U-value of ground (0.3 W/m².K) should not be decreased to the maximum with the aim to allow the heat escape through the ground in summer. The low WWR (10%), and well-insulated glazing are optimal to keep as low as possible the heat loss through windows to/from the external environment.

It should be mentioned here that the indoor natural lighting, which is directly affected by the WWR, is not addressed in this study. Even a low value of WWR (10%) is appreciated to enhance the building energy performance, but in practice, it must be accurately determined according to the indoor lighting requirements.

The results obtained in Table 3. 11 reveal that the objective functions were significantly improved after optimization. It is obvious that the implementation of the optimal combination of envelope passive design parameters leads to considerable energy and LCC savings.

In cold climates, the reduction of annual heating load ranges from 65% in Kotelny Island and Khabarovsk up to 74% in Nancy compared to the base case building model. Likewise, the annual cooling load savings for hot climates vary from 45% in New Delhi and Douala up to 54% in Dakar. For category 3, the heating load reaches a value less than 15 kWh/y.m² in Milan, Cedars and Kunming, while the cooling load becomes less than 10 kWh/y.m² in Sacramento, Esfahan, and Kunming. Consequently, the reduction of thermal loads leads to a clear decrease of LCC in all cities.

The National Renewable Energy Laboratory (NREL) [263] developed a benchmark for low energy building’s envelope. When comparing the obtained optimal decision variables in this study with the benchmark recommendation, it can be noticed that the results are within the acceptable range for most passive parameters; see Table 3. 12. Noting that the slight difference is due to the fact that the LCC is one of the objective functions to be minimized in this study.

Table 3. 12 Comparison of the optimal decision variables with the benchmark recommendation

Category	WWR		Ug (W/m ² .K)		U (W/m ² .K)					
					Walls		Roof		Ground	
	Optimal	Benchmark	Optimal	Benchmark	Optimal	Benchmark	Optimal	Benchmark	Optimal	Benchmark
1			1.26	1.98	0.2	0.27-0.31	0.2	0.11	0.2	0.15-0.2
2	10%	15%	1.26	2.1	0.6	0.43	0.6	0.18	0.5	0.43
3			0.86-1.26	1.98	0.2	0.31-0.43	0.2	0.15	0.3	0.2-0.3

Most previous studies on building envelope optimization are limited to keep as low as possible the energy demands without considering the occupants’ comfort. Thus, the next paragraph will be concerned with inspecting occupant’s adaptive comfort in the optimized building for each city, as well as the integration of adequate passive cooling strategies (blinds and/or natural ventilation) to guarantee occupants’ thermal comfort.

6. Thermal comfort evaluation

In this section, a thermal assessment is performed to inspect the impact of optimal passive designs on indoor thermal comfort. It is essential to ensure a comfortable indoor climate regardless of the outdoor climate. In this study, the thermal comfort is investigated alone without being implemented within the optimization problem as a constraint. The intention behind this step is to ensure the comfort of each room separately and to visualize what is happening in each room after implementing successively the optimal designs, then the passive cooling strategies, and finally controlling the AC system. On the other hand, this choice demonstrates the fact that even though the minimal thermal loads and LCC are attained, it doesn’t mean that the low energy building is now comfortable for occupants.

6.1. Adaptive comfort model

Buildings' energy consumption is strongly dependent on the benchmarks adopted during the design phase for internal cooling and/or heating set points, ventilation rates, lighting, systems operation and comfort analysis. The European standard EN 15251 [233], adopted in this study, specifies different criteria for thermal comfort as well as indoor air quality according to the indoor level of expectation.

In residential building, for periods during which the cooling system is turned off (or do not exist), the acceptable indoor operative temperature's upper and lower limits, $T_{i\ max}$ and $T_{i\ min}$, are derived as a function of the exponentially weighted running mean of outdoor dry-bulb air temperature (T_{rm}) as follows in Eq. 3. 4, Eq. 3. 5, and Eq. 3. 6 [233]. Where, T_{ed-k} is the daily mean external temperature for the k th previous day.

$$T_{i\ max} = 0.33T_{rm} + 18.8 + 3; 10^{\circ}\text{C} < T_{rm} < 30^{\circ}\text{C} \quad \text{Eq. 3. 4}$$

$$T_{i\ min} = 0.33T_{rm} + 18.8 - 3; 15^{\circ}\text{C} < T_{rm} < 30^{\circ}\text{C} \quad \text{Eq. 3. 5}$$

$$T_{rm} = (1 - \alpha)(T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} \dots); \alpha \text{ is recommended to be } 0.8 \text{ [233]} \quad \text{Eq. 3. 6}$$

The long-term assessment of the thermal comfort conditions according to EN ISO 7730 is estimated based on the method "Percentage outside the range" [264]. In order to avoid the overheating, i.e. uncomfortable hot feelings, the percentage of occupied hours during which the difference ($T_i - T_{i\ max}$) is greater than or equal to 1°K during the period from May to September inclusive shall not surpass 3% in each room [265]. The optimal model's overheating level is tested for all cities of categories 1, 2 and 3 accordingly. Then the percentage of overheating hours of the whole building is computed according to Eq. 3. 7.

$$\% \text{ overheating hours} = \frac{\sum \text{occupied overheating hours in all rooms}}{\sum \text{occupied hours in all rooms}} \quad \text{Eq. 3. 7}$$

The overheating percentage is zero in all cities of category 1. Figure 3. 16 illustrates the percentage of overheating hours for categories 2 and 3. It can be noticed that the percentages of overheating hours range from 43% in Dakar (Hot semi-arid climate) up to 81% in Singapore (Tropical rainforest climate), and from 27% in Milan (Humid subtropical climate) up to 45% in Esfahan (Cold desert climate). Afterward, to lessen the obtained high discomfort values, some passive

cooling strategies (blinds, natural ventilation) are integrated into the model to find the appropriate combination that decreases the discomfort level to the minimum.

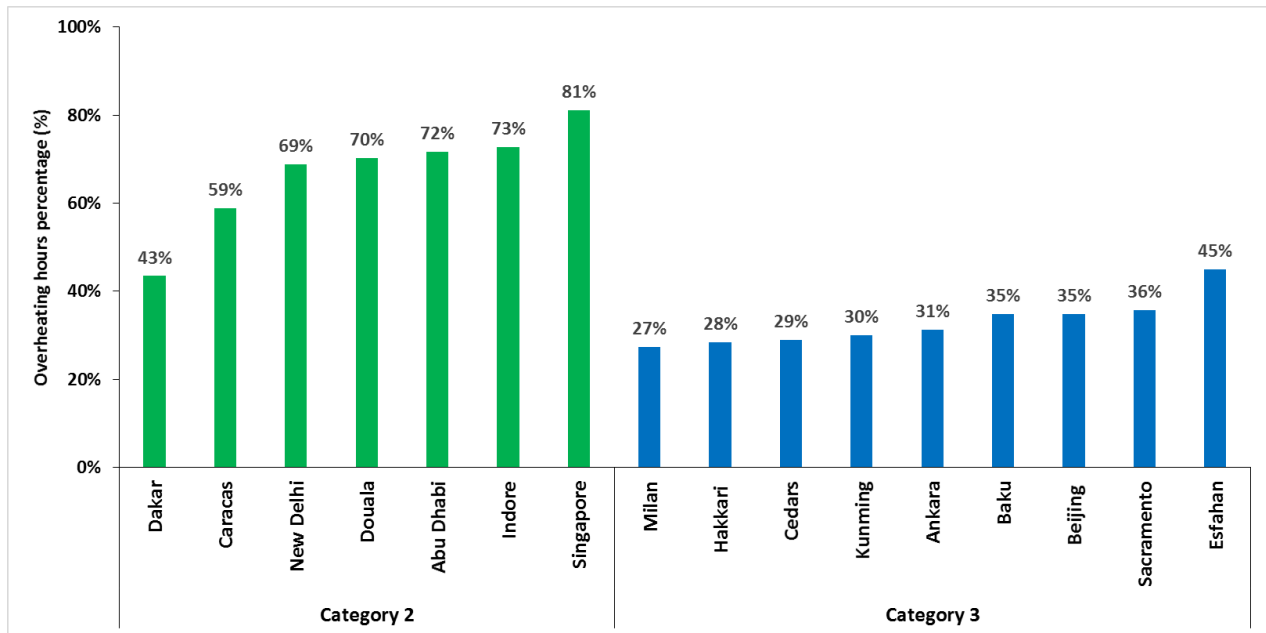


Figure 3. 16 Percentage of overheating hours for categories 2 and 3

6.2. Enhancement of occupants adaptive comfort, cooling load and LCC

In this section, passive cooling strategies including blinds and natural ventilation are investigated to examine their influence on overheating hours, cooling load, and LCC. Other conditions that may influence the control of natural ventilation and blinds, such as glare evaluation, illumination level from the sun, external natural views, and psychology of occupants, are not addressed in this study.

The integrated blinds are external white color roller shutters from ISOTRA [266]. Blinds characteristics according to the standards CSN EN 13363-1+A1 are as follows: reflectivity = 0.7, absorption capacity = 0.3, total solar transmittance factor = 0.047, and reduction coefficient = 0.061. The selection of an external shade is due to its better performance in decreasing the cooling loads than the internal ones [267].

Natural ventilation is an effective passive cooling strategy to reduce cooling demand in buildings. The natural ventilation through windows is due to wind and buoyancy effect. Natural ventilation performance is measured through the air change rate. Gidds and Phaff [268] derived the air change

rate (Air Changer per Hour, ACH) in terms of parameters related to the external environment, window size, and room volume as given by Eq. 3. 8.

$$ACH = \frac{1}{2} \times \frac{3600}{V} \times A_w \times \sqrt{0.001 V_w^2 + 0.0035 H \Delta T + 0.01} \tag{Eq. 3. 8}$$

Where V is the room’s volume (m^3), A_w is the window area (m^2), H is the window height (m). V_w stands for the site mean wind speed (m/s) and ΔT is the mean temperature difference between inside and outside ($^{\circ}K$).

The main challenge associated with natural ventilation design is to find the best flow rate (% of window opening) and the time during which the window must be opened in order to appropriately adjust its control. The obtained minimum sufficient air flow rates of natural ventilation including the control settings are summarized in Table 3. 13.

Table 3. 13 Options of passive cooling design strategies

Strategy	Passive strategies	Control settings
0	No Passive strategies	
1	Blinds during daytime	Category 2: All months Category 3: May-October
2	Ventilation ACH=1, nighttime 9 PM-6 AM	Category 2: Bedrooms, Living, and dining: April-November Kitchen: All months
3	Ventilation ACH=1, all hours	
4	Ventilation ACH=1.5, nighttime 9 PM-6 AM	Category 3: Bedrooms, Living, and dining: May-October Kitchen: All months
5	Ventilation ACH=1.5, all hours	

The presented different cases of natural ventilation are combined with the case of blinds to find the best configuration that ensures the maximum occupants’ comfort. Afterward, in case the passive cooling strategies are not able to ensure the requested occupants’ adaptive comfort during the occupied periods, the AC is turned ON at $26^{\circ}C$ in the room where the overheating could not be treated. The corresponding percentage of window opening might be controlled using Eq. 3. 8. For example, under the weather conditions of Indore region, 1 ACH corresponds to 10% of the window opening in bedrooms and 15% of windows opening in kitchen and living room. Table 3. 14 summarizes the recognized best passive cooling strategies combination for each city. Moreover, the updated percentage of overheating hours is calculated accordingly and represented in Figure 3. 17.

Table 3. 14 Summary of the optimal passive cooling design strategies for each city

City	Passive Strategies	City	Passive Strategies
Category 2		Category 3	
Indore	All rooms: Strategy 1 + Strategy 2	Baku	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 2
Caracas	Bedrooms: Strategy 0 Kitchen: Strategy 1+ Strategy 4 Living and dining: Strategy 4	Esfahan	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 2
New Delhi	All rooms: Strategy 1	Milan	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 2
Singapore	Bedrooms: Strategy 0 Kitchen: Strategy 1 Living and dining: Strategy 1 + Strategy 2	Sacramento	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 4
		Ankara	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 4
Dakar	Bedrooms: Strategy 0 Kitchen: Strategy 1+ Strategy 3 Living and dining: Strategy 1	Cedars	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 5
Abu Dhabi	All rooms: Strategy 1+ Strategy 4	Hakkari	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 3
Douala	Bedrooms: Strategy 0 Kitchen, Living and dining: Strategy 1+ Strategy 4	Kunming	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 3
		Beijing	Bedrooms, Living and dining: Strategy 1 Kitchen: Strategy 1+ Strategy 2

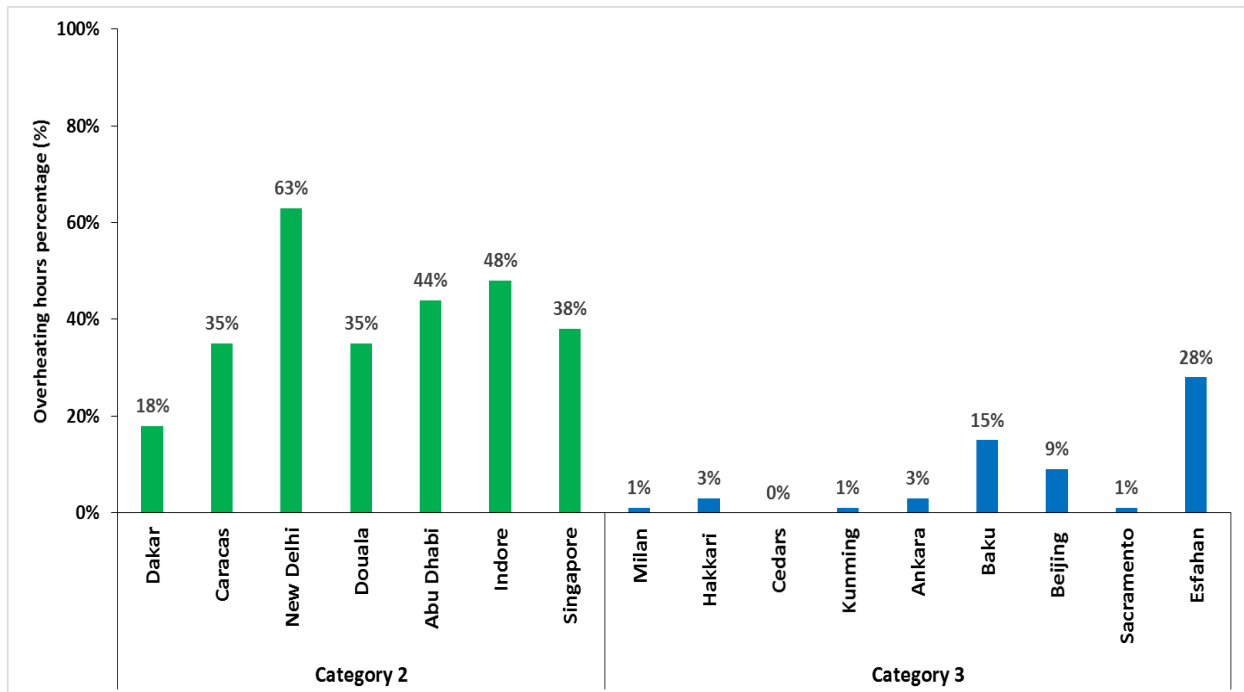


Figure 3. 17 Percentage of overheating hours after implementing the passive cooling strategies

It could be observed that the implementation of passive cooling strategies is practical since the overheating diminution is considerable in almost all cities. The major decrease is found in Singapore, where the introduction of blinds in kitchen and living rooms in addition to the nighttime ventilation (ACH=1) in living room leads to an overheating percentage decrease of 43%. On the other hand, it is clear that the building's average overheating percentage is almost eliminated in many cities of category 3 as shown in Figure 3. 17. The best combinations allow reduction of overheating to become lower than 3% in Milan, Hakkari, Kunming, Ankara, and Sacramento. Besides, 0% overheating is found in Cedars where the AC is no longer crucial. Moreover, the optimal model was sufficient to guarantee the bedrooms' adaptive comfort in Caracas, Singapore, Dakar and Douala climates. The blinds in bedrooms and living room are enough to ensure occupants' comfort in all cities of category 3, see Table 3. 14.

Contrariwise, it is noticed that the natural ventilation in New Delhi doesn't significantly influence the comfort, the natural ventilation plays a drawback role by increasing the cooling needs. Besides, introducing blinds in all rooms of the building in New Delhi is found to be the best solution to slightly decrease the discomfort level from 69% to 63% of overheating hours.

It is important to mention that the increase of the ventilation rate is not a necessary condition to obtain better energy or comfort performances. The nighttime natural ventilation is a fundamental passive cooling strategy for decreasing discomfort as well as cooling load in zones with high internal heat generation such as kitchens.

It can be observed from Table 3. 15 the months during which the AC is switched ON in each room, since the optimal passive cooling strategies failed to completely ensure the occupants' adaptation. It is clear that the AC is turned OFF in bedrooms and living room in all cities excluding Indore, Abu Dhabi, and New Delhi. While in kitchen, where there is a high internal heat generation, the AC must be switched ON for all the year in some regions such as Caracas, Douala, and Singapore. According to results in Table 3. 16, one can notice that the percentages of cooling load savings are considerable, with savings exceeding 50% in all regions except in Indore (13%) and New Delhi (27%).

It is worth mentioning that even though one optimal passive parameters combination is derived for each category (Table 3. 10) when talking about occupants' comfort, each climate has its own scenario and must be treated separately (Table 3. 15 and Table 3. 16).

Table 3. 15 Summary of AC control months in each room

Category	City	AC ON at 26°C		
		Bedrooms	Living and dining	Kitchen
2	Indore	March-September		February-November
	Caracas	OFF	OFF	January-December
	Douala	OFF	OFF	January-December
	Singapore	OFF	OFF	January-December
	Dakar	OFF	OFF	May-November
	Abu Dhabi	April-July		March-September
	New Delhi	May-August	April-September	March-November
	Baku	OFF	OFF	June-August
3	Esfahan	OFF	OFF	May-September
	Milan	OFF	OFF	June-August
	Sacramento	OFF	OFF	June-August
	Ankara	OFF	OFF	June-August
	Cedars	OFF	OFF	OFF
	Hakkari	OFF	OFF	July-August
	Kunming	OFF	OFF	April-August
	Beijing	OFF	OFF	June-August

Table 3. 16 Summary of buildings' cooling load, LCC, and savings after introducing passive cooling strategies and taking into account the occupants' adaptive comfort

Category	City	Cooling Load (kWh/y.m2)	% Savings against optimal case	LCC (1000\$)	% Savings against optimal case
2	Indore	48.92	43%	44.40	8%
	Caracas	33.25	59%	28.37	10%
	Douala	31.72	64%	58.03	25%
	Singapore	33.87	62%	61.18	25%
	Dakar	19.98	71%	69.41	26%
	Abu Dhabi	42.42	57%	30.07	7%
	New Delhi	63.77	27%	46.73	8%
	Baku	6.05	76%	53.79	5%
3	Esfahan	11.81	68%	41.35	4%
	Milan	2.74	80%	105.47	6%
	Sacramento	3.59	85%	81.16	13%
	Ankara	4.51	73%	69.58	6%
	Cedars	0.00	100%	84.13	9%
	Hakkari	3.61	81%	73.56	6%
	Kunming	3.15	76%	45.69	3%
	Beijing	5.89	71%	51.00	4%

7. Conclusion

The high potential of buildings towards energy efficiency has drawn special attention to the passive design parameters and passive strategies. In the present chapter, a multi-objective decision making optimization is performed on a residential building model under twenty-five different climates of Köppen-Geiger classification. Climates are classified into three categories according to the dominant load (heating, cooling, or both) with the aim to recommend one optimal solution for each category. The implemented methodology is composed of four steps: building energy simulation, optimization, MCDM, and sensitivity study to test the robustness of the obtained optimal result, in addition, passive strategies integration to ensure the occupants' adaptive comfort. The desired envelope optimal solution is that which minimizes at the same time the building's cooling and/or heating and LCC. A wide range of passive design parameters is investigated including wall and roof insulation levels, windows glazing type and WWR at all facades. Besides, to ensure adaptive thermal comfort by decreasing overheating hours, both external shading devices and natural ventilation are examined.

This study has shown that, in severely cold climates, it is efficient to restrict the heat flow through a high level of insulation. Hence the selection of low U-value of $0.2 \text{ W/m}^2\cdot\text{K}$ for building walls, roof, and ground and $1.26 \text{ W/m}^2\cdot\text{K}$ for windows. However, in hot climates, the thermal insulation of building envelope has a restrictive role. It is not needed to use high levels of insulation in walls, roof, and ground. The appropriate U-values of walls, roof and ground are $0.6 \text{ W/m}^2\cdot\text{K}$, $0.6 \text{ W/m}^2\cdot\text{K}$ and $0.5 \text{ W/m}^2\cdot\text{K}$ respectively. In mixed climates, it is noticed that walls and roof must be well insulated (U-Value = $0.2 \text{ W/m}^2\cdot\text{K}$), whereas the U-value of ground ($0.3 \text{ W/m}^2\cdot\text{K}$) should not be decreased to the minimum with the aim to allow the heat evacuation through the ground in summer. Even a low value of WWR (10%) is valuable to enhance the building energy performance, but in practice, it must be accurately determined according to the indoor lighting requirements.

The implementation of the optimal combination of envelope passive design parameters leads to considerable energy and LCC savings. The reduction of annual heating loads, cooling loads and LCC reached up to 87% in Kunming, 54% in Dakar and 52% in Barentsburg respectively compared to the base case model.

Moreover, the integrated passive cooling strategies, blinds and natural ventilation, have demonstrated their competency since they lead to significant cooling load savings that exceeded 50% in almost all regions against the optimal design model. Furthermore, it is clear that the

building's average overheating percentage is almost eliminated depending on the category, it becomes lower than 3% in Milan, Hakkari, Kunming, Ankara, and Sacramento, while 0% overheating is found in Cedars where the AC is no longer crucial. Moreover, the optimal model is sufficient to guarantee the bedrooms' adaptive comfort in Caracas, Singapore, Dakar, and Douala climates. Blinds in bedrooms and living room are enough to ensure occupants' comfort in mixed climates. The nighttime natural ventilation with $ACH = 1-1.5$ is a fundamental passive cooling strategy for decreasing discomfort as well as cooling load in kitchens.

Chapitre 4: Conception optimale des systèmes énergétiques et de production d'énergies renouvelables pour les bâtiments à consommation énergétique nette nulle

Résumé en Français

Le développement des BCENN est considéré comme une solution efficace pour limiter la consommation croissante d'énergie et les émissions polluantes des bâtiments. Les caractéristiques des systèmes énergétiques et de production d'ER adoptés dans les BCENN doivent être sélectionnées avec soin pour garantir l'objectif de performance prévu.

Pour aider les concepteurs de BCENN, ce chapitre étudie, optimise et compare de façon systématique, six ensembles de systèmes énergétiques et de production d'ER pour passer d'un bâtiment à basse consommation énergétique (chapitre précédent), à un BCENN, dans trois régions représentative des climats a besoin de refroidissement dominant (Indore), a besoin de chauffage dominant (Tromso) et mixte (Beijing). Les ensembles de solutions étudiés comprennent les systèmes de production d'énergie fréquemment mis en œuvre dans la littérature. L'optimisation est réalisée à l'aide de la méthodologie d'ADM introduite au chapitre 2. La performance des BCENN est évaluée en termes de performance combinée, composée d'indicateurs économiques (coût sur le cycle de vie, coût actualisé de l'énergie, délai de retour sur investissement), environnementaux (émissions en CO₂eq), énergétiques (indice d'autosuffisance énergétique, indice de réponse à la demande énergétique), et d'indicateur liés au réseau (indice d'interaction au réseau).

Il a été constaté que, en plus de l'utilisation d'une surface appropriée de panneaux photovoltaïque et/ou d'éoliennes résidentielles dans toutes les régions, à Indore, l'ensemble de solutions composé de capteurs solaires thermiques et d'une pompe à chaleur à source froide sur l'air intérieur est bénéfique en termes de fiabilité, d'indépendance et de faible tension vis-à-vis du réseau de distribution électrique et de respect de l'environnement. En termes de rentabilité économique, il est recommandé d'utiliser un générateur utilisant du biodiesel couplé à un refroidisseur à absorption. A Tromso, l'utilisation d'un générateur à biodiesel est prometteuse en termes d'adaptation aux besoins électriques, de faible contrainte sur le réseau et de rentabilité économique. D'autre part, l'utilisation de pompes à chaleur géothermiques est recommandée du fait des très faibles émissions de CO₂eq et d'une couverture importante du besoin de chauffage. Enfin, à Beijing, l'adoption de pompes à chaleur géothermique est bénéfique en termes de fiabilité, de faible tension sur le réseau et d'indépendance mensuelle sur le réseau de distribution et de

respect de l'environnement, alors qu'en termes de faisabilité économique, l'ensemble de solutions composé d'un refroidisseur électrique et d'une chaudière à gaz naturel à condensation est relativement rentable.

Ce chapitre est basé sur l'article de revue :

Fatima Harkouss, Farouk Fardoun, Pascal Henry Biwole. Optimal design of renewable energy solution sets for net zero energy buildings, preprint, 2018

Chapter 4: Optimal design of renewable energy solution sets for net zero energy buildings

Abstract

Net-zero energy buildings (NZEBs) have been considered as an efficient solution to limit the growing energy consumption and pollution emissions from buildings. The configurations and the capacities of the implemented renewable energy systems in NZEBs should be wisely selected to ensure the intended performance objective. This study aims to optimize, investigate and compare six renewable energy solution sets for designing NZEBs in Indore (cooling dominant), Tromsø (heating dominant), and Beijing (mixed climate). The optimization is carried out using a multi-criteria decision making methodology. The implemented methodology is composed of two phases. In the first phase, the optimal sizes of solution sets in each climate are derived and analyzed. The effectiveness of optimal solution sets is evaluated with respect to economy, environment, energy and grid stress. In the second phase, recommendations for each region are offered according to the overall performance evaluation results. The evaluation criteria include: life cycle cost, payback period, levelized cost of energy, CO₂eq emissions, grid interaction index, load matching index, and total energy consumption. The analyses show that, in Indore, the solution set composed of flat plate solar collectors and air source heat pump is beneficial in terms of reliability, low grid stress, monthly independency on the utility grid and environment-friendly. Meanwhile, in terms of economic feasibility, it is recommended to use biodiesel generator with a thermally driven absorption chiller. In Tromsø, the use of biodiesel generator is promising in terms of high load matching, low grid stress, and economic feasibility. On the other hand, the utilization of solar assisted ground source heat pump is convenient with regard to very low CO₂eq emissions and significant load coverage. In Beijing, the adoption of ground source heat pump is beneficial in terms of reliability, low grid stress, monthly independency on the utility grid and environment-friendly. Although, in terms of economic feasibility, the solution set composed of an electric chiller and natural gas condensing boiler is relatively profitable

Keywords: Net zero energy building, Optimization, Decision making, Renewable energy systems, Climate, Load matching index, Grid interaction index, Pollution, Economy

1. Introduction

Globally, energy security conservation and environment protection have become fundamental due to the growing demand on sustainable energy and social development. Net-zero energy buildings (NZEBs) have been considered as an efficient solution to limit the growing energy consumption and pollution emissions from buildings, the third-largest energy consumer [1].

Researchers worldwide are evaluating and optimizing the integration of renewable energy (RE) systems in NZEBs. The configurations and capacities of the implemented RE systems in NZEBs must be wisely selected to guarantee the intended performance objective. Garde et al. [269], under the framework of the International Energy Agency (IEA) “Towards Net-Zero Energy Solar Buildings” program, reported 30 fully documented international NZEBs case studies. They aimed to develop, test and recommend NZEBs solution sets for cold, moderate and hot climates. An overview on some recently investigated RE energy generation systems, employed in NZEBs case studies and simulations, including optimized/enhanced systems’ components and adopted evaluation criteria is presented in Table 4. 1. From the literature review, it can be observed that the inspected evaluation criteria suggested for NZEBs’ performance assessment are various and address a diversity of needs. The indicators are related to (i) energy self-sufficiency: load matching index, energy saving ratio, design mismatch ratio, NZE balance as well as embodied energy; (ii) environment: Carbon dioxide equivalent (CO_2eq) emissions as well as global warming potential (GWP); (iii) economy: Levelized cost of energy (LCOE), life cycle cost (LCC), net present value (NPV), investment costs, operational costs, cost/benefit ratio, simple payback period as well as energy payback period; (iv) grid stress impact: grid interaction index, contribution of electricity generated by RE to the grid as well as energy transmitted from grid to ZEB in addition to transmission losses; (v) others: heat pumps coefficient of performance (COP), exergy efficiency, solar thermal fraction, solar coverage, solar system efficiency, RE ratio as well as power losses. Moreover, the systems used to offset NZEBs’ cooling loads include but are not limited to the following: Electric chiller, absorption chiller with high temperature hot water supplied from evacuated tube solar collectors (ETSC), biodiesel generator (BDG) or biomass combined cool heat and power (CCHP), air sourced, ground sourced and solar assisted heat pumps (HP). Furthermore, the systems employed to cover NZEBs’ heating and domestic hot water (DHW) demands include the following: ETSC, flat plate solar collectors (FPSC), concentrating solar collector, solar air collector (SAC), ground source heat pump (GSHP), biomass fired boiler, biomass combined heat

and power (CHP), air source heat pump (ASHP), solar assisted GSHP and photovoltaic-thermal (PV/T). At last, the systems used to generate electricity in order to cover NZEB's electric demand and ensure the zero energy balance include but are not limited to: Photovoltaic (PV), PV/T, building integrated photovoltaic (BIPV), solar tracking PV, residential wind turbines (WT) and biomass CHP.

The objective of the current chapter is to optimize and evaluate six RE solution sets to go from low energy building to NZEB in one representative city of cooling dominant, heating dominant and mixed climates. The investigated solution sets include the frequently implemented or considered energy production systems. The optimization is carried out using a multi-criteria decision (MCDM) methodology [232]. Its main features include four steps: building simulation using, optimization process, MCDM and testing solution's robustness. The performance of NZEB is evaluated in terms of combined performance comprised of economic indicators (LCC, LCOE, and simple payback period), an environmental indicator (CO₂eq emissions), an energy balance and self-sufficiency indicator (load matching index), energy efficiency indicator (total energy consumption) and a grid stress indicator (grid interaction index). Therefore, this chapter aims to assist NZEB designers to select the suitable design options based on a systemic evaluation.

Firstly, basic information of the building model, design conditions, investigated climates and energy demands are introduced in section 2. Then, different investigated solution sets are presented in section 3. Subsequently, formulation of the optimization problem including methodology, objective functions, and decision variables is reported in section 4. The results from the optimization process are analyzed and recommendations for each investigated region are discussed in Section 5.

Table 4. 1 Some recently investigated NZEB energy production systems, and adopted evaluation criteria

Reference	Year	Region (Investigated load)	Building type	Energy production systems (Capacity)	Evaluation criteria
[270]	2018	Hong Kong (Cooling)	Hotel	PV (346 m ²) Battery (1000 kWh storage capacity) Water cooled chiller	Economic cost Load matching Grid interaction
			Office	WT (186 kW) Battery (1000 kWh storage capacity) Water cooled chiller	
			Shopping center	PV (200 m ²) WT (80 kW) Battery (1000 kWh storage capacity) Water cooled chiller	
[271]	2018	USA (Cooling-heating)	Residential	PV (10.24 kW) Option 1: ASHP (Cooling: 7 kW, COP: 2.92. Heating: 8 kW, COP: 3.78 + 10 kw Electric heater) + Dehumidification 2*PPSC (each 2.1 m ²) + HPWH + 3.8 kW resistive heating element. HRV or ERV: 195 m ³ /h, 0.15 ACH Option 2: GSHP (Cooling: 6.68 kW, COP: 4.4. Heating: 4.96 kW, COP: 3.5) + Dehumidification ERV: 195 m ³ /h, 0.15 ACH	Energy performance: Net energy, Energy saving ratio. Thermal comfort: PMV, PPD Payback period Heat pump annual COP
[227]	2017	Greece (Cooling-Heating)	University	HP (290 kW, COP=5.8) PV (470.11 m ²) AC (3.5 kW)	Payback period CO ₂ emissions Energy consumption
[137,272,273]	2017	Hong Kong (Cooling)	Construction Industry Council	PV (1015 m ²) BDG (100 kW) Absorption chiller (70 kW, COP: 0.7) 3*Electric chiller (70 kW, COP: 4.2)	Annual total cost CO ₂ emissions Grid interaction index Design mismatch ratio
[274]	2017	Japan (Not specified)	Residential	PV Batteries	Contribution: contribution of electricity generated by RE to the grid Dependence: Energy transferred from grid to ZEB including transmission loss

					Energy loss: Power loss through battery utilization Total CO ₂ emissions Electricity cost
[275]	2017	Ireland (Heating)	Residential	Case 1: Biomass boiler FPSC(6.46 m ²) PV (4 m ²) Case 2: HP FPSC (6.46 m ²) PV (2 m ²)	LCC Life cycle global warming potential Life cycle energy
[276]	2016	China (Cooling-Heating)	Office	PV (1759 m ²) Batteries GSHP (Cooling: 175 kW, COP: 5.9. Heating: 168 kW, COP: 4.5)	Energy production and consumption Payback period
[48]	2016	Ireland (Heating)	Residential	Gas boiler ETSC (3.23 m ²) PV	Global warming potential Construction costs Operational costs Embodied energy Operational energy
[277]	2016	China (Cooling-Heating)	Office	FPSC 2*GSHP (50 kW, 100 kW) Absorption chiller	Heat pump COP Supply and return water temperature for boreholes, heat pump and chiller.
[278]	2016	Hong Kong (Cooling)	Office + Hotel	PV (440 m ²) 15*WT (6 kW) Water cooled chiller	Initial cost Grid interaction index Failure time in which the supplied cooling cannot meet the cooling demand
[108]	2016	Hong Kong (Cooling)	Academic building	Water cooled chiller (Rated capacity: 195.91 kW, rated COP: 5.02) PV (1009 m ²) 13*WT (Rated power each 20 kW)	Annual energy balance reliability Grid stress Initial investment

[43]	2016	Kuwait (Cooling)	University department	<u>Scenario 1:</u> 4*Air cooled chiller (Capacity: 400 kW each, COP: 2) PV (3560 m ²) <u>Scenario 2:</u> 4*Water cooled chiller (Capacity: 350 kW each, COP: 3.5) PV (3560 m ²) <u>Scenario 3:</u> Solar cooling (ETSC (1264 m ²), absorption chiller (COP: 0.7), heat exchanger) PV (2296 m ²)	CO ₂ emission Simple payback period Energy payback period LCOE Solar thermal fraction Solar system efficiency
[113]	2016	Germany (Not specified)	Residential	Fossil fueled CHP PV	Grid impact NPV
[279]	2015	Hong Kong (Cooling)	-	PV (1015 m ²) WT (50 kW) BDG (100 kW) 3*Electric chillers (70 kW each) + Absorption chiller (COP: 0.7, 70 kW)	Total annualized cost CO ₂ emission Grid interaction index Mismatch ratio
[44]	2015	Norway (Heating)	Residential	PV (30 m ² , 6 kW) AWHP (7 kW)	Zero energy balance Solar thermal fraction
[105]	2015	Canada (Cooling-Heating)	Residential	Biomass boiler (200 kW) WT (73 kW)	RE ratio Net present cost CO ₂ emission
[88]	2015	Greece (Cooling-Heating)	Residential	PV (3 kW) SC (24 m ² in Florina, 16 m ² for Thessaloniki and 12 m ² for Athens and Heracleion + (Natural gas or fuel) boiler AC (COP: 3.5)	Payback period NPV Solar coverage Annual energy savings
[280]	2014	Romania (Not specified)	Multi-purpose building at university campus	Horizontal GSHP (10 kW) FPSC + ETSC PV (10 kW) Gas boiler	Initial investment cost Exploitation cost Payback time Cost/benefit ratio CO ₂ emission savings
[126]	2014	Lebanon (Cooling-Heating)	Residential	WT (10 kW) Battery DG (2 kW) PV/T (12 kW)	Net present cost Energy and exergy efficiencies LCOE CO ₂ emissions RE fraction
[281]	2014				

[282]	2014	Denmark, Sweden (Heating)	Residential	PV (10.6 kW in Denmark, 10 kW in Sweden) FPSC / HP	Load matching indicators: Load cover factor, supply cover factor and loss of load probability. Grid interaction indicators: Graphical representation of generation, load and net exported electricity, generation multiple dimensioning rate, connection capacity credit.
		Spain (Cooling-Heating)	Residential	PV (38 kW)	
		Singapore (Cooling)	Office	PV (190 kW) Electric driven chiller	
		Finland (Heating)	Residential	Micro wooden pellets CHP (1.38 kW)	

2. Building model, design conditions and energy demands

The investigated model is a generic residential building composed of three typical floors. Each floor is divided in two apartments noted A and B, as shown in Figure 4. 1. Each apartment is housing a family of four occupants. Buildings’ net area (excluding balconies, bathrooms, lobbies and non-conditioned spaces) is 432.6 m².

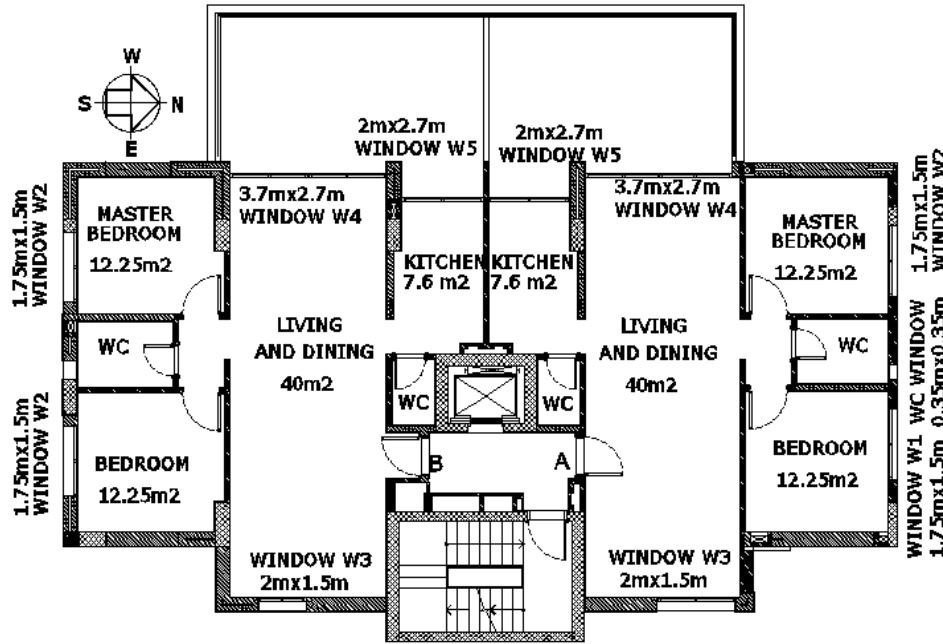


Figure 4. 1 Typical floor plan of the Base case building

The building is studied in three different climates: heating dominant, cooling dominant and mixed climate. One representative city from each climate is chosen: Indore, Tromso and Beijing. Table 4. 2 represents the selected cities’ geographical information in addition to cooling degree days (CDD) based on reference value 10 °C and heating degree days (HDD) based on reference value 18 °C which are computed using TRNSYS software.

Table 4. 2 Selected cities and climate characteristics (Data source: [244,245])

City	Altitude (m)	Longitude, Latitude	CDD base 10°C	HDD base 18°C
Indore (India)	567	75.80°E, 22.70°N	5400	54
Tromso (Norway)	102	18.95°E, 69.65°N	120	5525
Beijing (China)	55	116.28°E, 39.93°N	2125	3046

The building envelope parameters are optimized in different regions using MCDM methodology presented in [232] with the aim to produce best practices to reducing building’s energy demands

(for cooling and heating) in addition to the LCC. In this respect, the implemented methodology is composed of five phases: building energy simulation, optimization, MCDM, sensitivity study, and finally an adaptive comfort analysis.

The optimal thermal transmittance (U-value) of building’s envelope parameters are represented in Table 4. 3. Windows use low emissivity double glazing with Argon 4/16/4, U-value of 1.26 W/m².K, g-value of 0.39 and double glazing with Krypton 4/16/4, U-value of 0.86 W/m².K, g-value of 0.59. Window to wall ratio (WWR) of 10% at all façades is found to be valuable to enhance building’s energy performance.

Table 4. 3 Optimal U-value of building’s envelope elements in each region

Region	U-Value (W/m ² .K)								
	External Walls	Internal Walls	Roof	Ground	Internal Floor	Glazing			
						North	South	East	West
Tromso	0.2		0.2	0.2		1.26	1.26		
Indore	0.6	3.30	0.6	0.5	2.65	1.26	1.26	1.26	1.26
Beijing	0.2		0.2	0.3		0.86	0.86		

Furthermore, in order to reduce the overheating hours and to ensure the occupants’ adaptive thermal comfort, passive strategies including blinds and natural ventilation are integrated appropriately. The integrated blinds are external white color roller shutters [266].

Moreover, the lighting illuminance is selected based on recommendations of EN 12464-1 for residential buildings [242]. An illuminance level of 100 lux is chosen for bedrooms and 200 lux for kitchens and dining rooms. Accordingly, fluorescent lighting fixtures with a luminous efficiency of 60 lm/W are employed based on occupants’ schedule of presence. The assumed electric appliances per apartment comprise a computer in bedrooms, TV in living rooms, washing machine, refrigerator, electrical oven, extraction hood in kitchens, and toilet exhaust fans [207,243].

The temperature settings for sizing cooling and heating systems comply with the comfort range recommended by EN 15251 [233], i.e. 26 °C and 20 °C respectively. The air conditioners (AC) are regulated according to the occupants’ schedule of presence in each room, as shown in Figure 4. 2, and following the monthly control of Table 4. 4.

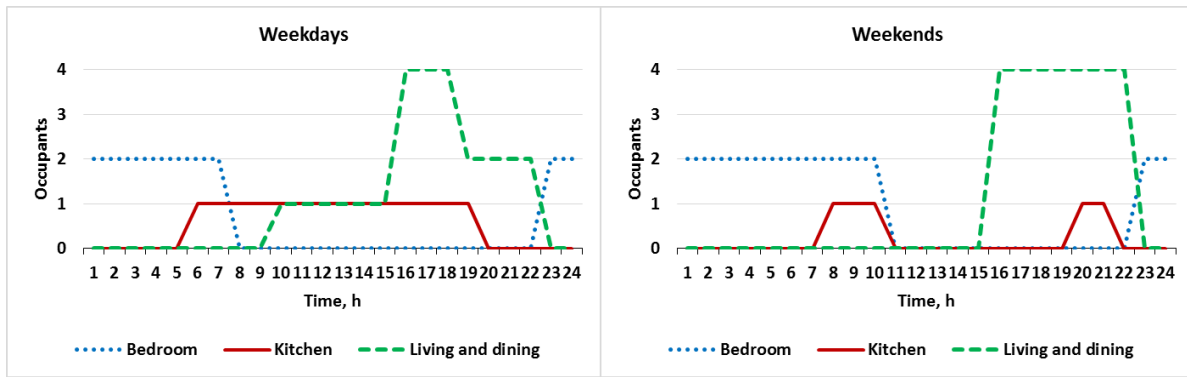


Figure 4. 2 Occupants’ schedule of presence in Living and dining, kitchen and bedrooms

Table 4. 4 Monthly AC control in each room

Region	Bedrooms	Living and dining	Kitchen
Indore	AC ON: March-September		AC ON: February-November
Beijing	OFF	OFF	AC ON: June-August

The adopted hourly DHW consumption profile is derived from Ahmed et al. [283] and Chmielewska et al. [284] by multiplying the monthly and hourly DHW consumption factors by the average daily DHW consumption for an apartment of four occupants. The obtained profile is shown in Figure 4. 3.

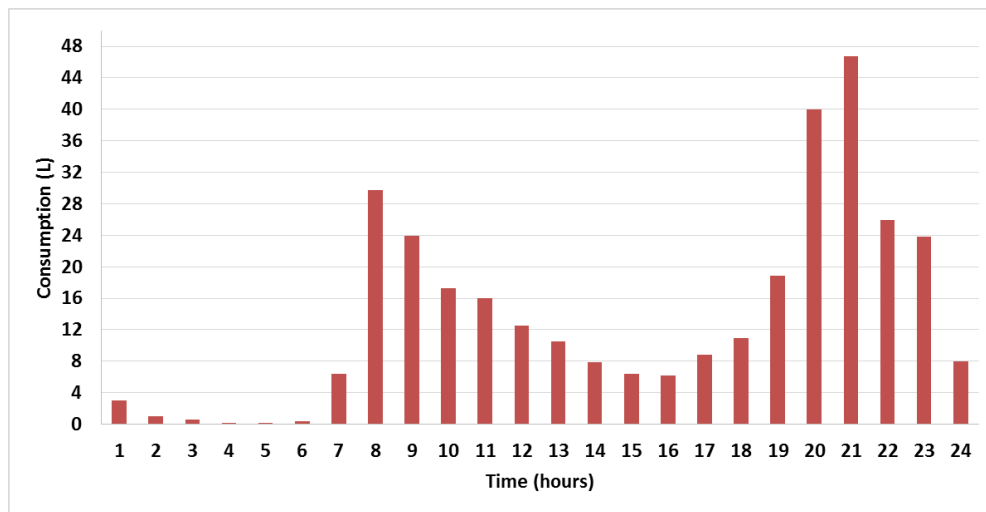


Figure 4. 3 Hourly DHW consumption (L)

After implementing the optimal configuration of envelope passive parameters and strategies in the building model, the reduced monthly cooling and heating loads, Q_{cool} (kWh/y.m²) and Q_{heat} (kWh/y.m²), for the low energy building in each region are derived and illustrated in Figure 4. 4. The total cooling loads are 48.92 kWh/y.m² and 5.89 kWh/y.m² in Indore and Beijing respectively,

while the total heating loads are 76.11 kWh/y.m² and 32.59 kWh/y.m² in Tromso and Beijing respectively. It can be noticed that the cooling months range from June till August and from March till October for Beijing and Indore respectively. The monthly peak cooling load is equal to 11.7 kWh/m² in Indore on May. On the other hand, the heating months range from November till March and from September till June for Beijing and Tromso respectively. The monthly peak heating load is equal to 11.5 kWh/m² in Tromso on January and December.

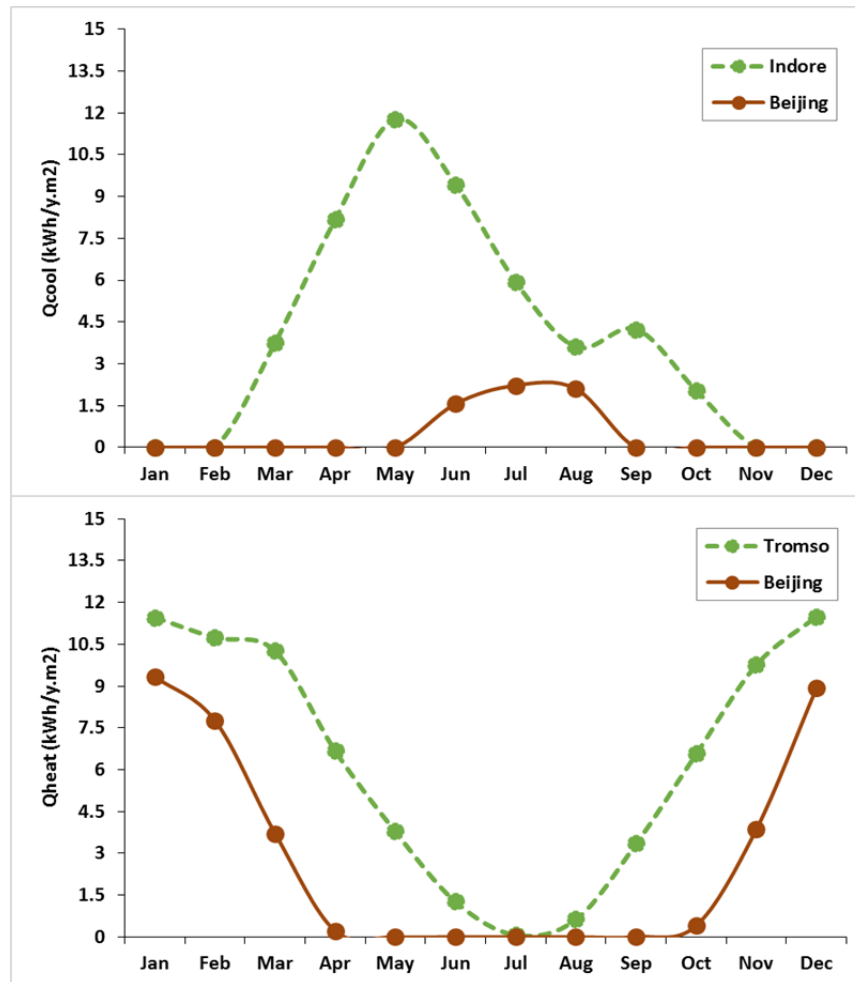


Figure 4. 4 Monthly cooling and heating loads for different regions

With the aim to go from low energy to NZEB, RE systems are essential to cover DHW, cooling, heating, and electric loads in addition to maintain the yearly NZE balance. In this study, six solution sets are considered for the design of NZEB in different regions.

3. Description of solution sets

Herein, the six investigated solution sets (SS) will be specified, including the principle of operation and components characteristics.

SS1 is composed of evacuated tube solar collectors to produce hot water for space heating during cold season and to drive an absorption chiller during hot season. Besides, flat plate solar collectors are used to produce DHW. SS2 includes a ground source heat pump composed of water to water heat pump (WWHP) and a vertical U-type borehole heat exchanger (HX) for heating, cooling and DHW production. SS3 involves an air source heat pump for cooling and a flat plate solar collector to deliver hot water for heating and domestic usage. SS4 comprises a solar assisted ground source heat pump for heating, cooling and DHW. SS5 is composed of a biodiesel generator. The biodiesel generator is scheduled according to the dominant load: cooling or heating. The hot exhaust gas passes through a first heat exchanger to heat up water for heating or driving and absorption chiller. Then, the output of the first heat exchanger is connected to a second heat exchanger to heat up water for domestic usage. This system also includes an auxiliary electric air cooled chiller as a backup when the absorption chiller fails to meet the desired cooling load. Finally, SS6 includes a natural gas condensing boiler (NGCB) to produce hot water for heating and domestic use. The cooling loads in this system are covered by an electric air cooled chiller.

All sets include storage tanks to store hot water for heating, domestic usage, and driving the absorption chiller in addition to cold water storage tank for cooling. Moreover, a natural gas condensing boiler is added as an auxiliary heater to all sets when the hot water stored from the main system is not sufficient for either heating, driving the absorption chiller or domestic use.

In order to produce the necessary electricity for lighting, appliances, electric chiller, ASHP, pumps, cooling tower and to provide with NZEB balance, a PV system as well as WT are implemented in all solution sets. The building uses the generated electricity from the RE systems to meet its demands. The excess generated electricity is sent to the utility grid for direct consumption. Table 4. 5 summarizes the six investigated solution sets including the components used for heating, cooling, DHW and electricity generation.

Table 4. 5 Summary of the investigated solution sets

Solution set	Heating	Cooling	DHW	Electricity
SS1	ETSC Auxiliary: NGCB	ETSC, Absorption chiller Auxiliary: NGCB	FPSC Auxiliary: NGCB	PV, WT
SS2	GSHP Auxiliary: NGCB	GSHP	GSHP Auxiliary: NGCB	PV, WT
SS3	FPSC Auxiliary: NGCB	ASHP	FPSC Auxiliary: NGCB	PV, WT
SS4	GSHP, FPSC Auxiliary: NGCB	GSHP	GSHP, FPSC Auxiliary: NGCB	PV, WT
SS5	BDG Auxiliary: NGCB	BDG, Absorption chiller, Auxiliary: Electric chiller	BDG Auxiliary: NGCB	CCHP, PV, WT
SS6	NGCB	Electric chiller	NGCB	PV, WT

3.1. Evacuated tube solar collectors

ETSCs are employed to generate high temperature hot water to drive the absorption chiller at 95°C. ETSCs are considered because they guarantee a positive thermal efficiency even while seeking high outlet temperature [285]. The collectors are south oriented and tilted depending on the latitude of the studied region. Table 4. 6 summarizes the considered ETSC characteristics from manufacturer data [286]. ETSCs are modeled in TRNSYS using Type 71.

Table 4. 6 ETSC characteristics (Data source: [286])

Characteristics	Value
Number of tubes	20
Area (m ²)	2.01
Intercept efficiency	0.75
Negative of first order efficiency coefficient (W/m ² .K)	1.18
Negative of second order efficiency coefficient (W/m ² .K ²)	0.0095
Rated flow rate per one collector (kg/h)	120
Stagnation Temperature (°C)	168

3.2.Flat plate solar collectors

FPSCs are used to produce hot water for heating at 45 °C and domestic usage at 55 °C. The collectors are also south oriented and sloped depending on the local latitude of the studied region. The employed FPSC characteristics are presented in Table 4. 7. FPSCs are modeled in TRNSYS by means of Type 1.

Table 4. 7 FPSC characteristics (Data source: [208])

Characteristics	Value
Collector area, m ²	2.09
Collector flow rate, Kg/h	70
Efficiency curvature, W/m ² K ²	0.0056
Efficiency slope, W/m ² .K	3.48
Intercept efficiency	0.79

3.3. Absorption chiller

In this study, a high efficiency Lithium bromide (LiBr) hot water single-effect absorption chiller, COP equals to 0.8, is employed [287]. This chiller is driven by hot water at 95 °C stored directly from ETSC or from recovering hot exhaust gases of BDG, the leaving hot water temperature being at 72 °C. The chilled water temperature to the cold storage tank is set to 7 °C while the chilled water return is around 13 °C. The electric consumption of the absorption chiller is due to the operation of solution pumps, of power 2.6 kW. The absorption chiller is simulated in TRNSYS via Type 107.

3.4. Cooling tower

The cooling water leaves the absorption chiller at 36.5 °C [287]. This water is cooled by the cooling tower to reach 5 °C above the wet-bulb ambient temperature. The cooling tower is composed of one axial fan of 16650 m³/h nominal air flow and 1.5 HP rated motor power [288]. The fan speed is adjusted appropriately to maintain the desired inlet and outlet water temperature difference. Type 510 is used to model the cooling tower in TRNSYS.

3.5. Electric air cooled chiller

A high efficiency air cooled screw type compressor chiller is selected to store chilled water at 7 °C. The chiller has a rated COP of 3.2 [287]. Besides, it works as an auxiliary and provides the deficit cooling load when the absorption chillers fails to meet the required load. The electric air cooled chiller is simulated in TRNSYS by means of Type 655.

3.6. Natural gas condensing boiler

A clean combustion, high efficiency NGCB is used to produce hot water for heating at 45 °C and domestic use at 55 °C. Besides, it is selected as an auxiliary when the temperature of stored hot water from the main heating system is below the desired set-point. The boiler has a combustion

and thermal efficiencies of 95% and 97% respectively [289]. Type 700 is used to model the NGCB in TRNSYS.

3.7. Ground source heat pump

A vertical U-type borehole HX is considered as the heat source of the GSHP. The working fluid is a mixture of antifreeze ethanol-water [290,291]. The fluid collects heat from the ground through the U-type heat exchanger. Then, the heat is pumped to the heat pump’s evaporator where heat exchange takes place between the working fluid and the heat pump’s refrigerant. The characteristics of storage volume of the borehole, U-type HX and the working fluid are presented in Table 4. 8. The GSHP is modeled in TRNSYS using ground heat exchanger Type 557a and WWHP Type 927.

Table 4. 8 Characteristics of borehole, U-type HX and working fluid (Data source: [290,291])

Characteristics	Value
Borehole Depth (m)	100
Borehole radius (m)	0.07
Storage thermal conductivity (kJ/h.m.K)	11.1
Storage heat capacity (kJ/m ³ .K)	20403
Fill thermal conductivity (KJ/h.m.K)	2.1
Pipe outer and inner radius (m)	0.02, 0.019
Pipe thermal conductivity (kJ/h.m.K)	1.5
Fluid specific heat (kJ/kg.K)	3.4
Fluid density (kg/m ³)	974
Working fluid flow rate during operation (kg/h)	1821

3.8. Photovoltaic array

The employed PV array is composed of monocrystalline silicon modules [210]. The array is south oriented and tilted to the latitude of the investigated region. The technical characteristics of the employed PV module are specified in Table 4. 9. Type 94a is used in order to model the PV array in TRNSYS.

Table 4. 9 Parameters of PV module (Data source:[210])

Panel characteristics	Value	Panel characteristics	Value
Short circuit current (A)	9.32	Open circuit voltage (V)	45.92
Current at maximum power (A)	8.85	Number of cells in series	72
Voltage at maximum power (V)	37.38	Panel area (m ²)	1.94
Temperature coefficient of open circuit voltage (V/K)	-0.318	Module efficiency (%)	17
Temperature coefficient of short circuit current (A/K)	0.042	Nominal output (Wp)	295.3

3.9. Residential wind turbines

The technical characteristics of the employed WT are listed in Table 4. 10. The quantity WTs is optimized in a later stage with the aim to find the total required turbines output power. Type 90 is used to model the WT in TRNSYS.

Table 4. 10 Characteristics of WT (Data source: [292])

Characteristics	Value
Turbine rated power output (kW)	1.3
Turbine type	3 blades, horizontal axis
Blade Diameter (m)	2.9
Start-up Wind Speed (m/s)	3
Rated Wind Speed (m/s)	11
RPM at Rated Power (RPM)	800
Tower Height to Nacelle (m)	14.5

4. Formulation of the optimization problem

In this research work, to evaluate the NZEB performance for different solution sets, four objective functions are considered: LCC, CO₂eq emissions, total energy consumption ($E_{building}$) and the grid interaction index ($f_{grid,year}$). The following constraint is set: the difference between RE electricity generation and building's electric load must be equal to 10 kWh/y.m². This constraint is imposed as a safety factor in order to guarantee the minimum zero balance, despite the existence of potential errors due to uncertainties in building and systems characteristic values, numerical approximations, and solution sets real-life implementation.

4.1. Optimization procedure

The multi-objective optimization (MOO) follows the methodology detailed in [232]. MOO is performed using MOBO, a Multi-Objective Building Optimization tool developed by Palonen et al. [179]. The adopted algorithm is the non-dominated sorting genetic algorithm (NSGA-II), developed by Deb et al. [180]. This algorithm is selected because of its reliability, good performance and effectiveness [181–183]. The input parameters' setting of the NSGA-II in this research are listed in Table 4. 11. These parameters are chosen based on preliminary researches to get the best compromise between the precision of Pareto front and the computational time of MOO [142].

Table 4. 11 Input parameters' setting of NSGA-II

Parameters	Value
Population size	40
Generation number	25
Crossover probability, %	70
Mutation probability, %	2

The MOO is followed by a MCDM process in order to choose one optimal solution among the available options. ELECTRE III (Elimination and Choice Expressing the Reality) MCDM technique [193] is employed to classify the solutions according to the decision maker preferences.

4.2. Objective functions

4.2.1. The life cycle cost

The LCC analysis is an economic assessment of projects cost efficiency. It is an appropriate technique to evaluate the financial benefits of building’s RE design options over their lifetime [47] [214]. The LCC is given by Eq. 4. 1 and Eq. 4. 2.

$$LCC = IC + O\&M_t + USPW (N, rd) \times EC \tag{Eq. 4. 1}$$

$$USPW (N, rd) = \frac{1 - (1 + rd)^{-N}}{rd} \tag{Eq. 4. 2}$$

where IC is the investment cost for implementing the design features of the RE system (\$), $O\&M_t$ are the total preventive maintenance including operation, repair and servicing costs (\$), $USPW (N, rd)$ is the uniform series present worth factor (year), rd is the annual discount rate (%), N is the life period (year) and EC is the annual energy cost needed to maintain building’s indoor comfort (\$). In this study, the lifetime and discount rate are set to 20 years and 5% respectively. The implementation cost (C) of different design options are listed in Table 4. 12. The annual preventive maintenance including operation, repair and servicing costs (O&M) in percentage of the initial investment are reported in [293–295].

Table 4. 12 Implementation cost of different design options (Data source: [160,311,312,315,316,322,338,363–367])

Component	Cost expression (\$)	Definition
Single-effect absorption chiller	$C = 540 \times (\dot{Q}_{abc})^{0.872}$	\dot{Q}_{abc} is the absorption chiller rated capacity (kW)
Electric chiller	$C = (482 \times (\dot{Q}_e)^{-0.07273} - 159.7) \times \dot{Q}_e$	\dot{Q}_e is the electric chiller rated capacity (kW)
Evacuated tube solar collector	$C = 2450 \times N_{ETSC}$	N_{ETSC} is the number of ETSC
Flat plate solar collector	$C = 800 \times N_{FPSC}$	N_{FPSC} is the number of FPSC
Storage tank	$C = 4042 \times (V_{\text{tank}})^{0.506}$	V_{tank} is the storage tank volume (L)
Natural gas condensing boiler	$C = 0.15 \times P_B^3 - 10.44 \times P_B^2 + 242.6 \times P_B + 1037$	P_B is the NGCB capacity (kW)
Cooling tower	$C = 1.22 \times P_{CT}^2 - 56.88 \times P_{CT} + 5145.6$	P_{CT} is the cooling tower nominal cooling capacity (RT)
Wind turbine including tower 15 m, inverter and controller	$C = 6.4 \times P_{WT}^2 + 2415.7 \times P_{WT} + 6207$	P_{WT} is the WT rated power (kW)
Photovoltaic	$C = 378.17 \times A_{PV}$	A_{PV} is the area of PV array (m ²)
Pumps	$C = 800 \times (P_{\text{Pump}}/10)^{0.26} \times ((1 - \eta_{\text{Pump}})/\eta_{\text{Pump}})^{0.5}$	P_{Pump} is the pump rated power (kW) η_{Pump} is the overall pump efficiency
Air source heat pump	$C = 780 \times P_{ASHP}$	P_{ASHP} is the cooling capacity of ASHP (RT)
Heat exchanger	$C = 130 \times (A_{HX}/0.093)^{0.78}$	A_{HX} is the heat exchanger area (m ²)
Biodiesel generator	$C = 205.53 \times P_{BDG}$	P_{BDG} is the capacity of BDG (kW)
Water to water heat pump	$C = 2500 \times P_{WWHP}$	P_{WWHP} is the cooling capacity of WWHP (RT)
Borehole	$C = 65 \times D$	D is the depth of borehole (m)
Electricity/Indore (India)	0.068 \$/kWh	
Electricity/Beijing (China)	0.045 \$/kWh	
Electricity/Tromso (Norway)	0.16 \$/kWh	
Natural gas/Indore (India)	0.024 \$/kWh	
Natural gas/Beijing (China)	0.024 \$/kWh	
Natural gas/Tromso (Norway)	0.078 \$/kWh	
Biodiesel	1.3 \$/L	

Table 4. 13 Annual O&M costs in percentage of the initial investment [293–295]

Component	O&M costs in percentage of the initial investment (%)
Air conditioning units	4
Condensing boiler	2
Heat pumps	3
Circulating pumps	2
Solar collectors (Evacuated tube, flat plate)	0.5
Storage tanks	1
Fans	4
Diesel motors	4
Photovoltaic	4
Wind turbines	4

4.2.2. The Carbon dioxide equivalent emissions

The building sector is expected to provide one of the largest contributions to the reduction of CO₂eq emissions. With the aim to decrease CO₂eq emissions to the atmosphere from energy consumption during NZEB operation, CO₂eq emissions are analyzed in the current optimization study to offer an environmental impact indicator. Methane (CH₄) and nitrous oxide (N₂O) emissions are multiplied by their 100-year GWP, i.e. 25 and 298 respectively, in order to convert them to CO₂eq [301]. Table 4. 14 reports the CO₂eq emissions per kWh of electricity produced in each of the investigated regions (CO₂eq emissions per kWh depend on how electrical energy is generated in each region) in addition to the emissions from natural gas and biodiesel burning.

Table 4. 14 CO₂eq emissions per type of energy source (Data source: [1,301,302])

Type of energy source	CO ₂ eq (g/kWh)
Electricity produced in Tromso (Norway)	16.69
Electricity produced in Beijing (China)	766.09
Electricity produced in Indore (India)	912.39
Natural gas	367.69
Biodiesel	457.21

4.2.3. The total energy consumption

The building’s total energy consumption ($E_{building}$) is equal to the electric consumption of lights, appliances, energy systems components such as heat pumps, electric chiller, cooling tower and circulating pumps as well as energy consumption of natural gas and biodiesel (if any).

4.2.4. The grid interaction index

The grid interaction index ($f_{grid,year}$) is defined as the standard deviation of the monthly net exported energy normalized on the maximum absolute exported energy over the period of a year [282], as shown in Eq. 4. 3.

$$f_{grid,year} = STD\left(\frac{\text{Monthly net exported energy}}{\text{Max}(|\text{Net exported energy}|)}\right) \quad \text{Eq. 4. 3}$$

It describes the fluctuation of the exchanged energy between the NZEB and the utility grid. Besides, it is an indication of the average stress that the building places on the utility grid. A low grid interaction index is usually favored as it signifies enhanced grid friendliness [272].

4.3. Decision variables

Table 4. 15 presents the list of different solution sets’ decision variables considered in the optimization analysis, including their possible range of values. One optimal combination will be found for each solution set in each region in order to attain the NZE balance while minimizing the previously stated objective functions.

Table 4. 15 Different options of decision variable used in the optimization problem

Description	Units	Values	Step
FPSC total area	m ²	2 to 80	4
ETSC total area	m ²	2 to 80	4
PV total area	m ²	20 to 400	10
WT total capacity	kW	10 to 40	2
DHW storage tank	L	1200 to 3000	300
Cold water storage tank	L	1200 to 3000	300
Heating water storage tank	L	1200 to 3000	300
Absorption chiller capacity	RT	20, 25, 30, 35, 40, 45, 50, 55, 60	-
Electric chiller capacity	RT	20, 25, 30, 35, 40, 45, 50, 55, 60	-
Gas boiler capacity	kW	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	-
ASHP capacity	RT	10, 15, 20, 25, 30, 35, 40, 45, 50	-
WWHP cooling capacity	RT	10, 15, 20, 25, 30, 35, 40, 45, 50	-
WWHP heating capacity	kW	35, 52, 70, 87, 105, 123, 140, 158, 175	-
Number of boreholes	-	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	-
BDG capacity	kW	5, 10, 15, 20, 25, 30, 35, 40, 45, 50	-
HX efficiency	-	0.4, 0.5, 0.6, 0.7, 0.8	-

5. Optimization results, analysis and recommendations

The MOO results are represented in Table 4. 16 and Figure 4. 5. Table 4. 15 shows the optimal decision variables for each solution set in Indore, Beijing and Tromso. The implementation of these optimal design options in the building model yields a NZEB with a positive energy balance, between load and generation, ranging from 7 kWh/y.m² to 10 kWh/y.m². Figure 4. 5 illustrates the optimized objective functions for each solution set in the studied regions. A comprehensive assessment between the six investigated solution sets with respect to economy, environment, energy and grid stress is conducted in this section.

Table 4. 16 Summary of the optimal decision variables for each solution set in different regions

Decision variable	SS1			SS2			SS3			SS4			SS5			SS6		
	Indore	Beijing	Tromso	Indore	Beijing	Tromso	Indore	Beijing	Tromso	Indore	Beijing	Tromso	Indore	Beijing	Tromso	Indore	Beijing	Tromso
FPSC total area, m ²	27	73	44	-	-	-	40	46	84	6	19	15	-	-	-	-	-	-
ETSC total area, m ²	30	70	38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PV total area, m ²	68	388	97	19	49	184	39	165	97	29	49	136	146	631	136	78	49	78
WT total capacity, kw	40	52	13	5	1.3	1.3	1.3	5	13	5	9	9	33	43	30	26	30	17
DHW storage tank, L	2.8	2.9	2.5	2.9	2.4	2.4	2.9	1.9	2.5	2.3	3.0	1.9	1.5	2.9	2.8	1.8	1.8	1.5
Cold water storage tank, L	1.5	1.2	-	1.3	2.3	-	-	-	-	1.5	1.7	-	2.7	1.9	-	2.5	1.2	-
Heating water storage tank, L	2.3	1.6	2.2	-	-	-	-	2.8	2.2	-	-	-	1.3	1.6	2.9	-	2.3	2.3
Absorption chiller capacity, RT	45	25	-	-	-	-	-	-	-	-	-	-	35	55	-	-	-	-
Electric chiller capacity, RT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15	15	-
Gas boiler capacity, kw	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	8	8
ASHP capacity, RT	-	-	-	-	-	-	30	20	-	-	-	-	-	-	-	-	-	-
WWHP cooling capacity, RT	-	-	-	10	10	-	-	-	-	15	15	-	-	-	-	-	-	-
WWHP heating capacity, kW	-	-	-	52	105	35	-	-	-	35	70	140	-	-	-	-	-	-
Number of boreholes, -	-	-	-	1	1	2	-	-	-	11	1	2	-	-	-	-	-	-
BDG capacity, kw	-	-	-	-	-	-	-	-	-	-	-	-	40	40	15	-	-	-
HX efficiency, -	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.4	0.7	-	-	-

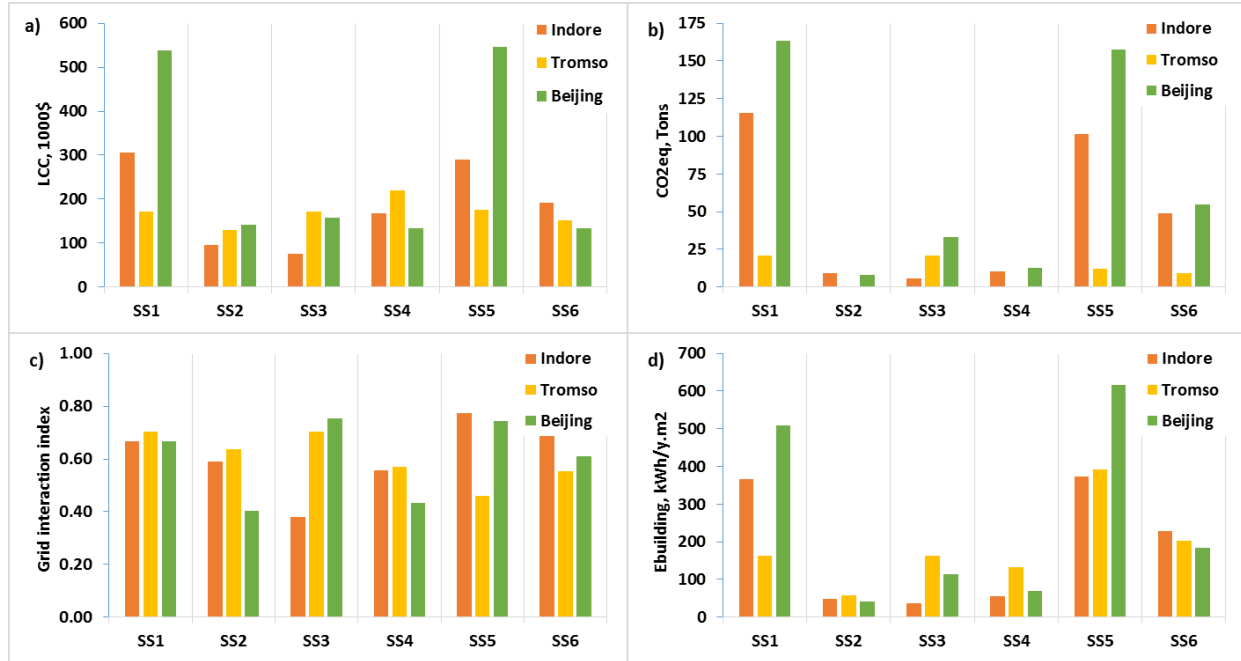


Figure 4. 5 Optimized objective functions for each solution set in different regions. a: Life cycle cost, b: CO_{2eq} emissions, c: Grid interaction index, d: Total energy consumption

5.1. Economic impact analysis

From Figure 4. 5a, it can be observed that the 20 years-LCC in Indore ranges from about 76000 \$ when adopting SS3 to become four times higher, more than 300000 \$, when adopting SS1. In Tromso the 20 years-LCC variates from around 130000 \$ when implementing SS2 to double, more than 220000 \$, when implementing SS4. Moreover, The 20 years-LCC in Beijing ranges from about 133000 \$ when adopting SS4 or SS6 to become four times higher, more than 539000 \$, when adopting SS1 or SS5. The inspected energy system may appears the more expensive solution at its inception, but in the long term, the building may present negative operating costs which is considered as an economic profit. Therefore, the simple payback period is computed to evaluate the economic feasibility of each solution set. The simple payback period is obtained using Eq. 4. 4 [43].

$$\text{Simple payback period (years)} = \frac{\text{Investment cost (\$)}}{\text{Net Energy Savings (\$/year)} - \text{O\&M (\$/year)}} \quad \text{Eq. 4. 4}$$

Figure 4. 6 illustrates the simple payback period for each solution set in different regions. For Tromso, Indore and Beijing the lowest payback periods correspond to 5, 23 and 34 years for

adopting solution sets SS5, SS5 and SS6 respectively. So, with regard to economic feasibility, adopting SS5 for Tromso and Indore and SS6 for Beijing is beneficial.

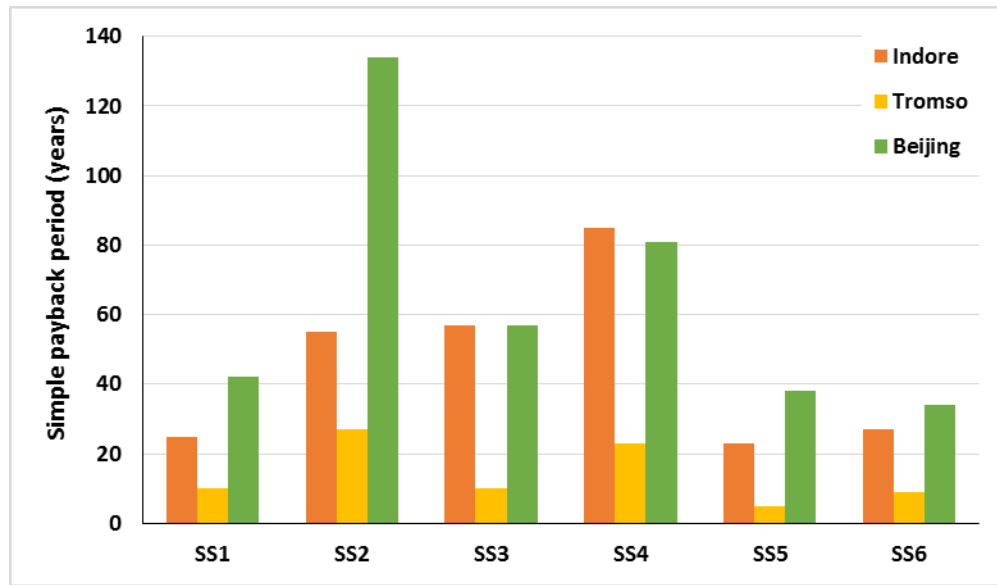


Figure 4. 6 Simple payback period of each solution set in different regions

The equivalent LCOE for 20 years and 5% discount rate is also computed. The LCOE is the implied cost (\$/kWh) of the energy produced by the RE system [43], Eq. 4. 5.

$$LCOE(\$/kWh) = \frac{\text{Investment cost (\$)} + O\&M (\$) \times USPW (N, rd)}{\text{Annual Energy Output (kWh/year)} \times USPW (N, rd)} \quad \text{Eq. 4. 5}$$

Figure 4. 7 illustrates the LCOE for each solution set in different regions. The LCOE (20 years, 5%) for integrating SS5 and SS6 in Indore and Beijing respectively is about 0.11 \$/kWh. This implies that these solution sets will generate electricity over the next 20 years at a cost of 0.11 \$/kWh. The LCOE is higher than the current utility rate of Indore and Beijing, i.e. 0.068 \$/kWh and 0.045 \$/kWh respectively. However, if the utility rates increase in the near future, this solution set will be cost competitive. Contrariwise, the LCOE (20 years, 5%) in Tromso for using SS5 is about 0.06 \$/kWh, which is lower than the utility rate of 0.16 \$/kWh. Consequently, this solution set, i.e. SS5, is cost competitive in Tromso.

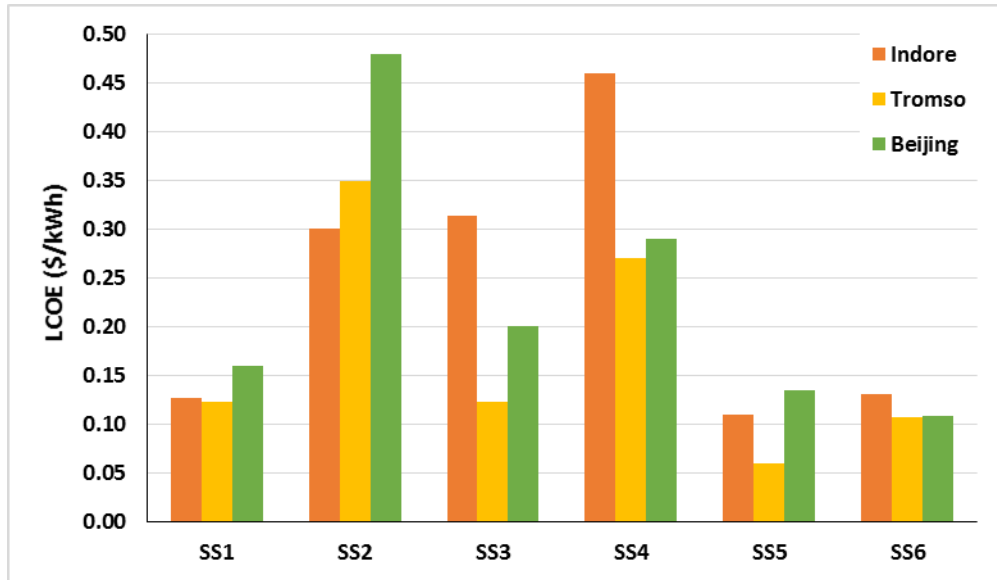


Figure 4. 7 LCOE for each solution set in different regions

5.2. Environmental impact analysis

The yearly CO₂eq emissions due to the power imported from the utility grid, BDG, and NGCB are reported in Figure 4. 5b for each solution set in Indore, Beijing and Tromso. Note that these CO₂eq emissions, in a comprehensive view, are counterbalanced by the surplus RE exported from the building to the utility grid. However, this research work aims to minimize, the emissions due to the electricity imported from the utility grid, in order to avoid the resulting environmental damage. In Indore, it is noticed that the CO₂eq emissions range from about 6 metric tons for SS3, up to 115 metric tons for SS1. In Beijing, the emissions variate between about 8 metric tons when adopting SS2, to more than 160 metric tons when adopting SS1. In addition, for Tromso, the emissions range from 0.23 metric tons up to 21 metric tons when implementing SS2 and SS1 respectively. Consequently, the adoption of the solution set SS1 is the most polluting to the atmosphere. That is due to the fact that this solution set has the highest amount of imported electricity from the utility grid, which is 195 kWh/y.m² in Indore, 283 kWh/y.m² in Beijing and 67 kWh/y.m² in Tromso. On the other hand, the imports for SS3 in Indore as well as SS2 in Beijing and Tromso are relatively low, 15 kWh/y.m², 24 kWh/y.m² and 32 kWh/y.m² respectively. For this reason, the corresponding solution sets, SS3 in Indore as well as SS2 in Beijing and Tromso, are considered as environmentally friendly.

5.3. Building’s energy analysis

Here, the variation of building’s annual energy load and RE generation for the inspected regions under different solution sets is examined. The load matching index is also computed for each design option. The load matching index (f_{load}) is a measure of the overlapping degree between RE generation and building’s energy demand [270], Eq. 4. 6.

$$f_{load} = \frac{\sum_{year} \min(1, \frac{g(m)}{l(m)})}{12} \tag{Eq. 4. 6}$$

where, $g(m)$ and $l(m)$ are the monthly RE generation (kWh).and load (kWh) respectively.

The load matching index for different solution sets in different investigated regions is represented in Figure 4. 8. Moreover, Figure 4. 9 depicts the variation of building’s annual energy load and RE generation for the solution sets with the highest value of load matching index in Indore, Tromso and Beijing. Generally, it can be noticed that the load matching index variates between 0.7 and 1, as shown in Figure 4. 8. The NZEB in Indore achieved the highest load coverage, i.e. 100%, for adopting SS3. Which indicates that the building’s energy load is fully met by the on-site RE generation. Consequently, the building is grid independent in monthly basis. The maximum obtained load matching index in Tromso is 0.97 for implementing SS4. In this case, the NZEB is independent of the grid from February till August in monthly basis, as shown in Figure 4. 9b. For Beijing, the adoption of SS2 yields to a load matching index of 0.95%. The energy imports from the grid are zero in all months except in July and December where the load is slightly higher than the RE generation, as revealed in Figure 4. 9c.

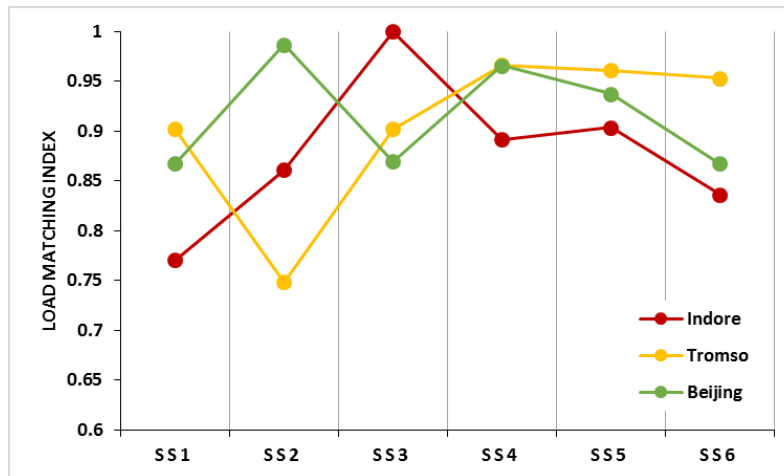


Figure 4. 8 Load matching index for each solution set in different regions

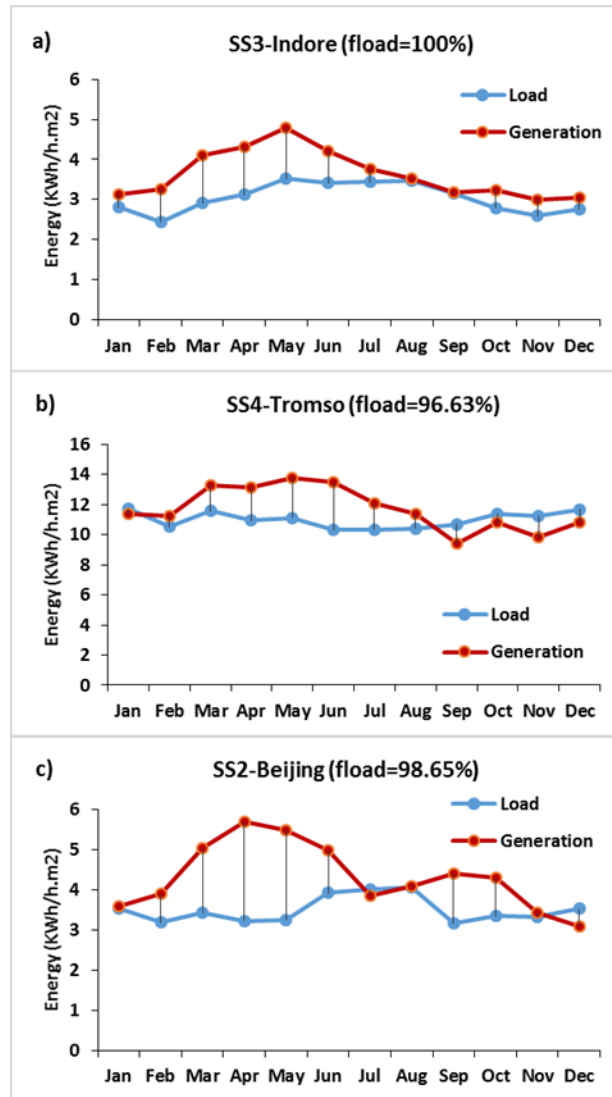


Figure 4. 9 Variation of building’s annual energy load and RE generation. a) Indore, b) Tromso, c) Beijing

5.4.Grid stress analysis

The grid interaction index refers to the energy exchange between the NZEB and the utility grid. From Figure 4. 5c, it can be noticed that solution sets SS3, SS5 and SS2, for Indore, Tromso and Beijing respectively, are the optimal scenarios to improve the NZEB grid friendliness and reliability. In fact, the computed grid interaction indices for these solution sets are the lowest among other scenarios: 0.38 for SS3 in Indore, 0.46 for SS5 in Tromso and 0.4 for SS2 in Beijing. It is worth to mention that these optimal solution sets reduce the stress on the grid while maintaining the energy power balance. Contrariwise, the solution sets SS6 in Indore, SS1 in

Tromso and SS3 in Beijing are found to have the highest grid interaction indices: 0.79, 0.7 and 0.75 respectively. Consequently, the associated grid stress caused by the NZEB-grid energy exchanges, due to the implementation of these solution sets, is significant.

5.5.Recommendations

In this section, recommendations about the favorable solution sets in each region are offered. These recommendations are derived from the above presented and analyzed MOO results. Table 4. 17 summarizes the optimal solution sets in each region according to different evaluation criteria.

Table 4. 17 Optimal solution sets in each region in function of evaluation criteria

Evaluation criteria	Indore		Tromso		Beijing	
	SS3	SS5	SS4	SS5	SS2	SS6
Load matching index	1	0.9	0.97	0.96	0.98	0.86
Grid interaction index	0.38	0.77	0.57	0.46	0.40	0.61
Yearly CO ₂ eq emissions (tons)	5.98	101.65	0.48	11.89	7.98	54.75
Payback period (Years)	57	21	22	5	134	30
LCOE, 20 years, 5% discount rate (\$/ kWh)	0.31	0.11	0.27	0.06	0.48	0.11

5.5.1. Indore

In Indore, hot climate, the utilization of 40 m² FPSC to produce DHW, 30 RT ASHP to cover the cooling load in addition to 39 m² PV and 1.3 kW WT to produce electricity is beneficial in terms of reliability, low grid stress (0.38 grid interaction index), monthly basis independency on the utility grid (1 load matching index) and environment friendliness (5.98 tons CO₂eq emissions per year). However, in terms of economic feasibility, the solution set SS5 composed of 40 kW BDG to produce both electricity and hot steam for DHW and to drive a 35 RT absorption chiller, in addition to 146 m² PV and 33 kW WT to generate electricity, is relatively profitable when compared to other solution sets (payback period of 23 years and LCOE of 0.11).

5.5.2. Tromso

In Tromso, cold climate, the solution set SS5 composed of 15 kW BDG to produce both electricity and hot steam for heating as well as DHW use, in addition to 136 m² PV and 30 kW WT to generate electricity, is promising in terms of high load matching (0.96), low grid stress (0.46 grid interaction index) and economic feasibility (payback period of 5 years and LCOE of 0.06). On the other hand, the utilization of combined solar thermal of 15 m² FPSC and 140 kW

GSHP as well as 136 m² PV and 9 kW WT to produce electricity is convenient with regard to very low CO₂eq emissions (0.48 tons per year) and significant load coverage (0.97 load matching index).

5.5.3. Beijing

In Beijing, mixed climate, the adoption of (10 RT cooling, 105 kW heating) GSHP for cooling, heating and DHW purposes in addition to 49 m² PV and 1.3 kW WT to generated electricity is beneficial in terms of reliability, low grid stress (0.4 grid interaction index), monthly basis independency on the utility grid (0.98 load matching index) and environment friendliness (7.98 tons CO₂eq emissions per year). However, in terms of economic feasibility, the solution set SS6 composed of 15 RT electric chiller for cooling, 8 kW NGCB for heating and DHW, in addition to 49 m² PV and 30 kW WT to generate electricity, is relatively profitable among other solution sets (payback period of 34 years and LCOE of 0.11).

5.5.4. Solution sets ranking

In order to provide one recommended solution set for each region, ELECTRE III method can be applied to rank the six solution sets from the best to the worst according to the decision maker preferences. The investigated evaluation criteria, shown in Table 4. 16, are assumed of equal importance level with respect to the decision maker. So, they have been assigned the same weights. Indifference, preference and veto thresholds of ELECTRE III are calculated relative to the average value of each evaluation criteria, Table 4. 17.

Table 4. 18 ELECTRE III method thresholds

Threshold	Percentage relative to evaluation criteria average
Indifference	5%
Preference	10%
Veto	30%

The ranked solution sets are graphically represented for each region, as shown in Figure 4. 10, on (x-y plan) through an ascending (ordinary axis, selection starts with the worst to the best solution set) and descending (abscissa axis, selection starts with the best to the worst solution set) filtration procedures. From Figure 4. 10, it can be noticed that the preferred solution sets for Indore, Tromso and Beijing are SS3, SS5, and SS6 respectively.

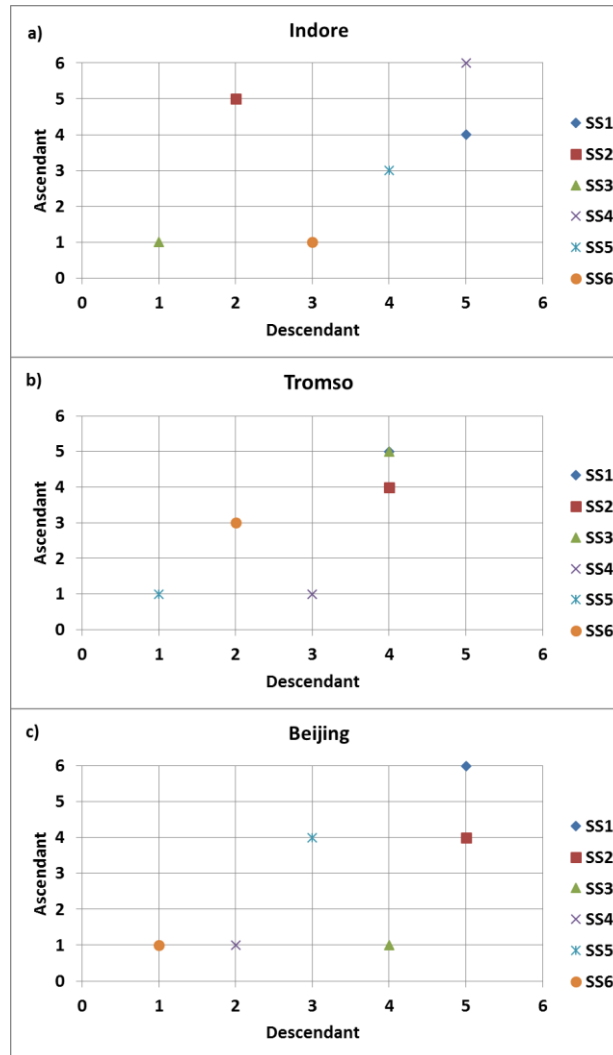


Figure 4. 10 ELECTRE III graphical representation. a) Indore, b) Tromso, c) Beijing

6. Conclusion

Researchers worldwide are evaluating and optimizing the integration of RE systems in NZEBs. The configurations and capacities of the implemented RE systems in NZEBs must be appropriately selected to guarantee the intended performance objective.

This study presents a systematic analysis of the performance evaluation of a NZEB designed with six typical solution sets to go from low energy building to NZEB. It aims to assist NZEB designers to select the suitable design options based on a systemic evaluation. The solution sets are optimized by means of a MCDM methodology. Its main features include four steps: RE systems simulation, optimization process, MCDM and testing solution's robustness.

One representative city of cooling dominant, heating dominant and mixed climates is studied: Indore, Tromso, and Beijing respectively. The performance of NZEB is evaluated in terms of combined performance of (i) economic indicators: LCC, LCOE, and simple payback period, (ii) environment indicator: CO₂eq emissions, (iii) energy balance and self-sufficiency indicator: load matching index, (iv) grid stress indicator: grid interaction index, and energy efficiency indicator (total energy consumption). Subsequently, recommendations for each region are derived.

In this research work, it is found that, besides to the utilization of appropriate size of PV panels and residential wind turbines in all regions, in Indore the solution set containing FPSC and ASHP is beneficial in terms of reliability, low grid stress (0.38 grid interaction index), monthly basis independency on the utility grid (1 load matching index) and environment-friendly (5.98 tons CO₂eq emissions per year). However, in terms of economic feasibility, it is recommended to use a BDG with a thermally driven absorption chiller (payback period of 23 years and LCOE of 0.11). In Tromso, the use of BDG is promising in terms of high load matching (0.96), low grid stress (0.46 grid interaction index), and economic feasibility (payback period of 5 years and LCOE of 0.06). On the other hand, the exploitation of solar assisted GSHP is convenient with regard to very low CO₂eq emissions (0.48 tons per year) and significant load coverage (0.97 load matching index). In Beijing, the adoption of GSHP is beneficial in terms of reliability, low grid stress (0.4 grid interaction index), monthly basis independency on the utility grid (0.98 load matching index) and environment-friendly (7.98 tons CO₂eq emissions per year). Although, the solution set containing an electric chiller and NGCB is relatively profitable in terms of economic feasibility (payback period of 34 years and LCOE of 0.11).

According to the decision maker preferences, relative to the evaluation criteria, one recommended solution set for each region could be provided. In hot climates, it is recommended to utilize FPSC to produce DHW and ASHP to cover the cooling load. In cold climates, it is recommended to use BDG to produce both electricity and hot steam for heating as well as DHW use. In mixed climate it is recommended to utilize electric chillers for cooling and NGCB for heating and DHW.

An exhaustive study focusing on the influence of uncertainty quantification of energy costs and RE systems components' costs and characteristics on the final results will be carried out in the future.

Conclusions and perspectives

The aim of this thesis is to develop an understanding of NZEBs design concepts. Besides, it aims to assist NZEB designers to select the suitable design options of passive and RE systems based on a systemic evaluation in different climates.

First, a comprehensive review on definitions, concepts, rating indices, drawbacks, typical case studies and buildings' simulations according to climate, optimization methods, software's employed for design and assessment of NZEB is carried out. The most commonly used electric and thermal RE applications in different climates are presented. Three detailed flowcharts representing the three stages of designing, optimizing, and categorizing of a NZEB are suggested.

The second part of this thesis introduces a multi-criteria decision-making methodology for NZEB design optimization with the aim to enhance its energetic and economic performances. The proposed optimization methodology is a powerful and useful tool to improve NZEBs design and to facilitate decision-making in early phases of building design. The methodology is applied through the combination of energy simulation and optimization programs (TRNSYS and MOBO) coupled with a ranking decision-making technique (ELECTRE III). The stability and robustness of the optimized solution, to ensure its independence of the DM preferences, is carried out through a sensitivity analysis. Extensive simulations are carried out to evaluate the most cost-effective passive strategies and RE systems that should be implemented to a NZE-design for a typical residential building located in various climatic zones in France and Lebanon. The results of the analysis clearly indicate that, regardless of the climate, for designing a residential NZEB, it is essential to minimize space thermal load through passive strategies which are ensured by a building envelope with high thermal performance. Moreover, the remaining energy demands (thermal, hot water, lighting, and appliances) are covered to the maximum extent, by RE sources. Furthermore, in all climates more emphasis should be placed on air conditioning set points control, taking into account the occupants comfort. The adaptive comfort approaches are effective methods to reduce the required times for cooling, heating, and ventilation.

The third part aims at comprehensively investigating the optimal passive design for a case study residential building. Twenty-five different climates from Köppen Geiger classification are simulated with the aim to produce best practices to minimize building energy demands (cooling and heating) in addition to the LCC. Climates are classified into three categories according to the

dominant load with the intention to recommend one optimal solution for each category. The occupants' adaptive thermal comfort is also inspected aiming at getting more practical and detailed passive design solutions. The study has shown that in severely cold climates, it is efficient to restrict the heat flow through a high level of insulation. Hence the selection of low U-value of $0.2 \text{ W/m}^2\cdot\text{K}$ for building walls, roof, and ground and $1.26 \text{ W/m}^2\cdot\text{K}$ for windows. However, in hot climates, the thermal insulation of building envelope has a restrictive role. It is not needed to use high levels of insulation in walls, roof, and ground. The appropriate U-values of walls, roof and ground are $0.6 \text{ W/m}^2\cdot\text{K}$, $0.6 \text{ W/m}^2\cdot\text{K}$ and $0.5 \text{ W/m}^2\cdot\text{K}$ respectively. In mixed climates, it is noticed that walls and roof must be well insulated (U-Value = $0.2 \text{ W/m}^2\cdot\text{K}$), whereas the U-value of ground ($0.3 \text{ W/m}^2\cdot\text{K}$) should not be decreased to the minimum with the aim to allow the heat evacuation through the ground in summer. Even a low value of WWR (10%) is valuable to enhance the building energy performance, but in practice, it must be accurately determined according to the indoor lighting requirements. Moreover, the integrated passive cooling strategies, blinds, and natural ventilation, have demonstrated their competency since they lead to significant cooling load savings that exceeded 50% in almost all regions against the optimal design model. Furthermore, it is clear that the building's average overheating percentage is almost eliminated depending on the category.

The last part conducts a systematic analysis of the performance evaluation of a NZEB designed with six typical RE solution sets to go from low energy building to NZEB. The solution sets are optimized by means of MCDM methodology. One representative city of cooling dominant, heating dominant and mixed climates is investigated, Indore, Tromso, and Beijing. The performance of NZEB is evaluated in terms of combined performance comprised of economic, environment, energy balance, self-sufficiency, and grid stress indicators. It has been found that, in addition to the utilization of appropriate size of PV and wind turbines WT in all regions, in Indore the solution set composed of FPSC and ASHP is beneficial in terms of reliability, low grid stress, monthly basis independency on the utility grid and environment-friendly. Whereas, in terms of economic feasibility, it is recommended to use a BDG with an absorption chiller. In Tromso, the use of BDG is promising in terms of high load matching, low grid stress, and economic feasibility. On the other hand, the utilization of solar assisted GSHP is convenient with regard to very low CO_2eq emissions and significant load coverage. In Beijing, the adoption of GSHP is beneficial in terms of reliability, low grid stress, monthly basis independency on the utility grid and environment friendliness.

Whereas, in terms of economic feasibility, the solution set composed of an electric chiller and NGCB is relatively profitable.

NZEBs is a very wide domain that needs a lot of research studies concerning its enhancement and optimization. As future work, some ideas are worth investigating, those include the following:

1. The potential of integrating advanced passive and efficient energy technologies in NZEBs including: (i) controlled smart windows (electrochromic and thermochromic) which reduce energy consumption and improve thermal and visual comfort mainly by controlling the solar gain and daylight entering into the building, (ii) Thermal energy storage materials (sensible heat storage, phase change and thermochemical storage materials) which improve the thermal performance and energy management of buildings, and (iii) integrated RE systems (building integrated photovoltaic, windows with semi-transparent PV, etc.) which can be utilized to cover large roof and façade surfaces.
2. Impact of cost assumptions including energy prices, investment and maintenance costs, discount rate, renewable energy technologies life-time, and calculation periods on the economic optimality and benefits of NZEBs.
3. Influence of uncertainty quantification on optimal design of NZEB with respect to the adopted evaluation criteria. In order to guarantee a commercially feasible design, it is essential to provide reliable confidence limits for the optimal NZEB characteristics in the early design stage and not just annual simulations for nominal conditions.
4. Retrofitting of existing buildings towards NZEB performance from economic, environmental, and stress on the existing energy grid perspectives. Since the number of existing buildings is larger than new ones, more concern should be emphasized on the strategies and technologies to convert existing buildings into NZEBs in different climates.
5. The feasibility to incorporate and optimize NZEBs towards achieving smart cities including their dynamic interaction with the city's energy management system and urban energy grid through the merging of automated systems, and information and communication technologies (ICT).

Conclusions et perspectives

Le but de cette thèse est de développer une compréhension des concepts de dimensionnement des BCENN. En outre, elle vise à aider les concepteurs de BCENN à sélectionner les options de conception appropriées des systèmes passifs et des énergies renouvelables en se basant sur une évaluation systémique dans différents climats.

Tout d'abord, il est réalisé une revue complète des définitions, concepts, critères d'évaluations, inconvénients, études de cas typiques et simulations de bâtiments en fonction du climat, ainsi que des méthodes d'optimisation et des logiciels utilisés pour la conception et l'évaluation de BCENN. Les systèmes de production électriques et thermiques à base d'énergies renouvelables les plus couramment utilisées dans les différents climats sont présentés. Trois organigrammes détaillés représentant les principales étapes de la conception, de l'optimisation et permettant de catégoriser les BCENN sont suggérés.

La deuxième partie de cette thèse introduit une méthodologie d'ADM pour l'optimisation de la conception des BCENN dans le but d'améliorer ses performances énergétiques et économiques. La méthodologie d'optimisation proposée est un outil utile pour améliorer la conception des BCENN et faciliter la prise de décision dans les premières phases de la conception des bâtiments. La méthodologie est appliquée à travers les logiciels de simulation et d'optimisation énergétique TRNSYS et MOBO couplés à une technique de classement (ELECTRE III). La stabilité et la robustesse de la solution optimisée sont réalisées grâce à une analyse de sensibilité pour assurer son indépendance vis-à-vis des préférences du décideur. Des simulations sont effectuées pour évaluer les stratégies passives les plus rentables et dimensionner les systèmes d'énergies renouvelables (ER) qui devraient être mises en œuvre pour une conception d'un BCENN résidentiel typique, situé dans différentes zones climatiques, en France et au Liban. Les résultats de l'analyse indiquent clairement que, indépendamment du climat, pour concevoir un BCENN résidentiel, il est essentiel de minimiser les besoins thermiques grâce à des stratégies passives qui sont assurées par une enveloppe de bâtiment à haute performance d'isolation thermique. Les demandes d'énergie restantes (besoin de chaud ou de froid, eau chaude sanitaire, éclairage et appareils électroménagers) sont couvertes au maximum, par des sources d'ER. De plus, dans tous les climats, il faut mettre l'accent sur le contrôle des températures de consigne de la climatisation et du chauffage, en tenant compte du confort des occupants. Les approches de confort

adaptatif sont des méthodes prometteuses pour réduire les temps requis pour le refroidissement, le chauffage et la ventilation.

La troisième partie vise à étudier de manière exhaustive la conception passive optimale d'un modèle de bâtiment résidentiel. Vingt-cinq climats différents de la classification de Köppen Geiger sont simulés dans le but de produire les meilleures pratiques pour minimiser la demande en énergie du bâtiment (refroidissement et chauffage) et son coût global sur la durée de son cycle de vie (hors déconstruction). Les climats sont classés en trois catégories selon le besoin thermique dominant, avec pour but de recommander une solution optimale pour chaque catégorie. Le confort thermique adaptatif des occupants est également inspecté dans le but d'obtenir des solutions de conception passive acceptables pour l'occupant. L'étude a montré que dans les climats très froids, il faut limiter le flux de chaleur grâce à un haut niveau d'isolation. D'où la sélection d'une faible valeur du coefficient de transmission thermique U de $0,2 \text{ W} / \text{m}^2 \cdot \text{K}$ pour les murs extérieurs, le toit et le sol, et de $1,26 \text{ W} / \text{m}^2 \cdot \text{K}$ pour les fenêtres. Cependant, dans les climats chauds, il n'est pas nécessaire d'utiliser des niveaux élevés d'isolation dans les murs, le toit et le sol. Les valeurs de U appropriées des murs, du toit et du sol sont respectivement de $0,6 \text{ W} / \text{m}^2 \cdot \text{K}$, $0,6 \text{ W} / \text{m}^2 \cdot \text{K}$ et $0,5 \text{ W} / \text{m}^2 \cdot \text{K}$. Dans les climats mixtes, on remarque que les murs et le toit doivent être bien isolés (valeur $U = 0,2 \text{ W} / \text{m}^2 \cdot \text{K}$), alors que la valeur U du sol ($0,3 \text{ W} / \text{m}^2 \cdot \text{K}$) ne doit pas être réduite au minimum dans le but de permettre l'évacuation de la chaleur à travers le sol en été. Même une faible proportion de surface de vitrage (10%) est utile pour améliorer la performance énergétique du bâtiment, mais en pratique, elle doit être déterminée avec précision en fonction des exigences d'éclairage intérieur. De plus, les stratégies intégrées de refroidissement passif, telles que les occultations et la ventilation naturelle sont efficaces puisqu'elles conduisent à des baisses significatives des besoins de refroidissement, qui dépassent 50% dans presque toutes les régions, par rapport au modèle de conception optimal sans occultations ni ventilation naturelle. Ainsi, le pourcentage de surchauffe moyen du bâtiment est presque éliminé, en fonction de la catégorie climatique.

La dernière partie mène une analyse systématique sur l'évaluation de la performance d'un BCENN conçu avec six ensembles de systèmes énergétiques typiques pour passer d'un bâtiment à faible consommation énergétique à un BCENN. Les ensembles des systèmes sont optimisés au moyen de la méthodologie d'ADM présentée dans la deuxième partie. Trois villes représentatives

des climats à besoins de refroidissement dominants, à besoins de chauffage dominants et mixte, respectivement Indore, Tromso et Beijing, sont étudiées. La performance du BCENN est évaluée en termes d'une performance combinée composée d'indicateurs économiques, environnementaux, d'équilibre énergétique, d'autosuffisance et d'interaction au réseau.

Le domaine des BCENN est un domaine très vaste qui nécessite de nombreuses études pour l'amélioration de leur conception. En tant que travaux futurs, certaines idées méritent d'être étudiées, notamment:

1. Le potentiel d'intégration des technologies énergétiques avancées, telles que (i) les fenêtres intelligentes contrôlées (vitrage électrochrome et thermochrome) qui réduisent la consommation d'énergie, et améliorent le confort thermique et visuel, principalement en contrôlant le gain solaire et les flux lumineux, (ii) les matériaux de stockage de l'énergie thermique (matériaux de stockage de chaleur sensible, matériaux à changement de phase, et matériaux de stockage thermo-chimique) qui améliorent la performance thermique et la gestion énergétique des bâtiments, et (iii) les systèmes d'ER intégrés à l'enveloppe des BCENN (photovoltaïque intégré au bâtiment, fenêtres avec vitrage photovoltaïque semi-transparent, etc.) qui peuvent être utilisées pour couvrir de grandes surface de toiture et de façade.
2. L'impact des hypothèses de coûts, incluant les prix de l'énergie, les coûts d'investissement, le taux de réduction, la durée de vie des technologies d'ER, et les périodes de calcul sur l'optimalité économique et bénéfiques des BCENN.
3. L'influence de la quantification de l'incertitude sur la conception optimale du BCENN par rapport aux critères d'évaluation adoptés. Afin de garantir une conception commercialement réalisable, il est essentiel de fournir des limites de confiance fiables pour les caractéristiques optimales des BCENN au stade de la conception initiale et pas seulement des simulations annuelles pour les conditions nominales.
4. Le réaménagement des bâtiments existants en fonction des performances économiques, environnementales, et des interactions aux réseaux existants. Etant donné que le nombre de bâtiments existants est plus important que les nouveaux, il convient de mettre davantage l'accent sur les stratégies et les technologies permettant de convertir les bâtiments existant en BCENN dans différents climats.

5. La potentialité d'intégrer et d'optimiser les BCENN dans la réalisation des villes intelligentes, y compris leur interaction dynamique avec le système de gestion de l'énergie ainsi que le réseau énergétique urbain, par la fusion de systèmes automatiques et des technologies de l'information et de la communication (TIC).

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