



The assessment of district heating potential in a context of climate change and building renovation

Ivan Andric

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Ivan Andric. The assessment of district heating potential in a context of climate change and building renovation. Chemical and Process Engineering. Ecole nationale supérieure Mines-Télécom Atlantique; Instituto superior técnico (Lisbonne), 2017. English. NNT : 2017IMTA0033 . tel-01646810

HAL Id: tel-01646810

<https://theses.hal.science/tel-01646810>

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Thèse de Doctorat

Ivan ANDRIĆ

*Mémoire présenté en vue de l'obtention du
grade de Docteur de L'Ecole nationale supérieure Mines-Télécom Atlantique Bretagne-
Pays de la Loire - IMT Atlantique
sous le sceau de l'Université Bretagne Loire,
et du grade de Docteur de Instituto Superior Técnico de Lisbonne, Portugal*

École doctorale : SCIENCES POUR L'INGENIEUR

Discipline : Energétique, Thermique et Combustion

Spécialité : Energétique

Unité de recherche : GEPEA UMR CNRS 6144

Soutenue le 22 Septembre 2017

Thèse N° : 2017 IMTA 0033

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JURY

Rapporteurs : **José TEIXEIRA**, Professeur, Universidade do Minho
Paula ANTUNES, Professeur, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa

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I dedicate this thesis in memory of my sister, Mirjana Andrić.

ACKNOWLEDGMENTS

I would like to acknowledge Erasmus Mundus Joint Doctorate SELECT+ program Environomical Pathways for Sustainable Energy Services, funded with the support from the Education, Audiovisual, and Culture Executive Agency (EACEA) (Nr 2012-0034) of the European Commission for funding this thesis.

I would like to express my gratitude to my principal supervisor Olivier Le Corre for his guidance, scientific contribution and everlasting support in pursuing various research projects during the thesis. Moreover, I would like to thank my co-supervisors Paulo Ferrão and Bruno Lacarrière for their support, insights and countless creative discussions over the course of the thesis that ultimately resulted in an additional thesis contributions.

I would also like to thank Dr. André Pina and Prof. Carlos Silva for their scientific contributions and support during my tenure at Instituto Superior Técnico. Moreover, I would like to thank all my colleagues from the IN+ Center for Innovation, Technology and Policy Research (Instituto Superior Técnico) and Département Systèmes Énergétiques et Environnement (IMT Atlantique) for all creative discussions and their effort to make me feel comfortable during my stay. Additionally, I truly appreciate the support of my office colleagues Nadia Jamali-Zghal, Charlotte Marguerite and José Fiakro Castro Flores at the very beginning of my research path.

I would also like to thank the research and management team from the thesis industrial partner, Veolia Research and Innovation - Jérémy Fournier, David Mouquet, Franck Gelix and François Nicol for providing additional inputs and industrial insights that fuelled the discussions during the thesis progress meetings, and their hospitality during my tenure at Veolia premises.

Moreover, I would like to thank Prof. José Teixeira and Prof. Paula Antunes for accepting to review and provide a report on the manuscript, as well as Prof. Christian Inard, Prof. Benoit Beckers and Prof. Carlos Silva for accepting the thesis jury invitations and participating in thesis defence.

Furthermore, I would like to acknowledge Inno Energy PhD School for providing funding and support for an additional international education within the area of business management and innovation, and additional financing during my industrial mobility. The knowledge gained by attending these courses broadened my insights on energy related issues,

which helped me to develop additional ideas within my research scope. I sincerely appreciate the efforts of Isabelle Schuster, Fabien Gauthier, Marion Dequick and Christine Dominjon for managing all the processes during my involvement with the PhD school.

Finally, I would like to express my deepest appreciation to my parents, family and friends who provided endless support, encouragement and love during my studies.

A handwritten signature in black ink, appearing to read 'Andric', with a long horizontal flourish extending to the right.

Ivan ANDRIĆ

Nantes, June 2017

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LIST OF ABBREVIATIONS USED

ADP - Abiotic Depletion Potential;

AP – Acidification Potential;

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers;

BPIE - Building Performance Institute Europe;

CAPEX - Capital expenses;

EP - Eutrophication Potential;

EPBD - Energy Performance of Buildings Directive;

EPS – Expanded polystyrene

GIS – Geographical Information System;

GPP – European Green Public Procurement;

GWP – Global Warming Potential;

HTP – Human Toxicity Potential;

IAEA - International Atomic Energy Agency;

IEA – International Energy Agency;

IGD - L' Institut de la Gestion Déléguée;

INETI - Instituto Nacional de Engenharia, Tecnologia e Inovação;

IOM - International Organization for Migration;

IPCC - Intergovernmental Panel on Climate Change;

ISO – International Organization for Standardization;

IWEC - International Weather for Energy Calculations;

LCA - Life-cycle Assessment;

NZEB – Near Zero Energy Buildings;

ODP - Ozone Layer Depletion;

OPEX – Operating expenses;

POCP - Photo Oxidant Creation Potential;

RD – Resource depletion;

UEV – Unit Energy Value;

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NOMENCLATURE

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Item	Unit	Description
A_d	[km ²]	Overall district surface;
$A_{o,f}$	[m ²]	Clear floor surface;
$A_{o,r}$	[m ²]	Surface of the clear roof;
$A_{o,w}$	[m ²]	Opaque walls surface (without glazing);
$A_{o,wd}$	[m ²]	Total surface of the windows (glazing area);
A_t	[m ²]	Total area of the element (including thermal bridges);
C_{en}	[J/K]	Average thermal capacity of the zone;
C_f	[J/m ² K]	Specific heat capacity of the floors;
C_r	[J/m ² K]	Specific heat capacity of the roof;
C_w	[J/m ² K]	Specific heat capacity of the walls;
c_a	[J/kgK]	Specific air heat capacity;
c_{wt}	[J/kgK]	Specific water heat capacity;
d_{ee}	[-]	The elementary effect
$f_{dhw,j}$	[-]	Fraction of the consumption profile for the regarded hour;
$f_{ea,h,j}$	[-]	Working profile fraction of the h-th appliance;
$f_{o,j}$	[-]	Occupancy profile fraction;
G_r	[%]	Building glazing ratio;
h_z	[m]	Zone height;
$I_{gh,j}$	[W/m ²]	Global solar radiation for the regarded j-th hour;
$I_{gh,th}$	[W/m ²]	Global solar radiation threshold value for lighting;
K_{en}	[W/K]	Thermal conductance between the external envelope surface and internal envelope surface;
$K_{en,e}$	[W/K]	Thermal conductance between the outdoor air and external surface of the envelope;
$K_{en,i}$	[W/K]	Thermal conductance between the internal surface of the envelope and internal ambient air;
K_{wd}	[W/K]	Thermal conductance through the windows;
K_{wd}	[W/K]	Thermal conductance through the window;
K_{wf}	[W/K]	Thermal conductance through the floor;
K_{wr}	[W/K]	Thermal conductance through the roof;
K_{ww}	[W/K]	Thermal conductance through the walls;
L	[m]	Length of the regarded thermal bridge;
L_c	[m]	Length of the building corners;
L_f	[m]	Length of the floor thermal bridge;
L_p	[m]	Length of the parapet;
L_{sl}	[m]	Length of the interfloor slabs;
L_{wd}	[m]	Length of the windows thermal bridges;
l_{wd}	[m]	Average length of one windows side;
n_c	[corners]	Number of corners per building;
n_o	[oc.]	Total number of occupants;
n_{sl}	[slabs]	Number of interfloor slabs;
n_{wd}	[windows]	Number of windows;
P_{si}	[W/m ²]	Specific installed power of lighting equipment;
P_z	[m]	Zone perimeter;
P_{za}	[m]	Attached zone perimeter;
p_{ee}	[-]	El. effect analysis selected levels in the space of the model input factors

Q_{dh}	[Wh/yr]	Total district heat demand for the regarded period (year/heating season);
Q_{dh}	[W]	District heat demand (in [W]);
Q_{dhd}	[Wh/km ² /yr]	District heat demand density;
$Q_{dhw,i,j}$	[Wh]	Domestic hot water heating demand of i-th building for the j-th hour;
$Q_{dhw,j}$	[W]	Hourly heat demand for the domestic hot water preparation;
$Q_{ea,h}$	[W]	Heat released from the h-th appliance;
$Q_{ea,j}$	[W]	Hourly heat release from the electric appliances;
Q_{ea}	[W]	Heat gain from electrical appliances;
Q_{in}	[W]	Internal heat gains;
$Q_{l,j}$	[W]	Hourly heat release from the lighting equipment;
Q_l	[W]	Heat gain from the lightning equipment;
$Q_{oc,j}$	[W]	Hourly heat release from the occupants;
Q_{oc}	[%]	Heat gain from the occupants;
$Q_{sh,i,j}$	[Wh]	Hourly heat space heating demand of i-th building for the j-th hour;
Q_{sh}	[W]	Heat gains from the heating system;
Q_{s1}	[W]	Solar heat gain on the external surface of the building envelope;
Q_{s2}	[W]	Solar heat gain on the internal surface of the building envelope;
Q_v	[W]	Heat exchange due to the natural/mechanical ventilation;
q_{dhw}	[kg/oc./h]	Domestic hot water demand per occupant for the regarded hour;
$q_{o,s}$	[W/oc.]	Specific heat release from one occupant;
r_v	[vol./s]	Level of air exchange in the zone;
S_f	[m ²]	Floor surface area
S_r	[m ²]	Roof surface area
S_w	[m ²]	Wall surface area
S_{wd}	[m ²]	Window surface area
$T_{a,i}$	[K]	Internal ambient air temperature;
$T_{dhw,p}$	[K]	Temperature of water for domestic hot water preparation;
T_{dhw}	[K]	Temperature of the prepared domestic hot water;
$T_{en,e}$	[K]	Temperature of the external envelope surface;
$T_{en,i}$	[K]	Temperature of the internal envelope surface;
T_{st}	[K]	Internal set point (comfort) temperature;
t_o	[°C]	Outdoor air temperature (in [°C]);
U_{cl}	[W/m ² K]	Thermal transmittance of the clear element;
U_{en}	[W/m ² K]	The mean U-value of the envelope
U_f	[W/m ² K]	Clear floor thermal transmittance;
U_r	[W/m ² K]	Thermal transmittance of the clear roof;
$U_{t,f}$	[W/m ² K]	Total thermal transmittance of the floor;
$U_{t,r}$	[W/m ² K]	Total thermal transmittance for the roofs;
$U_{t,w}$	[W/m ² K]	Total thermal transmittance of walls;
$U_{t,wd}$	[W/m ² K]	Total thermal transmittance for windows;
U_t	[W/m ² K]	Total thermal transmittance of the regarded envelope element;
U_w	[W/m ² K]	Thermal transmittance of the clear wall (without glazing and thermal bridges);
U_{wd}	[W/m ² K]	Thermal transmittance of clear windows;
V_z	[m ³]	Zone volume;
W_A	[%]	The fraction of solar radiation that penetrates through windows and affects the internal ambient temperature;
W_W	[%]	The fraction of total solar radiation that penetrates through windows and affects the internal wall temperature;
α	[W/°C]	Heat demand –outdoor air temperature function slope coefficient;
α_{ef}	[W/m ² K]	Heat convection coefficients on the external side of the floor;
α_{er}	[W/m ² K]	Heat convection coefficients on the external side of the roof;

α_{ew}	[W/m ² K]	Heat convection coefficients on the external side of the walls;
α_{ewd}	[W/m ² K]	Heat convection coefficients on the external side of the windows;
Δ	[%]	Percentage error for the annual heat demand;
$\Delta_{RC/report}$	[%]	The difference between the RC model calculated results and APUR/Tabula reports;
Δ_{ee}	[-]	El. effect analysis step of parameter change
η_l	[%]	The efficiency of the installed lighting equipment;
θ	[W]	Heat demand –outdoor air temperature function intercept;
θ_b	[-]	Correction coefficient for incident beam;
θ_{bs}	[-]	Correction coefficient to account for shading from the surrounding buildings;
θ_{gs}	[-]	Correction coefficient to account for the shading from the surrounding greenery;
θ_o	[-]	Correction coefficient to account for building orientation;
θ_s	[-]	Correction coefficient due to the windows blinds/shades;
μ_{ee}	[-]	El. effect analysis mean value
$\mu_{m,ee,i}$	[-]	El. effect analysis modified mean value
ρ_a	[kg/m ³]	Average air density;
σ	[SD]	Standard deviation between the heat demand hours;
σ_{ee}	[-]	El. effect analysis deviation value
χ	[W/K]	The point thermal transmittance;
ψ	[W/mK]	Linear thermal transmittance of the regarded heat bridge;
ψ_c	[W/mK]	Linear thermal transmittance of the corner;
ψ_f	[W/mK]	Linear thermal transmittance of the floor-to-ground transition;
ψ_p	[W/mK]	Linear thermal transmittance of the parapet heat bridge;
ψ_{sl}	[W/mK]	Linear thermal transmittance of the interfloor slab;
ψ_{wd}	[W/mK]	Linear thermal transmittance of the window-to-wall thermal bridge;
Ω_{ee}	[-]	El. effect analysis Region of experimentation of the model inputs

Part II (in alphabetical order)

Item	Unit	Description
a	[-]	Ground albedo;
A_b	[m ²]	Total useful building floor surface;
A_{cs}	[m ²]	Construction site surface (footprint);
$C_{aet,max}$	[kg]	Additional elements delivery vehicle transportation maximum capacity;
$C_{amt,max}$	[kg]	Maximum capacity of the vehicle used for the delivery of an additional material for network infrastructure placement;
$C_{bst,max}$	[kg]	Building subsystem elements transportation vehicle maximum capacity;
$C_{egt,max}$	[kg]	Excess ground transportation vehicle maximum capacity;
$C_{ft,max}$	[kg]	Fuel delivery vehicle maximum capacity;
$C_{hs,max}$	[kg]	Heat production unit material transportation vehicle maximum capacity;
$C_{ptr,max}$	[rolls]	Pipe transportation vehicle maximum rolls capacity;
$C_{pts,max}$	[pipes]	Maximum segment capacity of pipe transportation vehicle;
$D_{bs,t}$	[km]	Building subsystem elements transportation distance for one delivery;

D_{et}	[km]	Daily distance crossed by one employee;
D_{et}	[km]	Daily distance crossed by one employee;
$D_{hs,t}$	[km]	Transportation distance during one delivery of materials for heat production unit construction;
$D_{ni,aet}$	[km]	Transportation distance per one delivery of additional elements;
$D_{ni,amt}$	[km]	Transportation distance for delivering an additional material used for network infrastructure placement;
$D_{ni,egt}$	[km]	Excess ground transportation distance per one delivery;
$D_{ni,pt}$	[km]	Transportation distance per one delivery of pipes;
$D_{o,ft}$	[km]	The delivery distance crossed by the fuel delivery vehicle per each fuel delivery;
$d_{p,g}$	[m]	Diameter of the g -th pipe type placed;
d_{tr}	[m]	Network trench depth;
$E_{bs,m}$	[sej]	Emergy flow of materials and resources used for the building subsystem elements;
$E_{bs,m}$	[sej]	Emergy flow of building subsystem materials and resources used for the building subsystem elements installation;
$E_{bs,t}$	[sej]	Emergy flow of building subsystem elements transportation;
$E_{c,bs}$	[sej]	Building subsystem construction emergy flow;
$E_{c,bs}$	[sej]	Building subsystem emergy flow;
$E_{c,hl}$	[sej]	Emergy flow of human labor required for the construction of each system component and final assembly;
$E_{c,hs}$	[sej]	Heat production unit construction emergy flow;
$E_{c,ni}$	[sej]	Network infrastructure placement emergy flow;
$E_{c,s}$	[sej]	System construction emergy flow;
$E_{cle,j}$	[sej/emp/yr]	Individual emergy flows of employees with college education;
E_{cm}	[sej]	Emergy flow of heavy construction machines;
E_{cwt}	[sej]	Emergy flow of construction workers daily commuting;
E_{eg}	[sej]	Emergy flow of fuel used for on-site electricity generators;
$E_{el,o}$	[sej]	Emergy flow of electricity consumed from the grid;
$E_{elf,rf}$	[sej]	Emergy flow of end-of-life phase without building renovation;
$E_{elf,rn}$	[sej]	Emergy flow of end-of-life phase after building renovation;
$E_{f,e}$	[sej/yr]	Emergy flow of the e -th fuel type combusted;
E_h	[sej/yr]	Emergy flow of heat used for heating the premises during the building lifetime;
$E_{hs,t}$	[sej]	Emergy flow of heat production unit material transportation;
E_{hs}	[sej]	Heat production unit materials and assembly emergy flow;
$E_{hse,j}$	[sej/emp/yr]	Individual emergy flows of employees with high school education;
$E_{mt,j}$	[sej]	Emergy flow of transportation for each j -th material;
$E_{ni,ae}$	[sej]	Additional elements emergy flow;
$E_{ni,aem}$	[sej]	Emergy flow of network infrastructure additional elements assembly;

$E_{ni,aet}$	[sej]	Emergy flow of network infrastructure additional elements transportation;
$E_{ni,am}$	[sej]	Emergy flow of additional material used for network infrastructure placement;
$E_{ni,amt}$	[sej]	Additional material transportation emergy flow;
$E_{ni,egt}$	[sej]	Excess ground transportation emergy flow;
$E_{ni,p}$	[sej]	Emergy flow of the pipes used;
$E_{ni,pl}$	[sej]	Pipe laying process emergy flow;
$E_{ni,plm}$	[sej]	Emergy flow of pipe laying process with heavy machines;
$E_{ni,pm}$	[sej]	Pipe materials emergy flow;
$E_{ni,pt}$	[sej]	Pipe transportation emergy flow;
$E_{ni,te}$	[sej]	Trench excavation emergy flow;
$E_{o,et}$	[sej/yr]	Emergy flow of employees home-to-work daily commuting;
$E_{o,f}$	[sej/yr]	Emergy flow of resources used for heat generation;
$E_{o,ft}$	[sej/yr]	Emergy flow of heat generation resources transportation;
$E_{o,hl}$	[sej/yr]	Emergy flow of human labor required to operate the system;
$E_{o,hl}$	[sej]	Emergy flow of human labor used during the construction/renovation phase;
$E_{o,s}$	[sej/yr]	Annual emergy flow of system operation;
$E_{o,tot}$	[sej/J]	Emergy flow of the operation phase over the total system lifetime;
$E_{op,rf}$	[sej]	Building operation emergy flow for a reference building state;
$E_{op,rf}$	[sej]	Emergy flow of building operation within its reference state;
E_{rn}	[sej]	Emergy flow of building renovation;
$E_{s,e}$	[sej]	Soil erosion emergy flow;
E_{scs}	[sej]	Emergy flow of solar radiation on a building construction site;
E_{sg}	[sej/yr]	Emergy flow of annual solar gains on the building envelope;
$E_{ss,i}$	[sej]	Emergy flow of i -th subsystem construction;
$E_{t,rf}$	[sej]	Total building emergy flow without renovation phase;
$E_{t,rn}$	[sej]	Total building emergy flow with renovation phase;
$E_{w,co}$	[sej]	Emergy flow of water consumed during the building construction phase;
$E_{w,op}$	[sej]	Emergy flow of water consumed during the building lifetime;
EIR	[sej]	Emergy investment ratio;
ELR	[sej]	Emergy loading ratio;
EYR	[sej]	Emergy yield ratio;
e_s	[J/kg]	Soil energy content;
F	[sej]	Purchased resources consumed by the system;
$FC_{aet,fl}$	[l/km]	Additional elements delivery vehicle fuel consumption with full load;
$FC_{aet,wl}$	[l/km]	Additional elements delivery vehicle fuel consumption without a load;
$FC_{amt,fl}$	[l/km]	Fuel consumption with full load of the vehicle used for transporting an additional material for network infrastructure placement;

$FC_{amt,wl}$	[l/km]	Fuel consumption without a load of the vehicle used for transporting an additional material for network infrastructure placement;
$FC_{bst,fl}$	[l/km],	Building subsystem elements transportation vehicle fuel consumptions with full load;
$FC_{bst,wl}$	[l/km],	Building subsystem elements transportation vehicle fuel consumption without a load;
$FC_{c,et}$	[l/km]	Average fuel consumption of the passenger cars used by the employees for home-to-work commuting;
$FC_{c,et}$	[l/km]	Passenger car average fuel consumption;
$FC_{cm,fl}$	[l/h]	Hourly fuel consumption of the machine considered with a full load;
$FC_{cm,wl}$	[l/h]	Hourly fuel consumption of the machine without a load;
$FC_{egt,fl}$	[l/km]	Excess ground transportation vehicle fuel consumption with full load;
$FC_{egt,wl}$	[l/km]	Excess ground transportation vehicle fuel consumption without a load;
$FC_{ex,fl}$	[l/h]	Trench excavation machine hourly fuel consumption with full load;
$FC_{ex,wl}$	[l/h]	Trench excavation machine hourly fuel consumption without a load;
$FC_{ft,fl}$	[l/km]	Fuel delivery vehicle fuel consumption with full load;
$FC_{ft,wl}$	[l/km]	Fuel delivery vehicle fuel consumption without a load;
$FC_{hs,fl}$	[l/km]	Heat production unit material transportation vehicle fuel consumption with full load;
$FC_{hs,wl}$	[l/km]	Heat production unit material transportation vehicle fuel consumption without a load;
$FC_{pt,fl}$	[l/km]	Pipe transportation vehicle fuel consumption with full load;
$FC_{pt,wl}$	[l/km]	Pipe transportation vehicle fuel consumption without a load;
f_{os}	[%]	The amount of organic substance in soil;
H_{dm}	[MJ/yr]	Annual heat demand;
H_{dm}	[J]	Total heat demand (with losses accounted) ;
$h_{cm,op}$	[h]	Number of operating hours for the machine considered;
h_{ex}	[h]	Number of hours for excavation required by an adequate machine;
h_{ic}	[m]	Pipe infrastructure height;
h_{om}	[h]	Time required for excavating machine to make one complete excavating move;
$I_{sr,a}$	[J/m ² /yr]	Annual amount of solar radiation for the studied location;
LHV_d	[J/l]	Diesel fuel low heating value;
LHV_f	[MJ/kg] [MJ/m ³]	Regarded fuel low heating value;
l_{ic}	[m]	Pipe infrastructure length;
l_n	[m]	Network length;
l_{pr}	[m]	Length of a pipe in one roll;
l_{ps}	[m]	Length of one pipe segment;
l_{tr}	[m]	Network trench length;
$m_{aem,s}$	[kg]	Mass of the materials used for s-th additional element;
$m_{am,sd}$	[kg]	The amount of sand and gravel mixture used to cover placed network infrastructure;

$m_{am,x}$	[kg]	The amount of x -th material used during network infrastructure placement;
$m_{bsm,v}$	[kg]	The amount of the v -th material used for building subsystem elements installation;
$m_{hsm,i}$	[kg]	The amount of i -th type of material used for heat production unit construction;
$m_{i,j}$	[kg]	The amount of j -th material used during the subsystem construction (of total n materials);
$m_{ni,eg}$	[kg]	The amount of excess ground material to be transported to the landfill;
$m_{tl,sc}$	[kg/m]	The specific mass of concrete used for network covering;
$m_{tl,sp}$	[kg/m]	The specific mass of pavement used for trench covering;
N	[sej]	Indigenous non-renewable resources consumed by the system;
$ND_{bs,t}$	[del.]	Number of deliveries for building subsystem elements transportation;
$ND_{hs,t}$	[del.]	The number of material deliveries for heat production units construction;
$ND_{ni,aet}$	[del.]	Number of deliveries for the additional elements transportation;
$ND_{ni,amt}$	[del.]	Number of deliveries for an additional material used for network infrastructure placement;
$ND_{ni,egt}$	[del.]	Number of excess ground transportation deliveries;
$ND_{ni,pt}$	[del.]	Number of pipe deliveries;
$ND_{o,ft}$	[del.]	Number of deliveries for fuel transportation;
n_{cd}	[days]	Number of days required for the system construction and assembly;
n_{cd}	[days]	Number of days required to complete building construction;
$n_{ch,d}$	[h]	Number of hours worked daily by one employee;
$n_{cle,j}$	[emp.]	The number of employees with college education engaged in the j -th process;
n_{cw}	[emp.]	Number of employees used for system construction;
n_{cw}	[c.w.]	Number of engaged construction workers;
$n_{ex,m}$	[mov.]	Number of excavating moves made by machine;
n_h	[h/day/emp.]	Number of hours per day worked by one construction worker;
$n_{hse,j}$	[emp.]	The number of employees with high school education engaged in the j -th process;
n_{lf}	[yr]	Expected system lifetime;
n_{oc}	[oc.]	Number of occupants;
n_{od}	[days]	Number of working days;
$n_{oh,d}$	[h/day/emp.]	Hours per day worked by one employee;
n_{ow}	[emp.]	Number of employees required for system operation;
n_{pr}	[rolls]	Number of required pipe rolls;
n_{ps}	[segments]	Number of pipe segments;
Q_h	[J/yr]	The amount of heat consumed annually during the heating season;
Q_{sg}	[J/yr]	Annual solar gains on the building envelope during the heating season;
$q_{aemr,w}$	[J]	The amount of an additional w -th energy resource used for an additional element assembly;

$q_{bsmr,t}$	[J]	The amount of an additional w -th energy resource used for building subsystem elements installation;
$q_{f,e}$	[kg][m ³]	The amount of each fuel type combusted;
$q_{hsr,j}$	[J]	The amount of j -th additional energy resource used for the heat production unit assembly;
R	[sej]	Indigenous renewable resources consumed by the system;
T_{hsn}	[K]	Heat sink temp. for Carnot efficiency calc.
T_{hsr}	[K]	Heat source temp. for Carnot efficiency calc.
t_{cs}	[yr]	Time required for building construction;
$t_{op,rf}$	[yr]	Time of building operation within the reference state;
$t_{op,rf}$	[yr]	Period of building operation within its reference state;
t_{op}	[yr]	Total time of building operation;
$U_{aem,s}$	[sej/kg]	UEV of the s -th material used for s -th additional element;
$U_{aemr,w}$	[sej/J]	UEV of an additional w -th energy resource used for an additional element assembly;
$U_{am,x}$	[sej/kg]	UEV of the x -th material used;
U_b	[sej/m ²]	Building UEV;
$U_{bsm,v}$	[sej/kg]	UEV of the v -th material used for building subsystem element installation;
$U_{bsmr,t}$	[sej/J]	UEV of the w -th energy resource used for building subsystem elements installation;
$U_{c,hl}$	[sej/h]	UEV of human labor used for system construction;
$U_{c,hl}$	[sej/h]	UEV of human labor of construction workers;
U_d	[sej/J]	Diesel fuel UEV;
$U_{el,i}$	[sej/J]	The UEV value of i -th electricity production source;
U_{el}	[sej/J]	UEV of the electricity produced for the case study location;
$U_{f,e}$	[sej/kg] [sej/m ³]	UEV of each fuel type combusted;
U_h	[sej/J]	UEV of heat delivered;
U_{heat}	[sej/J]	UEV of the heat delivered to the consumer;
$U_{hl,j}$	[sej/h]	The UEV of human labor for each j -th process;
$U_{hsm,i}$	[sej/kg]	UEV of the i -th heat production unit material;
$U_{hsr,j}$	[sej/J]	UEV of j -th additional energy resource used for the assembly;
$U_{i,j}$	[sej/kg]	UEV of the regarded material;
U_{lu}	[sej/J]	Land use UEV;
$U_{o,hl}$	[sej/h]	UEV of human labor for network operation;
U_s	[sej/J]	Solar energy UEV;
U_w	[sej/kg]	Water UEV;
V_{exb}	[m ³]	Excavating machine the bucket volume;
V_{exs}	[m ³]	Volume of the soil excavated;
V_{grf}	[m ³]	The amount of excavated soil used for trench refilling;
V_{pp}	[m ³]	Volume of the pipe infrastructure placed in the excavated trench;
V_{tr}	[m ³]	Volume of the trench to be excavated;
V_w	[m ³]	Volume of the water used during the building construction phase;
W_e	[J/yr]	Annual electricity consumption;
w_{ic}	[m]	Pipe infrastructure width;
w_{tr}	[m]	Network trench width;
α_s	[%]	The share of soil in the mixture for network trench filling;

δ_e	[%]	Fuel share in annual heat production;
γ_{aet}		Additional elements delivery vehicle fuel consumption ratio;
γ_{amt}	[-]	Fuel consumption ratio of the vehicle used for transporting an additional material for network infrastructure placement;
γ_{bst}	[-]	Building subsystem elements transportation vehicle fuel consumption ratio;
γ_{cm}	[-]	Fuel consumption ratio of the machine considered;
γ_{egt}	[-]	Excess ground transportation vehicle fuel consumption ratio;
γ_{ex}	[-]	Trench excavation machine fuel consumption ratio;
γ_{ft}	[-]	Fuel delivery vehicle fuel consumption ratio;
γ_{hs}	[-]	Heat production unit material transportation vehicle fuel consumption ratio;
γ_{pt}	[-]	Pipe transportation vehicle fuel consumption ratio;
Δ_s	[sej]	Energy saving achieved by renovation measures;
$\varepsilon_{el,i}$	[%]	The regarded i -th electricity production source share in total electricity production;
η_c	[%]	Carnot efficiency of the system;
η_{hp}	[%]	Heat production unit energy transformation efficiency;
η_{net}	[%]	Network efficiency;
θ_{deg}	[l/m ²]	Generator fuel consumed to produce the required amount of electricity on construction site during the construction phase;
ρ_{eg}	[kg/m ³]	Excavated soil average density;
ρ_s	[kg/m ³]	Average soil density;
ρ_{sd}	[kg/m ³]	Average density of sand and gravel mixture;
ρ_w	[kg/m ³]	Water density;
ϑ_e	[m ³ /oc./day]	Specific daily water consumption per occupant;

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AWARDS AND ACHIEVEMENTS

1st Pitching prize, *4th Annual Inno Energy Scientist Conference*, Berlin, Germany, 20th – 20nd October 2015;

1st Pitching prize, *4th International DHC+ Summer School*, Warsaw, Poland, 21st – 27th August 2016;

3rd prize, *Iberdrola Energy Challenge 2017*, Madrid, Spain, 31st January – 10th July 2017;

Best Pitch Prize, *Energy Solutions Design for Eco-Districts*, Grenoble, 3rd-7th July 2017;

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EXTENDED ABSTRACT/ RÉSUMÉ ÉTENDU (in French/en français)

Le changement climatique est un phénomène sans équivoque, établi sur la base des températures observées dans les couches de l'atmosphère et dans les océans, la superficie des surfaces enneigées et sur la fonte des glaces induisant une augmentation du niveau moyen des océans. Différents rapports d'institutions internationales recherchant les causes, les potentiels impacts et les conséquences de ce changement climatique suggèrent qu'il est *extrêmement probable* que l'augmentation de gaz à effet de serre dans l'atmosphère, dégagés par l'activité anthropique, est l'un des principaux facteurs de ce changement climatique. Comme le chauffage de l'immobilier est l'un des secteurs émettant le plus de gaz à effet de serre, et que ce secteur est, de surcroît, en constante progression (en lien avec l'augmentation de la population), la réduction de cette consommation d'énergie et de ces émissions afférentes de gaz à effet de serre pourrait contribuer significativement à limiter le changement climatique.

Les réseaux de chaleur sont communément proposés dans la littérature comme une solution technique pertinente d'un point de vue environnementale pour fournir les besoins de chauffage dans les logements, les magasins et les entreprises. Ces réseaux ont de multiples intérêts, tels que : une production centralisée pouvant être hors du cœur des centres villes, une large gamme d'utilisation d'énergie renouvelable et/ou de déchets, et une amélioration du confort et de la sécurité de la chaleur fournie. Par conséquent, le développement des réseaux existants ainsi que la construction de nouveaux réseaux sont bien documentés, y compris dans les rapports stratégiques officiels de l'Union Européenne (EU) traitant de la « décarbonisation » des systèmes énergétiques dans l'UE. Cependant, la construction de tels réseaux nécessite des investissements financiers conséquents, amortis par la vente de chaleur sur des longs temps de retour. Toute réduction de consommation d'énergie d'un tel réseau impacterait sa rentabilité (ou même sa faisabilité).

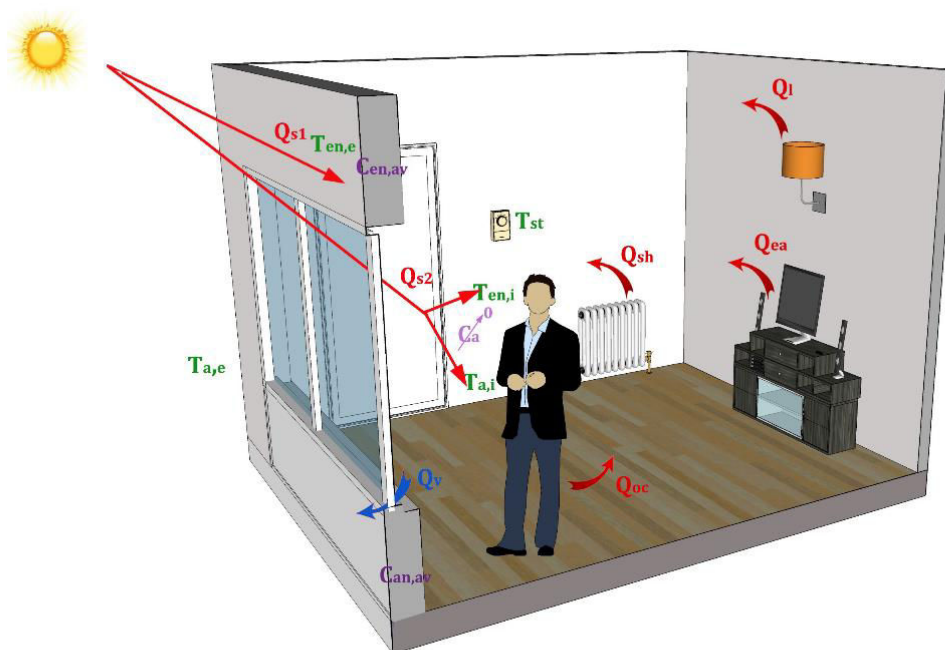
Ces réductions de consommation peuvent être qualifiées de directes ou indirectes, par rapport au phénomène du changement climatique. D'une part, la différence entre la température interne d'un bâtiment (celle de confort pour les occupants) et son environnement (augmentation future de la température extérieure) devrait se réduire, limitant la quantité de chaleur à fournir, notamment celle des clients connectés à un réseau de chaleur. Cet aspect peut être classé comme un impact direct du changement climatique sur la demande de chaleur des bâtiments. D'autre part, les politiques incitant à la sobriété énergétique dans le secteur du bâtiment (comme la directive de performance énergétique des bâtiments ou la directive 2010/31/EU) ont été (ou sont en cours d'être) transcrites dans les textes officiels nationaux afin d'encourager la

renovation dans ce secteur partout en Europe. L'amélioration des performances de l'enveloppe d'un bâtiment rénové induit une diminution de la consommation d'énergie pour son chauffage. Cet aspect peut être classé comme un impact indirect du changement climatique.

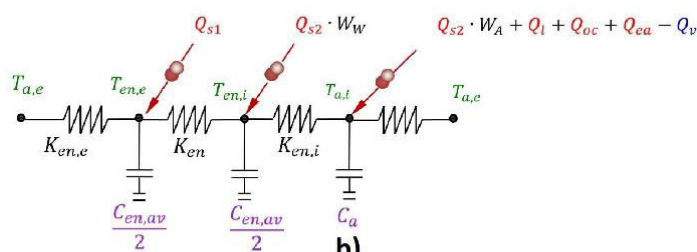
Cependant, l'évaluation de la performance énergétique d'un système, quel qu'il soit, considérée sur la seule base de ces émissions pendant sa phase opérationnelle pourrait amener à des résultats erronés : les impacts environnementaux associés pendant la phase de construction sont fréquemment pris en compte. Plus précisément, cette évaluation est d'autant plus importante pour les réseaux de chaleur urbains que ces réseaux sont composés d'éléments (unité centralisée de production de grande capacité, réseau de distribution avec des tuyaux de grands diamètres et connections aux bâtiments au niveau des sous-stations ou de systèmes assimilés) à fort impact environnemental (tel que l'acier etc...). Par conséquent, l'impact de toutes les ressources consommées, directement ou indirectement, pendant toute la durée de vie d'un système (comme un réseau de chaleur) doit être pris en considération afin d'avoir une évaluation adéquate de la performance de ces-dits systèmes. En outre, afin de caractériser la performance environnementale d'un réseau urbain de chaleur dans son environnement, cette performance doit être comparée à celle d'une solution de référence fournissant le même besoin de chaleur. De plus, cette caractérisation doit être effectuée en tenant compte de la manière dont la chaleur consommée par les bâtiments connectés au réseau de chaleur affecte la performance environnementale du bâtiment lui-même (i.e. changement de perspective de l'analyse environnementale, du propriétaire du réseau de chaleur à celui du bâtiment).

Le champ de recherche de cette thèse peut être scindé suivant deux approches principales:

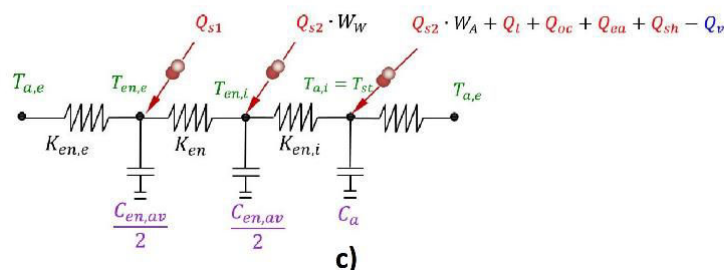
- L'évaluation de l'impact du changement climatique sur les réseaux urbains de chaleur, en tenant compte des aspects direct et indirect, décrits précédemment.
- L'évaluation de la performance environnementale des réseaux urbains de chaleur dans son environnement, en tenant compte de toutes les ressources consommées sur la durée de vie du système (et de ses équipements), de la phase amont de la construction à sa phase de fonctionnement.



a)



b)



c)

Figure : Modèle thermoélectrique pour l'estimation du besoin de chaleur d'une enveloppe à température intérieure contrôlée;

Pour évaluer les impacts (direct et indirect) du changement climatique sur les réseaux urbains de chauffage, un modèle basé sur une analogie thermoélectrique de l'enveloppe d'un bâtiment (voir figure ci-dessus) a été créé et comparé à d'autres logiciels ou méthodes (CCWorldWetaherGen, ArcGIS, LiDAR). La méthodologie ainsi proposée permet d'évaluer les impacts directs du changement climatique. Le modèle thermoélectrique de demande de chaleur d'un bâtiment a été comparé d'une part avec le logiciel Design Builder v4.6 (Energy Plus v.8.3), logiciel de référence dans la simulation de la demande énergétique d'un bâtiment, et d'autre part avec des données statistiques de demande de chauffage provenant de rapports nationaux d'institutions gouvernementales des pays étudiés. Les résultats des validations de la

demande annuelle de chauffage sont satisfaisants : d'une part, la différence entre le modèle thermoélectrique et le logiciel Energy Plus est en moyenne de 4.5 %, d'autre part, la différence entre le modèle thermoélectrique et les données statistiques (comportant le type de bâtiment et sa période de construction) issues de rapports d'agence nationale est entre 8 % à 10 %. Dans ces validations, la marge d'erreurs est faible et est inférieure à la limite maximale communément reportée dans la littérature (20 %), pour les modèles simplifiés de demande de chauffage. Après cette validation, la méthodologie a été appliquée à deux cas : à un quartier de Lisbon (Portugal), nommé Alvalade se composant de 655 bâtiments, et à un quartier de Nantes (France) nommé St. Félix se composant de 622 bâtiments. Pour ces 2 cas, de multiples scénarii ont été considérés, i.e. des données météorologiques venant de modèles du GIEC (Groupe International d'Expert du Climat) et de rénovation (programmation et « intensité » de rénovation). Pour compléter ces résultats, une étude spécifique consistant à imaginer un même bâtiment construit à 5 endroits du globe a été menée. La finalité de cette étude est de voir si les conclusions des 2 cas précédents sont généralisables.

Pour évaluer la performance environnementale d'un réseau urbain de chauffage dans son environnement, l'approche méthodologique de l'empreinte énergétique (appelée eMergie dans la littérature) a été considérée dans cette thèse. Dans cette partie, les premiers travaux de cette thèse s'intéressent plus particulièrement à la performance environnementale de la production-distribution des réseaux de chauffage urbains, en tenant compte des ressources amont et aval consommées pendant la durée de vie d'un réseau : construction, fonctionnement (la phase de démolition n'a pas été considérée car il n'existe pas de cas de démolition d'un réseau, même après plusieurs décades de fonctionnement – selon la bibliographie consultée et la connaissance approfondie de l'auteur). La méthodologie développée peut être appliquée à un réseau urbain de chauffage quelconque : les applications dans cette thèse considèrent différents modes de production de chaleur. Dans cette partie, les secondes analyses environnementales de cette thèse s'intéressent plus particulièrement au consommateur final dans le bâtiment. L'analyse tient compte, comme précédemment, de la phase de construction, de fonctionnement du bâtiment mais aussi la phase de démolition ainsi que la phase de rénovation éventuelle. La méthodologie développée peut être appliquée à un bâtiment quelconque, indépendamment de sa période de construction, à condition que les données d'entrée soient disponibles. Cette méthodologie a été d'abord appliquée pour comparer 2 types de réseaux de chaleur : un réseau moderne à 4 tuyaux ESPEX et un réseau traditionnel à 2 tuyaux. Les moyens centralisés associés à la production ont été comparés à une production décentralisée et individuelle utilisant du gaz naturel de ville. Ces différentes configurations ont été appliquées sur un quartier de Värnamo (Suède), nommé Vråen. Afin d'évaluer dans quelle mesure la chaleur consommée par

ce quartier peut impacter la performance environnementale, la méthodologie a aussi été mise en œuvre sur un immeuble d'habitation situé dans la ville de Šabac (Serbie).

A partir des résultats obtenus de ces études de cas, il est possible de conclure que les réseaux urbains de chaleur pourraient avoir un grand potentiel pour atteindre les objectifs « soutenables » des politiques de l'UE, si et seulement si les aspects suivants sont pris en considération dès la phase de conception :

- Production de chaleur à partir de ressources renouvelables ;
- Utilisation de réseaux urbains modernes, avec une infrastructure compacte, utilisant des matériaux ayant un impact environnemental faible;
- Capacités de production conçues pour une potentielle baisse de la demande de chaleur due à l'impact direct ou indirect du changement climatique (par exemple, installation de 2 chaudières en base, d'une capacité cumulée égale à celle d'une grande chaudière);
- Utilisation de combustibles les moins nuisibles à l'environnement pendant les périodes de pointe;
- Prise en compte de l'effet du changement climatique selon les régions sur la demande de chaleur;
- Développement de plans de financement alternatif afin d'éviter l'augmentation des prix du kilowatt-heure chaleur ayant pour conséquence éventuelle la déconnection de clients.

Des pistes de travaux supplémentaires peuvent être suggérées:

- validation du modèle thermoélectrique sur des mesures sur site ;
- développement d'une partie climatisation dans le modèle ;
- développement d'une communication avec d'autres logiciels commerciaux, afin d'intégrer les impacts du changement climatique sur la « soutenabilité » de l'environnement urbain, et plus particulièrement de ses réseaux de chaleur et de froid.

INTRODUCTION

CHAPTER 1: INTRODUCTION

1.1 Research motivation

Climate change is unequivocal, as proved by the observed global air and ocean temperature rises, widespread snow and ice melting and the rise in average sea level (IPCC, 2014). Human influence on the climate system is clear – anthropogenic greenhouse gas emissions have significantly increased since the dawn of the industrial era due to the rapid economic and population growth. Consequently, these emission patterns have led to currently all-time high atmospheric concentrations of greenhouse gases. The effects have been detected throughout the whole climate system. The summary of recent scientific reports suggests that it is *extremely likely* that increased concentration of greenhouse gases and previously mentioned anthropogenic drivers have been the dominant cause of observed warming (IPCC, 2014). Additionally, there is a high probability that heat waves will occur more often and have a longer duration in the future. Climate change already has a widespread impact on human and natural systems, and the continuous emission of greenhouse gases would cause further warming and long-term changes in all components of Earth's climate system. In the summary report by the IPCC (Intergovernmental Panel on Climate Change), it was concluded that cumulative emissions of CO₂ in all scenarios would significantly determine global mean surface warming by the late 21st century and beyond (IPCC, 2014). These long term changes would increase the possibility of severe and irreversible impacts for global society and ecosystems. Thus, substantial emissions reductions in the decades to come could limit climate change risks, foster the effective adaptation measures, reduce the climate change mitigation costs and contribute to environmental pathways for sustainable future.

According to the Climate Analysis Indicators Tool (World Resources Institute, 2016), 64.5% of global anthropogenic greenhouse gas emissions comes from the energy sector. Worldwide, about 18% of total energy end-use is consumed in the building residential sector (U.S. Energy Information Administration, 2013). However, in developed countries, this sector is the main source of CO₂ emissions. For example, in the U.S.A., about 44.5% of total CO₂ emissions originate from this sector, which is significantly more than the industrial and transportation sectors (21.1 % and 30.7 %, respectively (Architecture 2030, 2015)). Considering the constant increase in built environment due to population increase (predicted to reach 10 billion in 2056 (United Nations, 2015)), migrations from rural to urban areas (current

urban population of 3.9 billion is estimated to grow to 6.4 billion by 2050 (IOM, 2015)) and increase in global gross domestic product per capita, the reduction of energy consumption and related greenhouse gas emissions from the building sector in the future presents a challenging task.

Theoretically, buildings consume different forms of energy in order to provide specific services, and maintain their performance constant in time with respect to various variable conditions, such as climate (Pulselli et al. 2007). Considering that the activity most responsible for energy consumed in buildings is typically maintaining comfort conditions (especially heating in the countries with continental climate – for example 32 % in U.S.A, (U.S. Department for Energy, 2008)), enabling sustainable heating systems for the increasing urban environment could significantly contribute to proposed global climate change mitigation measures.

District heating systems are commonly proposed in the literature as an environmentally friendly solution for providing heating services for the built environment due to their benefits, such as centralized heat production located outside city centers, large scale utilization of renewable heat sources (solar, geothermal etc.) and waste heat, overall environmental and economic efficiency, comfort and the security of supply for the consumers. In 2014, there was about 6000 district heating systems operating in Europe with an overall distribution network length of 200,000 km (Connolly et al., 2014). Considering the scarcity of these systems in Europe (for example, in Scandinavian countries district heating systems cover up to 40-60 % of total heat demand (Swedish Energy Agency, 2012) while in France this share is only 5 % (IGD, 2009)), the expansion of such systems is already suggested in the literature. The subject has been widely researched in several scientific reports, such as “Heat Roadmap Europe 2050” (Connolly et al., 2012), “Decarbonizing heat in buildings 2030-2050” (IAEA, 2012), and “Towards decarbonizing heat: maximizing the opportunities for Scotland” (The Scottish Government, 2012). Additionally, in the report on an EU Strategy on Heating and Cooling (European Parliament, 2016), it was stated that “*more must be done in order to switch remaining (heat) demands away from burning imported fossil fuels in individual boilers towards sustainable heating and cooling options*”. Connolly et al. (2014) explored the benefits of combining district heating with heat savings to decarbonize the EU energy system. The conclusions were that district heating should be considered an essential cost-effective technology for the EU energy system decarbonization. As a successful example, energy transition in Sweden by using low-carbon district heating within the 1950 – 2014 period was thoroughly described in the paper of Di Lucia & Ericsson, (2014). Moreover, Lake et al. (2017)

concluded that there are numerous opportunities towards sustainable communities which lay in the expansion of district energy systems, such as the utilization of renewable energy resources, pollution reduction, decrease in imported energy sources and possibilities to create countless opportunities for engineers, economists, investors and policy makers. Additionally there is a potential for using the district heating systems in order to decarbonize the industrial sector (as found in “Decarbonization of heat in industry” report (Ricardo-IAEA, 2013)). Thus, according to the current bibliography, the expansion of existing district heating systems and the construction of new ones could be a widely successful mitigation measure for reaching the sustainability goals set.

However, the construction of district heating systems requires high investment costs (especially in the case of renewable energy systems) due to the significant amount of infrastructure to be placed and obstacles to be crossed during the trench excavation. With current business models, the investment is returned through heat sales, and thus it is highly dependent on heat demand. Thus, the change in heat demand in years to come could impact the feasibility of such systems.

Predicted increase in air temperatures (according to all current weather scenarios) would reduce the difference between outdoor air temperature and building internal comfort temperature, consequently reducing the amount of heat required to reach comfort conditions. This effect will be addressed in further text as the direct impact of climate change on heat demand. Additionally, due to climate change policies, new directives have been legislated to improve building energy performance. For example, the European Parliament has legislated the EPBD (Energy Performance of Buildings Directive, or the Directive 2010/31/EU), where it is noted that “major renovations of existing buildings, regardless of their size, provide an opportunity to take cost-effective measures to enhance energy performance.” (European Parliament, 2010). Accordingly, the renovation of the existing building stock could further decrease heat demand - with higher insulation levels, building heat losses to the environment decrease, consequently further lowering heating energy requirements. This effect will be further addressed in this thesis as an indirect impact of climate change on heat demand (considering that the proposed building renovation policies are a part of climate change mitigation measures). The combined effect of these heat demand reductions could significantly prolong the investment return periods for district heating systems. Moreover, this effect could impact the system operational parameters. The base load in the future could decrease, causing heat production units to run with lowered capacity which would reduce their efficiency. Additionally, the decrease in heating hours during the year could cause frequent starts and stops

in heat production, further decreasing the efficiency of heat production units and increasing the fuel consumption (and consequently increasing the operational costs). Consequently, according to the existing business models, the operational costs would increase which would result in either higher heating prices and/or prolonged the investment return period. Thus, the decrease in heat demand caused by the direct and indirect impacts of climate change could compromise the role of district heating systems in the future. Previously, this long term evolution of heat demand was out of focus of local authorities, urban planners and district heating operators. Consequently, there seems to be a need for a tool that is able to forecast the long term heat demand on a district scale, and account for these climate change impacts on system feasibility and operational parameters.

However, evaluating the environmental performance of a system based solely on the emission levels during the system operation could be misleading. The environmental impacts associated with both construction and operation phases of such systems are frequently overlooked. These impacts could be significant for systems with large infrastructure, such as district heating systems. These complex systems require the construction of high capacity heat production units, distribution networks with significant pipe diameters and connections with buildings through the use of substations. The construction and placement of these infrastructure components require high volume of environmentally intensive materials (such as different types of steel and iron, for example). Thus, all processes related to their construction and operation should be taken into account to provide an overall environmental performance assessment. Life-cycle Assessment (LCA) is a structured, comprehensive and internationally standardized method that quantifies all relevant emissions and sources consumed during the lifetime of a product/service, and consequent environmental and health impacts, along with resource depletion issues (European Commission, 2010). LCA has been widely used in the literature to broaden the outlook on environmental impacts of various systems by creating an inventory of all relevant energy and material inputs of the studied system and evaluating the potential impacts. This methodology was previously already used by a group of authors from Chalmers University of Technology to evaluate the environmental impact of district heating networks (Fröling & Svanström, 2004, Fröling & Svanström 2005, Persson et al. 2007). Another environmental accounting method is the emergy approach. Emergy is defined as the available energy of one form that is used up in transformations directly and indirectly to make a product or a service (Odum, 1996). By using this concept, different types of energy and resources (for example sunlight, electricity and human labor) can be expressed in the same unit and thus compared on the same basis. Each type of energy is created by a certain transformation process

in nature, and has a different ability to support work in both natural and human systems. This quality difference is a key concept of the emergy theory. Raugei et al. (2012) compared in detail these two approaches and concluded that the main difference between the concepts is that LCA is more user-side oriented while emergy is a more donor-side oriented accounting method. From a user-side perspective, the focus of the analysis is limited on the amount of resources directly consumed during the product/service lifetime, and these inputs are evaluated based on their user-side value (i.e. the amount of outputs the user is able to extract from inputs) and scarcity. On the other hand, a donor-side perspective accounts for all resources directly and indirectly provided by the nature to support a product/service, regardless in which period these inputs were provided, and independently of their user-side value (on the life cycle scale). However, emergy analysis has not been applied to district heating systems within the existing bibliography. Thus, there is an existing opportunity to develop an emergy accounting methodology for urban heating systems environmental performance evaluation, and provide a donor-side oriented insight in the environmental performance of such systems.

1.2 Thesis scope and outline

The main scope of this thesis is to evaluate the role of district heating systems in promoting a sustainable energy transition, from the aspect of climate change related impacts and their environmental performance. The thesis consists of two main parts:

- Within the Part I of the thesis, the effect of direct (changed weather variables) and indirect (building renovation) impacts of climate change on district heat demand is evaluated. A heat demand model, based on the thermo-electrical analogy methodology, was developed and validated for this thesis. The model is capable of taking into account all relevant building parameters, but does not require significant calculation time or computing power. The direct impact of climate change was considered through the use of several weather scenarios, while the indirect impact is considered through the use of building renovation scenarios developed for this thesis. The methodology was applied to multiple case studies in order to account for different potential consequences of the impact, as well as climate and building stock differences. The first case study addresses the direct and indirect impacts of climate change on heat demand related parameters, while the second case study within this thesis part was performed in order to evaluate the impact of decreased heat demand on district heating system techno-economic parameters. Finally, an additional study was conducted in order to account for weather differences between the different climate types suitable for heating services;

- Within the Part II of this thesis, the study focus was on evaluating the environmental performance of district heating systems within the urban environment. In order to do so, the environmental footprint of district heating systems was evaluated by using the energy evaluation approach. Multiple types of district heating systems were addressed in the case study, and their environmental performance was compared with the environmental performance of competitive technologies for providing the heating services to an urban environment. Furthermore, both fossil and renewable energy production units for district heating systems were considered. However, to evaluate the scale of the district heating systems impact on the environmental performance of urban environment, an overall energy footprint of such environment which is supplied with heat has to be defined. In order to do so, energy evaluation methodology was utilized in order to assess the environmental performance of a multi-apartment residential building, taking into account all renewable, non-renewable and purchased inputs used during the building construction, operation (use), demolition and landfilling/recycling phases. Taking all of these phases into account provided an insight to which extent the environmental footprint of heat provided from district heating system contributes to the overall building environmental performance over the building lifetime. In addition, several building renovation scenarios were included in the study. Moreover, multiple time frames for the suggested renovation measures were considered;

Part I and II should not be considered as separate, but rather complementary parts of this manuscript, focusing on the two relevant aspects of the district heating potential in the context of climate change. Additionally, considering that the work presented in each part could be of interest for various scientific communities (building energy consumption & district heating and environmental assessment scientific communities), this layout should enable the readers with different backgrounds to find their results of interest within this manuscript in a more efficient manner.

PART I: THE DIRECT AND INDIRECT IMPACTS OF CLIMATE CHANGE ON DISTRICT HEATING SYSTEMS

CHAPTER 2: LITERATURE SURVEY, PART I

Within this chapter, an overview of the previous research efforts that addressed the topic of potential climate change impacts on building heat demand in the future is presented. The methodology used by the authors within each case study and the results obtained are described, along with relevant conclusions and the discussion concerning the research gaps identified.

2.1 The direct and indirect impacts of climate change on building heat demand

The impact of climate change on building energy consumption (including heat demand) has been previously addressed within the existing bibliography on multiple occasions. In general, the studies either directly considered the change in heat transfer rate between the building and environment, or expressed heat demand evolution as a function of other non-physical parameters (such as the potential changes in economic parameters, population increase and migration etc.). However, the issue with expressing heat demand evolution without modelling the heat transfer between the building and environment could be in sampling errors, construct validity and correlation-versus-causation related problems. Thus, in this thesis, only modelling approaches that in some form take into account heat transfer through the building envelope or historically measured heat consumption data are considered. Previous studies with this scope could be divided into three main groups, based on the study scale:

- **Representative building simulation studies** - the first group of authors selected a most common building type(s) for their case study location based on the certain criteria and then performed energy consumption simulations for the future weather scenarios that they have developed. The criteria for a representative building selection was based in most cases on the recurrence level of certain building type within the observed building stock (either geographically clustered building stock or buildings grouped based on the type and/or construction period);
- **Representative building simulation studies with in-country climate variations** - this group of authors also studied one or more representative building types, but considered climate differences between the different locations within the studied country, to account for potential differences in climate regions;

- **Large scale building simulation studies** - the third group of authors considered case studies on a larger scale (city, country or even on a global level) for extensive number of buildings.

Within this section, the methodology used and main findings from all three groups are discussed and reviewed from the thesis scope point of view.

2.1.1 Representative building(s) simulation studies

The direct impact of climate change on building heating and cooling demand in Switzerland was studied by Frank (2005). A generic representative building was created (30 m long, 12 m wide and 10 m tall residential building with 30 % glazing area) based on the existing Swiss residential building stock data. The façade and thermal insulation levels were varied in order to represent the different building code frameworks from the 1970-2003 period. For the creation of future weather scenarios, suggested mean annual temperature increase rates from IPCC reports were applied on reference weather data for Zurich-Kloten area (that can be considered as a representative location for the climatic situation in the Swiss Central Plateau, according to the authors), provided by the Swiss Federal Office of Meteorology and Climatology. Building energy demand simulations were performed in HELIOS software. The results showed a 39-81 % decrease (depending on the weather scenario considered) in annual heat demand for the studied period (2050-2100), as well as possible shortening of the heating season for 31-52 days out of reference 185-262 days (depending on the weather scenarios and insulation level assumed).

Berger et al. (2014) studied the direct impact of weather change on office buildings energy consumption in Vienna. As a case study, nine representative office building types in Vienna were used. Representative building selection was based on the construction periods and materials used for the building stock in Vienna over the last century. Current and future weather data sets were obtained by downscaling the results from the regional climate model developed at Max Planck Institute in Hamburg, Germany. Building energy demand was modelled by using Thermal Analysis System (TAS) software, version 9.1.4.1, developed by Environmental Design Solutions. The authors concluded that heat demand could decrease up to 30 % (depending on the building age) until 2050.

The direct impact of climate change on Stockholm's building stock energy performance was studied by Nik & Kalagasidis (2013). As a case study, a 153 building sample from Stockholm residential sector was used as a case study. These buildings were chosen based on

the statistical approach developed by the Swedish National Board of Housing and Planning. The climate data used in this study was obtained from the Rossby Centre regional climate model for the city of Stockholm. To create weather scenarios for the future, several uncertainty factors of climate data were considered: global climate models, regional climate models, emission scenarios and the initial weather conditions. Finally, twelve different weather scenarios for the future were developed. To simulate heat demand of the studied building stock, the authors used an energy model they have previously developed for another case study (Mata et al., 2013). The model is based on the lumped system analysis approach, where each building is assumed to be a unitary thermal zone. The model incorporates transient calculations of thermal zone heating and cooling energy demand, and it was validated through the comparison with other models and empirical methods. The results of the case study indicated that the heat demand could decrease for the period 2081-2100 for 25 %-30 % compared to a 2011 reference value, depending on the weather scenarios considered.

In another study, the authors (Nik et al. (2015)) studied both direct and indirect impacts of climate change by assessing the efficiency and the robustness of the retrofitted building envelope against climate change. For this study, the authors used 184 buildings they found representative for the residential building stock of Gothenburg. These buildings were chosen statistically based on the research performed by the Swedish National Board of Housing, Building and Planning. To calculate heat demand, the authors used the same model as in the previous case study (Mata et al., 2013). Weather data and scenarios were obtained by downscaling the results from five global circulation climate models (ECHAM5, CCSM3, CNRM, HadCM3 and IPSL). Four different building envelope renovation measures were considered separately: thermal improvement of walls, floors, roofs and windows. The authors concluded that the installation of thermally efficient windows could decrease building heat demand more than any other renovation measure considered within this study (16.59 % on an annual level).

The combination of direct and indirect impacts of climate change on heating and cooling energy demand for a residential building in The Netherlands was studied by Van Hooff et al. (2016). As a representative building, a typical Dutch terraced house was selected, based on the available national report on the building stock properties and configuration. For a scenario creation, weather data from year 2006 was used to represent the future climate conditions, due to the fact that this year was drastically warmer than the average for The Netherlands. In addition, six building adaptation measures were considered: improvements in thermal resistance of the envelope, thermal mass, change in short-wave reflectivity (albedo) of the

envelope, addition of vegetated roofs, solar shading and natural ventilation. Building energy demand was simulated with Energy Plus, considering one future weather scenario. Considering the direct impact, the results indicated that the total energy demand could decrease by 8% due to the higher decrease rate in heat demand than the increase rate in cooling demand. Regarding the adaptation measures, it was found that energy demand for heating is mostly dependent on the insulation type (decreases up to 57% in heat demand), while the changed albedo values and the addition of vegetative roof had a negligible effect - less than 2 % of change in energy demand. The authors also noted that results were valid for a Dutch climate, and that the work should be extended to include other climate types.

2.1.2 Representative building simulation studies with climate type variation

The direct impact of climate change and urbanization (the effect of urban canyons) on building performance in different climate regions was evaluated by Crawley (2008). To represent the different climates, 25 locations around the world were selected (based on the Köppen climate classification). Two office building prototypes were created for the case study, based on the Commercial Building Energy Consumption survey published by the U.S. Energy Information Administration in 2002. Weather data and future weather scenarios for the year 2100 were developed based on the results from the HadCM3 global circulation model. Building energy consumption was calculated with Energy Plus software. The author found that in cold climates, the net change to annual energy use in buildings could decrease for 10 % or more (due to the fact that in these climates, most of the energy in buildings is consumed in order to satisfy heating demand that decreases due to the climate change). On the other hand, in tropical climates, there could be an increase in overall building energy consumption for more than 20 % (due to the fact that in these climates, most of the energy in building is used to cover cooling demand, which increases due to the climate change). Finally, it was concluded that temperate climates could see the most significant change on energy demand profiles, due to the significant reduction in heat demand (25 % or more) and increase in cooling demand (15 % or more).

Dolinar et al. (2010) conducted a study for a sample building, assumed to be located in two climatic zones of Slovenia - subalpine represented by the city of Ljubljana and mediterranean, represented by the city of Portorož. The sample building is consisted of two apartments, a greenhouse and an unheated garage. Typical reference weather year was created based on the historical weather data for the two locations considered, while future weather scenarios were developed by linearly increasing the reference air temperatures and solar radiation levels. Linear offset levels were obtained by empirically downscaling the weather

change projection across Europe that was based on four general global circulation models. For the building energy consumption simulations, TRNSYS simulation software was used. Study results showed that the heat demand could decrease within the range of 16-25 % (depending on the scenario considered) in subalpine climate within the next 50 years. On the other hand, the authors concluded that heat demand decrease in warmer Mediterranean climate was insignificant. The authors also noted that on the national level, the influence of climate change on building energy demand could be even more emphasized, especially since the existing building stock in Slovenia has lower thermal insulation levels than it was presumed in the case study.

The potential direct impact of climate change on building energy demand for the residential housing in Australia was investigated by Wang et al. (2010). Five different locations were considered to account for regional climates in Australia that vary from cold to hot and humid: Alice Springs, Darwin, Hobart, Melbourne and Sydney. As a representative building, a modern four bedroom house common for Australia was used. Future weather scenarios for all locations were projected based on the historical data, three IPCC emission scenarios and the outputs from nine global circulation models. Energy demand was simulated by using the AccuRate software package. The conclusion was that in cold and temperate climates, heat demand would decrease for 19-26 % until 2050 and 27-48 % until 2100. Moreover, the authors noted that the reduction in heat demand prevailed in a relatively cold temperate climate (Hobart).

Xu et al. (2012) evaluated the impact of climate change on building heating and cooling patterns for 16 common building types in Californian cities. Sixteen commercial and residential building prototypes were used, previously developed within the Lawrence Berkeley laboratory. These building prototypes were based on the trends in building technologies and building code. Present and future weather scenarios were created by downscaling the data from global circulation models. Building energy demand simulations were performed with DOE-2.1E software. The results indicated that heat demand decreases (with values depending on the building type) within the next 100 years, for all weather scenarios considered. For example, heat demand of large office buildings could be reduced by almost 50 % in all regions considered. The authors also noted that heat demand reduction rate would be higher in warmer southern California climate compared to colder northern Californian climate, which is in accordance with the findings of Crawley (2008) and contradictory to the findings of Dolinar et al. (2010). However, these heat demand reduction patterns were justified by the fact that buildings in the southern Californian climate barely have the need for heating services, even

with the reference weather conditions. Additionally, the authors concluded that the reduction in heat demand could be generally higher for smaller buildings compared to large buildings, due to the fact that smaller buildings are more sensitive to weather changes due to their low volume to surface ratio.

The optimization of annual energy demand in office buildings under the influence of climate change in Chile was addressed by Rubio-Bellido et al. (2016). Nine cities were selected to represent nine climatic zones that can be found in Chile. The cities selected also represent a wide range of climates according to the Köppen-Geiger climate classification. For a case study building, the authors considered a parallelepiped volume with rectangular plans with the gross area of 1500 m², divided into three floors. Reference weather data was obtained through the use of Meteonorm tool, while the future weather scenarios for years 2020, 2050 and 2080 were developed with CCWorldWeatherGen tool, developed at the University of Southampton. Building energy demand calculation procedure in this paper relied on the model defined in ISO 13790:2008 standard (Thermal Performance of buildings – Calculation of energy use). The authors found that for the selected locations, heat demand could decrease by between 2.62 and 0.54 kWh/m²/yr, while the cooling demand could increase between 4.47 and 0.53 kWh/m²/year, depending on the scenario studied.

Nik et al. (2016) evaluated both impacts of climate change on heat demand by comparing different energy retrofitting measures for future climatic conditions in Sweden. In this study, representative buildings for three major cities in Sweden were analyzed, chosen based on a statistical survey (Stockholm (153 sample buildings), Lund (184 sample buildings) and Gothenburg (52 sample buildings)). The authors used the same methodology for building selection and energy demand modelling as in the previous studies (Nik et al. (2013, 2015)). Five scenarios of future weather conditions for the period 1961 - 2100 were forecasted by using global circulation models, and thirteen different renovation measures were considered. The measures were based on the separate renovation of envelope elements (walls, roofs, floors and windows), along with complete envelope and ventilation/lightning equipment renovation. The results indicated that the improvement of the whole building envelope, as well as windows replacement, could decrease heat demand on average by 30 % (within all 20 year periods considered during 1961-2100), compared to the building reference state (without any renovations conducted). The authors also stated that climate uncertainties play an important role in assessing the future performance of buildings, except in the case when the relative performance of renovated buildings is compared to a non-renovated one. Additionally, the study proved that it is possible to rely on a single 20-year period (as an example, 2081 – 2100) when

comparing retrofitting measures on different temporal scales, instead of calculating seven 20 year periods over the course of 1961-2100 period.

The direct impact of climate change on U.S. buildings energy use was studied by Shen (2017), by considering sample residential and office buildings and four climate regions of the United States. Four cities were chosen to account for climate variations within the U.S: Philadelphia (mix-humid), Chicago (cold), Phoenix (hot-dry), and Miami (hot-humid). A typical low-rise residential building was used as a representative residential building, while for the representative office building, a 6-storey high-rise building was considered. The outputs from the HadCM3 global circulation model were integrated to typical year weather file to downscale and forecast hourly weather data for the studied locations in regard of the horizon 2040-2069. Building models and their energy demand were simulated with EnergyPlus software. Simulation results showed that there could be a rise in cooling demand and decrease in heating demand for all locations studied. However, the rates of increase/decrease varied between the studied locations. The most significant decrease in heat demand occurred for hot-dry climate (Phoenix, 48.9 % decrease) and hot-humid climate (Miami, 23.7 % decrease). Moreover, the authors noted that climate change could shorten the duration of the heating season. These findings are in accordance with the results from the studies of Xu et al. (2012) and Crawley (2008), and in contrast with the findings of Dolinar et al. (2010), considering that heat demand decrease rate was significantly higher in warmer climates in comparison with the colder climates.

2.1.3 Large scale building stock simulation studies

Olonscheck et al. (2011) considered future energy demand under changed climate conditions and renovation measures applied on the existing building stock. German residential building stock was used as a case study and building data was obtained from the reports created by the German Institute for Building and Environment (IWU). Weather data and scenarios were obtained from STARII regional statistical climate model (based on recorded meteorological data from the 1951-2006 period) and regional dynamic model CCLM. Furthermore, the impact of building renovation was also considered in this study with renovation scenarios assumed (due to the lack of available data in the bibliography). These renovation scenarios were developed based on the building age/construction period and current thermal performance. Building energy demand calculations were conducted in accordance with the German industrial DIN-4108-6 standard. The results suggested that building heat demand could decrease for 44-78 % over the studied period (2031-2060 compared to 1961-1990). The authors also noted that

future heating energy demand will be mainly influenced by applied building envelope renovation measures, which further highlights the importance of renovation measures for reducing energy consumption in the building sector.

The direct impacts of climate change on heat demand for the Reykjavik's building stock was studied by Fazeli et al. (2016). The authors evaluated how the monthly energy demand for space heating changed according to the weather conditions in Iceland, on the basis of past outdoor air temperature variability. Additionally, the impact of gross domestic product (GDP) per capita was taken into account. The authors developed a linear model for monthly energy demand per capita estimation, based on the historical values of GDP, energy demand and outdoor temperature. The results showed that 1 °C increase in average temperatures resulted in 1.80 % reduction in annual energy demand (compared to current energy demand for space heating). Additionally, the authors highlighted the significance of taking into account the impacts of climate change during energy systems expansion plans design phase, in order to ensure their operational efficiency under future conditions. The authors further suggested that the results should be of interest for both district utility companies and energy policy decision makers. However, it was noted that econometric models are useful only for short-term forecasts, and that their results for long term should be interpreted carefully, considering the model limitations to represent changes in system structure.

Isaac & van Vuuren (2009) studied the direct and indirect impacts of climate change on heating and cooling demand on a global level and took into account possible changes in building space and population in the future. Data on the current average floor areas was obtained from the United Nations Urban Indicators program and Eurostat database. To create the scenarios for the future, the authors used the TIMER/IMAGE reference scenarios that were used for the ADAM project (MNP, 2007). For energy demand modeling, the approach developed within the Energy Indicator Project by International Atomic Energy Agency (IAEA, 2004) was used. The authors concluded that global heat demand would have a decreasing trend of 0.8 %/yr within the period 2000-2030, and that decrease rate would reduce afterwards. Overall, for the reference scenario the authors studied, climate change could decrease the global heat demand for over 30 % up to 2050. However, the authors also noted that the global heat demand could increase in the year 2100 due to the gradually rising floor space.

2.1.4 Comparison of the approaches previously used

An overview of the approaches previously used to address the direct and indirect impacts of climate change on building heat demand are presented in Table 2.1 (in order of publication

year). It can be seen that most of the studies (12 out of 15) considered a representative building (s) as a case study. However, urban environment is usually consisted of various building types originating from different construction periods that can differ drastically in both size and geometry. Thus, up-scaling the heat demand for the whole district, based on a calculation for a representative building(s) could provide misleading results. In all these studies, the authors used a complex simulation models in order to calculate heat demand (Energy Plus, AccuRate, TRNSYS etc). On one hand, simulating heat demand for a specific building with complex simulation software available enables dynamic simulations with detailed building input data. On the other hand, modeling large number of buildings with this type of approach is both time and computing power consuming. Due to this reason, studies that addressed building stock simulation on a large scale, used simplified models or building heat consumption based on the statistical reports. Modeling the demand based on the statistical data is a faster approach compared to complex simulations with commercial software, but the dynamics of the simulations are on a low level (heat demand for multiple buildings is estimated based on the simulation of one building with similar properties (usually expressed as kWh/m²/yr, without the ability to provide adequate demand profile on an hourly basis that accounts for thermal inertia, change in hourly gains/losses etc.)).

Concerning the impacts of climate change, only 4 out 16 studies considered the combined effect of direct and indirect impacts of climate change. Based on the climate change predictions from the scientific reports (such as the IPCC Fifth Assessment Report (2014)) and upcoming building renovation polices (as defined in the EPBD directive), it seems relevant to account for both impacts in order to evaluate future heat demand evolution. In addition, the results from 6 studies that accounted for climate differences imply the relevance of studying climate change impacts on heat demand in different climates, in order to define the impact scale in different climate types.

Thus, it appears that there is an existing need to develop a dynamic heat demand model, that is capable of dynamic heat demand calculations on a large scale (for the building stock on a neighborhood, city or possibly a country level), but without significant calculation time nor computing power required. However, the model should be able to take into account all relevant building properties (geometry, thermal properties, occupancy profiles etc.). Additionally, the model should be capable to account for different weather and building renovation scenarios for the future. Consequently, editing the input weather data (for different locations and weather scenarios), as well as building data (for building reference state and renovation scenarios) should not be a complicated and time-demanding process.

Table 2.1 Overview of the studies addressing the impact of climate change on building heat demand (green – representative building simulation studies, blue - representative building simulation studies with in-country weather variations, red - large scale building simulation studies);

Study	Climate change impacts		Energy demand calculation		Case study		Climate variations	
	Direct	Indirect	Complex ¹ model	Simple model	Representative buildings(s)	Building stock ²	In-country	Global
Frank (2005)	✓		HELIOS		✓			
Crawley (2008)	✓		Energy Plus		✓			✓
Isaac & van Vuuren (2009)	✓	✓		From IAEA		✓		✓
Dolinar et al. (2010)	✓		TRNSYS		✓		✓	
Wang et al. (2010)	✓		AccuRate		✓		✓	
Olonscheck et al. (2011)	✓	✓		By the authors		✓		
Xu et al. (2012)	✓		DOE-2.1E		✓		✓	
Nik & Kalagasidis (2013)	✓		By the authors		✓			
Berger et al. (2014)	✓		TAS 9.1.4.1		✓			
Nik et al. (2015)	✓	✓	By the authors		✓			
Van Hooff et al. (2016)	✓	✓	Energy Plus		✓			
Nik et al. (2016)	✓		By the authors		✓			
Fazeli et al. (2016)	✓			By the authors		✓		
Rubio-Bellido et al. (2016)	✓		By the authors		✓		✓	
Shen (2017)	✓		Energy Plus		✓		✓	

¹According to the ISO 13790:2008 standard; ²Building stock on a neighborhood (500+ buildings), city, country or a global scale;

2.2 Building energy demand models based on thermo-electrical analogy

The thermo-electrical analogy approach for modeling building energy demand (i.e. resistance-capacitance (RC) model) is based on the analogy between the electrical current and heat transfer by using the analogy of the following pairs: electric voltage – temperature and electric current – heat flux density. The analogy was firstly introduced with the experimental works of Paschkis & Baker (1942) and Paschkis & Heisler (1944) with their laboratory rack consisted of resistors and capacitors they have named the “heat and mass analyzer”. This approach has been widely accepted and used for heat transfer calculations ever since. In the previous two decades, this methodology has been widely used in the literature for building energy demand simulation models, due to the simplicity of calculations and the ability to describe the dynamic behavior of buildings.

Dewson et al. (1993) studied a least squares parameter estimation of a reduced order thermal model (based on the thermo-electrical equivalency) for an experimental building. The experimental building considered was considered to be a single thermal zone with overall dimensions 2.35x2.35x2.74 m. The experimental data set (consisted of external and internal air and wall temperatures) used for model validation was collected by the Energy Monitoring Company, and it was recorded with one minute intervals during the month of July. The results of comparison between the RC model and the experimental data showed that the model is able to predict the internal air temperature with an average error of 1 °C. However, it was also noted that the model consistently underestimated the internal air peak temperature.

A version of the RC model with 2 resistors and 2 capacitors (2R2C) was developed by Schultz & Svendsen (1998) in the form of WinSim modelling tool. To evaluate the model precision, the tool was tested against the detailed building simulation program tsbi3. Both models were used to simulate energy consumption of a simplified office situated in a multi-storey building. The results of comparison indicated that while there was a small difference in calculated energy demand, larger discrepancies were found in the calculated number of hours with high internal air temperatures. However, the authors noted that this behavior was expected considering that WinSim calculations were performed on a 5 min basis, while the tsbi3 calculations were performed on an hourly basis.

Fraisse et al. (2002) studied how to transform a multi-layer wall into a 3 resistances and 4 capacitors model (3R4C). The authors used this analogy to simulate a single thermal zone with floor heating. The walls were represented by a 3R4C model, while the floor heating system was represented with a simplified 1R2C model. These models were integrated within the

TRANSYS software, which integrates elementary models of the studied systems or particular functions. As a case study, a room equipped with floor heating, located in the university L'école Supérieure D'ingénieurs De Chambéry was used, with an overall floor surface of 95 m². The authors concluded that the 3R4C model is capable of reproducing conductive transfers accurately, based on the comparison with the measured data. However, the authors noted that the validity of the model corresponds only to the periods of internal inputs higher than 3 h. In addition, several walls were aggregated into only one 3R4C model. The validity of this aggregation approach is heavily dependent on the assumption that the surfaces aggregated have the same thermal properties.

A dynamic building energy simulation tool Building Calc., based on a version of the RC model with 3 resistors and 2 capacitors (3R2C), was presented by Nielsen (2005). The model is able to conduct heat transfer calculations on an hourly basis, and it was validated through the comparison with the detailed building simulation tool BSim, developed by the Danish Building and Urban Research project. As case study for model comparison, a reference office from the commercial building located in Copenhagen (Denmark) was used. As a main comparison criteria, indoor air temperatures calculated by both models were compared for two weeks (one in February and one in July) and the authors found the results to be satisfactory (the difference in results was always below 1°C). The comparison of monthly calculated heating and cooling demand also showed good resemblance between the results from two models. However, the authors noted that heating and cooling demand calculations were very sensitive to solar heat gains.

Kämpf & Robinson (2007) developed the RC model with 5 resistors and 2 capacitors (5R2C) as a part of a project to simulate energy flows within the urban districts. The model was validated through the comparison with the ESP-r software simulation. For a comparison, 8 hypothetical rooms were used that differed in glazing surface and wall properties. The margin of error was below 7% in all cases considered, which the authors found to be satisfactory. When these zones were replicated to represent a building with multiple thermal zones, the margin of error remained the same. Finally, the authors concluded that the 5R2C model developed provided reasonably accurate results for a variety of different wall constructions.

Another RC model, TEAM (ThermoElectricity Analogy Model), was developed by Peng & Wu (2008), in order to compute the periodic heat transfer in building envelopes, as well as the decay rates, time lags and other thermal properties. As a case study, a multi-layer wall construction with an air cavity was modeled. The authors found that the TEAM model

significantly reduced the difficulty of computing the decay rates and time lags of building constructions. Thus, it was concluded that the TEAM model could be suitable for analysis of periodic thermal conduction through the multilayer wall constructions. The authors suggested that the model could be implemented in building energy calculations and thermal comfort forecasting.

A group of researchers from Massachusetts Institute of Technology used the RC analogy to represent the heat transfer between the buildings and urban environment. In the paper of Bueno et al. (2012), an RC model was developed to analyze the interactions between the energy performance of buildings and the urban climate. To validate the developed model, the authors compared the model results with advanced simulation tool (Energy Plus coupled with the urban canopy model). Three different case studies were considered: residential and commercial buildings in summertime conditions, and a residential building in a wintertime conditions. Based on the results of the comparison, it was concluded that due to the simplicity and computational efficiency of the proposed model, suggested model could be a useful tool for civil engineers and urban planners in order to evaluate the interactions between the buildings and urban environment. Within the following study, the authors (Bueno et al., 2013) presented an Urban Weather Generator model, also based on the RC analogy. The model was developed in order to forecast weather differences between the urban canyons and rural environments, where the measuring meteorological stations are usually located. Validation of the model was performed through the comparison with field measured data from two experiments (BUBBLE experimental campaign conducted in Basel (Switzerland) and CAPITOUL, conducted in Toulouse (France)). The comparison showed satisfactory results, with an average external air temperature prediction error of 1 K. The authors concluded that the model could be integrated into existing software in order to account for site-specific urban weather files.

A combination of 5R2C model with GIS (Geographic Information System) was used by Darakdjian (2013) in order to evaluate heat demand on a district level. The district of St. Felix, located in the city of Nantes (France), was used as a case study. To validate the model results, the author conducted a comparison with the statistical heat demand data from the national reports. The author found that the 5R2C model provides satisfactory results, and that it could be used for building energy modelling on a large scale.

Zhu et al. (2014) also considered a 5R2C model as a dynamic simplified thermal model of active pipe-embedded building envelopes. Frequency-Domain-Finite-Difference theoretical model was used to calculate reference theoretical frequency, characteristic for this structure.

Four variations of 5R2C model were considered, namely: (a) whose parameters were identified only by considering the external wall surface temperature disturbance; (b) whose parameters were identified only by considering the internal wall surface temperature disturbance; (c) whose parameters were identified by only considering the internal pipe surface temperature disturbance; and (d) whose parameters were identified by considering the external wall, internal wall and the internal pipe surface temperatures. Three wall types were considered for pipe embedding in order to evaluate the model: light weighted wall (stucco, light density concrete and plaster), a medium weighted wall (face brick, high density concrete, and plaster), and a heavy weighted wall (face brick, high density concrete and insulation). The results showed that the model can predict satisfactory frequency responses of the heat flux on the regarded surfaces, when the external surface temperature disturbance is much concerned. However, when the internal wall surface temperature disturbance or internal pipe surface temperature was much concerned, the model could not predict good frequency responses. The results were similar for models (b) and (c), while the model (d) proved to be the optimal model in all situations.

Oliveira et al. (2016) conducted a validation of a lumped RC model for thermal simulation of a double skin natural and mechanical ventilated test cell. In this study, the authors considered a 5R1C model proposed in EN ISO 13790 standard. Additionally, the model was further improved by the authors in order to allow the prediction of internal air temperature of a free-running building with double skin facades. As a test cell, a room of total area of 58.04 m² was considered, assumed to be consisted solely of external walls, roof and ground floor (thus, without any internal partitioning walls, ceilings or floors), and the model results were compared with simulation results from Energy Plus software. The authors concluded that the simplification used in the RC model did not affect the accuracy of simulation results, due to the fact that the mean absolute error in internal air temperature calculation was approximately 1 °C. Additionally, the model results were in accordance with Energy Plus simulations even after the modeling complexity was significantly increased by changing the position of window blinds. However, the authors noted that the limitations of the model were the excessive oscillations of the predicted internal air temperature.

Thus, based on the previous research efforts from the bibliography, it seems that the models based on a thermo-electrical analogy are suitable for evaluating the building heat demand on a large scale, due to their calculation efficiency and satisfactory precision. However, within the scope of this thesis, such model should be able to perform the calculations on an hourly basis, for multiple weather and building renovation scenarios. Additionally, considering the variety of factors incorporated within these scenarios, the model should be able to calculate

a general parameter that could be used to express the combined effect of these factors in a simple manner.

2.3 Representation of climate change impacts on building heat demand

To represent the impacts of climate change on building heat demand, decrease rates in annual heat demand, specific heat demand (heat demand per unit of surface area per year) or number of days with heat demand during the heating season are commonly used (as it can be seen based on the previous research efforts within the bibliography presented in section 1.1 of this thesis part). However, further forecasts cannot be made directly based on these parameters and predicted future conditions. For instance, let's assume that heat demand is forecasted for the year 2030 taking into account weather and renovation scenarios. It is not possible to forecast heat demand directly for year 2040 based on the 2030 heat demand value and predicted future conditions for the year observed (2040). Primarily, the connection between the heat demand decrease rate and weather and building scenarios should be established. Thus, an additional parameter expressed based on these dependencies between the heat demand and scenarios should be used.

Hekkenberg et al. (2009) studied the dynamic temperature dependence patterns in future energy demand models in the context of climate change, and suggested the use of regional dependence energy demand factor on hot (β) and cold stress (α or the heat demand slope coefficient in further text) for future energy demand estimations. The coefficient itself is defined as the slope of the energy demand – outdoor temperature function (see Fig.2.1). T_{ht} and T_{cl} are defined as heating and cooling threshold temperatures while β is defined as the cooling demand slope coefficient. As the outdoor temperature independent demand, heat demands for the domestic hot water and industrial processes are considered. The authors noted that usually this obtained temperature-dependent pattern is static, considering that α and β are derived by regression of aggregated temperature-dependent data. Consequently, the effect of non-temperature related impacts (such as socio-economic parameters, building renovation, etc.) is not clear. However, it was also noted that these function parameters could be adjusted to incorporate not only dependency on outdoor temperature variation, but also additional dynamics (for example, in their study, the authors considered the incorporation of socio-economic dynamics). Thus, the building energy demand – outdoor air temperature function parameters (i.e. temperature dependent pattern coefficients) could be suitable to incorporate the dynamics of direct and indirect climate change impacts on heat demand in the future.

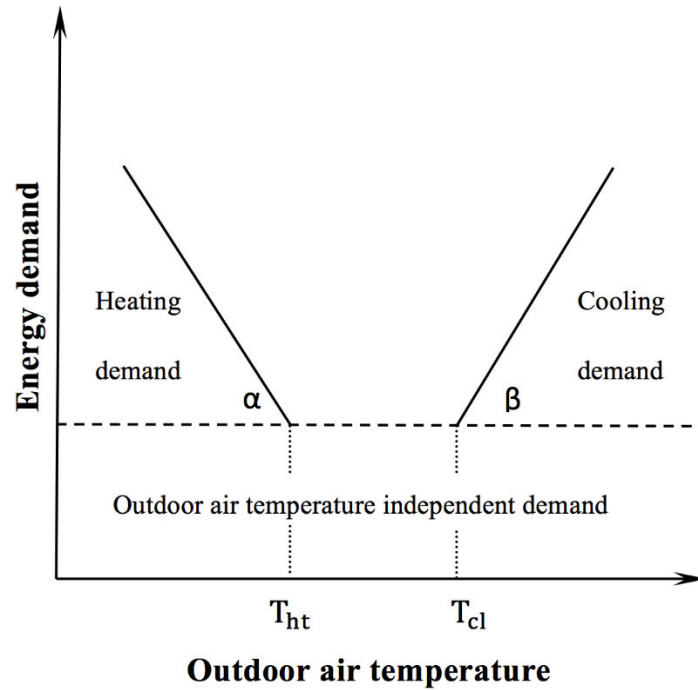


Figure 2.1 Building energy demand – outdoor air temperature function (temperature dependent pattern);

2.4 Preliminary conclusions from the literature survey

Based on the literature survey, it can be concluded that the research on the topic of climate change impacts on future building energy consumption gained momentum over the course of the last two decades. However, within the previous research efforts, the authors either estimated heat demand reduction by simulating a representative building in a complex software, or simulating building stocks with simplified models or statistical methods. Urban environment is usually consisted of various building types that were constructed during different construction periods and can differ significantly in both size and geometry – thus, using representative building for estimation of climate change impacts on building energy consumption could provide misleading results. On the other hand, simulating energy consumption of building stocks consisted of large number of buildings with complex simulation software is both time and computing power demanding. Thus, it seems that there is an existing need for a dynamic building heat demand simulation tool that is able to take into account all relevant building parameters (geometrical and thermal), along with weather and building renovation scenarios, but does not require significant computing resources or time to perform calculations.

Based on a bibliography survey, it can be concluded that building energy demand models based on the thermo-electrical analogy seem to be suitable for the suggested scope.

Different versions of the models (2R2C, 3R2C, 3R4C, 5R2C) were previously developed and validated within the bibliography. Based on a comparison with complex building energy demand simulation software, it was proved that these models are able to estimate building heat demand with a satisfactory precision. However, the ability to account for different weather and building renovation scenarios should be integrated in such models in order to evaluate the impacts of climate change on building heat demand.

Additionally, the impacts of climate change on building heat demand should not solely be represented through “traditional” parameters (such as decrease rates in heat demand and the duration of heating season), but also through the parameters that would enable further heat demand forecast based on the predicted weather and renovation scenarios. Based on previous findings within the bibliography, energy demand – outdoor air temperature function parameters (function slope and intercept) could be suitable for such a purpose.

CHAPTER 3: METHODOLOGY, PART I

The layout of the methodology used within the Part I of the thesis in order to evaluate the direct and indirect impacts of climate change on district heat demand and district heating system operational parameters is illustrated on Fig.3.1. The methodology consists of 6 major blocks, presented in the order starting from the collection of required input data, calculation process and the analysis of the output:

- 1) **Reference weather data** – weather variables data collection for the reference year of the timeline considered;
- 2) **Weather scenarios** – forecast of the future weather variables based on the reference weather data and climate change scenarios for the timeline considered;
- 3) **Reference building data** – data collection (geometry, orientation, position, thermal properties) for the case study buildings in their reference (current) building state;
- 4) **Building renovation scenarios** – development of building renovation scenarios for the timeline considered, taking into account three main criteria: building selection criteria, renovation level and renovation depth;
- 5) **Heat demand model** – calculation of heat demand and related parameters for the case study buildings;
- 6) **Climate change impacts evaluation** – evaluation of the climate change impacts based on the obtained heat demand results. In some case studies, an additional software package was used (developed by the industrial partner) in order to evaluate the impact on techno-economic parameters.

These methodology blocks are explained in detail within the following subsections.

3.1. Reference weather data

Outline of the methodology used to obtain weather variables for a reference year is given on Fig.3.2. Based on the measured historical weather data, a typical meteorological year for a certain location can be obtained from meteorological institutions, usually provided in the form of Typical Meteorological Year 2 (TMY2) weather format. Typical meteorological year is considered a more suitable reference than a measured data for one isolated year, due to the fact that certain years have exceptional heat or cold waves that do not occur with high frequency (thus, selecting weather data from solely one year as representative could provide misleading

results). For this reason, in this type of studies, typical meteorological year is used, which is usually created based on 40 or more years of measured data.

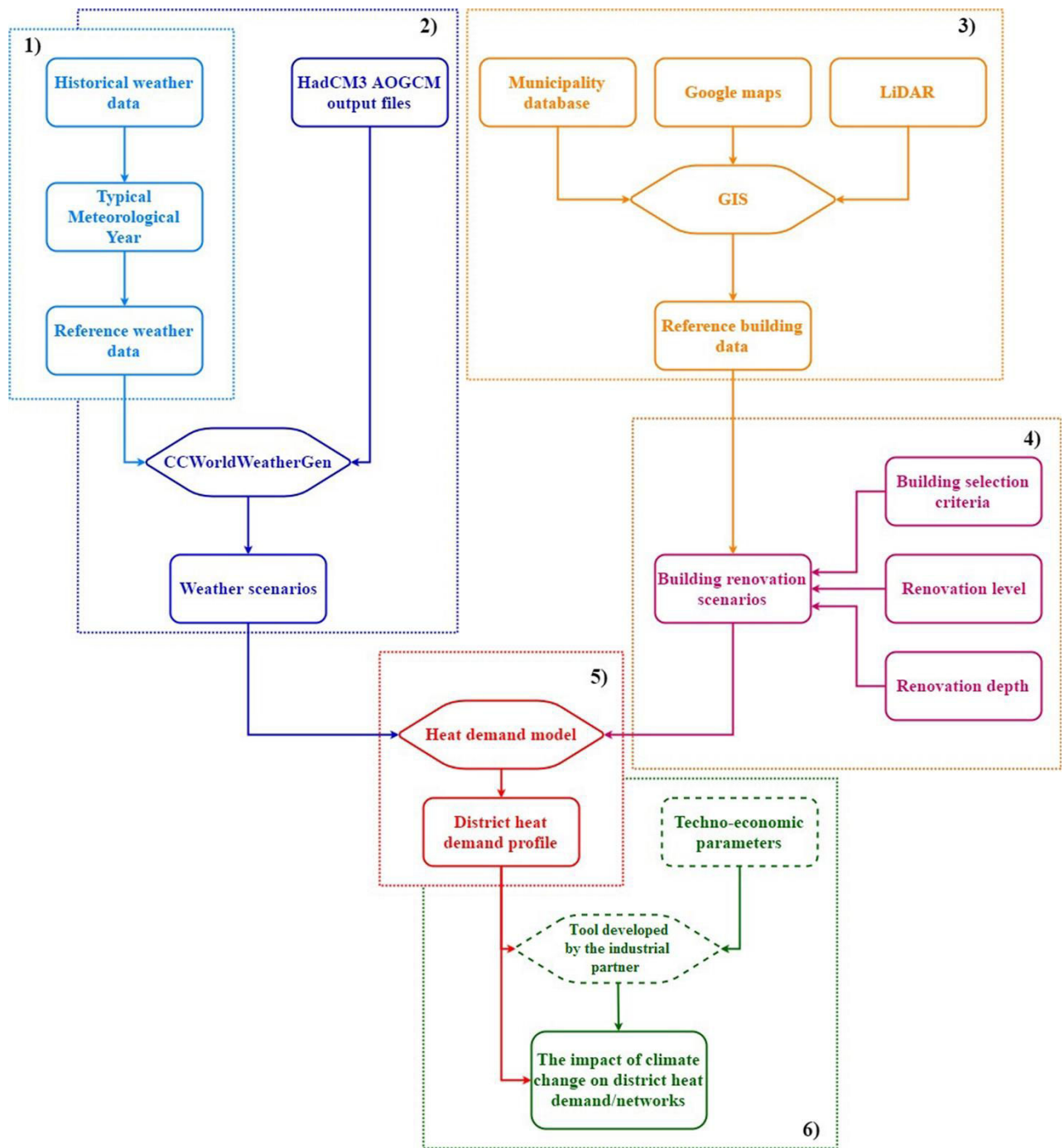


Figure 3.1 Outline of the methodology used in Part I of the thesis;

Based on the TMY2 format, Crawley et al. (1999) introduced the *.epw* weather format. The *.epw* weather files are defined as a text-based format, derived from the TMY2 weather format (U.S. Department of Energy, 2015), but it (the format) was rearranged to enable easier visual inspection of the data (TMY2 is a strict and position specific format). The *.epw* weather file format has been widely used in the bibliography ever since (Unzeta et al. (2009), de Wilde

& Tian (2012), Robert & Kummert (2012), Jentsch et al. (2013)). The format contains hourly values for 25 weather parameters, including the dry bulb and wet bulb temperatures, humidity, solar radiation levels, wind speed and direction etc. However, for the heat demand model used in this part of the thesis, only dry bulb temperature and global horizontal solar radiation levels are used (due to the fact that the main scope of the study is to develop a simplified model, focused on heat demand). Within this thesis, an .epw weather files from Energy Plus weather database were used, available for multiple locations in the world and free for download from the U.S. Department of Energy website (U.S. Department of Energy, 2015).

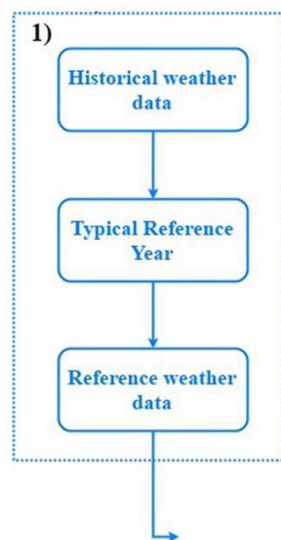


Figure 3.2 The methodology used for the reference weather data collection;

3.2 Weather scenarios

For the creation of weather scenarios, Climate Change World Weather File Generator (CCWorldWeatherGen) tool developed by Sustainable Energy Research Group (University of Southampton) was used. The tool was firstly introduced in the paper of Jentsch et al. (2008) and later used by Kolokotroni et al. (2012), Wong et al. (2012) and Yi & Peng (2014) in their case studies. The software uses the .epw files as a primary input. Other required inputs are the output climate scenario files (for the A2 family of the IPCC scenarios) from the HadCM3 (Hadley Centre Coupled Model, version 3) - coupled atmosphere-ocean general circulation model (AOGCM), developed at the Hadley Centre located in the United Kingdom (see Fig.3.3). As an output, CCWorldWeatherGen produces morphed hourly weather data for three years: 2020, 2050 and 2080. However, within this study, obtained results were used to develop three weather scenarios:

- **Low scenario** – the weather data calculated for year 2020 is used as the weather data for the year 2050;
- **Medium scenario** - the weather data calculated for year 2050 is used as the weather data for the year 2050;
- **High scenario** - the weather data calculated for year 2080 is used as the weather data for the year 2050;

For all three scenarios, weather data for the years 2020, 2030 and 2040 was linearly interpolated between the values for a reference year (2010) and the values for the year 2050. For a validation, simulations with weather files for several locations around the world were conducted, and suggested global mean temperature increase from the IPCC report was used for a comparison. We found that our low, medium and high scenarios correspond well to RCP2.6, RCP6.0 and RCP8.5 IPCC scenario (respectively), within the uncertainty range (potential variation of the predicted temperatures) defined within the IPCC report (IPCC, 2014).

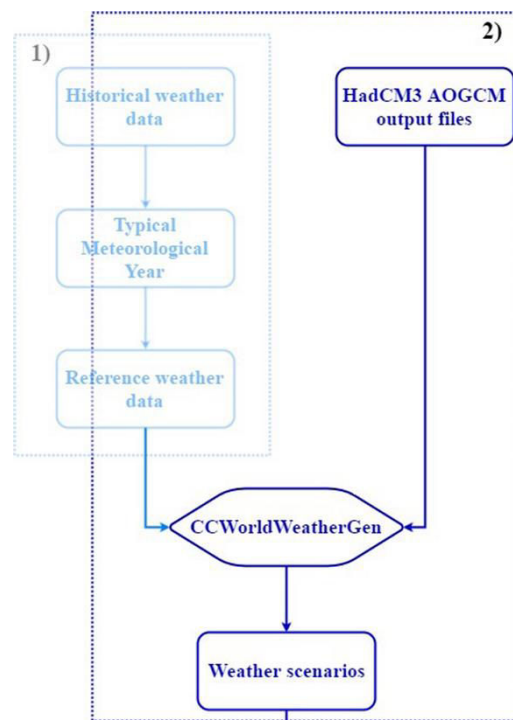


Figure 3.3 The methodology used for the creation of future weather scenarios;

3.3 Reference building data

Reference building data consists of building geometrical and thermal parameters for each building studied. Geometrical and geographical building parameters (building footprint, perimeter, number of facades, position within the district and building height) were obtained through the use of municipality database, GIS (Geographic Information Software), Light

Detection and Ranging (LiDAR) and Google Maps. GIS was used to derive basic building parameters (footprint, perimeter, attached perimeter etc.) from the available municipality data and/or Google maps layout, while LiDAR was used to obtain the altimetric data (in the case that building height data or number of floors were not available within the municipality database). In those cases, the flight with a LiDAR camera was performed (as it was done within the study of Santos et al. (2014)), creating a surface image (that was verified by the second flight conducted). Created Digital Surface Model (DSM) of the area by LiDAR camera has a spatial resolution of 1 m. After a comparison with the Digital Terrain Model (DTM) of the area, which is obtained from a municipality cartography database, DTM was subtracted from DSM image, providing the information on building height. This approach was previously used, validated and explained in detail within the study of Santos et al. (2014). GIS tools allow users to analyze spatial information, edit data in maps and present the results of all of these operations. Furthermore, GIS has been commonly used for building data collection and energy consumption mapping within the urban environment on different scales (Möller & Lund (2010), Geiß et al. (2011), Finney et al. (2012a), Finney et al. (2012b), Gils (2012)). Additionally, within this thesis, GIS was used to estimate the shadowing between the buildings over the year (through the use of buffer technique (buffers in GIS create an area defined by a bounding region determined by a set of points at a specified maximum distance around a geometry) and/or Sun Shadow Volume tool within the ArcGIS software). For other building parameters, such as number of inhabitants, type (purpose) and construction period (which is used to define reference structure and materials of the envelope elements, i.e. thermal properties of walls, roofs, floors and windows), the data was obtained from the local municipality censuses and reports.

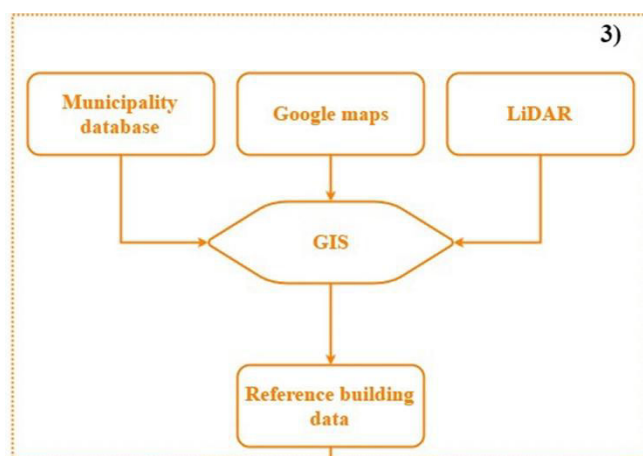


Figure 3.4 The methodology used for reference building data collection;

3.4 Building renovation scenarios

Within the building renovation scenarios, potential future modifications in building envelope that will improve the thermal performance of buildings are considered. If the urban environment is considered on a larger scale (district, city), not all buildings within such an environment would necessarily be renovated at each renovation step (for example, in this thesis considered to be 10 years). Thus, building selection criteria for conducting renovation measures should be defined. Additionally, the amount of buildings within the selected category that are going to be renovated should be defined. Finally, the level of building renovation should be considered, taking into account building current (reference state) and renovation measures (that include for example the application of new insulation layers on walls, roofs and floors, along with the installations of new windows). Thus, three parameters should define buildings renovation scenario on a district/city scale (that are based either on previous renovation rates data, local urban development plans, proposed energy efficiency legislative measures or the combination of all three):

- **Building selection criteria** – the parameter that defines the building selection criteria for renovation measures (for example building location, type, construction period or energy consumption level);
- **Renovation depth** – defines the number of buildings (within the buildings selected by the criteria previously defined) that will be renovated with each measure;
- **Renovation level** – building envelope improvement level which defines new thermal properties;

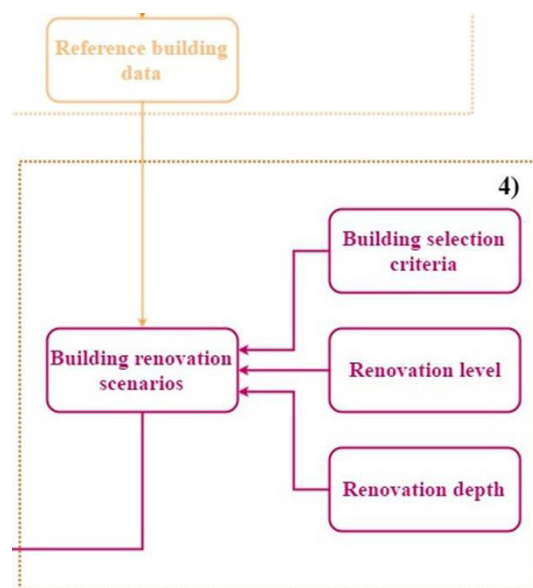


Figure 3.5 The methodology used for the development of building renovation scenarios;

3.5 Building heat demand model

3.5.1 Model description

Building heat demand (for space heating (SH) and domestic hot water (DHW)) is calculated through the developed resistance-capacitance model that is based on the model previously used by Kämpf & Robinson (2007) and preliminary work of Darakdjian (2013). The reason why this particular RC model was chosen as a basis is the model ability to adequately represent heat capacity and thermal inertia within the building walls. As necessary inputs, the model requires weather (reference and/or weather scenarios) and building (reference and/or renovation scenarios) data, in order to provide the hourly heat demand profile for the studied building/district as an output (as represented on Fig.3.6).

Since heat demand can be evaluated on different levels (room, building floor, the whole building), a general thermal zone in the form of a single room was selected to explain the model used in this study. The model is represented on Fig.3.7 and it is based on thermo-electrical analogy. Temperature nodes (external envelope surface and air) receive heat from the solar energy (Q_{s1} and Q_{s2} [W]), internal heat gains (Q_{in} [W]) and heating system (Q_{sh} [W]). Solar radiation is divided into two amounts: one part of the radiation reaches the external surface of

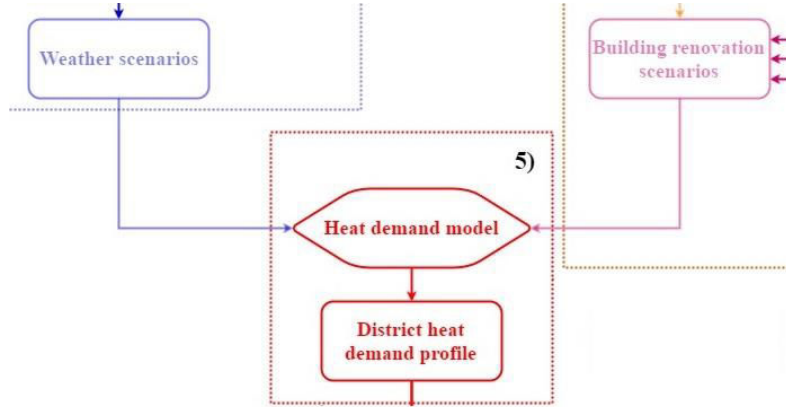


Figure 3.6 Main heat demand model inputs and outputs;

the envelope (Q_{s1}), impacting the temperature of the external envelope surface ($T_{en,e}$ [K]), while the other part (Q_{s2}) penetrates the room through glazing, impacting the internal envelope surface and internal ambient air temperature ($T_{en,i}$ [K] and $T_{a,i}$ [K], respectively). The amounts are defined with W_W [%] (the fraction of total solar radiation that penetrates through windows and affects the internal wall temperature) and W_A [%] (the fraction of solar radiation that penetrates through windows and affects the internal ambient temperature). Internal heat gains consist of heat gains from the occupants (Q_{oc} [W]) heat gain from the lighting equipment

($Q_l[W]$) and heat gain from the electrical appliances ($Q_{ea}[W]$). Heat exchange, due to the natural and/or mechanical ventilation, is represented as ($Q_v[W]$).

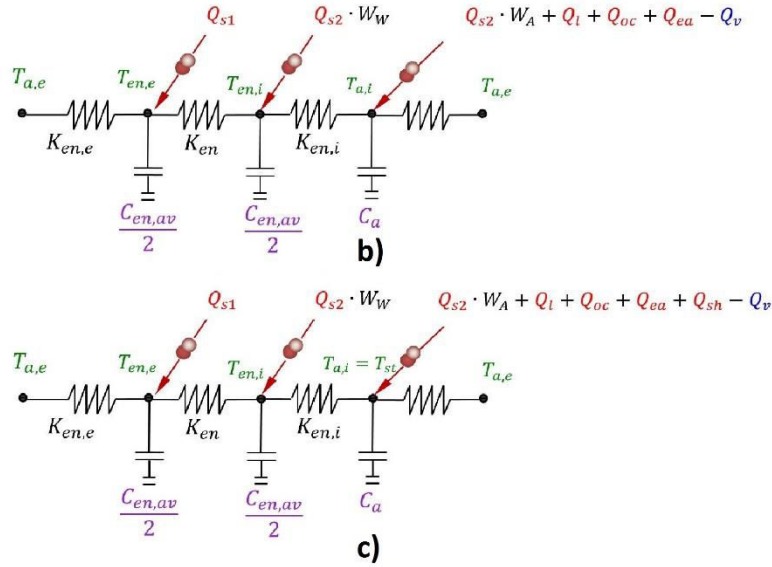
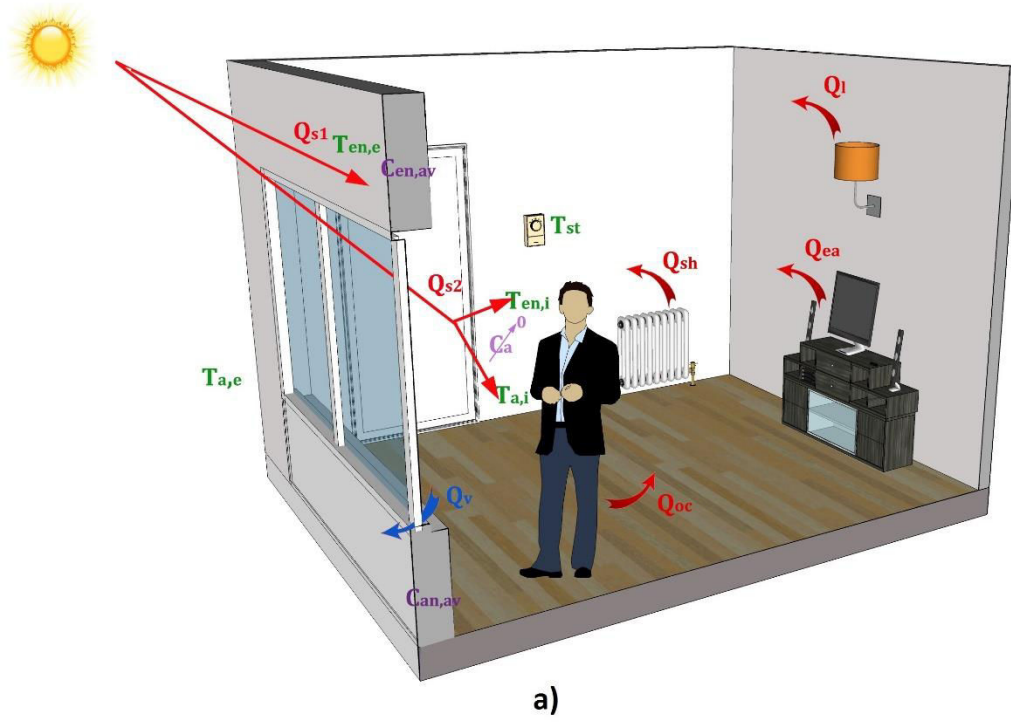


Figure 3.7 Physical representation of the model and the corresponding RC analogies ((a) physical representation of the model, (b) RC model when the ambient temperature is higher or equal to the set point temperature, (c) RC model when ambient temperature is lower than the set point temperature);

Considering that heat loss caused by the conductance through the windows and ventilation depends on different factors, these losses have been addressed separately in this model. $K_{en,e}$

and $K_{en,i}$ [W/K] represent the conductance between the outdoor air and external surface of the envelope, and conductance between the internal surface of the envelope and internal ambient air (respectively), while K_{en} [W/K] is the thermal conductance between the external envelope surface and internal envelope surface. The conductance to the environment through the windows is defined as K_{wd} [W/K], while the average thermal capacity of the building is represented as C_{en} [J/K]. The model takes into account the ability of the envelope to store heat and cause thermal inertia (i.e. to release the accumulated heat within the hours when the ambient air temperature inside the building is lower than the wall temperature. If there is no requirement for heating (ambient temperature is higher or equal to the set point temperature, $T_{a,i} \geq T_{st}$), there is no heat demand ($Q_{sh} = 0$), and the ambient temperature is “free” (calculated based on the heat gains and losses, see Fig.3.7b). However, if it is not the case ($T_{a,st} < T_{st}$), heat demand is calculated so that the setpoint temperature is reached (i.e. $Q_{sh} \neq 0$, $T_{a,i} = T_{st}$), as shown on Fig.3.7c.

Within the model, it is considered that the zone envelope is consists of four elements: walls, roof, floor and windows. In most of the studies within the bibliography, the U-values for the clear elements (without thermal bridges accounted) are used - this approach considers that the rate of heat exchange through the elements is equal over the whole surface. However, this is not true in reality, due to the existence of thermal bridges (areas and/or objects on the envelope elements that have different thermal properties than the element material) that increase the rate of heat exchange with the environment and reduce the overall thermal insulation level of the envelope. To take into account thermal bridges (in the case where thermal bridging is not already accounted within the U-value), total thermal transmittance of the envelope element is defined as (Morrison Hershfield, 2014):

$$U_t = \frac{\sum \psi \cdot L + \sum \chi}{A_t} + U_{cl} \quad (3.1)$$

where the U_t [W/m²K] is the total thermal transmittance of the element, ψ [W/mK] is the linear thermal transmittance of the regarded heat bridge, L [m] is the length of the regarded thermal bridge, while χ [W/K] is the point thermal transmittance. A_t [m²] is the total area of the element (including thermal bridges) and U_{cl} [W/m²K] is the thermal transmittance of the clear element (without thermal bridges). Linear transmittance represents the additional heat flow caused by the element details that are linear, such as slab edges, corners, parapets and transitions between assemblies. On the other hand, point transmittance represents the heat flow that occurs only at a single, infrequent location (such as intersections between the linear details etc.). Within the current version of the model, only the effect from the linear transmittance is considered, due to

the fact that point transmittances are infrequent and highly specific for each envelope. Thus, the thermal bridges on the envelope elements considered in this thesis are (Fig.3.8):

- Thermal bridge on the interfloor slab;
- Thermal bridge on the zone corners;
- Thermal bridge on the parapet on the wall-to-roof transition;
- Thermal bridge on the windows-to-wall transition;
- Thermal bridge in the floor-to-ground transition;

These thermal bridges have been described in detail in the Building Envelope Thermal Bridging Guide (Morrison Hershfield, 2014). Thus, the total element transmittance for the envelope walls is calculated as:

$$U_{t,w} = \frac{\psi_{sl} \cdot L_{sl} + \psi_c \cdot L_c}{A_{o,w}} + U_w \quad (3.2)$$

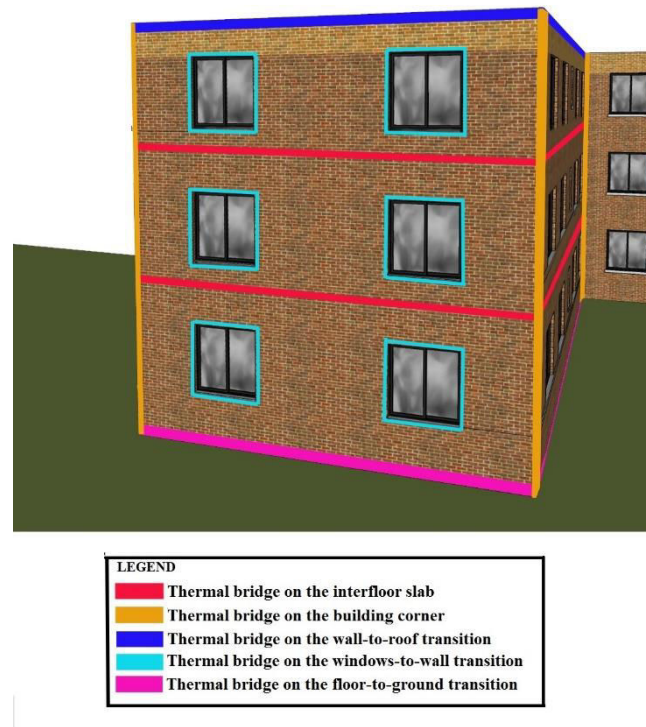


Figure 3.8 Considered thermal bridges within the model;

where $U_{t,w}$ [W/m²K] is the total thermal transmittance of the walls, ψ_{sl} [W/mK] is the linear thermal transmittance of the interfloor slab, L_{sl} [m] is the length of the slabs, ψ_c [W/mK] is the linear thermal transmittance of the corner, L_c [m] is the length of the corners while $A_{o,w}$ [m²] are the opaque walls surface (without glazing) and U_w [W/m²K] is the thermal transmittance of the clear wall (without glazing and thermal bridges). Length of the slabs thermal bridges (L_{sl}

[m]) and length of the corners thermal bridges (L_c [m]) are obtained through the eq. (3.3) and eq. (3.4), respectively:

$$L_{sl} = (P_z - P_{za}) \cdot n_{sl} \quad (3.3)$$

$$L_c = n_c \cdot h_z \quad (3.4)$$

where P_z [m] and P_{za} [m] are the zone perimeter and attached zone perimeter (length of the zone perimeter that is attached to another zone) and h_z [m] is the zone height. Number of interfloor slabs is represented as n_{sl} [slabs], n_c [corners] is the number of corners per building (equal to the number of building facades) and h_z [m] is the zone height. The total opaque surface of the walls $A_{o,w}$ [m²] is calculated as:

$$A_{o,w} = (P_z - P_{za}) \cdot h_z \cdot (1 - G_r) \quad (3.5)$$

where G_r [%] stands for the glazing ratio (the ratio between the glazing area and the total wall area). The total thermal transmittance for the roofs $U_{t,r}$ [W/m²K] is given as:

$$U_{t,r} = \frac{\psi_p \cdot L_p}{A_{o,r}} + U_r \quad (3.6)$$

ψ_p [W/mK], L_p , [m] $A_{o,r}$ [m²] are the linear thermal transmittance of the parapet heat bridge, length of the parapet and surface of the clear roof (respectively), while U_r [W/m²K] is the thermal transmittance of the clear roof. It is considered that the clear surface of the roof is equal to the surface of the zone footprint. Length of the parapet heat bridge is:

$$L_p = P_z - P_{za} \quad (3.7)$$

For the floors, the total thermal transmittance $U_{t,f}$ [W/m²K] is expressed as:

$$U_{t,f} = \frac{\psi_f \cdot L_f}{A_{o,f}} + U_f \quad (3.8)$$

where ψ_f [W/mK] is the linear thermal transmittance of the floor-to-ground transition, L_f [m] is the length of the floor thermal bridge, $A_{o,f}$ [m²] is the clear floor surface and U_f [W/m²K] is the clear floor thermal transmittance. It is assumed that the clear floor surface is equal to the zone footprint and that the length of the thermal bridge is equal to the zone perimeter. The total thermal transmittance for windows $U_{t,wd}$ [W/m²K] is calculated as:

$$U_{t,wd} = \frac{\psi_{wd} \cdot L_{wd}}{A_{o,wd}} + U_{wd} \quad (3.9)$$

where ψ_{wd} [W/mK], L_{wd} [m] and $A_{o,wd}$ [m²] are the linear thermal transmittance of the window-to-wall thermal bridge, length of the windows thermal bridges and the total surface of the windows (glazing area), respectively, and U_{wd} [W/m²K] is the thermal transmittance of clear windows. The surface of the glazing is expressed as:

$$A_{o,wd} = (P_z - P_{za}) \cdot h_z \cdot G_r \quad (3.10)$$

$$L_{wd} = n_{wd} \cdot l_{wd} \cdot 4 \quad (3.11)$$

$$n_{wd} = \frac{A_{o,wd}}{l_{wd}^2} \quad (3.12)$$

where n_{wd} [-] is the number of windows, l_{wd} [m] is the average length of one windows side (it is considered that the windows have the square shape). The next step is the calculation of the thermal conductance. $K_{en,e}$ [W/K], the conductance between the outdoor air and external zone envelope surface is given as:

$$K_{en,e} = \alpha_{ew} \cdot A_{o,w} + \alpha_{er} \cdot A_{o,r} + \alpha_{ef} \cdot A_{o,f} + \alpha_{ewd} \cdot A_{o,wd} \quad (3.13)$$

where α_{ew} , α_{er} , α_{ef} , and α_{ewd} [W/m²K] are the heat convection coefficients on the external side of the walls, roof, floors and windows (respectively). The internal conductance (between the internal surface of the envelope and the ambient air) $K_{en,i}$ [W/K] is given as:

$$K_{en,i} = \alpha_{iw} \cdot A_{o,w} + \alpha_{ir} \cdot A_{o,r} + \alpha_{if} \cdot A_{o,f} + \alpha_{iwd} \cdot A_{o,wd} \quad (3.14)$$

where α_{ew} , α_{er} , α_{ef} , and α_{ewd} [W/m²K] are the heat convection coefficients on the internal side of the envelope surface. It should be noted that these general equations (eq.(3.13) and eq.(3.14)) must be adapted to the zone position (i.e. zone environment, the location of the zone within the building if building is considered to consist of multiple zones rather than a single zone for example). The conductance through the walls K_{ww} , floor K_{wf} , roof K_{wr} and windows K_{wd} [W/K], are calculated through:

$$K_{ww} = U_{t,w} \cdot A_{o,w} \quad (3.15)$$

$$K_{wf} = U_{t,f} \cdot A_{o,f} \quad (3.16)$$

$$K_{wr} = U_{t,r} \cdot A_{o,r} \quad (3.17)$$

$$K_{wd} = U_{t,wd} \cdot A_{o,wd} \quad (3.18)$$

The total heat capacity of the building (C_{en} [J/K]) is:

$$C_{en} = C_w \cdot A_{o,w} + C_f \cdot A_{o,f} + C_r \cdot A_{o,r} \quad (3.19)$$

where C_w , C_f and C_r [J/m²K] are the specific heat capacities of walls, floor and roof (respectively). With zone geometry and thermal properties defined, heat gains and losses defined on Fig.3.7 can be calculated. Heat gain due to the solar radiation that reaches the wall surface (Q_{s1} [W]) is equal to:

$$Q_{s1,j} = I_{gh,j} \cdot \theta_b \cdot A_{o,w} \cdot \theta_o \cdot \theta_{bs} \cdot \theta_{gs} \quad (3.20)$$

where $I_{gh,j}$ [W/m²] is the global solar radiation for the regarded j -th hour, θ_b [-] is the correction coefficient for incident beam, θ_o [-] is the correction coefficient to account for building orientation, θ_{bs} [-] is the correction coefficient to account for shading from the surrounding buildings and θ_{gs} [-] is the correction coefficient due to the shading from the surrounding greenery. Correspondingly, heat gain from the solar radiation that penetrates through the windows $Q_{s2,j}$ [W] at the regarded j -th hour is calculated as:

$$Q_{s2,j} = I_{gh,j} \cdot \theta_b \cdot A_{o,wd} \cdot \theta_o \cdot \theta_s \cdot \theta_{bs} \cdot \theta_{gs} \quad (3.21)$$

where θ_s [-] is the correction coefficient to account for windows blinds/shades. As explained in the previous section, one part of this heat gain impacts the internal wall temperature (solar radiation that penetrates the windows and reaches the internal walls, $Q_{s2} \cdot W_W$), while the other part impacts the internal air temperature ($Q_{s2} \cdot W_A$).

Hourly internal heat gain ($Q_{in,j}$ [W]) consists of hourly heat releases from the occupants ($Q_{oc,j}$ [W]), lighting ($Q_{l,j}$ [W]), and electric appliances ($Q_{ea,j}$ [W]):

$$Q_{in,j} = Q_{oc,j} + Q_{l,j} + Q_{ea,j} \quad (3.22)$$

$$Q_{oc,j} = f_{o,j} \cdot n_o \cdot q_{o,s} \quad (3.23)$$

where $f_{o,j}$ [-] is the occupancy profile fraction (percentage of the total number of occupants that is present during the regarded hour), n_o [oc.] is the total number of occupants and $q_{o,s}$ [W/oc.] is the specific heat release from one occupant (based on the activity conducted within the zone).

To calculate the heat gain from the lighting, the period when the lights are turned on has to be defined. In the current version of the model, three boundary conditions are used to define the hours during the day when the lights are turned on:

- the amount of solar radiation – the amount of solar radiation for the regarded hour is lower than the threshold value for lighting ($I_{gh,j} < I_{gh,th}$);
- occupancy – at least 1 occupant for the regarded hour has to be present ($f_{o,j} > 0$);
- “nighttime limit” – the regarded period is not within the period when it is assumed that the occupants are sleeping (for example, 00:00 h – 06:00 h);

Only if all of three conditions are satisfied, the internal gain from the lighting (for each zone) is calculated as:

$$Q_{l,j} = (1 - \eta_l) \cdot P_{si} \cdot A_{o,f} \quad (3.24)$$

where η_l [%] and P_{si} [W/m²] are the efficiency and the specific installed power of lighting equipment, respectively.

$$Q_{ea,j} = \sum_{h=1}^g f_{ea,h} \cdot Q_{ea,h} \quad (3.25)$$

$f_{ea,h,j}$ [-] is the working profile fraction of the h -th appliance (fraction of the profile that defines if the device is turned on or off within the regarded period), and $Q_{ea,h}$ [W] is the heat released from the h -th appliance (of total g number of appliances) during one working period.

Hourly heat loss due to the air exchange (caused by the air tightness and/or ventilation of the zone) $Q_{v,j}$ [W] is expressed as:

$$Q_{v,j} = V_z \cdot r_v \cdot \rho_a \cdot c_a \cdot (T_{a,j} - T_{e,j}) = A_{zf} \cdot h_z \cdot r_v \cdot \rho_a \cdot c_a \cdot (T_{a,j} - T_{e,j}) \quad (3.26)$$

V_z [m³] is the zone volume, r_v [vol./s] is the level of air exchange, ρ_a [kg/m³] is the average air density and c_a [J/kgK] is the air specific heat capacity.

Considering that heat demand for domestic hot water can be provided from the same heat source as space heating, this demand was included in the total zone heat demand. Hourly heat demand for the domestic hot water preparation $Q_{dhw,j}$ [W] is given as:

$$Q_{dhw,j} = q_{dhw} \cdot n_o \cdot f_{dhw,j} \cdot c_{wt} \cdot (T_{dhw} - T_{dhw,p}) \quad (3.27)$$

where q_{dhw} [kg/oc/h] is the domestic hot water demand per occupant for the regarded hour, $f_{dhw,j}$ [-] is the fraction of the consumption profile for the regarded hour, c_{wt} [J/kgK] is the water specific heat capacity while T_{dhw} [K] and $T_{dhw,p}$ [K] are the temperatures of the prepared domestic hot water and the temperature of water for preparation.

In this thesis, the RC equivalency scheme from Fig.3.7 was solved by using the explicit Euler scheme with the code developed in MATLAB (MATLAB Release 2015a, The MathWorks, Inc., Natick, Massachusetts, United States). The average annual heat demand (on an hourly basis) calculation time for one building was 35 seconds.

3.5.2 Model validation

3.5.2.1 Model results comparison with another energy demand software

To validate the model, primarily a comparative analysis with Design Builder v4.6. (Energy Plus v.8.3, U.S. Department of Energy) software was conducted, due to the fact that Energy Plus was verified on multiple occasions within the bibliography. Three buildings were selected (Fig. 3.9) from the district of Alvalade located in Lisbon (Portugal), to represent the most common morphological situations in urban environment:

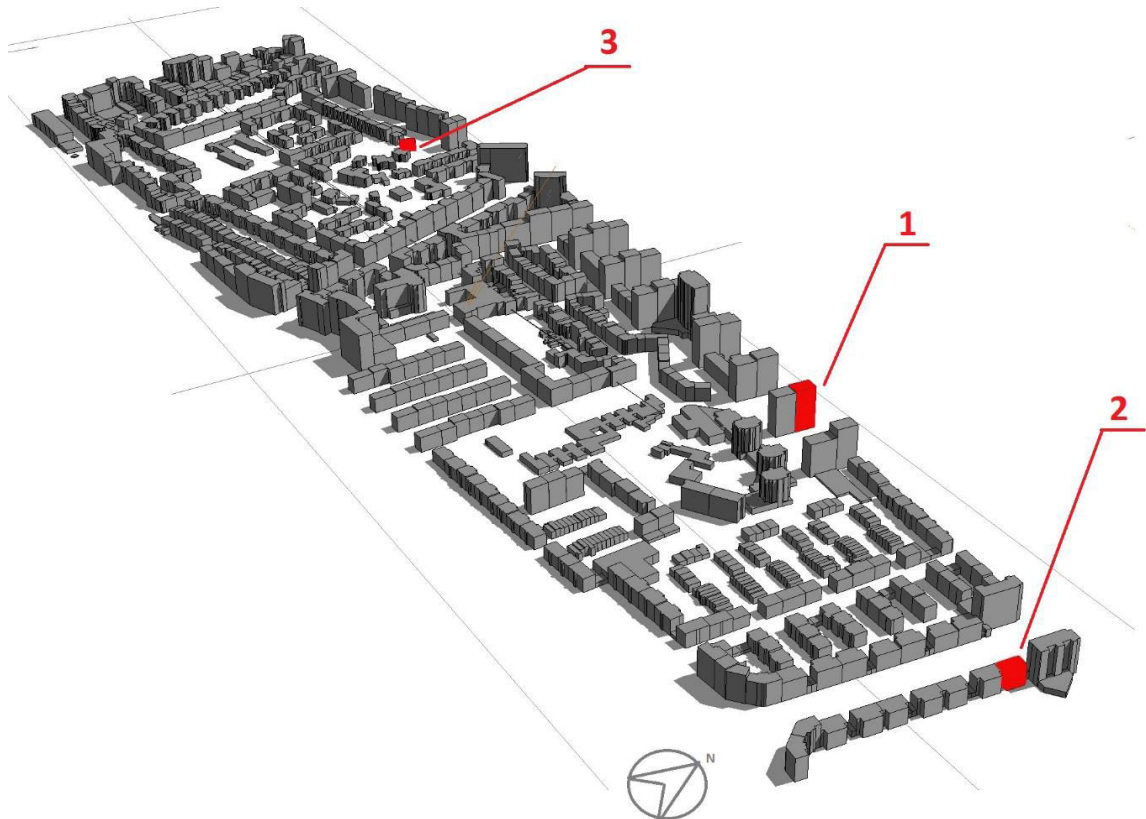


Figure 3.9 Selected buildings for model verification;

- **Case 1:** High-raise attached building without shading from surrounding buildings;
- **Case 2:** High-raise attached building with shading from surrounding buildings;
- **Case 3:** Low-raise building, detached and with shading from surrounding buildings;

Identical weather data, occupancy profiles, geometrical and thermal properties of each building as well as surrounding urban environment were used as an input in both models. To compare the results from the models, percentage error for the annual heat demand (Δ [%], eq.(3.28)) and standard deviation (σ [SD], eq.(3.29)) were used to estimate the difference in calculated heat demand on an annual and hourly level between the two models (index RC for the developed model and DB for Design Builder (Energy plus)), for three selected buildings:

$$\Delta_1 = \frac{(\sum_{j=1}^{8760} Q_{shRC,j} - \sum_{j=1}^{8760} Q_{shDB,j})}{\sum_{j=1}^{8760} Q_{shDB,j}} \cdot 100 \quad (3.28)$$

$$\sigma = \sqrt{\frac{\sum_{j=1}^{8760} (Q_{shRC,j} - Q_{shDB,j})^2}{8760}} \quad (3.29)$$

The results of model comparison are presented in a table below. Considering that the acceptable margin of error for simplified models is 10-20 % (Pappas & Reilly, 2011), and taking into account rather small standard deviation, we find the results of our model encouraging and the model suitable for the application on a large scale. The version of the model used by Kämpf & Robinson (2007) had similar margin of error on an annual level. Annual heat demand percentage error was higher in Case 2 compared to Case 1 and case 3, since heat demand is sensitive on the amount of solar gains, and the studied building in Case 2 receives significant amount of shading (please refer to Fig. 3.9). Design Builder has significantly more complex shading calculation algorithms on an hourly basis, which causes the difference in calculated solar gains between the two models and thus the heat demand (however, annual heat demand percentage error is still well below the suggested limit).

Table 3.1 Outcomes of the model comparison;

Case	Δ_1 [%]	σ [SD]
1	3.19	2.69
2	6.32	3.46
3	3.92	2.04
Average	4.47	2.73

3.5.2.2 Model results comparison with statistical building energy consumption data

The second validation step was to compare the results from the RC model with statistical building energy consumption data for the national building stock, based on the building construction period and type. In order to further diversify the model validation process, different district than Alvalade was rather used for a comparison, located in another climate zone. Thus, in this step of comparison, French national building stock was considered. The district of St. Félix, located in the city of Nantes, France, was used as a case study. This district was chosen due to the fact that it is mostly residential (with the exception of two industrial objects that were excluded from this study), and it consists of buildings that can be considered as representative for the French building stock (based on the comparison with French building stock prototypes available in TABULA report (TABULA WebTool, 2016)). The district is mainly residential and consists of single-family houses and multi-apartment buildings that were built during various periods over the 20th century, which can be divided into five main construction period intervals (pre 1915, 1915-1948, 1948-1975, 1975-1989 and post 1990). Building thermal characteristics were obtained from the national report (APUR (2007)) and assigned to each building based on the construction period. Simulations were performed with RC model for all 622 residential buildings within the district, and the average specific annual consumption [kWh/m²/yr] was calculated for each construction period, and compared with the data from two reports (APUR (2007), TABULA (2016)), as presented within the Table 3.2. The difference between the RC model calculated results and APUR/TABULA reports ($\Delta_{RC/report}[\%]$) was calculated as:

$$\Delta_{RC/report} = \frac{|Q_{hd,sp,RC} - Q_{hd,sp,report}|}{Q_{hd,sp,RC}} \cdot 100 \quad (3.30)$$

where $Q_{hd,sp,RC}$ and $Q_{hd,sp,report}$ [kWh/m²/yr] are the average specific annual heat demands of buildings, calculated by RC model and obtained from the national reports, respectively. The results of the comparison indicate that the specific annual demand calculated by the RC model is usually in-between the values provided within the APUR and TABULA reports. The only case where the specific demand was higher than the one in the reports was for the buildings constructed before 1915. However, due to the fact that this construction period covers long period of time where various construction materials were used, a higher variation in heat demand for this particular construction period is expected. Moreover, for all construction periods, the difference was less than the limit for simplified models (20%) proposed by Pappas & Reilly (2011), with the average difference of 10.2% and 8.1% (compared to specific annual

building heat demand values provided in APUR and TABULA reports, respectively) when all construction periods are accounted.

Table 3.2 Comparison of the RC model results and statistical build. energy consumption data;

Construction period	Specific annual heat demand [kWh/m²/yr]			Difference [%]	
	RC	APUR	TABULA	$\Delta_{RC/APUR}$	$\Delta_{RC/TABULA}$
<i>Pre 1915</i>	153.7	130	124.4	15.4	19.06
<i>1915 - 1948</i>	139.9	130	144.2	7.1	3.07
<i>1949 - 1974</i>	131.8	133	129.7	0.9	1.6
<i>1975 – 1989</i>	88.3	77	89.3	12.8	1.15
<i>Post 1990</i>	47.94	39	55.6	15.1	15.9
<i>Average difference</i>				10.2	8.1

3.5.2.3 Model results comparison with on-site measured data

During the model validation stage, a comparison with measured building heat demand data was planned. The idea was to collect hourly measured data from several substations owned and operated by the thesis industrial partner (Veolia), along with the required RC model input data (geometry, thermal properties etc.) for the buildings connected to the substations. Concerning the weather data, recorded hourly weather data that correspond to the year of measured heat consumption data was supposed to be used. However, during the data collection process, the industrial partner faced multiple obstacles and unpredicted costs, and was not able to provide accurate data during the thesis project duration. Thus, a comparison of model results with measured data remains one of the thesis project future development tasks, which are addressed in the final chapter of this manuscript.

3.5.2.4 Elementary effect analysis of the developed model

Considering the amount of inputs required by the model, and the fact that the availability of these inputs could vary from one location to the other, the uncertainty analysis that evaluates the impact of input parameters on the model final output should be performed. The elementary effect method is the most commonly used screening method in order to differentiate between the highly-influential and non-influential inputs for computationally costly mathematical models, or for a model with a large number of inputs (such as the one developed within this thesis Part I). Thus, the elementary effects method provides qualitative sensitivity analysis, i.e. it allows ranking of the input factors in order of importance, but do not quantify exactly the relative importance of the inputs, as stated by the author of the methodology (Morris, 1991). As

defined by the author, the approach is based on two sensitivity measures for each input parameter of the model observed:

- The elementary effect mean (μ_{ee} in further text), which assesses the overall importance of an input parameter on the model output;
- The elementary effect standard deviation (σ_{ee} in further text), which describes non-linear effects and interactions;

These parameters are obtained based on the construction of series of trajectories in the space of the inputs, where one input parameter is varied, while all other are kept constant. Thus, each model input is assumed to vary across the p_{ee} selected levels in the space of the input factors (thus, the region of experimentation Ω_{ee} can be considered as k_{ee} -dimensional p_{ee} -level grid). Each trajectory is thus composed of $(k_{ee}+1)$ points due to the fact that input parameters change for one step Δ_{ee} .

The *elementary effect* (d_{ee}) along each trajectory for each input parameter is defined as (Morris, 1991):

$$d_{ee,i} = \frac{Y(X_1, \dots, X_{i-1}, X_{i-1} + \Delta_{ee}, X_{i+1}, \dots, X_{k,ee}) - Y(X)}{\Delta_{ee}} \quad (3.31)$$

where $X = (X_1, X_2, \dots, X_{k,ee})$ is any selected examined parameter value within the experimentation region for each index i . The number of elementary effects r_{ee} are estimated for each input $d_{ee,i}(X^{(1)}), d_{ee,i}(X^{(2)}), \dots, d_{ee,i}(X^{(r_{ee})})$ by randomly sampling r points $X^{(1)}, X^{(2)}, \dots, X^{(r_{ee})}$. The two proposed measures (μ_{ee} and σ_{ee}) can then be expressed as (Morris, 1991):

$$\mu_{ee,i} = \frac{1}{r_{ee}} \sum_{j=1}^{r_{ee}} d_{ee,i}(X^{(j)}) \quad (3.32)$$

$$\sigma_{ee,i} = \sqrt{\frac{1}{(r_{ee}-1)} \sum_{j=1}^{r_{ee}} (d_{ee,i}(X^{(j)}) - \mu_{ee,i})^2} \quad (3.33)$$

The author suggested that these two measures should be evaluated together on two-dimensional plot in order to properly rank model input parameters in order of performance.

However, this method was improved by Campolongo et al. (2007) who proposed the use of modified mean value $\mu_{m,ee,i}$:

$$\mu_{m,ee,i} = \frac{1}{r_{ee}} \sum_{j=1}^{r_{ee}} |d_{ee,i}(X^{(j)})| \quad (3.34)$$

The authors suggested that the use of absolute mean value resolves the problem of the opposite signs which occurs in non-monotonic models and which would cancel each other out, consequently decreasing the mean value. Thus, in this thesis the conclusions regarding the relevance of the input parameters are made based on the eq. (3.34), while the results of eq. (3.33) and eq. (3.34) are also presented in order to satisfy the potential interest of the reader.

In order to test the importance of input parameters for the developed RC model, the influence of non-geometrical building parameters (defined as X-es in the eq.(3.31)) on the model output (defined as Y in the eq.(3.31), which in this case is specific annual heat demand in kWh/m²) was evaluated. For this analysis, Case 1 building (high raise building) from Fig.3.9 was used (with added shading in order to account the impact of shading coefficient). Geometrical building parameters (such as footprint, number of floors etc.) are not considered in this analysis since they considered as basic parameters necessary to commence the study and are highly specific for each building. Instead, it seems more important to evaluate the parameters that were assigned to each building based on its construction period, type, position or similar assumption. Each of these parameters (given in Table 3.3) is increased/decreased for a random step (Δ_{ee} in the eq.(3.31)) of its reference value within the range of $\pm 50\%$ (i.e., $r_{ee}=10$ – the input parameter value randomly varies 10 times within the range of -50 % to +50 % of the parameter reference value), while all other parameters are kept constant.

The results of the elementary effect analysis for the RC model developed are given in Table 3.3 (organized by the order of impact, from highest to lowest). It can be concluded that glazing ratio had the highest impact on the final result, which can be justified by the fact that it heavily influences the amount of solar radiation that penetrates through the windows, impacting the internal air temperature and the temperature of inner wall surfaces (please refer to Fig. 3.7). Air infiltration rate that affects sensible heat losses had the second highest impact, while the internal air set point comfort temperature had the third highest impact. Other input parameters considered had a significantly lower impact. Considering the U-values of envelope elements, thermal characteristics of windows had the highest impact due to the fact that windows U-values of the studied building were higher than for the other elements (and thus having the highest impact of all elements).

However, several parameters could vary simultaneously when buildings from different case study locations are compared (for example element U-values and air infiltration rate, outdoor air temperature). The impact of simultaneous change of these parameters on the model

main output (heat demand) will be thoroughly evaluated within the following chapters through the use of weather and building renovation scenarios.

Table 3.3 Elementary effect analysis of the developed RC model

Input parameter	Mean $\mu_{ee,i}$	Deviation $\sigma_{ee,i}$	Absolute mean $\mu_{m,ee,i}$
Glazing ratio (G_r)	91.89	1.4013	91.89
Air infiltration rate (r_v)	35.25	0.0019	35.25
Set point temperature (T_{st})	11.49	1.0835	11.49
Shading correction coefficient (θ_{bs})	-7.79	0.0150	7.79
Window U-value	5.54	0.3138	5.54
Wall U-value	4.47	0.4682	4.47
Orientation correction coefficient (θ_o)	-2.83	0.0045	2.83
Roof U-value	1.28	0.0279	1.28
Floor U-value	1.27	0.0325	1.27
Temp. of the water for DHW preparation	-0.69	0.6954	0.69
Prepared DHW temp. (T_{dhw})	0.69	0.6953	0.69
Specific installed power of lighting equip. (P_{si})	-0.27	0.0002	0.27
Specific heat gain from the occupants ($q_{o,s}$)	-0.21	0.0013	0.21
Number of occupants (n_o)	-0.12	0.0002	0.12

3.6 Climate change impacts evaluation

To evaluate the effect of the direct and indirect impacts of climate change on district heating systems, three main groups of key performance indicators were used: heat demand related key performance indicators, CO₂ emission related key performance indicators, and district heating systems techno-economic indicators. Some of the key performance indicators can be calculated directly based on the obtained heat demand profiles, while others require the use of additional input data and additional model (Fig.3.10). Calculation of these indicators is explained in detail within the following subsections.

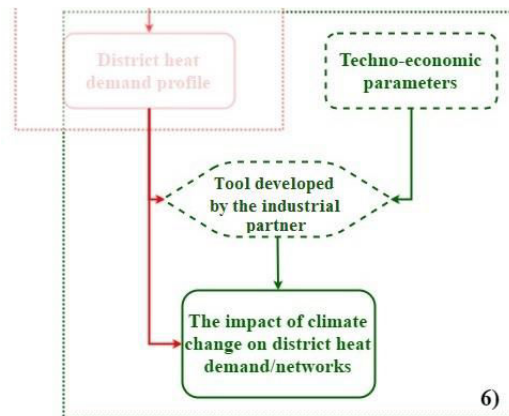


Figure 3.10 Climate change impacts evaluation methodology;

3.6.1 Heat demand related key performance indicators

District heat demand, district heat demand density and district heat demand – outdoor air temperature function parameters were used as heat demand related key performance indicators. Total district heat demand, Q_{dh} [Wh/yr]), for n number of buildings within the district was calculated as the sum of the demand for space heating ($Q_{sh,i,j}$ [Wh]) and domestic hot water preparation ($Q_{dhw,i,j}$ [Wh]):

$$Q_{dh} = \sum_i^n (\sum_{j=k}^l Q_{sh,i,j}) + (\sum_{j=1}^{8760} Q_{dhw,i,j}) \quad (3.35)$$

where j is the regarded hour, k and l are the first and the last hour of the year/heating season (depending on the period considered), and i is the regarded building. District heat demand density Q_{dhd} [Wh/km²/yr] was obtained through the following equation:

$$Q_{dhd} = \frac{Q_{dh}}{A_d} \quad (3.36)$$

where A_d [km²] is the overall land surface of the district. Heat demand - outdoor air temperature function parameters (function slope and intercept) can be obtained based on the following equation (please refer to Fig.2.1) and calculated district heat demand:

$$Q_{dh} = \alpha_{dh} \cdot t_o + \theta_{dh} \quad (3.37)$$

where Q_{dh} [W] is the district heat demand, α [W/°C] and θ [W] are the function slope and intercept (respectively) for the corresponding district, and t_o [°C] is the outdoor air temperature (in this particular equation, °C is used as a temperature unit instead of K in order to express α in W/°C - temperature data from meteorological stations and weather forecast models is usually provided in °C, and providing resulting α in this thesis on the same basis would enable accessible reuse of the parameter to other authors).

3.6.2 District heating systems techno-economic indicators

To evaluate the impact of climate change on district heating systems techno-economic indicators, a tool developed by the thesis industrial partner (Veolia Research and Innovation) was used. This model simulates heat production from the production units connected to a district heating system, for a given heat demand profile (input data). Production units are characterized by their design (maximal) power, technical minimum, efficiency (as a function of the load if any), and their availability. In addition, production schedule ranks the production units by the order of priority. The model requires annual heat demand profile on an hourly basis

as a main input data. Heat losses in the distribution network are based on a ratio in heat demand per m of network trench length (W/m), which is modulated depending on the season. Based on the heat demand profile, and for each hour, the model calculates the contribution of each production unit, by order of priority. Besides, it is considered within the model that production units cannot have a load lower than their technical minimum. The main model constraint is to always satisfy network heat demand, at any given moment of operation. An energy balance is made for each production unit (heat production, electricity production, electricity consumption, fuel consumption) as well as a calculation of the CO₂ emissions (direct CO₂ emissions from fuel combustion). CO₂ emissions are calculated based on the specific CO₂ content for the fuels used. At the scale of the whole district heating system, different technical key performance parameters can be calculated: energy mix (percentage of each production unit in the total production), emitted CO₂ content (per unit of energy delivered to the clients), and linear heat density (the ratio between total heat sold to the clients and the length of the network (not to be confused with district heat density (the ratio between the district heat demand and district surface))).

An economic section of the model calculates the operating expenses (OPEX, including fuel cost, maintenance and replacement costs) and capital expenses (CAPEX) associated to the district heating system (production and distribution equipment). Finally, heat production price can be calculated, defined as the price of heat that yields a targeted Internal Rate of Return (IRR) for a project lifetime of 20 years. Unless otherwise stated, heat production price, fuel costs, and annual operation & maintenance expenses, are supposed to be constant over the lifetime.

CHAPTER 4: APPLICATION OF THE MODEL DEVELOPED WITHIN

THE THESIS PART I

Within this chapter, the methodology previously described is applied on case studies, in order to test the developed approach suitability in regard to the scope of thesis Part I (evaluation of the climate change impacts on district heating systems). To account for possible weather and renovation scenarios variations between different locations and evaluate the impact on both heat demand related and techno-economic system parameters, the methodology was applied on two case studies. As a first case study, the district of Alvalade, located in Lisbon (Portugal) is studied in order to assess the direct and indirect impacts of climate change on district heat demand related parameters (district heat demand – outdoor air temperature function parameters (previously defined α and θ) and district heat demand density). Within the second case study, the district of St. Felix, located in Nantes (France) was considered in order to evaluate the direct and indirect impacts of climate change on district heating systems techno-economic parameters. For both case studies, sources for reference weather and district data are thoroughly described, along with the future weather and renovation scenarios used, followed by the results presentation and discussion. Finally, main conclusions from each case study are drawn.

4.1. Modelling the long-term impacts of climate change on district heat demand related parameters

The main goal of this model application is to evaluate the long-term impact of climate change on heat demand – outdoor air temperature function parameters and heat demand density. These two parameters are relevant from the district heating operator's point of view, since the function parameters could be used for preliminary forecast of heat demand in the future, while heat demand density is one of the main parameters used to estimate the feasibility of district heating projects. Primarily, the ability of the function to represent building heat demand signature is tested. Secondly, the feasibility of using the function parameters (slope and intercept, Fig.2.1), calculated for a reference weather and district state, in order to forecast future heat demand is evaluated through the comparison with the results obtained with dynamic heat demand modelling (through the use of the RC heat demand model developed). Finally, new values of function parameters and heat demand density were calculated for all scenarios to evaluate the impact of climate change on these parameters.

4.1.1 Reference district state and weather data

The district of Alvalade (Fig.4.1), located in Lisbon (Portugal), was selected for a case study. The district consists of 810 buildings of various types (purposes) that were built during various construction periods over the last century. Categorizing buildings by heating services, three groups can be distinguished: buildings that can be considered for district heating (single-family houses, multi-apartment buildings, hotels, office and educational buildings), buildings with self-providing heat (industry) and buildings without heating services required (religious buildings and garages). Since the focus of this case study is on district heat demand, only buildings that can be considered for district heating connection were considered (i.e. single-family houses, multi-apartment buildings, hotels, office and educational buildings - thus 665 buildings of 810 were considered). It was considered that the set point comfort temperature for single family houses, multi-apartment buildings and hotels is 20°C (for day and night during the whole week). On the other hand, for office and educational buildings, it was assumed that during the working days, set point temperature is 20°C during the day and 14°C during the night, while for the weekend it was considered to be 12°C (during both day and night). The duration of heating season considered is from 15th October until 15th of April, based on the data for the heating season duration for different regions in Portugal (Diario de Republica, 2013).



Figure 4.1 Alvalade district overview;

Reference weather data for Lisbon was downloaded from the Energy Plus weather database in the form of .epw file. The data was provided by the Instituto Nacional de Engenharia, Tecnologia e Inovação (INETI - Portuguese national laboratory for energy and

geology) and it is based on spatial interpolation of the public climate data published by Instituto de Metereologia (Portuguese national meteorology institute) within the period 1951-1980 and combined with the data already existing in the INETI database for later years.

Reference U-values for clear building elements (without thermal bridging, based on the building age and type) were obtained from the BPIE (Building Performance Institute Europe) database and verified by comparing the average values with clear U-values provided in the paper of Sousa et al. (2013). The values for Portugal that were used in this case study can be found in BPIE factsheet for Portugal (BPIE, 2015a). Thermal transmittances for the thermal bridges described within the methodology section were obtained from the ISO (International Organization for Standardization) standard for thermal bridges (ISO 10211:2007, 2007). The values were chosen based on the thermal bridge construction type, common for the buildings within the case study district.

Since the data for the glazing ratios was not available within the bibliography, building energy performance certificates for Lisbon were studied. Based on the sample of 1512 certificates, the results showed that the main factors for glazing ratios were the period of construction and number of floors. Glazing ratios obtained from this statistical survey are given in Table 4.1.

Table 4.1 Glazing ratios obtained for the Alvalade district;

Construction period	Glazing ratio [-]	
	One floor	More than 1 floor
<i>1921 - 1940</i>	0.32	0.13
<i>1941 - 1960</i>	0.34	0.14
<i>1961 - 1980</i>	0.31	0.23
<i>1981- 1989</i>	0.32	0.17
<i>1990 - 1999</i>	0.34	0.28
<i>2000 - 2005</i>	0.36	0.23
<i>2006 - 2010</i>	0.38	0.33

Data source: Survey from Portuguese energy certificates;

Considering the heat capacities, materials and the thicknesses of the material layers used in this case study are based on the wall types for Portuguese buildings (depending on the construction period) that were described in detail within the paper of Sousa et al. (2013). The values for heat capacities and densities of the materials (stone brick, hollow clay brick and concrete) were obtained from the online database (Engineering Toolbox (2015a, 2015b)). Heat capacity of the air gap layers within the walls were not taken into account due to the fact that

the air capacity of the thin air layers can be neglected, as proved in the thesis of Weitzmann (2004).

For the building orientation coefficient, that represents the correction coefficient for the amount of solar radiation that reaches the façade surface, the approach used in this case study consists of the following steps: primarily, the angle between each façade axis and north direction was determined in order to obtain the orientation of each façade (north is set to be 0° , east $90^\circ \pm 10^\circ$, south $180^\circ \pm 10^\circ$, west $270^\circ \pm 10^\circ$ and everything in between was set to be NE, NW, SE and SW, depending on the angle value). The tolerance of $\pm 10^\circ$ was used to ensure that the buildings that are oriented closely to the cardinal directions are not grouped within ordinal directions. If the facade is attached to another building, the value of the coefficient is set to be zero. Depending on the surface of each façade and the overall surface of all façades, weighted average coefficient is calculated (based on the coefficients provided within the report from (APUR, 2007) and assigned as the overall building orientation coefficient. The calculations were done in GIS software (ArcGIS).

As described within the methodology section of this thesis part, shading from the surrounding urban environment is taken into account through the use of shading correction coefficients, which are assigned based on the number of obstructions that cast a shadow on the observed building. In this case study, the following approach was used to obtain the number of obstructions for each building within the district. Primarily, 3D building volumes were created in GIS software based on the building position, footprint and height. Sun Shadow Volume tool was applied to create the volumes that originate from the light source (in this case Sun). The database for the sun path for multiple locations is available within the software (including Lisbon), enabling the calculations for any hour during the year. Considering the amount of time required for calculations, two criteria were evaluated for a representative day selection: sun position and amount of cloud cover (i.e. solar radiation) during the representative year. For sun positions, the days that represent the middle of each season were chosen. By analysing the solar radiation data from 2005 (that proved to be close to the average for the period 2000-2010), the average days for each season proved to be within the limit of ± 7 days from the days selected based on the first criteria. However, since the sun position has a higher effect on the shadow shape and size, it was decided for this case study to choose the days selected by the first criteria. Selected representative days for each weather season over the heating season were October 26th (autumn), January 27th (winter) and April 15th (spring). Furthermore, the length of the shadow also varies during the day. To take this behaviour into account, shadows were calculated for two hours (10 am and 3 pm) for each representative day, and the average value was used.

Finally, the volumes of buildings and shadows were intersected to obtain the number of obstructions for each building, thus enabling the coefficients based on the report from APUR (2007) to be used – for each obstruction the amount of solar radiation decreases by 10 % due to the shading (i.e. for two obstructions, $\theta_{bs}=0.8$ etc.). Thus, four shading coefficients were obtained for each building (one for each season during the year). In this case study, shading from the surrounding greenery was not considered, due to the fact that during the heating season (autumn-early spring) the surrounding greenery does not have crowns (there is no deciduous trees within the district). The authors note that in the case studies with deciduous trees in proximity of the buildings, trees should also be considered as obstacles (as explained in detail and validated within the work of Darakdjian (2013)).

The number of occupants was estimated based on the approach used in the study of Santos et al. (2014). Occupancy profiles for working days, Saturday and Sunday for different building types were obtained from the REVIT database and they are based on the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards (AutoDesk, 2015). For the specific heat gain per person (based on the conducted activity), the value of 100 W/oc. (seated at rest) was assigned for residential buildings and hotels. For the office and educational buildings, the value of 130 W/oc. (office work) was considered (Engineering Toolbox, 2015c). In this case study, we have considered only the sensible heat gain due to the fact that only heat demand is addressed. However, latent load should also be taken into account if cooling demand is considered, which was out of the scope of this thesis project.

Considering the heat gains from lighting, specific installed lighting power was estimated based on the allowed limits by the report from the European Union Green Public Procurement (GPP, 2012). After consulting several electrical and constructional engineers, the conclusion was that in the EU the common values in buildings are usually around 70 % of the suggested maximum, resulting in 6.3 W/m² for residential buildings and hotels, 7.7 W/m² for office buildings and 5.6 W/m² for educational buildings.

In this case study, internal gains from electronic appliances were neglected, due to the fact that the studied district is mostly residential, and thus without electronic devices with significant heat release (computer servers, industrial equipment etc.). The assumption is made based on the comparison of heat release levels from household appliances (ASHRAE, 2007) and other relevant heat gains (solar radiation, occupants, lightning etc.) calculated in this study. As for the ventilation, only the air exchange caused by the air tightness level was considered

(due to the fact that the buildings within the studied district do not possess mechanical ventilation systems). The values for air exchange rate for buildings (based on the construction period) provided by Monteil (2010) and BPIE (2015) were used.

For the domestic hot water consumption, the specific demand per occupant, estimated by National Renewable Energy Agency (NREL, 2011) was used to estimate the total amount of hot water required. The demand profile distributions for weekdays and weekends available within the paper of Ulseth et al. (2014) were used. In this study, it was considered that it is more suitable to use the specific hot water demand estimations per occupant ($\text{m}^3/\text{oc.}/\text{day}$) than per surface of the building ($\text{m}^3/\text{m}^2/\text{day}$). Other general parameters considered for this case study are provided in Table 4.2.

Table 4.2 General parameters of the case study;

Definition	Unit	Value
Average length of the window side	m	1.2 ^(a)
Correction factor for incident beam	-	0.7 ^(b)
Proportion of sol. rad. that impacts the internal walls	-	0.9 ^(b)
Proportion of sol. rad. that impacts the internal air	-	0.1 ^(b)
Correction coefficient for windows blinds/shades	-	0.85 ^(c)
Lights efficiency	-	0.7 ^(d)
Average air density	kg/m^3	1.225 ^(d)
Specific heat capacity of air	kJ/kgK	1.004 ^(d)
Specific heat capacity of water	J/kgK	4186 ^(d)
Domestic hot water temperature	$^{\circ}\text{C}$	55 ^(e)
Temperature of the water for preparation	$^{\circ}\text{C}$	12 ^(g)

Data source: (a) Neufert & Neufert, 2012; (b) Darakdjian, Q., 2013; (c) Engineering Toolbox, 2015d; (d) Engineering Toolbox, 2015e; (e) IEA, 1999; (g) assumed;

It should be noted that heat demand is calculated on an hourly time step for each year of the timeline considered within the scenarios. For example, if the timeline is considered to be 2010-2050 with a 10-year step, heat demand is calculated on an hourly basis for each of the years considered (i.e. year 2010, 2020, 2030, 2040 and 2050).

4.1.2 Weather and renovation scenarios

For the weather scenarios, CCWorldWeatherGen tool was used for morphing the weather file for Lisbon and three weather scenarios (low, medium, high) were created according to the analogy with IPCC scenarios, as described within the methodology section of this thesis. Considering the building renovation scenarios, three main renovation scenario parameters

(building selection criteria, renovation depth, and renovation level) were defined as described below:

- *Building selection criteria* – it was assumed that the building renovation in this scenario would be applied gradually over the district, refurbishing the buildings by the district section, considering that the districts are consisted of large number of buildings and the probability that the whole district will be renovated at once seems low (due to the price of renovations and time required for the renovation itself). The district was divided into five sections based on the census block groups (based on the work of Santos et al. (2014), assuming that different section will be renovated with each decade (i.e., Section 2 is renovated in 2020, Section 3 in 2030 etc., up to Section 5 in 2050). District sectioning is represented on Fig.4.2.



Figure 4.2 Proposed sectioning of the Alvalade district;

- *Renovation depth* – taking into account that the performance of the current building stock varies depending on the typology and the construction period, in this case study it is considered that it is less likely that all buildings would be renovated to the same level at the same renovation step within this scenario. Thus, in this case study, suggested renovation depths from the BPIE report (BPIE, 2012) were used: shallow, intermediate and deep. Within each path, certain percentage of building stock is renovated to a different level (minor, moderate, high, NZEB (near-zero energy buildings)). As an example, intermediate renovation path is explained in this section, while the detailed information for each renovation depth is provided in Table 4.3. Within this path, minor renovations are dominant within first two decades, with moderate and deep renovation levels steadily increasing with the late appearance of the NZEB (In the 2050, large portion of the building stock has sustained deep and moderate renovations, while the small portion (5%) of the buildings reached NZEB standards). However, in this study, it was considered that these percentages should be applied on the section level and not the whole district (due to the reasons explained within the previous subsection). For example, for the

regarded intermediate renovation path, in 2020, Section 2 is renovated (45% minor, 33%, moderate, 20% deep, and 2% NZEB). In 2030, Section 3 is renovated (5% minor, 58% moderate, 34% deep and 3% NZEB), etc. The same approach was used for the shallow and deep renovation paths.

Table 4.3 Renovation depths;

Amount of building renovated within the section				
<i>Shallow renovation path (%)</i>				
Year/level	<i>2020</i>	<i>2030</i>	<i>2040</i>	<i>2050</i>
Minor	70	55	40	25
Moderate	20	30	40	50
Deep	10	15	20	25
NZEB	0	0	0	0
<i>Intermediate renovation path (%)</i>				
Year/level	<i>2020</i>	<i>2030</i>	<i>2040</i>	<i>2050</i>
Minor	45	5	5	5
Moderate	33	58	40	25
Deep	20	34	51	65
NZEB	2	3	4	5
<i>Deep renovation path (%)</i>				
Year/level	<i>2020</i>	<i>2030</i>	<i>2040</i>	<i>2050</i>
Minor	5	5	5	5
Moderate	5	5	5	5
Deep	86	85	69	60
NZEB	4	5	21	30

Data source: BPIE, 2012;

- *Renovation level* – with district sections and renovation paths defined, the U-values for each level of renovation should be assigned. In this case study, first renovation step would be to refurbish the existing building stock to the current commercial level at the time of this study (the U-values for the buildings built within the 2010-2013 period) before upgrading it to higher levels of insulation. Thus, for each building type (and for its elements), upgrade to 2010 values is considered as a minor renovation, while for the NZEB level the values from the study of Olonscheck et al. (2011) are assigned. Accordingly, the values for the moderate and deep renovations are derived through the linear interpolation between these values. Obtained improvements for the studied building types are represented in Table 4.4.

4.1.3 Results and discussion

To begin with, the suitability of heat demand – outdoor temperature function to represent building heat demand signature was evaluated. Heat demand for each building within the district was primarily calculated for reference conditions (typical reference meteorological year weather data and reference building state) with the RC model developed. To estimate the

linearity between the heat demand and outdoor temperature, Pearson's product-moment correlation was used (commonly used within the bibliography as a measure of linear correlation between two variables). The coefficient itself is defined as the covariance of the two observed variables divided by the product of their standard deviations. The average value of Pearson's coefficient obtained was -0.91 (on scale from 0 to -1 for total negative correlation – negative due to the fact that heat demand decreases with an outdoor temperature increase), which proved high linearity between the heat demand and outdoor air temperature.

Table 4.4 Assumed U-values for the renovation levels;

U-value for clear envelope element [W/m ² K]				
Building Type				
<i>Single-family houses</i>				
Building element	Minor	Moderate	High	NZEB
Wall	0.58	0.44	0.29	0.15
Roof	0.84	0.59	0.35	0.10
Floor	1.15	0.81	0.46	0.12
Window	2.97	2.25	1.52	0.80
<i>Multi-apartment buildings</i>				
Wall	0.61	0.46	0.30	0.15
Roof	0.99	0.69	0.40	0.10
Floor	1.48	1.03	0.57	0.12
Window	3.00	2.27	1.53	0.80
<i>Hotels</i>				
Wall	0.54	0.41	0.28	0.15
Roof	0.48	0.35	0.23	0.10
Floor	0.78	0.56	0.34	0.12
Window	3.00	2.27	1.53	0.80
<i>Office buildings</i>				
Wall	0.56	0.42	0.29	0.15
Roof	0.49	0.36	0.23	0.10
Floor	0.80	0.57	0.35	0.12
Window	3.10	2.33	1.57	0.80
<i>Educational buildings</i>				
Wall	0.50	0.38	0.27	0.15
Roof	0.59	0.43	0.26	0.10
Floor	0.80	0.57	0.35	0.12
Window	3.20	2.40	1.60	0.80

Regarding the reference district state, obtained values for heat demand slope coefficient for each building are given on Fig.4.3, arranged depending on the building construction period. It can be observed that the office buildings built after the 1990 had the highest values of the slope coefficient (and thus the lowest heat demand, refer to Fig.2.1), while the oldest existing

single-family houses within the district had the lowest values of the coefficient (and correspondingly the highest heat demand). However, it should be noted that within the studied building population (based on type and the construction period) the number of buildings within categories was not on the same level (for example there were only six office buildings compared to several hundred residential multi-apartment buildings).

To assess the feasibility of using the reference function parameters (slope (α) and intercept (θ) calculated based on the reference weather and district data) to assess the heat demand in the future, heat demand for all weather and renovation scenarios was calculated with a dynamic RC model, and then compared with the results obtained (through the eq. (3.33)) by using the reference function parameters and forecasted weather data (through the use of weather scenarios). The comparison showed that the difference in annual heat demand for each building between the two calculation approaches was up to 12% when only weather scenarios were considered. However, when the renovation scenarios were taken into account, the difference was up to 60 %, due to the inability of the function to account for changes in building envelope (Fig.2.1), and which is well over the suggested limit for simplified heat demand calculation methods (20 %, as suggested by Pappas & Reilly, 2011). Thus, for each year considered in the scenario, heat demand – outdoor air temperature function slope and intercept should be re-calculated in order to estimate a connection between the heat demand decrease and the values of the function parameters. Additionally, due to the increased outdoor air temperatures and renovation measures conducted, the number of hours with heat demand during the heating season decreases (as a consequence of decreased heat demand). Thus, the hour dataset used for function parameters calculation changes. Consequently, the connection between the number of heating hours and function parameters should also be evaluated.

The evolution of function slope (α) and intercept (θ) along with the number of hours (n_{hh}) with heat demand during the heating season for all weather and renovation scenarios is given in Fig.4.4 and Fig.4.5. With the impacts of weather change and building envelope renovation taken into account, α coefficient values for 2050 are within the ranges of -1.9 MW/°C to -1.8 MW/°C (low temperature scenario, shallow and deep renovation path), -1.8 MW/°C to -1.7 MW/°C (medium temperature scenario, shallow and deep renovation path) and -1.7 MW/°C to -1.6 MW/°C (high temperature scenario, shallow and deep renovation path). On average, the value of the slope coefficient increased per decade within the range of 3.8 % - 8.1 % of the reference value, which corresponds to the decrease in the number of heating hours of 22 h – 139 h. As for the value of the θ coefficient, the value ranged from 36.9 MW to 33.9 MW for low temperature scenario (shallow and deep renovation path), 35.4 MW to 32.5

MW for medium temperature scenario (shallow and deep renovation path) and 32.8 MW 30.1 MW for high temperature scenario (shallow and deep renovation path). Overall, the function intercept decreased on average for 7.8 % to 12.7 % per decade (which corresponds to the decrease of heating hours within the range of 22 h – 139 h).

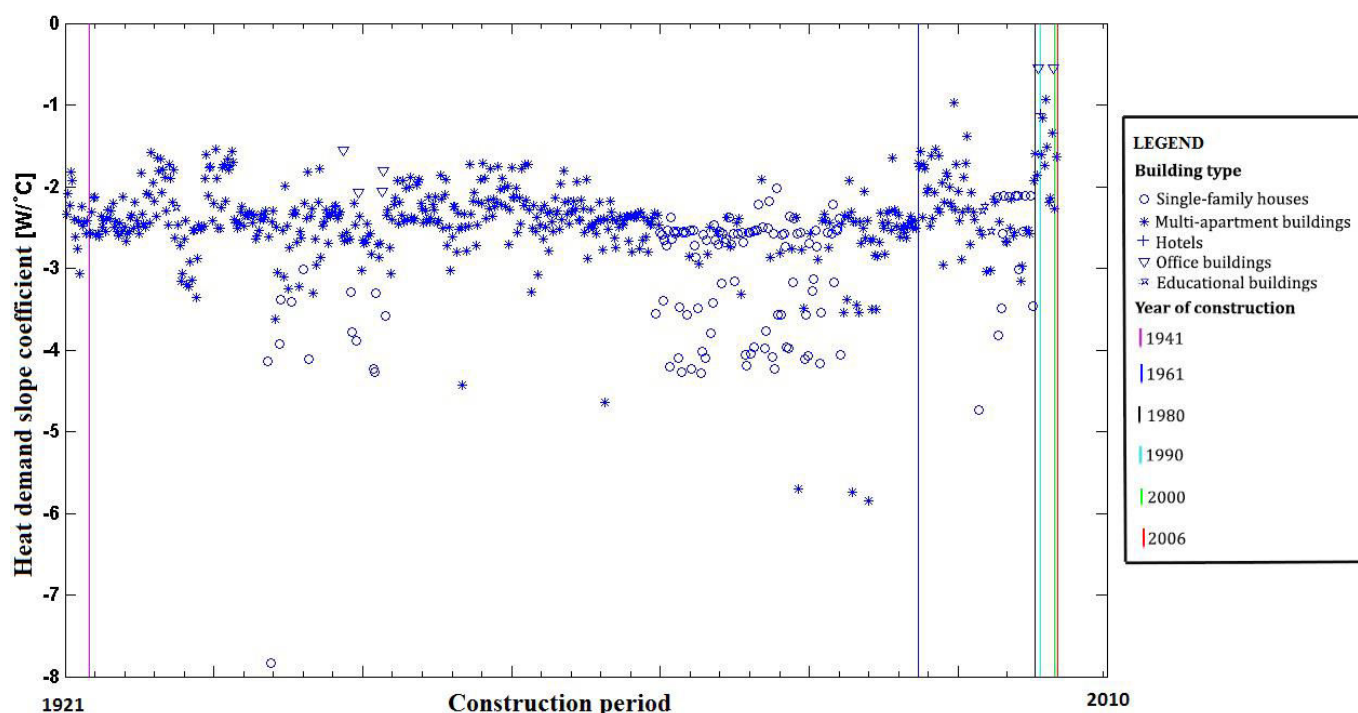


Figure 4.3 The overview of heat demand slope coefficients for each building within the Alvalade district;

The effects of direct and indirect impacts of climate change on district heat demand density are represented on Fig.4.6. The results suggest that solely due to the weather change, without any building renovation measures, heat demand density in the future could decrease for 1.7 % - 9.3 % (depending on the weather scenario) of the reference value (year 2010) per decade, resulting in total decrease in heat demand of 6.7 % - 37.1 % in 2050 compared to 2010. With the building envelope renovation scenarios combined with weather scenarios, the forecasted heat demand density decrease would be 6.9 % - 9.5 % of the reference value per decade (depending on weather scenario and renovation depth), culminating in the overall decrease of 22.3 % - 52.4 % in 2050 (compared to reference year). Additionally, from the results represented on this figure, it can be observed that the medium temperature scenario, combined with shallow and intermediate renovation path, would result in the same heat demand density as the high temperature scenario without any renovation measure. Thus, it seems that the building envelope renovation could have higher impact on heat demand in the future than the changed weather parameters.

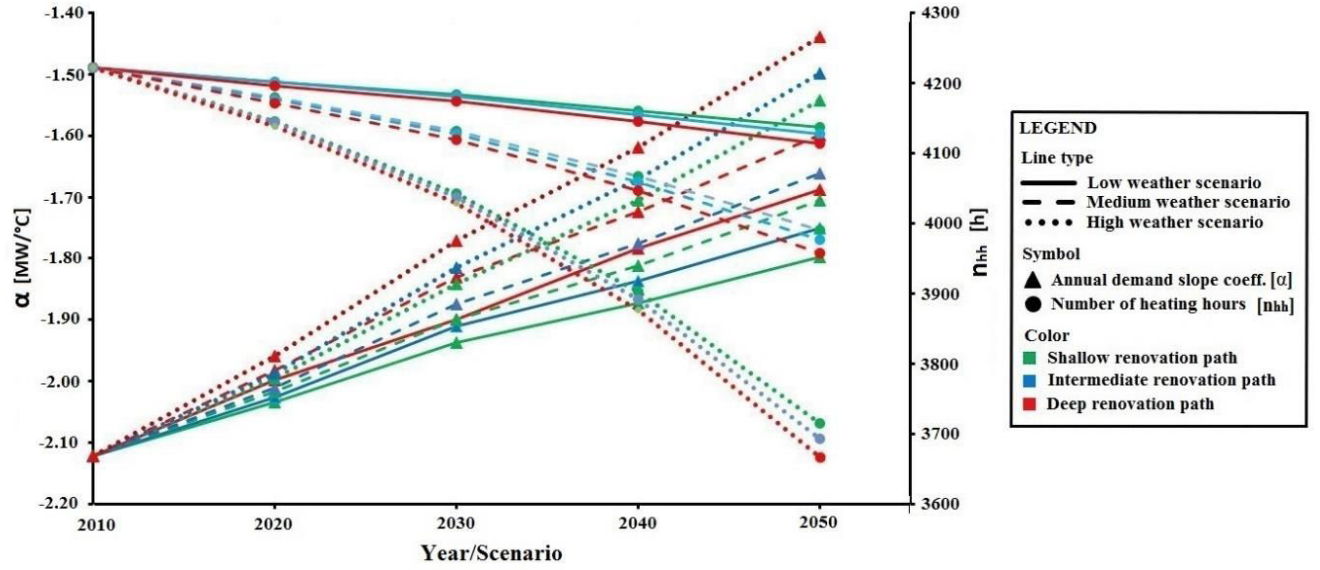


Figure 4.4 The impact of climate change on district heat demand – outdoor air temperature function slope and the number of heating hours;

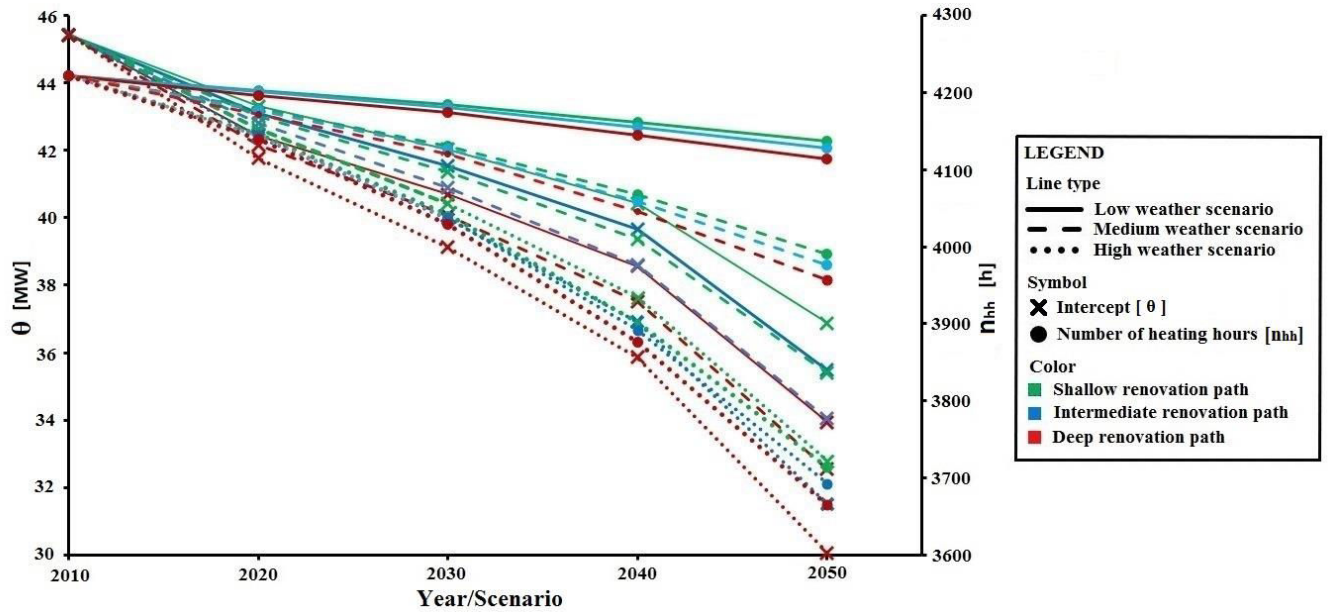


Figure 4.5 The impact of climate change on district heat demand – outdoor air temperature function intercept and the number of heating hours;

Additionally, the distribution of heat demand within the district for a reference year and the two most extreme scenarios (low temperature scenario with shallow renovation path and high temperature scenario with deep renovation path) is illustrated on Fig.4.7 through the specific annual heat demand of each building. Considering that the most common value used to define a minimum required heat demand density for district heating systems is 50 GWh/km²/yr (Frederiksen & Werner, 2013), the heat demand in 2050 is still sufficient for

system construction in all scenarios considered (with the lowest density of 57.3 GWh/km²/yr for high temperature scenario and deep renovation path). However, due to the heat demand reductions, the investment return period for the system construction would inevitably increase.

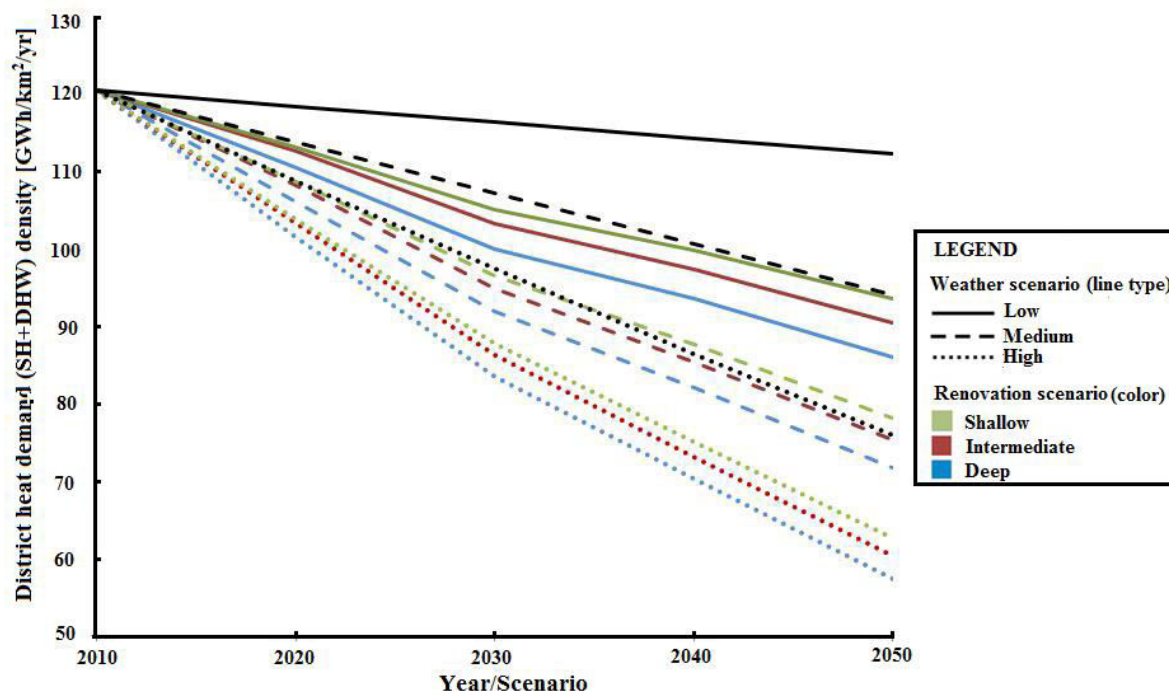


Figure 4.6 The effects of direct and indirect impacts of climate change on district heat demand density (for the district heating surface $A_d=0.6$ km²);

Figure 4.7 on the next page (due to resolution quality)

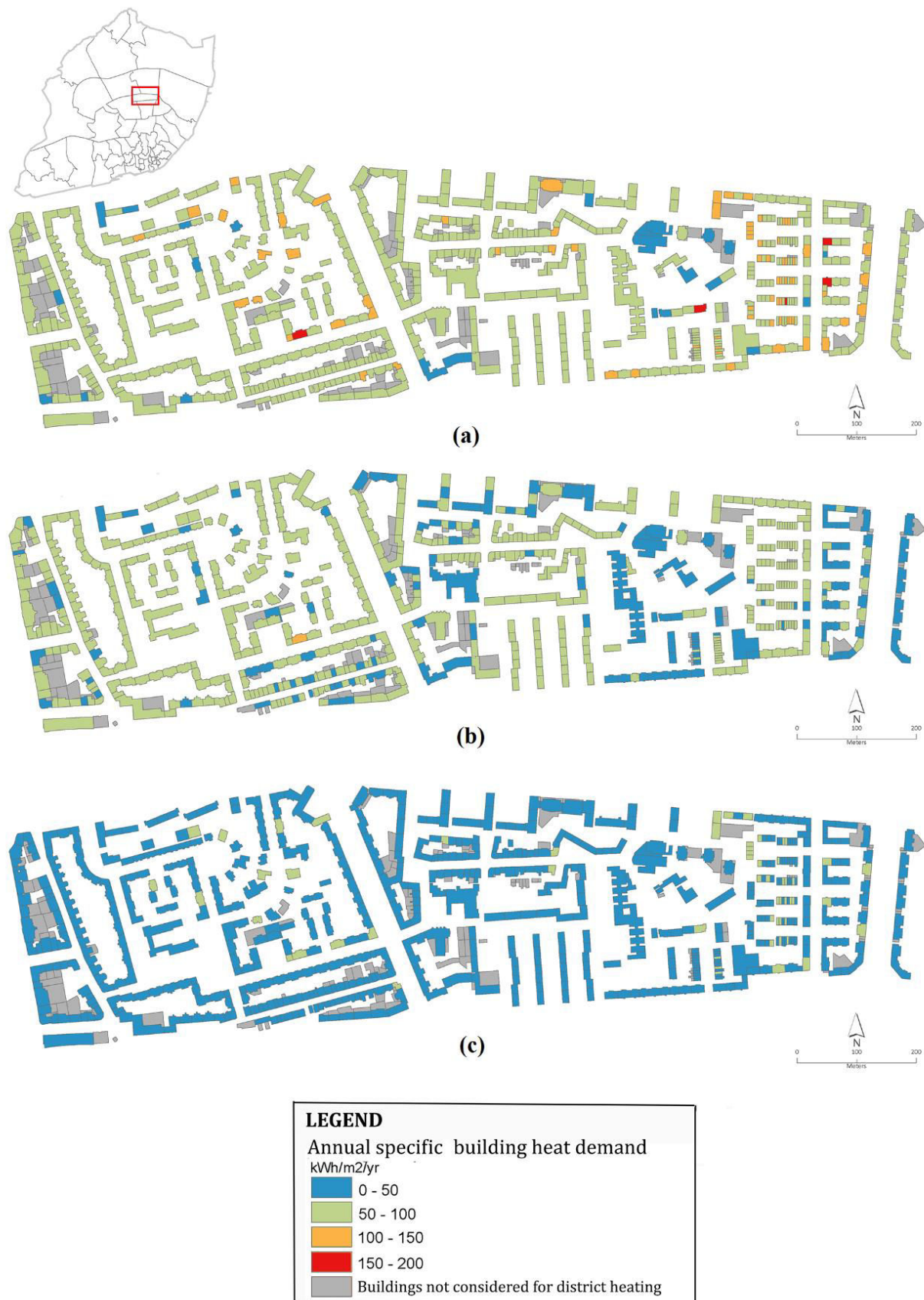


Figure 4.7 The specific annual heat demand distribution over the Alvalade district: reference year and district state (a); low temperature scenario and shallow renovation path, year 2050 (b); High temperature scenario and deep renovation path (c);

4.1.4 Conclusions

The main scope of this case study was to explore the direct (changed climate) and indirect (building renovation measures) impacts of climate change on district heat demand related parameters. District heat demand was calculated by using the model that is thoroughly described within the methodology chapter of this thesis. The methodology developed was applied on the district of Alvalade, located in Lisbon (Portugal), that consists of 810 buildings that vary in both typology and construction period. Only 665 were considered for this case study - garages, churches and other non-heated buildings were neglected. Three weather scenarios were developed (low, medium and high), along with three building renovation paths (shallow, intermediate, deep). Each of these renovation paths considers four building renovation levels (low, medium, high, and near-zero energy building level).

Calculations of Pearson's product-moment correlation between the building heat demand and outdoor air temperature proved a high linearity between these variables (the average value of the Pearson's coefficient for all buildings was -0.91), which proved the feasibility of using the heat demand – outdoor air temperature function to represent building heat demand signature. When the function parameters (slope coefficient and intercept) calculated for the reference state (typical reference meteorological year and reference district state) were used to estimate future heat demand solely for weather scenarios (by using solely predicted weather data, without any renovation measures) the difference in result compared to the output of the dynamic model was 12 % on average. However, when the renovation scenarios were taken into consideration, the difference was 60 %, due to the inability of the function to account for changes in building envelope thermal performance. Thus, function parameters should be re-calculated for all scenarios, for which the developed heat demand calculation model that does not require significant time nor computing power proved to be useful.

When the function parameters were recalculated for both weather and renovation scenarios, heat demand slope coefficient for the year 2050 was within the range of -1.9 MW/°C to -1.6 MW/°C, while the value of the intercept was within the range of 36.9 MW to 30.1 MW (when both weather change and building renovation scenarios are considered). Overall, for the decrease of heating hours of 22 h – 139 h, the values of the slope coefficient increased within the range of 3.8 % - 8.1 %, while the value of the intercept decreased within the range of 7.8 % - 12.7 % per decade.

The results showed that due to the weather change (without any renovation measure) heat demand density could decrease in 2050 within the range of 6.7 % - 37.1 % of the reference

value (year 2010), depending on the chosen weather scenario. Taking into account both weather change and renovation measures, heat demand density could decrease for 22.3 % – 52.4 % in 2050 (compared to 2010), depending on the considered combination of weather and renovation scenarios. Thus, it can be concluded that building renovation scenarios would have a significantly higher impact on heat demand in the future than the weather change.

However, even with all heat demand reductions, the district still remains feasible for district heating (with heat demand density higher than 50 GWh/km²/yr for all studied scenarios). However, the decrease in heat demand could prolong the investment return period for the construction/expansion of district heating systems. Consequently, to achieve the same investment return period, heating price for the clients would have to be increased. Another solution could be the reduction of heat production costs or the increase in the number of connected clients. However, both of these solutions require additional investments. Additionally, the value for minimal heat density for district heating feasibility is based on current district heating technologies, limitations and pricing, and could consequently change in the years to come.

Overall, from the methodology point of view, the approach developed for the estimation of direct and indirect climate change impacts on district heat demand related parameters proved to be suitable for this research scope. The simulations with the developed RC heat demand model were not time nor computing power consuming (average heat demand calculation time on an hourly time step was 35 s per building).

4.2. Modelling the long-term impacts of climate change on district heating systems techno-economic parameters

As proved in the previous model application, due to the direct and indirect impacts of climate change, heat demand in the future could decrease. Considering that the district heating system techno-economical parameters are highly dependent on heat demand/heat sales, heat demand reduction could impact the feasibility of such systems. If the heating system is designed based on the reference weather and building state, both required boiler capacity and heating season duration could be significantly reduced, causing frequent stops in production and impacting the system efficiency on multiple levels. For both existing and planned systems, as a consequence, the price of heating services for the customers could increase in the future (in order to reduce the investment return period increase or compensate for increased production costs caused by the lower production efficiency), which could further affect the heat sales. Considering that district heating systems are usually appreciated for the relatively stable prices

they offer, price increase could lead to customer disconnections and further heat demand decrease on a district level. Thus, the main goal of this case study is to evaluate the long-term impact of global warming and building renovation on district heating systems operational and economic parameters, such as linear heat density (the ratio between the heat demand and district heating network trench length), heat production fuel mix, and specific CO₂ emission levels (kgCO₂ emitted per unit of heat produced), heat sales and heat prices. Considering that the impacts of climate change could affect both the existing systems and systems planned for construction, two cases were studied in order to evaluate the impact on heat prices: case one, where the district heating system already exists within the district (thus, only operational costs are taken into account); and case two, where the district heating system is planned for construction based on a current district state (in this case capital investments costs for heat production units and network infrastructure construction were considered along with the operational costs). In both cases, it was assumed that 76 % of heat demand is covered by a base load biomass boiler, while 24 % is covered by the natural gas peak load boiler. Additionally, considering that the integration of distributed heat production units (such as solar thermal collectors) in district heating systems and the effect of such “prosumers” on the systems parameters is a rising topic within the district heating community (Brand et al. (2014), Brange et al. (2016), Rămă & Mohammadi (2017)), integration of such systems has been addressed in this case study. Even in the case that these individual systems are not directly connected to the network, but solely supply the building on which they are installed, they would still cause a decrease in district heat demand (if these individual systems fully or partially cover the building heat demand, the amount of heat purchased from the district heating system would decrease).

4.2.1. Reference district state and weather data

As a case study, a prototypical French district was created based on the district of St. Felix, which is located in Nantes (France), and currently not connected to district heating system. The district consists of 622 single-family and multi-apartment buildings that vary in construction period and that can be used as representative for the French building stock. The outline of the district and the position within the city of Nantes is given on Fig.4.8. Due to the fact that the building stock in the regarded district is residential, set point temperature of 20 °C (for day and night during the whole week) was assumed, as in the previous case study (potential difference in set point comfort temperatures are discussed in sensibility study of this thesis part). Heating season in Nantes was assumed to be from the 1st of October until the May 10th, as suggested in the work of Darakdjian (2013).

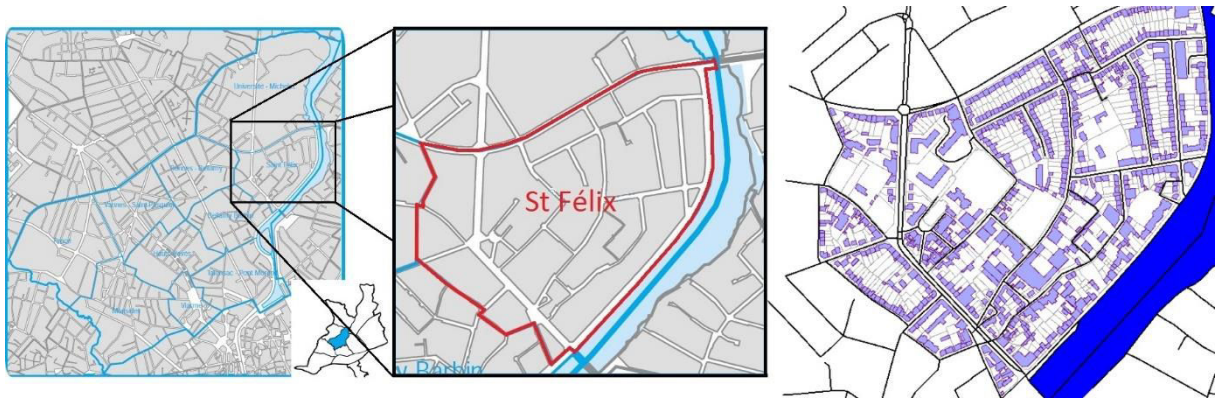


Figure 4.8 Position of the St. Felix district in within the city of Nantes and the outline of the residential building stock (data source: INSEE (2003) and Monteil (2010));

Reference weather data for Nantes was obtained from Energy Plus weather database in the form of .epw file. Weather data provided to the weather database is a part of IWEC (International Weather for Energy Calculations) data, which is a result of ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. IWEC data files are weather files considered suitable for use with building energy simulation programs for 227 locations outside the USA and Canada.

Reference U-values were obtained from the reports published by APUR (2007) and theses of Monteil (2010) and Darakdjian (2013), based on the building construction period and type. In this case, the average values for thermal bridging were included within the U-values presented in the reports. This conclusion was made based on the comparison with the U-values available at the BPIE website (BPIE, 2015b), and validated through the comparison of calculated heat demand results for sample buildings from each construction period available within the reports from APUR (2007) and TABULA (2016)).

Glazing ratios for the buildings in St. Felix district were obtained from the thesis of Darakdjian (2013), who conducted a statistical survey within the district, assigning the building glazing ratios based on the building construction period and the number of floors. The results of the statistical survey are given in Table 4.5. The values for heat capacities and densities of the materials (stone brick, hollow clay brick and concrete) were obtained from the online database (Engineering Toolbox (2015a, 2015b)). As in the previous case study, heat capacity of the air gap layers within the walls were not taken into account due to the fact that the air capacity of thin air layers can be neglected, as proved in the thesis of Weitzmann (2004). The number of obstructions required for the use of shading coefficients suggested in the report from APUR (2007) as well as building orientation required for the use of orientation coefficients

were also obtained from the work of Darakdjian (2013). The author has previously used GIS in combination with the available municipality data and Google Maps to determine the orientation of building facades. To estimate the number of obstructions from the surrounding environment that cast the shadow on the observed building, the author used the buffer technique in GIS software (for more details about the buffer technique, please refer to the work of Darakdjian (2013)).

Table 4.5 Glazing ratios for the district of St. Felix;

Construction period	Glazing ratio [-]	
Number of floors	Less than 2 floors	More than 2 floors
<i>Before 1915</i>	0.16	0.11
<i>1915 – 1948</i>	0.16	0.13
<i>1949 – 1974</i>	0.26	0.28
<i>1975 – 1989</i>	0.25	0.45
<i>After 1990</i>	0.32	0.43

Data source: Darakdjian (2013);

The number of occupants was estimated based on the population census published in INSEE reports and statistical findings about occupancy for different types of dwellings, available at Eurostat database (Eurostat, 2017). Occupancy profiles were obtained from the REVIT database for residential buildings (AutoDesk, 2015), while the specific heat gains from the occupants were assigned based on the activity and presence of the occupants during the day (heat gains data available at Engineering Toolbox, 2015c). As in the previous case study, heat gains from electrical appliances were neglected considering that the studied district is residential, while for the heat gains from lighting equipment, average density of installed lights of 6.3 W/m^2 was assumed, which is about 70 % of the allowed maximum. Domestic hot water consumption profiles were assigned based on the occupancy schedule, analogue to the findings of Ulseth et al. (2014). For other general parameters (such as specific heat capacities of air and water and correlation factors for incident solar beams), the values from Table 4.2 of this thesis were used.

The district heating network trench length required for the calculation of capital investment costs was estimated by the thesis industrial partner (Veolia Research and Innovation) engineers, based on the district data and district agglomeration. The estimated network trench length for the district of St. Felix is 4831 m. Thus, the layout and the building stock of the existing district were used, while the district heating network layout was created based on the district data.

4.2.2 Weather and renovation scenarios

For the weather scenarios, CCWorldWeatherGen tool was used for morphing the weather file for Nantes. For this case study, due to the fact that the impact of weather change proved to be minor compared to the building envelope renovations, only one weather scenario was considered (medium weather scenario, created by following the proposed methodology within the second chapter of this thesis). For the building renovation scenarios in this case study, three main renovation scenario parameters (building selection criteria, renovation depth, and renovation level) were defined as described below:

- *Building selection criteria* – considering that the scope of this particular case study was to evaluate the long-term impacts of climate change on district heating systems techno-economic parameters and feasibility of such systems in the future, the worst case scenario was assumed: at each renovation step (10 years), all buildings are selected for renovation measures;
- *Renovation depth* – analogue to the building selection criteria, all buildings within the district are considered for renovation measures;
- *Renovation level* – in this case study, a different point of view was used to develop renovation level criteria. As pointed out by Stefanović & Gordić (2016), in order to achieve significant reductions in heating energy consumption in the building sector through the implementation of energy efficiency policies, thermal improvements should be carried out at least on a city level. For integration of any technology on such a large scale, market saturation of that particular technology should be mature, i.e. economically viable and have a high market penetration rate. Market penetration rates of different renovation measures in developed and developing countries were addressed in the report by International Energy Agency (IEA, 2014). As stated in the cited report, the data on current market share is difficult or expensive to obtain in developed countries, while in the emerging markets it is not widely available. Thus, the IEA used assessments and inputs from experts worldwide to estimate three levels of market saturation: mature market (greater than 50 %), established market (approximately 5 % to 50%), and initial market presence (available but less than 5 %). Due to the fact that the majority of the buildings stock is still un-renovated (Enerdata, 2016), it was assumed in this case study that the buildings considered for renovation measures still had the original envelope thermal performance in 2010 (no renovations were made since the building was constructed). In 2020, with the first renovation policies being applied on a larger scale, the buildings are renovated by using currently mature renovation measures:

typical insulation, improvements in air sealing and installation of double glazed windows. For the year 2030, it is assumed that the measures that were previously established reached mature saturation and are thus applied (installation of triple glazed windows). However, it is likely that within this renovation step, additional improvements of the measures previously conducted (expanded polystyrene insulation and air sealing) would be applied - and thus they are also considered. For 2040, it is considered that the measures that had initial market presence (advanced insulation, energy plus windows (highly insulated with dynamic solar shading)), reached a mature phase and large scale application. Additionally, slight improvements of previously installed measures are considered, as in the preceding cases. Finally, in 2050, the implementation of new insulation technologies that were previously under development is considered, along with some minor improvements of previous renovation measures. This can be justified by the fact that when building renovation measures are conducted, it is common practice to improve more than one element. The results of the suggested scenario application on a case study building are presented on Fig.4.9 and Table 4.6. The improvements are based on the IEA report (IEA, 2014).

In addition, the installation of solar collectors was considered within a separate scenario. It was assumed that the solar thermal collectors were added within the first renovation step (2020) along with other renovation measures, due to the fact that they have a high market penetration rate. Heat production output from solar collectors was calculated by taking into account hourly values of solar radiation (extracted from the .epw files for each year of the scenario), available roof surface (extracted from the reference district data) and technical properties of the solar collectors considered, Jacques Giordano Industries C8/12.S.U. (obtained from the product certification (Certif, 2013)).

Table 4.6 Overview of the renovation scenarios used in St Felix case study (thermal properties after renovation measures);

Parameter	2020	2030	2040	2050
U_w [W/m ² K]	0.15	0.08	0.015	0.01
U_r [W/m ² K]	0.15	0.08	0.015	0.01
U_f [W/m ² K]	0.15	0.08	0.015	0.01
U_{wd} [W/m ² K]	1.8	1.1	0.6	0.3
n_h [h ⁻¹] ^a	0.5	0.4	0.3	0.2

^aOnly natural ventilation is considered in this paper (renovation per hour), due to the fact that the residential buildings from considered construction period had very low penetration of central ventilation units;

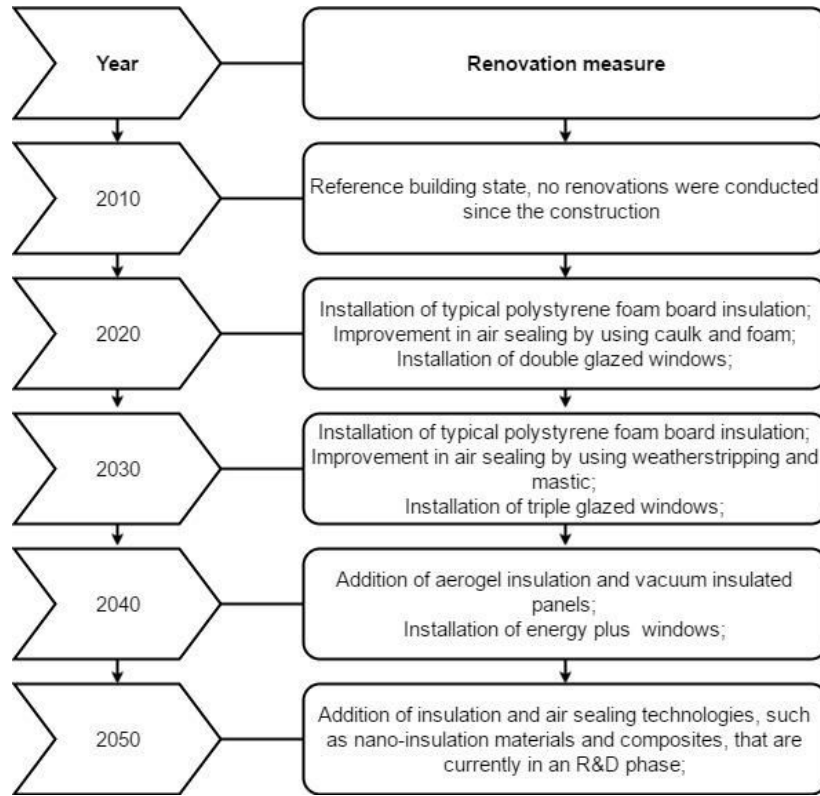


Figure 4.9 Overview of the building envelope renovation scenarios used in St. Felix case study (renovation measures);

4.2.3 Results and discussion

The impact of climate change and building renovation on district annual heat demand and linear heat density (heat demand per m of network trench length) is given on Fig.4.10. In this case, the network length and configuration was kept constant throughout all years of the regarded scenario. The decrease of heat demand proved to be the highest after the first year of renovation, decreasing for 52 % of the reference value. This decrease rate can be justified by the fact that the first renovation step includes major improvements in the building envelope thermal performance for all buildings within the district, while in the following renovation steps the levels of improvements are lower. For example, in 2020, for the building built in 1980s, a 40-year technology gap in envelope performance is bridged, while for the other years within the scenario, the gap is only 10 years (the decrease rate of 7 % of the reference heat demand value per decade). The value of linear heat density decreased accordingly. Considering that for the construction of traditional types of district heating systems, one of the main profitability assessment criteria is linear heat density of minimum 4 MWh/ml, these systems would be considered unprofitable after the first major district renovation in 2020. It should be noted that the 4th generation of district heating systems probably has lower feasibility limits. However, considering that there is a limited number of these systems in operation, and that in the most

cases each system is site-specific, we were not able to obtain the minimum linear heat density values for these system types. In addition, it should also be mentioned that district heating systems are currently eligible for substantial subsidies in certain countries. For example, in France, where the case study is located, The French Environment and Energy Management Agency (ADEME) offers subsidies to district heating projects with linear heat density higher than 1.5 MWh/ml. As it can be seen from Fig.4.10, linear heat density was higher than this minimal threshold value even in year 2050.

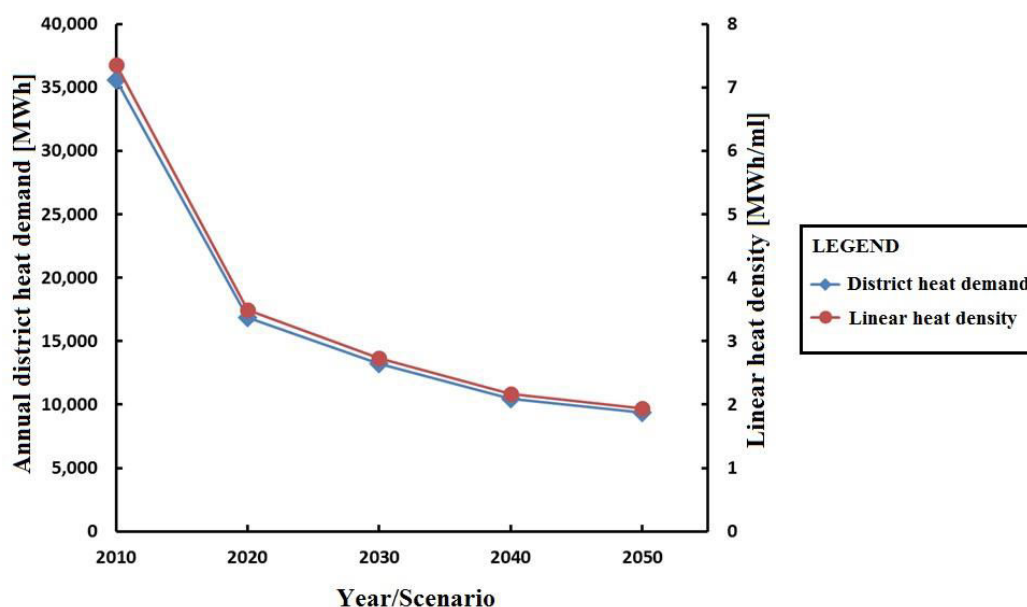


Figure 4.10 The impact of climate change on annual district heat demand and linear density;

The impact on heat production, losses and sales is given on Fig.4.11. It can be observed that the relative heat losses (in %) increase for 3 % (percentage points) on average for the decrease in heat demand by 18 % (on average). The highest heat losses (18 %) were for the year 2050 with the lowest heat demand. While the absolute losses remain constant, heat demand decreases, resulting in higher relative heat losses. Due to the losses, heat production has to be higher than the actual demand, which is especially notable after the renovation measures are performed.

From Fig.4.12, it can be observed that the evolution of heat demand would have a strong impact on energy production mix. The participation of natural gas boiler in heat production increases over the studied period, while the participation of biomass boiler decreases. The biomass boiler was designed to cover the base load, while the natural gas boiler was designed to cover the peak load. For the reference district state, energy production units were designed so that the 76 % of heat demand is covered by the biomass boiler, and 24 % of heat demand is covered by the natural gas boiler. However, in 2030, less than 50 % of heat demand would be

covered by the biomass boiler, considering that the number of hours with heat demand below the technical limit of the boiler would increase. In 2050, due to the further heat demand reductions, only 1 % of heat demand is covered by the biomass boiler. Due to the increased heat production from natural gas boiler, the level of CO₂ emissions increases on average for 49 kgCO₂/kWh per decade, reaching the peak in 2050 with 261 kgCO₂/kWh, which is almost five times higher than in the reference year (2010).

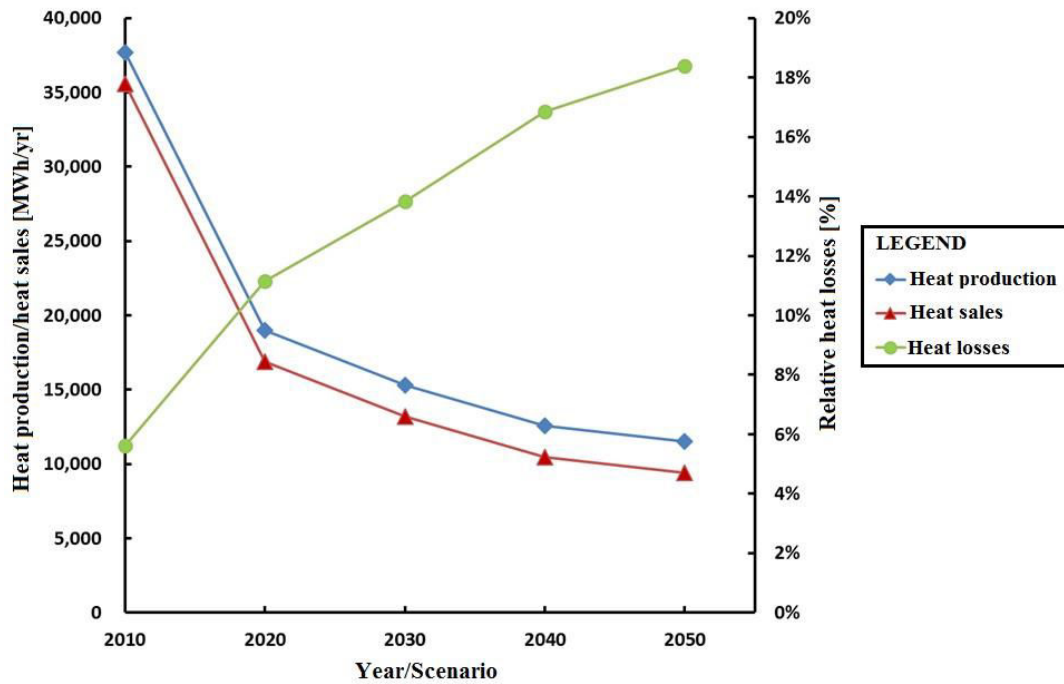


Figure 4.11 The impact of climate change on the heat production, sales and losses;

The evolution of heat production costs is presented in Table 4.7. The current version of the techno-economic model has a limitation for calculating the heat production costs only for the period of 20 years, since that is the assumed fixed lifetime of the system within the model. Thus, only values up to the year 2030 are calculated. The price within the table presents a suggested average cost for the regarded period in order to obtain the investment return at the end of the suggested lifetime. As described previously within this thesis chapter, two cases were considered: that the system already exists within the district (thus only OPEX costs are taken into account) and that the system is planned for construction based on the reference district heat demand (both CAPEX and OPEX costs are accounted). It can be seen that the costs of heat production increase in both scenarios, with higher increase rate for the scenario where the new district heating system is planned due to the capital investment costs for the heat production units and district heating distribution network. Consequently, heat prices would increase over the

next two decades, whereas district heating systems are usually appreciated for the relatively stable prices they offer. This could lead to consumer dissatisfaction and possible disconnections from the district heating systems in order to switch to another type of heating system that would seem more cost efficient for the consumer at that point (heat pumps, for example). These systems have higher investment costs compared to the district heating system connection cost, but the consumer could recognize the long term profitability due to the lower costs of energy production. It should be noted that the calculated heat production prices for the scenarios considered were more stable than initially expected by the author. However, this behaviour was caused by the amortization of economic balance (short-term incomes and expenses have the higher impact). It should also be mentioned that the district heating operators could also vary this price on an annual level, but it is expected to be close to the suggested average.

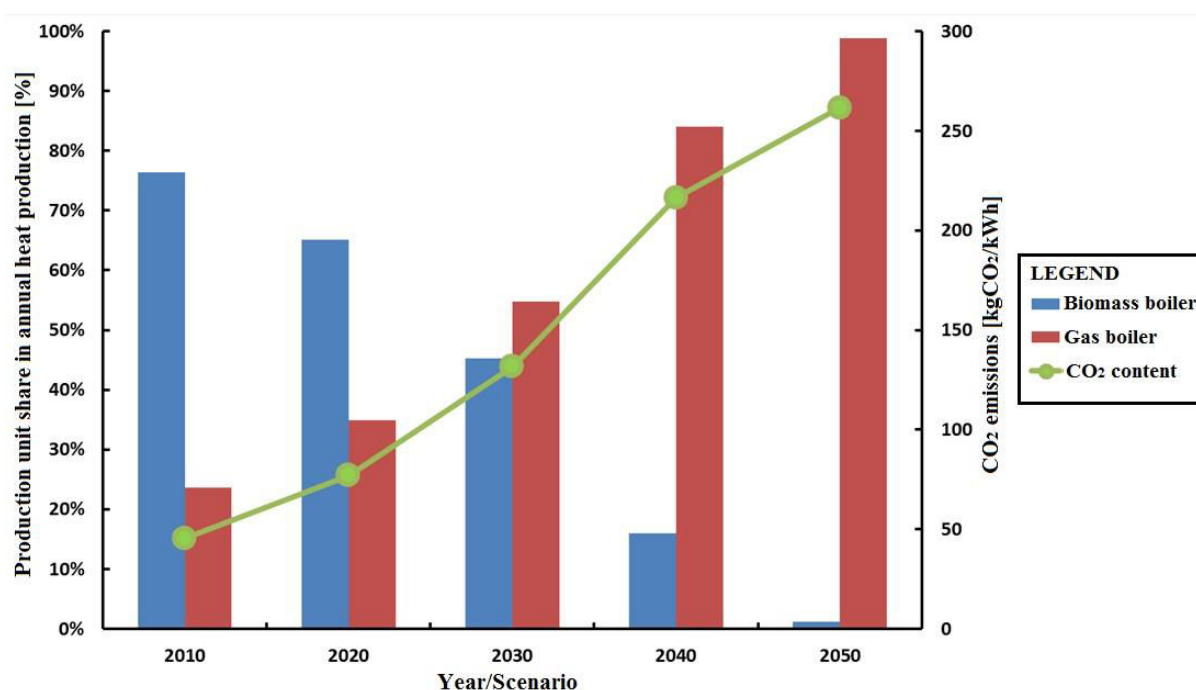


Figure 4.12 The impact of climate change on system production units and related CO₂ emissions;

Table 4.7 Heat production costs for the regarded scenarios;

Scenario/Year	Heat production cost [€/MWh]	
	2010	2010-2030
Existing DHN	47	49
New DHN	66	76

Considering the impact of solar collectors within the renovation measures, the result can be observed in Table 4.8. It can be seen that after the building envelope renovations, installed solar collectors are able to generate more heat than required on an annual level. Thus, buildings with solar thermal collectors could be considered as prosumers, feeding the excess heat into the network. However, this could affect the network operational parameters, which is an emerging topic within the bibliography. Moreover, the focus for this scenario was to evaluate the ratio between the district heat demand and heat production from solar thermal collectors. The production rate does not always match the demand rate, considering that solar collectors have the highest output during the summer months, when only domestic hot water heat demand exist. In addition, during the winter, there is a significant heat demand during the night-time period when there is no sunshine available. This effect can be observed by comparing the number of hours when solar thermal collectors do not satisfy the heat demand (SH+DHW) or exceed the heat demand (SH+DHW). For all years considered within the scenario, the number of hours when solar thermal collectors output does not satisfy heat demand is higher compared to number of hours when solar thermal collectors output exceeds the demand. However, this difference tends to decrease with the decrease in heat demand (1014 h difference in 2050 compared to 1682 h in 2020). Thus, to optimize the energy demand and energy production, thermal storages should be installed.

Table 4.8 Results of a scenario with solar thermal collectors;

Year/Scenario	Annual district heat demand [GWh]	Annual solar thermal collectors heat production [GWh]	Number of hours with space (SH) [h]	Number of hours when solar thermal collectors do not satisfy heat demand (SH+DHW) [h]	Number of hours when solar thermal collectors exceed heat demand (SH+DHW) [h]
2010	35.56	0	5654	0	0
2020	16.88	48.85	5219	5221	3539
2030	13.21	49.21	4626	5066	3695
2040	10.45	49.56	3204	4956	3804
2050	9.40	49.91	1438	4887	3873

4.2.4 Conclusions

The main scope of this methodology application was to evaluate the direct and indirect impacts of climate change on district heating systems techno-economic parameters. A generic district was created based on the district of St. Felix, located in Nantes (France). This particular district was selected based on a conclusion that it has a good representation of French national

building stock (based on the comparison with the reports from French governmental agencies). The district is residential, and it consists of 622 buildings that vary in construction period. One weather scenario was used (medium weather scenario) due to the fact that the results from the previous case study indicated that building renovation has a significantly higher impact on heat demand compared to changed weather variables caused by the climate change. Building envelope renovation scenario was based on the market penetration rate of renovation measures. Heat demand was calculated by using the developed heat demand model (please refer to the methodology section of this thesis), while the calculation of techno-economic parameters was performed by using the in-house tool developed by the thesis project industrial partner (Veolia). Furthermore, the addition of solar collectors as decentralized heat production sources was considered. Moreover, for the calculation of heat prices (influenced by the capital investment costs amongst other factors), two cases were considered. In the first case, the district heating system already exists within the neighborhood. On the other hand, in the second case, it was assumed that the district heating system is planned for construction based on the current heat demand (reference heat demand in 2010).

The results obtained indicated that the heat demand decrease would be the highest (52 % of the reference value) after the first year of renovation (2020), due to the fact that a 40-year technology gap in building envelope thermal performance is bridged (please refer to the *Weather and renovation scenarios section* of this case study). From the aspect of traditional district heating systems, heat demand linear density was below the profitability threshold value (4 MWh/ml) after the first renovation step within the scenario (renovation measures in year 2020). However, the threshold value for the 4th generation of district heating systems would probably be lower, but in most cases, these systems are site-specific, and the minimum linear density for these systems is currently not available within the bibliography to the best knowledge of the author. Moreover, district heating systems are currently eligible for substantial subsidies, which improve the system feasibility. For example in France, the subsidies are awarded for district heating project in areas with linear heat density higher than 1.5 MWh/ml. In this particular case study, linear heat density was higher than this lower threshold even in year 2050.

For the weather and building envelope renovation scenarios considered, relative heat losses in the network increase for 3 % (percentage points) on average for the decrease in heat demand by 18 % on average, reaching 18 % in year 2050. Additionally, heat demand reduction had a significant impact on heat production fuel mix. In reference year, it was assumed that 76 % of heat demand was covered by a base load biomass boiler, while 24 % was covered by the

natural gas peak load boiler. However, in 2030, less than 50 % of heat would be produced with the biomass boiler, due to the decreased number of heating hours with heat demand above the boiler technical minimum. In 2050, only 1 % of the demand would be covered by a base load biomass boiler. This aspect is of utter importance for countries such as France, where incentives and subsidies for district heating network projects are assigned based on the participation of renewable energy sources in heat production. As a consequence of increased heat production from fossil fuelled (natural gas) peak load boiler, the specific CO₂ emissions increased almost five times in 2050 compared to 2010 (261 kgCO₂/kWh compared to 45.4 kgCO₂/kWh respectively). Due to this increase in CO₂ content per unit of heat produced, district heating systems would become environmentally unfeasible, with better kgCO₂/kWh ratio possibly obtained with other alternatives for providing heating services to the urban environment, such as individual natural gas condensing boilers in each dwelling. These systems would be also affected by the climate change impacts, but on different scales.

Due to the climate change impacts, heat price would increase over the next two decades. One of the main reasons district heating systems are appreciated by the customers is due to the relatively stable prices they offer. Consequently, the increase in heat prices could lead to dissatisfaction and potential disconnections from the systems, further impacting the feasibility of such systems. The customers might find suitable to switch to other types of heating systems such as heat pumps. These systems have higher investment cost compared to connection to district heating system, but the customer could recognize the long term profitability due to the lower costs of energy production. However, it should be noted that the current version of the techno-economic model used in this study has a limitation for calculating the heat production cost only for the period of 20 years, since that is the assumed fixed lifetime of the system within the model. Thus, only values up to the year 2030 were calculated.

Considering the renovation scenarios with solar collectors, the results indicated that the annual thermal solar collectors' heat production was higher than the building annual heat demand even after the first envelope renovation step in 2020. Thus, buildings could become prosumers in the future, feeding the excess heat to the networks, which would affect the network operational parameters. However, heat production rate from the solar collectors does not always match the demand rate, on both daily and seasonal levels. Namely, the highest output from the solar collectors occurs during the summer months (on a seasonal level) and during the afternoon hours (on a daily level), which is opposite for the heat demand distribution – the highest heat demand occurs during the winter season and during the night-time. Thus, in order to optimize the energy demand and energy production, thermal storage should be incorporated in such

combination of district heating systems and decentralized heat production units such as solar thermal collectors.

Finally, from the methodology point of view, the developed approach and the RC heat demand model within the thesis proved to be feasible for the integration with an in-house modelling tool developed by the industrial partner. The combination of these two models enabled the estimation of climate change impacts on district heating systems techno-economic parameters without significant time or computing power requirements.

CHAPTER 5: THE EFFECT OF CLIMATE TYPE DIFFERENCES

Within the previous thesis chapter, the impacts of climate change on heat demand related parameters and district heating system techno-economic parameters were evaluated by applying the methodology developed on two case study locations (Lisbon (Portugal) and Nantes (France)), which differ in geographical position (and thus consequently climate conditions). However, there are other locations in different climate zones that are suitable for heating services (heat production and distribution), in which the direct and indirect impacts of climate change on district heating systems could be of different scale. Thus, the main scope of this study is to evaluate to which extent the potential impacts of climate change on district heating systems differs between the climates suitable for heating services. In order to do so, primarily, climate types suitable for heating services are defined, as well as the locations within those climate types that can be considered representative from the aspect of building energy demand modelling. However, properties of the building stock could differ in construction period and materials used between these locations (depending on the historical and economic background of the location). Thus, it would be difficult to create a generic district valid for all these locations in order to compare the results on the same basis. Instead, it seems more suitable to conduct a study on a single representative building - by doing so, it is possible to conduct an evaluation of climate type differences impact on a same basis (which is the main focus of this study), while the impact of potential differences in building thermal properties (such as U-values and air infiltration rates) can be observed on the results from the building renovation scenario application (in which the suggested parameters vary). Heat demand for such representative building was calculated through the use of developed RC model and by using the climate data and weather scenarios developed for each of the representative locations. As in the previous case studies, building envelope renovation was also taken into account through the building renovation scenario. Finally, the results for all locations were compared and analyzed to evaluate the differences between the climate change impacts on heat demand in different climate types.

5.1 Characteristic climate types definition

According to multiple climatic and meteorological studies, with the latest from Chen & Chen (2013), there are five major climate types in the world: tropical, sub-tropical, temperate, sub-polar and polar. Representative cities within these climate types, suitable for building energy modelling studies, were previously proposed by Mansy (2006). The study presented a

model and principal criteria for selecting international cities to represent the world's distinctive climatic regions. Within the suggested model, primarily, three locations were initially chosen to represent each of the five major climatic zones. Afterwards, a set of sub-criteria was used to narrow the selection by eliminating locations that did not meet certain conditions. First, candidate locations were selected to exhibit an even geographic distribution of the recorded weather data in the Northern Hemisphere. Within the second step, the selection was narrowed based on the site elevation, proximity to mountains and large bodies of water. Finally, the locations that satisfied all the previous criteria were validated with climate locations from the Köppen climate zones and ASHRAE standard climatic zones (i.e., if the locations selected also fit within these two climate divisions). The locations selected by the author (Mansy (2006)) were Singapore (tropical), Cairo (sub-tropical), Milan (temperate), Ft. Smith (sub-polar) and Resolute (Polar), located in Singapore, Egypt, Italy and Canada (Ft. Smith and Resolute), respectively. It was concluded that five suggested cities can be used in bioclimatic studies as reference locations for five world climate types, due to the fact that they are well distributed between the continents and longitudes. Additionally, it was noted that the comparative studies, which compare building performance in a variety of climates, may use these five locations to demonstrate the wide range of diversity in world climates. However, the author suggested that internal variations within the temperate region should be considered, since it is the most populated climate region in the world.

However, the focus in this thesis and this particular study is solely on climates suitable for heating services, considering the thesis scope. After comparing the weather data available within the Energy Plus weather database (U.S. Department of Energy, 2015) for multiple locations within five major climatic zones, tropical and subtropical zones were excluded from considerations due to their high air temperatures and solar radiation levels over the course of the year, which result in low heat demand and penetration rate of heating systems. Considering that the temperate and sub-temperate climate zones are densely populated and have a high penetration rates of heating systems, they were included in this study. Sub-polar and polar climate zones are sparsely populated, but most of the inhabited locations have centralized heating systems. Consequently, these two zones were also included into considerations.

Based on the conclusions and recommendations for future developments from the work of Mansy (2006), internal weather variations within the temperate climate zone were considered within this study. Three sub-zones were defined for the temperate climate based on multiple criteria such as latitude, temperature and solar radiation levels, location elevation, proximity of mountains and large bodies of water (considering that these factors significantly contribute to

in-type variations). Based on an analysis of the meteorological history for multiple locations around the world (available from the Energy Plus weather database), final characteristic locations were defined, as described in Table 5.1 and Fig.5.1. Selected locations were validated through the comparison with Köppen and ASHRAE standards climatic zones divisions (i.e., crosschecked if the locations selected also fit within these two climate divisions).

Table 5.1 Climate types considered and characteristic locations;

Climate		Position			Average annual values		
Type	Location	Lat. [°]	Elev. [m]	Body of water prox. [km]	Air temp. [°C]	Global sol. rad. [Wh/m ²]	Wind speed [m/s]
<i>Temperate -hot</i>	Madrid (ES)	40	667	415	27	190	2
<i>Temperate - mild</i>	Milan (IT)	45	107	188	12	147	0.9
<i>Temperate-cold</i>	Hamburg (DE)	53	6	92	9	109	4
<i>Sub-polar</i>	Yellowknife (CA)	62	206	0	-4	105	4
<i>Polar</i>	Resolute (CA)	75	67	0	-16	100	6



Figure 5.1 Locations selected for the case study;

5.2 Characteristic building case study selection

According to Pennestri (2013), most of the European building stock was constructed in the post-World War 2 era. The significant population growth that occurred in this period caused an exceptional increase in building construction, especially for the residential sector. The need to respond quickly to the pressing housing demand and the lack of energy efficiency legislation caused a proliferation of buildings that were satisfying rather quantitative than qualitative metrics. Thus, buildings from that particular period are characterized with high envelope U-values and air infiltration rates. Taking into account that three out of five locations used in this study to represent the climate types are located in Europe, a multi-apartment residential building from the post-war construction period was considered suitable as a case study.

Thus, a six-storey multi-apartment detached building was modelled, with the U-values for the elements and airtightness defined based on data available for multiple countries at the Building Performance Institute Europe data hub (BPIE, 2015c). The values used, which were common for most countries, were: $U_w=1.7 \text{ W/m}^2\text{K}$, $U_r= 2.56 \text{ W/m}^2\text{K}$, $U_f=2.93 \text{ W/m}^2\text{K}$ and $U_{wd}=3.92 \text{ W/m}^2\text{K}$ for external walls, roof, floor and windows, respectively, and air infiltration rate of $n_h=2.0 \text{ h}^{-1}$. Depending on the surface and orientation of each facade and the overall surface of all facades, building orientation has been calculated as a weighted average. It was considered that the building is heated by the radiator system connected to the district heating system. For the occupancy schedules, three profiles were created - a week day, Saturday and Sunday occupancy profile. The profiles are based on the residential occupancy schedules used in the REVIT database (AutoDesk, 2015). As in the previous case studies, the installed capacity of electrical appliances was not considered which will not have a significant impact as the studied building is used for residential purposes, and thus does not have installed electronic devices with significant heat release (such as computer servers, industrial equipment etc.). The assumption was made based on the comparison of heat release levels from household appliances (ASHRAE, 2007) and other relevant heat gains (solar radiation, occupants, lightning etc.) calculated in this study. Natural ventilation is considered in this study, as residential buildings from the considered construction period have a very low penetration of centralized ventilation units. Other relevant geometry and construction parameters are provided within a table below.

5.3 Weather and building renovation scenarios

Weather scenarios were created for each representative location by using the methodology developed within the Part I of the thesis. As previously (please refer to the *Model application* chapter of thesis Part I), 2010 – 2050 horizon was considered within this study with

a 10 year time step. Consequently, 75 weather files were created - five years for each of the three weather scenarios, and for all five locations (for more details, please refer to the *Methodology* section of thesis Part I).

Table 5.2 Case study building parameters;

Item	Unit	Value
Building footprint	m ²	200
Building perimeter	m	60
Attached perimeter*	m	0
Number of facades	-	4
Building height	m	21
Number of floors		6
Building orientation	-	East
Glazing ratio	-	0.3
Installed lights density	W/m ²	5
Number of occupants	-	33
Heating system	-	Radiator heating

*Perimeter attached to another building;

To account for potential building envelope renovation measures in the future, a renovation scenario based on the renovation measures market penetration rates developed for the second case study of this thesis (refer to section 4.2.2 of thesis Part I) was used. However, instead of expressing the impact of a single envelope element renovation, the mean U-value of the envelope is calculated (U_{en} [W/m²K]), that is a function of the element U-values and their participation in the whole building envelope surface:

$$U_{en} = \frac{U_w \cdot S_w + U_r \cdot S_r + U_f \cdot S_f + U_{wd} \cdot S_{wd}}{S_w + S_r + S_f + S_{wd}} \quad (5.1)$$

where U [W/m²K] and S [m²] are the U-value and surface area of the regarded element (indexes w-wall, r-roof, f-floor, wd-window), respectively. This can be justified by the fact that when building renovation measures are conducted, it is a common practice to improve more than one element. The air infiltration rate (n_h [W/m²K]) was not included into the U_{en} value since the U-values characterize only heat transfer between buildings and environment, while the air infiltration presents both mass and heat exchange. Thus, air infiltration is considered as a separate parameter. The results of the suggested scenario application on a case study building are presented in Table 5.3. The improvements are based on the IEA report (IEA, 2014).

Table 5.3 Overview of the thermal properties within the building envelope renovation scenarios;

Parameter	Year/Scenario				
	2010	2020	2030	2040	2050
U_{en}	2.46	0.53	0.31	0.15	0.08
n_h	2	1	0.8	0.6	0.4

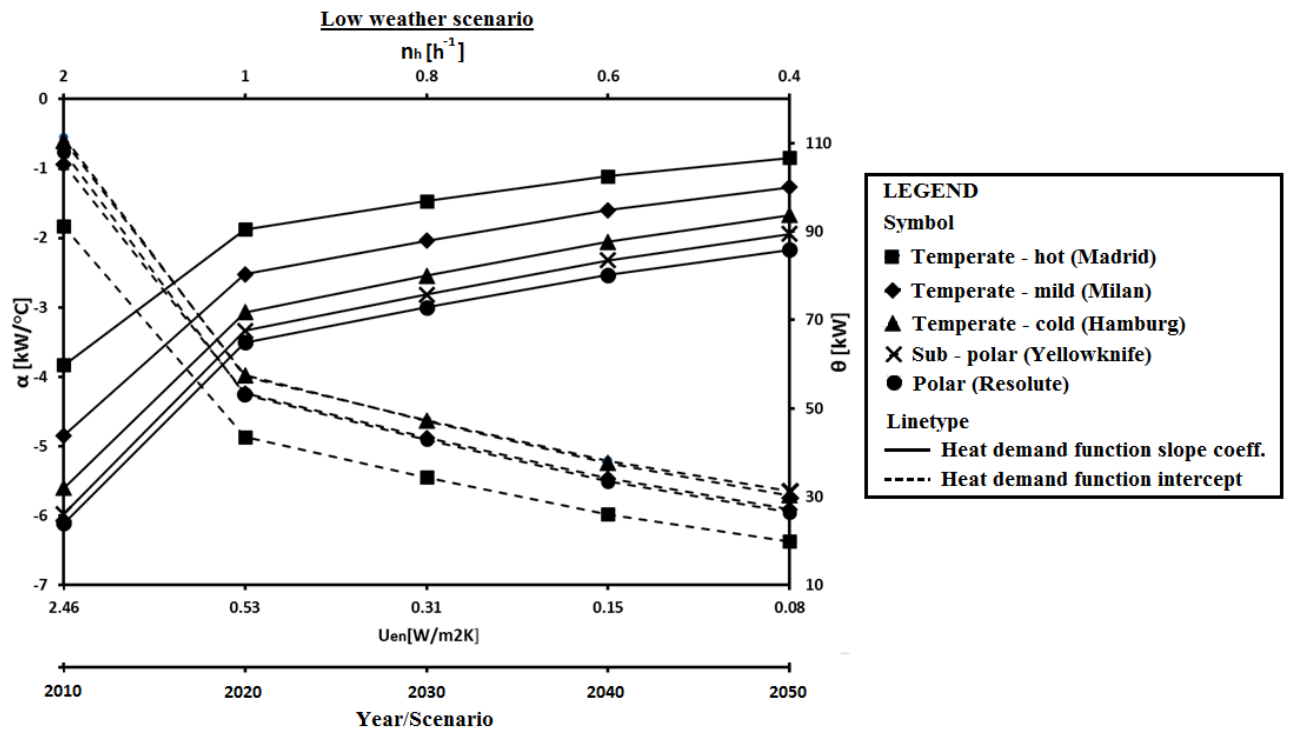
5.4 Heat demand calculation and the results representation

The annual heat demand on an hourly basis for each location was calculated by using the RC model developed for this thesis. For heat demand representation on an annual level, heat demand – outdoor temperature function parameters were used as in the first case study of this thesis (slope (α) and intercept coefficient (θ), refer to Fig.2.1). In addition, the impact of climate change and building renovation on heat demand in terms of energy is also provided by analyzing the building total annual heat demand and load duration curves. Finally, for a deeper insight in parameters relevant from the heating system operational perspective, quartile analysis was performed.

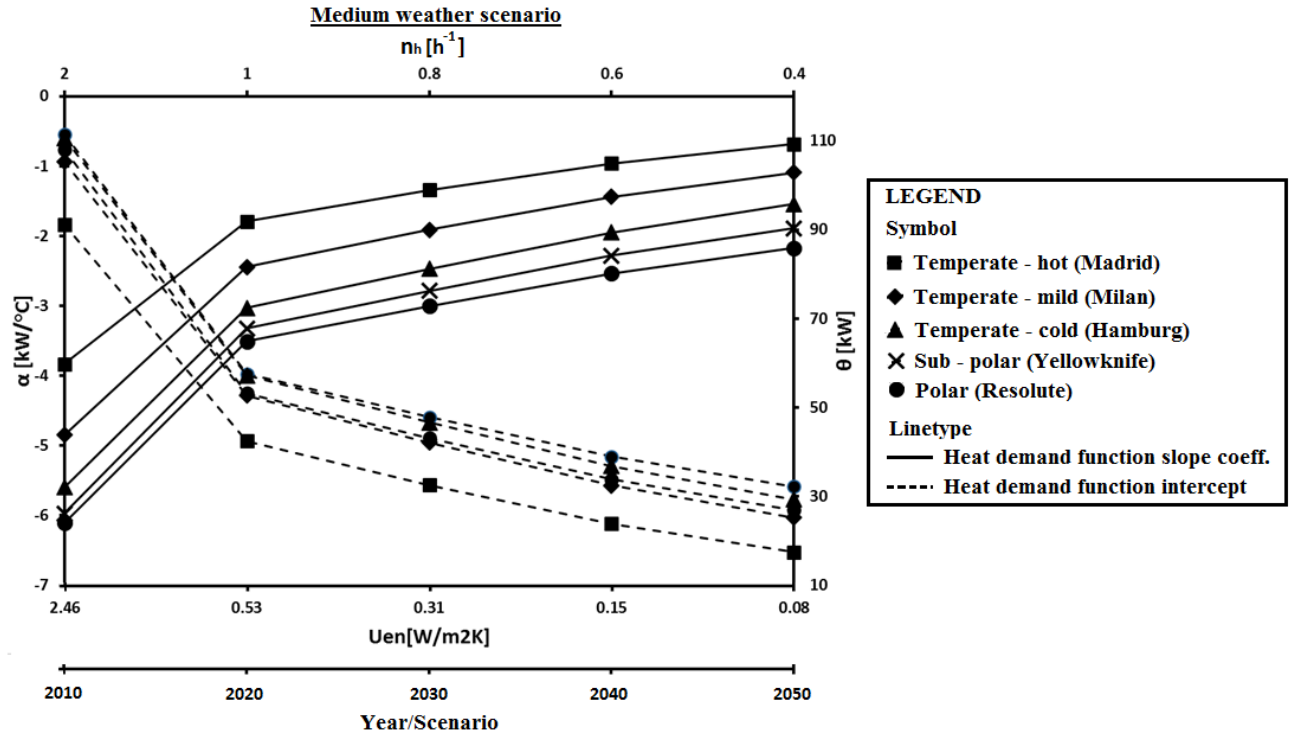
5.5 Results and discussion

The direct and indirect impact of climate change on building heat demand in different climates is represented on Fig.5.2. It can be observed that the trend in slope coefficient (α) and intercept (θ) was similar for all locations and all weather scenarios – the slope increases (considering the slope orientation, refer to Fig.2.1) after the initial building renovation in 2020 by 45 %-51 %, while the intercept decreases within the range of 48 %-51 %, depending on the weather scenario and location considered. The impact of further renovation measures was significantly lower, increasing the slope coefficient within the range of 7 %-10 % and decreasing the intercept by the same amount. The behavior was the same for the previous two case studies in this thesis and it can be explained by the fact that the first renovation step includes major improvements in the building envelope thermal performance (U_{en} and n_h decrease by 70 % and 50 %, respectively), while in the following renovations the levels of improvements are lower. In 2020, a 40-year technology gap in envelope performance is bridged, while for the other years within the scenario, the gap is only 10 years (refer to section 4.2.2 for more details). It can also be concluded that the impact of weather change was notably lower than the impact of building renovation, as in the previous case studies. When both impacts are considered, variations in results between weather scenarios for the suggested renovation path were less than 2 % for the same year, even for the warmest climate considered (temperate -

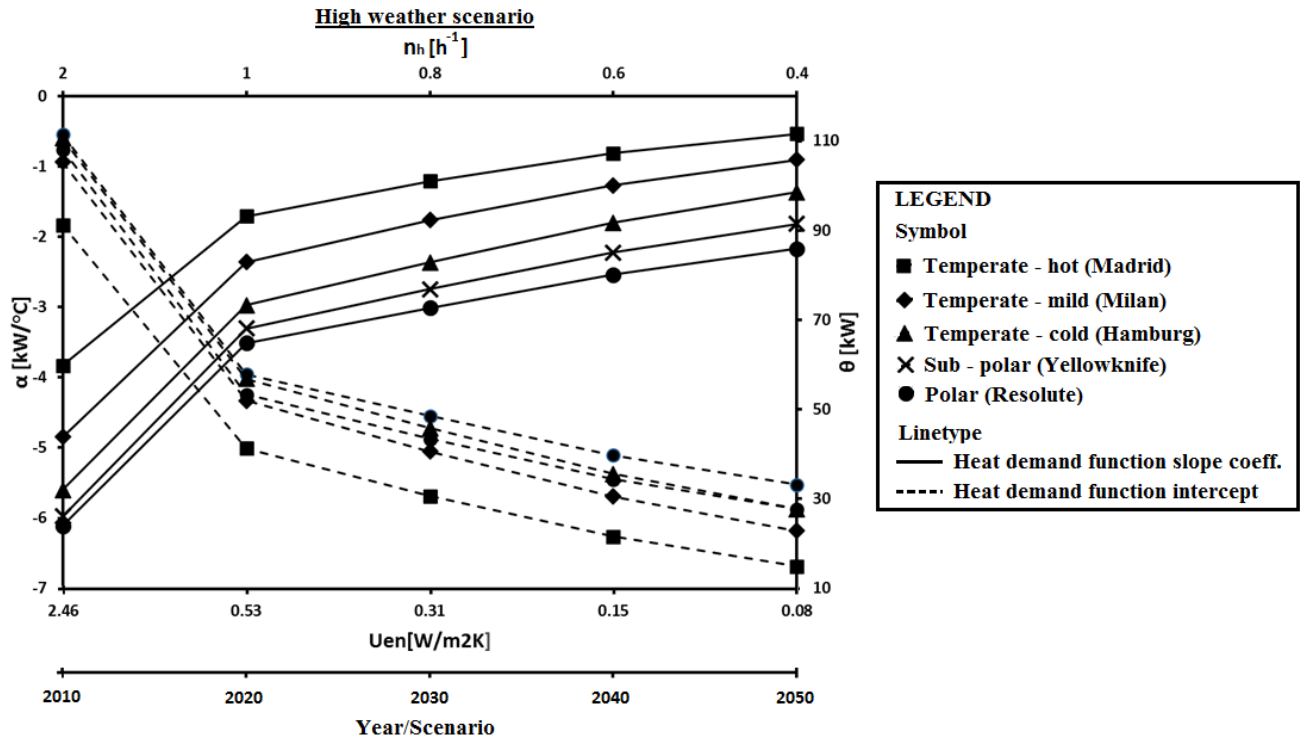
hot). Thus, for further comparisons, only results for a medium climate change scenario are used for analysis.



(a)



(b)



(c)

Figure 5.2 The direct and indirect impact of climate change on heat demand-outdoor temperature function parameters for selected locations ((a), (b), (c) – low, medium, high weather scenario (respectively));

The direct and indirect impacts of climate change on heat demand in terms of energy are given in Fig.5.3. Heat demand was significantly higher in polar and sub-polar climates for the reference year, considering the climate properties (low temperatures and solar radiation levels, please refer to Table 5.1) and building properties (please refer to section 5.2 of this thesis part and Table 5.3). In these two climates, with an average decrease in U_{en} value of $0.6 W/m^2K$ and air infiltration rate of $0.4 h^{-1}$, the annual heat demand decreased on average for 340 MWh and 225 MWh, respectively. For other climates considered and the same envelope improvements, decrease rates (per decade) in annual heat demand were 105 MWh (temperate-cold), 85 MWh (temperate-mild) and 67 MWh (temperate-hot). Compared to annual energy demand for heating in a reference year (before any renovation measures are conducted), the decrease rate after each previously mentioned average U_{en} and n_h improvement was ranging between 18 % and 21 % of the reference value, depending on the climate observed.

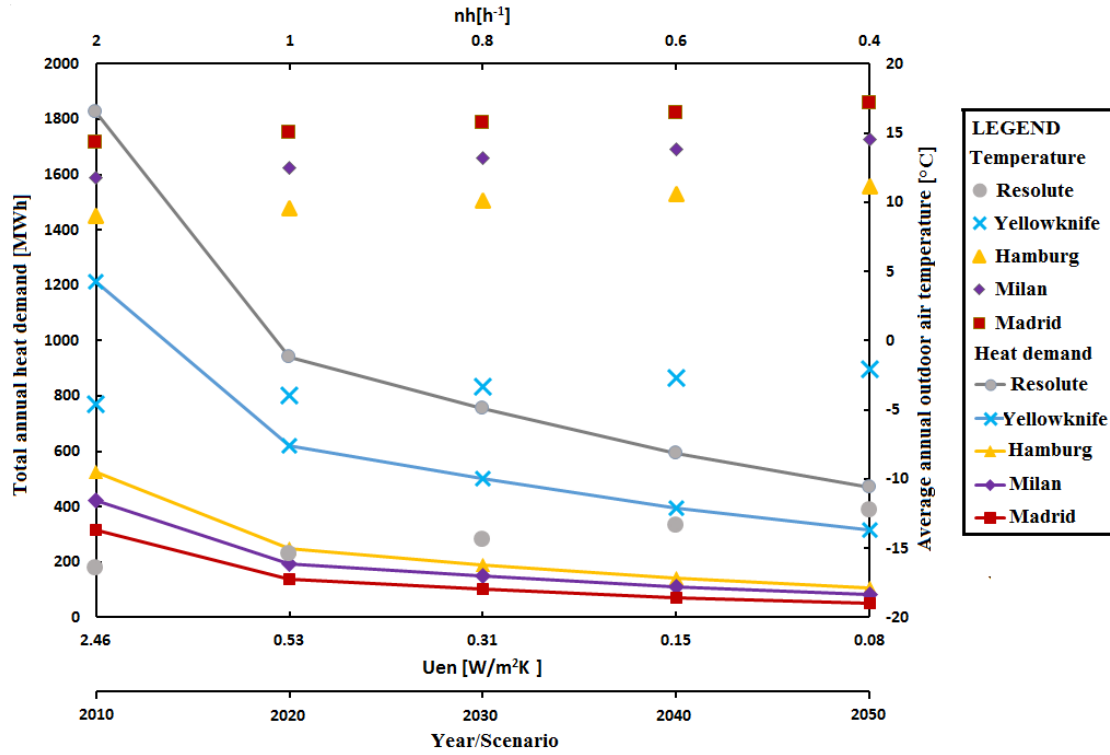
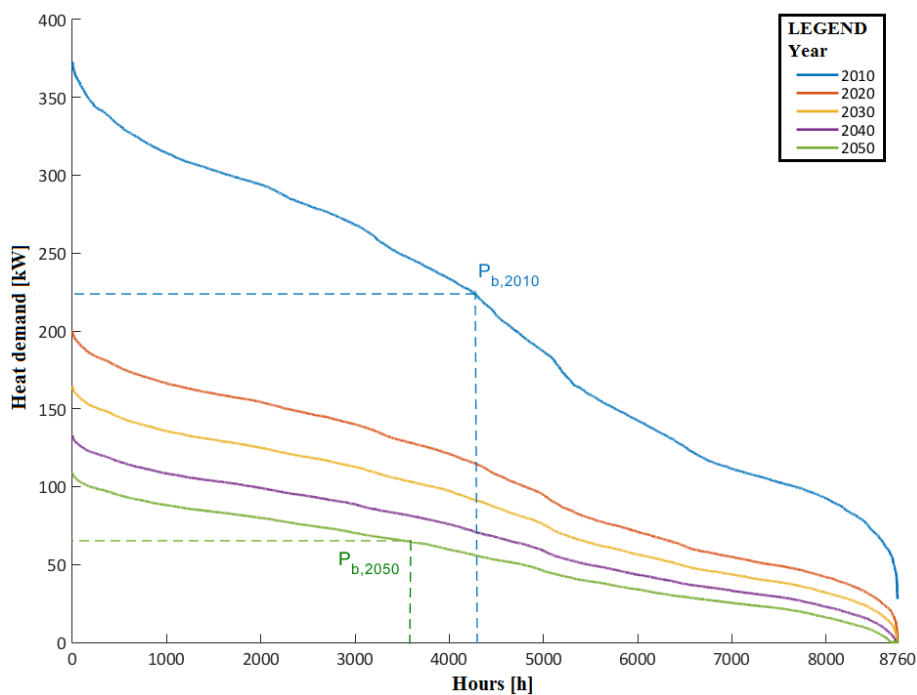


Figure 5.3 The direct and indirect impact of climate change on heat demand for selected locations, medium weather scenario and building renovation;

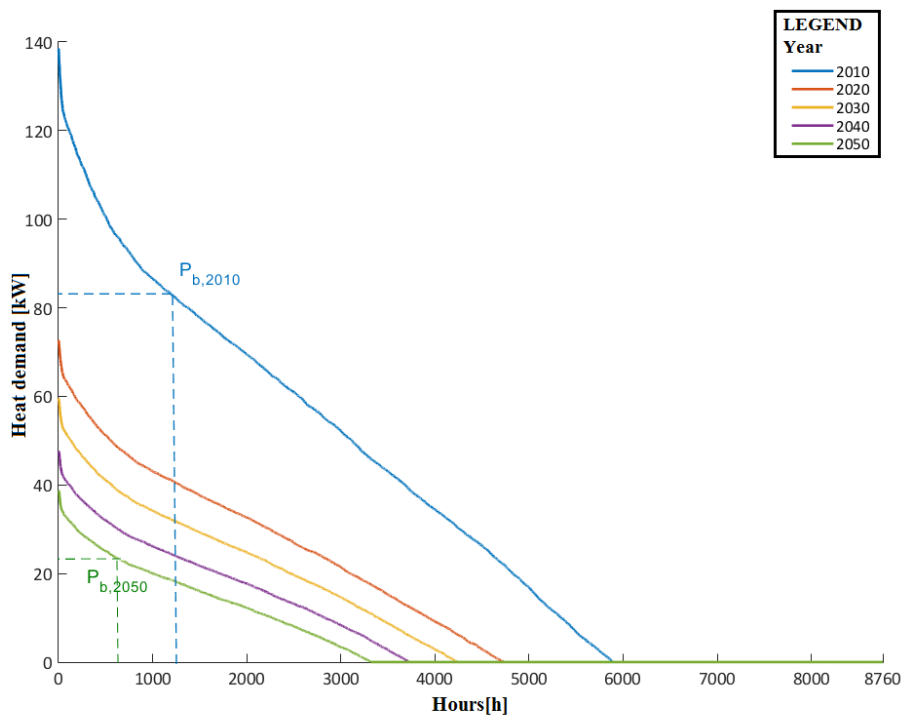
From the operational point of view, the impact on heat demand in different climate types may not be the same. For example, in warm climates, the decrease rate in the number of heating hours could be significantly higher compared to colder climates. To study the impact on operational parameters, load duration curves and number of heating hours were observed for the two most extreme climate types considered in this study: the coldest climate (polar, Resolute –Fig.5.4a) and the warmest one (temperate-hot, Madrid – Fig.5.4b). To evaluate the impact of climate type on heat demand profiles, medium weather scenario was used in combination with the renovation scenario previously described. From Fig.5.4, it can be seen that the base load, P_b , (chosen in this study as 60 % of the maximum load) in 2050 was 29 % and 28 % of the reference value (base load for reference weather and without any building renovation, i.e. in year 2010) for the Resolute and Madrid case, respectively. Thus, boilers designed for the reference heat demand would eventually run with significantly reduced capacity, which would lower their efficiency.

For a deeper insight, quartile analysis was applied on the number of heating hours for these two locations. From Fig.5.5, it is clear that the decrease rate in the number of hours with heat demand was significantly higher in temperate-hot climate (43 % decrease in 2050 compared to 2010) than in the polar climate (0.8 % decrease in 2050 compared to 2010).

Additionally, it can be observed in Fig.5.5a that in the polar climate 75 % of heating hours in 2010 had a heat demand lower than 80 % of the peak demand value.



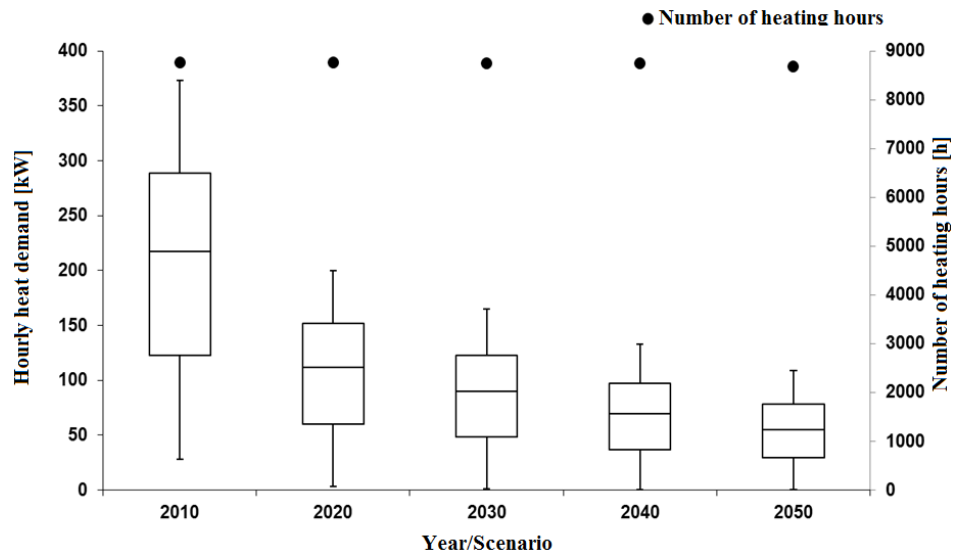
(a)



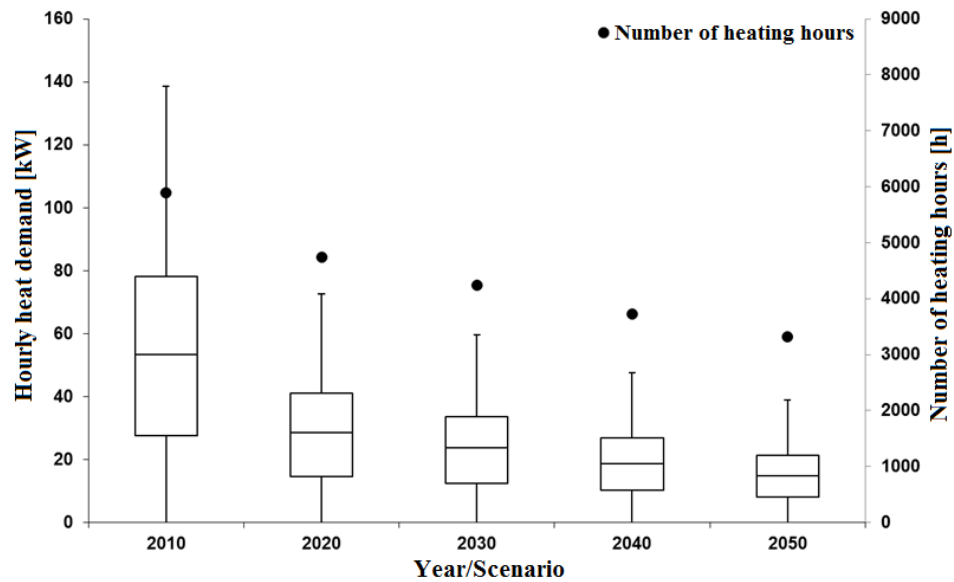
(b)

Figure 5.4 Load duration curves for Resolute (a) and Madrid (b), medium weather scenario and building renovation;

However, in 2050, for all heating hours, the demand was lower than 30 % of the peak demand for a reference year (i.e. peak demand in 2050 was lower than 30 % of the reference peak demand in 2010). Additionally, in this case, the lowest data distribution was within the third quartile. Considering the temperate-hot climate, heat demand was lower than 56 % of the peak value during 75 % of the heating hours in 2010. However, in 2050, the demand was just 15 % of the reference peak demand (peak in year 2010) for 75 % of heating hours. In this case, data distribution within quartiles was approximately equal.



(a)



(b)

Figure 5.5 The impact of climate type differences on heat demand decrease caused by the climate change (medium weather scenario and building renovation): (a) Resolute, (b) Madrid;

Considering that the internal comfort temperature that should be considered could vary depending on occupants' behavior, energy prices or guidelines for the thermal indoor climate, its impact on the annual heat demand was evaluated for these two locations. As such, internal comfort temperatures within the range of 19 °C-23 °C were considered with intervals of 1 °C. The results demonstrated that, with each 1 °C increase, the annual heat demand increased on average by 52 MWh and 37 MWh for the Resolute and Madrid case studies, respectively.

To conclude, for cold climates, if the heating system is designed based on the reference weather and building state, boilers could run with reduced capacity in the years to come, but during a similar number of hours. On the other hand, in warm climates, both capacity and duration could be significantly reduced, causing frequent stops in production and impacting the system efficiency on multiple levels. It should also be noted that the systems investment return period in colder climates is more sensible on heat demand reductions, especially for district heating systems, considering that the initial and operational investments are higher. In these climate conditions, systems usually require higher levels of insulation, more expensive pipe materials and deeper ground placement, along with more expensive labor costs in harsh conditions.

5.6 Conclusions

The main scope of this study was to evaluate the potential differences of the long-term impact of changed climate conditions (direct impact) and building renovation (indirect) on heat demand in the future in different climate types that are suitable for heating services. For each climate, characteristic locations were selected based on multiple criteria. In order to compare the results on a same basis, a characteristic building was modelled based on the data available for the European building stock, and heat demand was modeled by using a tool previously developed and validated by the authors. Three weather scenarios were developed for each location along with one building renovation scenario (based on the renovation measures market penetration rates).

The results indicated that when both impacts are considered, the variation in results between weather scenarios in the same year was lower than 2 %, even for the warmest climate considered (temperate - hot). The initial building renovation in 2020 resulted in a slope coefficient increase of 45 %-51 % and in an intercept decrease within the range of 48 %-51 % (depending on the weather scenario and location considered). The impact of further renovation measures was significantly lower, increasing the slope coefficient within the range of 7 %-10 % and decreasing the intercept by the same amount. However, even with a similar

decrease rate in heat demand (compared to the reference year), there was a discrepancy in the heating hours decrease trend within different climates. With an average decrease in U_n value of $0.6 \text{ W/m}^2\text{K}$ and air infiltration rate of 0.4 h^{-1} , heat demand decrease rate was ranging between 18 % and 21 % of the reference heat demand value, depending on the climate observed.

To evaluate the impact on operational parameters, changes in base load and the number of heating hours were observed for the two most extreme climates studied (polar and temperate-hot). The base load (chosen in this study as 60 % of the maximum load) in 2050 was 29 % and 28 % of the reference value (base load for reference weather and without any building renovation, i.e. in year 2010) for the Resolute and Madrid case, respectively. The change in the number of heating hours was almost negligible in the colder climate considered (polar, with a 0.8 % decrease in 2050 compared to 2010), while in the warmer climate (temperate-hot) the decrease rate was significant (43 %). Additionally, for the temperate-hot climate in 2050, for 75 % of the heating hours the demand was less than 15 % of the peak demand in the reference year (2010), while for the polar climate, for all heating hours in 2050, the demand was less than 30 % of the original peak demand (2010). This effect could impact heating systems efficiency on multiple levels (operational, financial, etc.) due to the fact that the heat production units would operate with a lower capacity and with frequent stops.

CHAPTER 6: CONCLUSIONS, PART I

The main scope of thesis Part I can be defined in two points:

- Develop a suitable methodology for evaluating the potential direct (changed weather variables) and indirect (building renovation) long term impacts of climate change on district heating systems;
- Draw the conclusions on the impacts of climate change on district heating systems relevant for the scientific community, industry and governmental bodies based on the methodology application on multiple case studies.

In order to do so, building heat demand should be evaluated and forecasted on a district scale (i.e. for large number of buildings) for the decades to come. Previous research efforts within the bibliography considered one of the three following approaches: representative building simulation studies, representative building simulation studies with in-country climate variations and large scale building simulations. After comparing the advantages and disadvantages of these approaches (from the point of view of calculation dynamics, time and computing power required, as well as the ability to account for climate change impacts), it was concluded that there is an existing need for a heat demand model, that is capable of dynamic heat demand calculations on a large scale (for a building stock on a neighborhood, city or possibly a country level), but without significant calculation time nor computing power required. Moreover, the model should be capable to account for different weather and building renovation scenarios, while editing the input weather data (for different climate types and weather scenarios), as well as building data (for building reference state and renovation scenarios) should not be a complicated and time-demanding process.

Thus, a model based on the thermo-electrical analogy was developed for this purpose, and used in combination with several other software and methods (CCWorldWeatherGen, ArcGIS, LiDAR) in order to develop the methodology for evaluating the climate change impacts on district heating systems. The heat demand model developed was verified through the comparison with Design Builder v4.6. (Energy Plus v.8.3) building energy demand simulation software and statistical heat demand data obtained from the national reports from governmental institutions of case study countries. The outcomes of the validation process were satisfactory, considering that the difference in calculated annual heat demand (for sample buildings) between the model developed and widely acknowledged Energy Plus software was

on average 4.5 %, while when compared with the statistical heat demand data (based on the building type and construction period) from two national agencies reports, the difference was 10 % and 8 %. In both cases, the margin of error was lower than the limit for the simplified models suggested within the bibliography (20 %). Third validation step with on-situ measured heat consumption data was planned in partnership with an industrial partner. However, during the required data collection process, the industrial partner faced multiple obstacles and unpredicted costs, and was not able to provide data with guaranteed accuracy during the thesis project duration. Thus, a comparison of model results with measured data remains one of the thesis project future development tasks, which are addressed at the end of this section. In order to identify the relevance of required model input data (and thus identify the focus of data collection process for future model applications), an elementary effect analysis was performed. The results indicated that the parameters with the highest impact on the final model output (building heat demand) were the building glazing ratio, air infiltration rate and the internal comfort set point temperature. Overall, the validation process indicated that the model and the methodology developed are suitable for the applications within the scope of this thesis.

In order to evaluate the direct (changed weather variables) and indirect (building renovation) impacts of climate change on district heating systems, the methodology developed was applied on two different districts (to account for potential differences between the climates). Several aspects of district heating systems were evaluated: heat demand related parameters such as heat density, heat demand – outdoor air function parameters, and techno-economic parameters. Moreover, an additional study was conducted in order to evaluate the potential impact differences between the various climate types suitable for heating services.

The first model application addressed the direct and indirect impacts of climate change on heat demand related parameters of district heating systems, such as district heat demand density and heat demand – outdoor air temperature function parameters. The study was conducted for a district of Alvalade, located in Lisbon, Portugal, consisted of 810 building that vary in both type (purpose) and construction period. However, non-heated buildings, such as garages and churches were excluded from the study, resulting in 665 buildings (residential, offices, hotels and educational buildings) considered in this study. Three weather scenarios (low, medium and high temperature increase) were developed for the future conditions, along with three building renovation scenarios (shallow, intermediate, deep renovation path). The calculation of Pearson's product-moment correlation between the building heat demand and outdoor air temperature proved the high linearity between these parameters, and the suitability of the heat demand – outdoor air temperature function to represent building heat demand

signature. However, when function parameters (slope and intercept) and forecasted outdoor air hourly temperature values were used to estimate heat demand (refer to eq. (3.33)) for future weather conditions (without considering potential building renovation), the error in annual heat demand estimation compared to dynamic calculations with the developed RC model was on average 12 %. However, when the renovation measures were taken into account the error was up to 60 % compared to the results from the RC model, due to the fact that the function is not able to account for building envelope modifications. Thus, function parameters should be recalculated for each year considered within the scenarios, for which the developed RC heat demand model that does not require significant time nor computing power proved to be useful. When the parameters were recalculated for each year, the results indicated that for the decrease in heating hours of 22 h-139 h (depending on the weather and renovation measure considered), the value of the slope coefficient increased within the range of 3.8 %-8.1 % per decade, while the value of the intercept decreased within the range of 7.8 %-12.7 % per decade. Additionally, the results showed that due to the weather change, district heat density could decrease in 2050 within the range of 6.7 %-37 % of the reference value (year 2010), depending on the weather scenario considered. When both weather and building renovation scenarios were considered, heat demand decreased for 22.3 %-52.4 % in 2050 (compared to 2010), depending on the combination of weather and renovation scenarios considered. Thus, it can be concluded that building renovation measures could impact the district heating systems on a larger scale compared to weather change. For the studied district, even in year 2050, the district still remained feasible for district heating services (heat demand density value higher than 50 Wh/km²/yr). However, it should be noted that the value of minimal heat density for district heating feasibility is based on current district heating technologies, limitations and pricing, and could consequently change in the decades to come.

The scope of the second methodology application was to evaluate the direct and indirect impacts of climate change on district heating systems techno-economic parameters. For this study, a generic district was created, based on the district of St. Felix, which is located in the city of Nantes (France). The district was selected due to the fact that it has a good representation of French national building stock (as concluded by comparing the district with reports that describe French national building stock). The district is residential and consists of 622 residential buildings that vary in construction period. In this case study, one (medium) weather scenario was used, considering that in the previous case study results indicated that building renovation measures have significantly higher impact on heat demand. New building renovation scenario was developed, which was based on the market penetration rates of building

envelope renovation measures. Moreover, the addition of thermal solar collectors was considered as an additional scenario (this scenario considers both envelope renovations and installation of solar collectors). Heat demand was calculated by using the developed RC model, while techno-economic parameters were calculated by using an in-house tool developed by the thesis industrial partner (Veolia). For the calculation of heat prices, two cases were considered: in the first case, the district heating system already exists within the district (thus capital investment costs for heat production units and the network infrastructure were not considered), while for the second case, it was assumed that district heating system is planned for construction. The results indicated that from the aspect of traditional district heating systems, linear heat demand density was below the profitability threshold value (4 MWh/ml) even after the first renovation measures (conducted in year 2020). However, it should be noted that the new generations of district heating systems could have a lower linear district heat density value. Moreover, in some countries, district heating systems are eligible for substantial subsidies (for example, in France, the subsidies are awarded for district heating project in areas with linear heat density higher than 1.5 MWh/ml). In this particular case study, linear heat density value was above 1.5 MWh/ml for all scenarios considered. Additionally, heat demand reduction had a significant impact on heat production fuel mix – in reference year 76 % of heat was produced by a base load biomass boiler, while in 2050, only 1 % of heat demand was covered by this source, and the rest (99 %) of demand was covered by a natural gas peak load boiler, since heat demand was far below the biomass boiler technical minimum. Consequently, the specific amount of CO₂ emitted per unit of heat produced increased about five times in 2050 compared to 2010 (261 kgCO₂/kWh compared to 45.4 kgCO₂/kWh respectively). This aspect is of utter importance for countries where incentives and subsidies for district heating system projects are assigned based on the participation of renewable energy sources in heat production (as in France for example). Moreover, study results indicated that heat prices would increase over the next two decades due to impacts of climate change discussed previously. This could result in disconnections of customers, considering that one of the main reasons (aside comfort) due to which customers decide to connect to heating systems in the first place are relatively stable heat prices. The results from a scenario which includes the installation of solar thermal collectors along with building envelope renovations, indicated that the annual heat production from solar collectors was sufficient to cover district heat demand after the first renovation step in 2020. However, on daily and seasonal basis, hourly heat production from the collectors do not always correspond to hourly heat demand. Thus, in order to enable efficient integration of decentralized solar systems in district heating systems, a sufficient heat storage should be installed as a part of the system.

Since the results from the previous applications indicated that the climate change impacts on heat demand could vary between different climate types, an additional study was conducted to evaluate the scale of this effect. Primarily, climate types suitable for heating services were defined, along with representative locations within each climate. The final selection included following climate types/locations: polar/Resolute, sub-polar (Yellowknife), temperate-cold (Hamburg), temperate-mild (Milan) and temperate-hot (Madrid). To compare the results on a same basis, a representative building was modeled and heat demand was simulated by using the developed RC model and weather and renovation scenarios for each climate. Thus, in this additional study, the scale considered was on a building level, considering that it would be difficult to create one representative district valid for all representative locations, due to the differences in building construction properties between the locations. Instead, to compare the results on a same basis (since the main scope is to evaluate the impact of climate differences), a representative building was created. As mentioned previously, building construction properties and materials used (and thus the thermal performance) could vary between the locations, but the impact of different thermal properties can be observed after the application of renovation scenarios (which change the envelope thermal performance) on such a single building (while on a district level, this impact would not be clearly visible since it is aggregated for all buildings within the district). Building renovation scenario based on renovation measures market penetration rates was used (as in the second (St. Felix) case study). The results indicated that although heat demand decrease rates (compared to a reference year) were similar in all locations studied, there was a discrepancy between the decrease rates in the number of heating hours. The decrease in heating hours is relevant from the operational aspect of district heating systems, since high decrease rates could cause frequent starts and stops in heat production, which would ultimately result in lower overall efficiency of the system. To further examine this effect, a quartile analysis was performed regarding the evolution of heating hours for the two most extreme climates studied – Resolute (polar) and temperate-hot (Madrid). The base load (assumed in this case to be 60 % of the maximum load) in 2050 was 29 % and 28 % of the reference value (base load in 2010) for Resolute and Madrid case, respectively. However, the heating hours decrease rate in polar climate was negligible (0.8 % decrease in 2050 compared to 2010), while in temperate-hot climate, decrease rate was significant (43 % in 2050 compared to 2010). Moreover, for the temperate-hot climate in 2050, during 75 % of heating hours the demand was less than 15 % of the peak demand in a reference year (2010), while for the polar climate, for all heating hours in 2050, the demand was less than 30 % of the original peak demand (2010). Thus, it can be concluded that in colder climates, due to the impacts of climate change, heat production units could operate during the similar number of

hours in the future, but with reduced capacity. On the other hand, in warmer climates, heat production units could operate during the reduced number of hours and with reduced capacity in the future. This effect could impact district heating systems on multiple levels, such as operational, financial etc.

Overall, the methodology developed proved to be suitable for the application within the scope of thesis Part I, i.e. the evaluation of climate change impacts on district heating systems. The model developed provides results with satisfactory precision (for simplified models), and does not require significant time nor computing power for long-term heat demand forecast on a district scale. The results from three model applications conducted within this thesis part provided an insight to the potential climate change impacts on district heating systems, and the differences in these impacts between the global climate types suitable for heating services. These results could help district heating operators and policy makers to adapt measures for the integration of such systems in global renewable energy transition.

Additionally, several steps can be suggested for further improvements of the approach developed in this thesis part. Comparison of the model simulation results with on-situ measurements would be a relevant contribution to the model validation process. The inclusion of cooling demand calculations would enable the evaluation of climate change impacts on total building energy demand in the future in climates suitable for cooling services (such as tropical and sub-tropical). The techno-economic model developed by the industrial partner could be improved to calculate heat production costs for periods longer than 20 years, which is the limit within the current model version. Moreover, integration of the model developed with other models could be expanded to include other operational district heating system models (that are able to account settings of supply and return network water temperatures), as well as further integrations with GIS software. This combination of models could result in methodology for identifying the future heat demand layouts and “hotspots” within the district, enabling the district heating operators an insight into the future requirements for supply and return temperature regimes within different distribution network segments.

PART II: THE ENVIRONMENTAL PERFORMANCE OF DISTRICT HEATING SYSTEMS

CHAPTER 7: LITERATURE SURVEY, PART II

While the focus of thesis Part I was to develop a dynamic heat demand model for the evaluation of long-term direct and indirect impacts of climate change on district heating systems, the main scope of thesis Part II is to develop a methodology in order to evaluate the environmental performance of district heating systems within the urban environment. Such environmental analysis of these systems could broaden the insight on the district heating potential in the future. An overview of the previous research efforts on this topic is presented within this thesis chapter. The scopes, methodologies used and the main conclusions of each study presented are discussed, along with the research gaps identified, that were the foundation for the methodology development within this thesis part.

7.1. Environmental performance assessment methods

In order to evaluate the environmental impact of complex systems (such as district heating systems) and/or services (such as heat delivered to the customer), all environmental impacts during the system/service lifetime should be considered. One of the methods that takes into account all environmental impacts associated with all the stages of a product's lifetime is the Life-cycle Assessment (LCA). LCA is a structured, comprehensive and internationally standardized method that quantifies all relevant emissions and sources consumed during the lifetime of a product/service, and consequent environmental and health impacts, along with the resource depletion issues (European Commission, 2010). LCA consists of four major phases (European Commission, 2010):

- **Scope definition** - describes the study scope and the expected outcomes, selected system boundaries and assumptions made based on the study scope;
- **Inventory creation** - within this phase, energy and raw material inputs and related environmental releases are quantified for each stage of the regarded system life-cycle;
- **Impact assessment** - assessment of the environmental releases (quantified within the previous phase) impacts on the human health and environment;
- **Interpretation of the results** - the final phase includes identification of relevant issues based on the impact results and evaluation of the study in regard of completeness, sensitivity and consistency checks, along with the identification of main conclusions, limitations of the study, as well as recommendations for further improvements.

LCA has been widely used in the literature to broaden the outlook on environmental impacts of various types of products and systems, such as heavy-duty trucks (Sen et al. 2017), iron and steel industry (Maden et al. 2015), food-bioenergy systems (Olmez et al. 2014), biofuels (Rocha et al. 2014) and various energy systems (for example, offshore wind power systems (Huang et al. 2017), concentrating solar systems (Lamnatou & Chemisana 2017) and sewage sludge incineration (Abuşoğlu et al. 2017)). One of the main advantages of LCA analysis is that it can be a solid basis for prioritization within the environmental improvement efforts of various organizations - an LCA analysis of their products or services can help to identify the most environmentally intensive processes. However, the LCA analysis is always a model-based representation of a real environmental impact. Thus, absolute impact of the regarded product or a service is beyond reach, as pointed out in the study of Guldbrandsson and Bergmark (2012). The authors also stated that the results of an LCA analysis are often valid only under the assumptions made for the selected case study, and have a substantial uncertainty, which has to be explored to a certain extent in order to fully understand the outcome of the analysis conducted.

Another environmental accounting method used to evaluate the environmental performance of complex systems and services is the emergy approach. The emergy concept is based on thermodynamics and was initially created by Howard T. Odum. The concept was introduced in the 1970s after more than two decades of research. Odum defined emergy of a product/service as *“the as the amount of equivalent exergies, directly or indirectly required, for their production and that takes the form of solar equivalent energy, denoted in sej (solar equivalent energy)”* (Odum, 1996). The unit of emergy is the emjoule. Solar emergy of a product/service is the emergy of the product/service expressed in the equivalent solar energy required to generate it (Brown and Ulgiati, 2004). The Unit Emery Value (UEV) is calculated based on the amount of emergy that is required to generate one unit of an output from a process. Thus, the lower UEV values indicate the lower emergy amount that was required to produce one unit of a service or a product. By using this concept, different types of energy and resources (for example sunlight, electricity and human labor) can be expressed in the same unit and thus compared on the same basis. Each type of energy is created by a certain transformation process in nature, and has a different ability to support work in both natural and human systems. This quality difference is a key concept of the emergy theory. Within the existing bibliography, emergy approach has been used for the environmental performance evaluation of various systems and services. Some examples are: livestock wastewater systems (Zhang et al. 2014), fish farm rearing (Vassallo et al. 2009), grain production systems (Wang et al., 2014), self-

sufficient villages (Listyawati et al. 2014), biogas-linked agricultural systems (Yang & Chen (2014)), biofuels production (Nimmanterdwong & Chalermssinsuwan, 2015), biodiesel production (Ju & Chen, (2011)), heat production (Jamali-Zghal et al. 2013), small hydropower plants (Pang et al. 2015), biogas systems (Wu et al. (2015) and Wang et. al (2014)) etc. The ability to compare various types of energy and resources on a same basis can be considered as one of the main advantages of the emergy approach. The approach has however been criticized for supposedly offering a form of energy theory of value in order to replace other theories of value (such as economic). However, considering that one of the scopes of emergy theory is to provide an ecocentric estimation of products and services, its purpose is not to replace the economic values, but rather provide complementary insight from another point of view.

The emergy approach has the same four major steps as the LCA (scope definition, inventory creation, impact assessment and result interpretation). The main difference between the concepts is that the LCA is more user-side oriented while the emergy is a more donor-side oriented accounting method. From a user-side perspective, the focus of the analysis is limited on the amount of resources directly consumed during the product/service lifetime, and these inputs are evaluated based on their user-side value (i.e. the amount of outputs the user is able to extract from inputs) and scarcity. On the other hand, a donor-side perspective accounts for all resources directly and indirectly provided by the nature to support a product/service, regardless in which period these inputs were provided, and independently of their user-side value (on the life-cycle scale). Further intercomparison between the two methods is provided within the paper of Raugei et al. (2012). The authors noted that the emergy accounting could be a valuable addition to LCA studies for assessing the environmental impacts.

7.2. The environmental performance district heating systems

The environmental impacts of district heating systems was addressed in multiple LCA studies, such as several studies conducted by the researchers from the Chalmers University of Technology. The first study tackled the environmental impact of network pipes production (Fröling & Svanström, 2004). Prefabricated polyurethane insulated district heating pipes were considered, consisted of a steel tube protected with a casing made of high-density polyethylene. Additionally, four different variations of these pipes were considered: a twin pipe (both return and supply pipe are within the same casing) with the dimension of DN25, and single pipes with the dimensions of DN25, DN100 and DN500. The authors concluded that the production of materials required for pipe assembly (especially steel, polyethylene, polyurethane and copper) was the major contribution (over 90 %) to the environmental impacts assessed (contribution to

the Global Warming Potential (GWP), acidification potential (AP), photo oxidant creation potential (POCP) and resource depletion (RD)). As a functional unit, 12 m pipe length was used in all cases, except for the DN500 pipe case, where the length of 16 m was considered. It was suggested that the pipe manufacturers could decrease the consumption of these resources to reduce the environmental impact of pipes produced. However, it was also noted that the impact of suggested changes on the environmental performance of the whole district heating system should be evaluated first, since it could have a negative overall impact. Namely, a reduction in pipe insulation thickness could increase the heat losses during the system operation phase, increasing the required heat production (and consequently fuel consumption), resulting in increased total environmental impact of the whole system. Moreover, reducing the protective casing thickness would increase the risk of water intrusion, potentially causing rapid pipe corrosion – as a consequence, damaged pipes would have to be replaced with new ones, which would increase the overall material input and negatively impact the environmental performance of the system. Additionally, water intrusion would also damage the foam insulation, which would again result in an increase of energy losses. Thus, the study provides an insight on the environmental impact of a certain element (supply and return pipes) of a large system (district heating system), but the results have a limited value until they are compared with the results for the whole system.

In the second study (Fröling & Svanström, 2005), the same group of authors considered solely network construction phase (thus without pipe and network elements production or network operation phase). The same types of pipes for the network infrastructure were considered as in the previous study (twin pipe DN25 and single pipes DN25, DN100 and DN500). Two environments were considered for network infrastructure placement: urban environment and green areas. As the authors stated, the main difference considered between these two cases is that in the urban environment, there is a need to break open and restore the asphalt cover, while also removing the excavated material from the site. On the other hand, it was assumed that the green areas are without an asphalt cover, and that a certain amount of excavated material can be left directly at the site for a potential future use. To assess the environmental impact, GWP, AP and POCP indicators were considered. As the functional unit, 100 m of the network (supply and return pipes) was used. The results indicated that the main strategy to reduce the impact from this phase could be to minimize the amount of excavation works, i.e. reduce the network trench dimensions (since this process resulted in highest environmental impact). However, the authors noted that there should be a limit in this reduction, in order to avoid affecting the working conditions of construction workers who perform the

network pipe placement and assembly. For example, significantly reduced trench dimensions could limit the ability of workers who are involved with pipe welding, foaming and muffing to comfortably approach the pipes, which could potentially reduce the quality of the manual operations performed. Reduced quality of these operations could result in shorter lifetime of the pipes placed, which would further require new excavation works and material input in order to replace the impaired pipes with the new ones. Concerning the two selected environments, the results indicated that the construction operations performed in an urban environment had a higher environmental impact, mostly due to the asphaltting procedure. When the authors compared the results of this study to the previous phase (pipe production) assessment results, they have concluded that for the larger pipe diameters, pipe production phase had a higher environmental impact compared to the network infrastructure placement phase. On the other hand, for the networks with smaller pipe diameters, the relevance of these two lifecycle phases was almost equal. As a suggested measure for the improvement of the environmental performance, co-utilization of trenches for the placement of different pipes and cables (for example heating pipes, waterlines, telephone and television cables etc.) was proposed by the authors.

In the third study by the authors (Persson et al. 2006), network operation phase was analyzed. The environmental impact from this phase was estimated based on the heat losses from the network (since in this case, district heating network has been addressed solely as the distribution system), which are the function of district heating pipes long-term performance. Thus, the environmental impact of district heating network as a distribution system was estimated based on the impacts of additional heat production required to cover these losses. Distribution heat losses were calculated for the pipe types considered within the previous two studies (twin pipe DN25 and single pipes DN25, DN100 and DN500). Two heat production options were considered – heat generation by utilizing the average (from year 2000) Swedish fuel mix (natural gas, coal, oil, waste heat and waste incineration, peat, geothermal heat pumps, electricity, biomass) and natural gas combustion. The functional unit used in the study was 100 m of district heating network over assumed 30-year lifetime. The environmental impact was assessed by analyzing the results in form of GWP, AP, POCP and RD. To draw the conclusions, results from the previous two studies were recalculated for the functional unit used in this study, in order to evaluate the impact in regard to the total environmental impact of all three phases considered in these studies (pipe production, network placement, network use as a distribution system). The authors concluded that the dominant phase in regard to the environmental impact depends on the type of the impact considered (GWP, AP, POCP or RD),

type of pipes used and the environment (urban or green) considered for network placement, as well as the type of fuel used for heat production. However, it was noted that the network use phase had the highest impact in most cases considered, indicating the importance of reducing the heat losses within the network. Considering that the second highest impact was caused by pipe production, the optimal solution for the system impact reduction would be a development of new district heating network types that have a low rate of heat losses, but do not require increased input of insulating materials that cause significant environmental impact.

In the previous three studies described, the authors evaluated the environmental impact of district heating systems with three life-cycle stages considered (pipe production, network (return and supply pipe) placement and the network use phase. However, within the use phase, the network was solely considered as a mean of heat distribution, without accounting for the environmental impact of heat production units and installations in buildings. It is usually considered that the complete district heating system consists of three main elements: heat production units/heat source (boiler in the heat plant or heat exchanger from the heat plant distribution pipe), distribution network, and required installations (i.e. substations) to connect the consumers (buildings) to the system, along with the heating installations in dwellings, without which the system cannot function purposefully. Thus, to evaluate the total performance of a district heating system, the environmental impact of all three main elements should be considered.

LCA of a modern four-pipe district heating network (ESPEX network type) was conducted in the paper of Perzon et al. (2007). The distribution network layout consist of a supply pipe, return pipe, domestic hot water distribution pipe and warm water recirculation pipe (used to recirculate a small amount of domestic hot water in order to maintain the required water temperature at the point of use (water taps)). Three life-cycle stages were considered (pipe production, network infrastructure placement and network use), without end-of life phase, since there is no known case of district heating system being dismantled described within the bibliography, even after several decades of operation. Heat source was considered in this study in a form of heat exchanger between the network and heat plant distribution pipe, as well as the installations for building connections (substations). As a case study, the only known application of ESPEX network was used – the network is used to provide heating services to the district of Vråen in the city of Värnamo, Sweden. As the functional unit, the use of 1m of network during the period of one year was considered (while the lifetime assumed was 30 years). The environmental impact was assessed through the use of GWP, AP, eutrophication potential (EP) and the use of finite resources. The authors concluded that the dominant environmental impact

was caused by the heat production required to cover heat losses within the network, despite the relatively high insulation levels of the ESPEX system (compared to the traditional two-pipe systems). Additionally, it was suggested that further environmental impact comparisons between the modern and traditional district heating networks should be performed in order to assess the environmental trade-off between the additional material use for thicker insulation levels and the heat loss reduction caused by such measures. Moreover, the authors did not consider the environmental impact of heat production units construction (but rather solely heat exchanger construction between the supply pipe from the heat plant and the network considered), since the heat plant and heat production units were assumed to be outside the system boundary. The environmental impact of dwelling heating installations was also not considered.

The environmental impact of district heating infrastructure in urban environment was also addressed in the study conducted by Oliver-Solà et al. (2009a). System infrastructure was divided into three system scales: neighborhood (heat plant, distribution network, its components and related construction operations), buildings (service pipes and components) and dwellings (system components within the dwellings). In this study, the functional unit used was the neighborhood infrastructure that serves to provide heating services to 240 dwellings for the total duration of 50 years. The impact categories considered were the GWP, AP, EP, human toxicity potential (HTP), ozone layer depletion potential (ODP) and abiotic depletion potential (ADP). The results indicated that the neighborhood system (heat plant, distribution network and its components and related construction operations) was the main contributor in most of the impact categories assessed (EP, GWP, ODP and ADP). The suggestions for the improvement of the system environmental performance were similar as the ones suggested by Persson et al. (2006): reduction of trench construction works by utilizing the same trench for multiple systems and cables (district heating system, water supply system, communication cables etc.), and potential reduction of heat losses without necessarily increasing the material input.

Within the previous studies described, LCA was used to estimate the environmental impact of district heating systems. However, different types of district heating system were considered as case studies, and on different scales – while some studies considered solely the distribution part of the district heating system, other included other relevant elements of such systems, such as heat production units and installations within the buildings (and dwellings), without which the system cannot function purposefully. Moreover, different functional units were used as a basis on which the impact was assessed, which makes the comparison between these different systems on a same basis rather difficult. Additionally, by using the LCA analysis,

various others forms of energy (such as human labor for example) and indirect inputs used during the system lifetime were overlooked. Thus, it seems that the environmental assessment by using the emergy approach would broaden the insight on the total environmental impact of the whole district heating system during all life-cycle phases. Additionally, by expressing all inputs in the same unit (solar emjoule), it would be possible to compare the environmental performance of different types of district heating systems (such as traditional two-pipe and ESPEX system for example) and other systems suitable for providing heating services to the urban environment (such as natural gas distribution network with individual boiler in each dwelling) on a same basis. Moreover, different heat production sources should be considered and compared (boilers on different fuel types, solar plant etc.). However, up to the best knowledge of the author, there was no existing emergy analysis of district heating systems within the bibliography, which presents one of the research gaps that will be addressed in this part of thesis.

However, in order to evaluate the environmental performance of district heating systems within the urban environment, the contribution of such systems to the total environmental impact of urban environment (that is a user of heating services provided by these systems) should be assessed. For example, if a certain building is a user of heating services provided by the system, it would be of interest to see to which extent the heat used from the system has an effect on the building environmental performance over its life-cycle. Thus, in order to adequately evaluate the environmental performance of district heating systems in urban environment, the environmental impact of connected building(s) during its life-cycle should also be evaluated.

7.3 The environmental performance of building during its life-cycle

Research on the topic of building life-cycle assessment gained momentum within the last two decades. Geng et al. (2017) provided an insight on the volume of publications that addressed this topic, by using bibliometric analysis. The authors found that within the 2000-2014 period, 2025 papers related to building LCA analysis were published, out of which 95 % were published in journals. The analysis also revealed that the topic of building environmental impact gained a rapid growth over the period of last 15 years. It was also noted that the most frequently covered topics within this research field were related to energy, material use, carbon emissions, sustainability and life cycle costs.

Cabeza et al. (2014) reviewed the studies available within the bibliography that addressed the life-cycle assessment and life-cycle energy analysis of buildings. The authors

found that the case studies previously found within the literature were difficult to compare, due to the specific properties of each case study, such as climate, comfort requirements, local regulations etc. Considering the scopes of the studies, while some studies focused solely on the material use for the building construction, other studies also considered the inputs required for building operation. Moreover, functional unit selected was not clearly mentioned in all studies, especially in the cases where the life-cycle impacts over the whole building lifetime were evaluated. Since there is currently no agreement on the functional unit to be used, the comparison between different studies was even more difficult. As for the lengths of building lifetime considered, most of the authors assumed a 50-year lifetime (50 % of the papers within the existing bibliography), while other lifetime lengths were more sparingly used (19 % assumed 40 years and 9 % considered 80 or 100 years). It was also noted that the studies that considered the whole building (rather than just elements) accounted for three life-cycle phases: construction, operation (use) and demolition. It was also found that almost all studies clearly presented type and location of the building studied, since in most studies, existing buildings were considered. Finally, it was pointed out that most of case studies selected were located in the United States or Western Europe. Thus, further case studies should be preferably located in other regions, in order to broaden the insights of building environmental impacts in different regions.

Several studies from the available bibliography that the author found to be related to certain extent to the thesis Part II are reviewed within the following paragraphs. Chang et al. (2013) studied life cycle energy of both urban and rural residential buildings in China, assuming a 50-year lifetime. Three building life-cycle phases were considered: construction, operation and demolition. The environmental impact was expressed through the energy intensity in kg of coal equivalent per m² of the building. The results of the study indicated that the energy intensity of urban residential buildings was 20 % higher than for rural residential buildings (or even 81 % higher if the biomass energy is excluded from consideration), due to the different construction materials and techniques used, as well as living standards and occupational habits. Additionally, life-cycle energy use of rural residential buildings was found to be more coal dependent, as a consequence of overwhelming use of coal for heating services in rural areas where district heating systems are not available. The authors concluded that the life-cycle energy use of urban residential buildings is highly affected by the operational energy (excluding the energy used for heating which was observed as a separate category). The second most important life-cycle category was found to be the energy intensity of heating services. It was noted that in the case that building operation energy intensity in China develops the same trend

in the future as the neighboring Japan (rapid increase caused by the increase in living standards and comfort levels), the operational phase energy intensity would increase dramatically, significantly affecting the overall life-cycle energy intensity. As a potential measure to alleviate this effect and reduce the energy intensity in the future, the authors proposed cultivation of awareness about the energy use and efficiency among the building occupants, along with energy saving behaviors and practices. Moreover, it was noted that building envelope refurbishments and the installation of renewable energy systems could also significantly reduce the intensity of the building operation phase. However, the impacts of building renovation measures were not further explored in this study.

Ortiz et al. (2009) conducted an LCA analysis for a typical two-storey semi-detached Mediterranean house located in Barcelona, Spain. Building life-cycle was divided into four phases: pre-construction of the required elements, their transportation to the construction site, building operation (use) with building maintenance (renovation included). Building lifetime assumed was 50 years, and the function unit used to express the impacts was a m^2 of building usable area with a suggested 50-year lifespan and four occupants. The research concluded that over the whole life-cycle considered, building operation (use) phase had the most critical environmental impact due to the high level of environmental burden emitted into the atmosphere (in terms of kgCO_2 -equivalent, 90.5 % of emissions occurred during the operation phase). The environmental impact during this phase was caused by the environmental loads from energy consumed for heating, ventilation and air-conditioning, lightning, electrical appliances and cooking. The authors suggested that the appropriate combination of construction measures (the use of less environmentally intensive resources and materials) and more environmentally friendly behavior of the occupants could both reduce the building environmental impact and improve the decision-making process for the construction industry. Additionally, it was noted that the application of approaches that take into account resource and material consumption over the building lifetime is relevant in identifying the opportunities to improve the sustainability of built environment. However, end-of-life phase was not taken into account within this study, which authors stated as one of their future projects.

Bastos et al. (2014) addressed the environmental impact of three multi-apartment building types from Lisbon residential area, taking into account construction, operation and renovation phases. The expected lifetime for these buildings was assumed to be 75 years, and two functional units were used to express the impacts: per m^2 of building floor area per year and per inhabitant per year. The authors concluded that for the buildings studied, operation (use) phase was dominant, accounting for 69 %-83 % of energy requirements and greenhouse

gas emissions over the considered lifetime. The results also indicated the importance of functional unit selection when multiple building types are compared. For example, larger buildings in the study had higher energy and greenhouse gasses emission per person, which was lower when they were expressed per person. The author also recommended the use of primary energy to quantify the building resource requirements during its lifetime. Moreover, it was noted that further studies are needed to account for different climatic and socio-economic aspects between the European countries. However, building demolition and potential recycling were out of the boundaries of the study conducted.

Van Ooteghem & Xu (2012) studied five single-storey retail buildings located in Toronto (Canada), with different structural properties (i.e. materials used), in terms of life-cycle primary energy use and GWP. The authors selected this building type as a case study since they found that the previous studies have neglected to consider the environmental impact of such buildings, leaving the understanding of the building environmental impacts in North America incomplete (according to the authors). Three phases were considered during the assumed 50-year lifespan: pre-occupancy phase (i.e. construction phase), occupancy phase (operational phase) and post-occupancy phase (demolition and recycling/landfilling). The results showed that the operating phase energy consumption and GWP are responsible for about 90 % of the total energy consumption and GWP during the considered lifetime (50 years). Consequently, it was concluded that measures that influenced directly or indirectly energy use reductions within the building operational phase are the best strategy for reducing the total environmental impact.

Compared to LCA building analysis, building energy analysis is nascent, but has started to gain momentum in the last couple of years. Moreover, building energy analysis could be a promising decision-making tool in sustainable buildings design in the future (Yi & Braham 2015). Additionally, as stated in the paper of Yi et al. (2017), building energy analysis could further grow in the future, especially with the appearance of net-zero energy buildings designs, due to the ability of the approach to evaluate indirectly embodied environmental cost invested in order to produce resources for renewable energy production. Several energy methodology applications available within the bibliography are described within the following paragraphs.

Meillaud et al. (2005) studied an academic building (Solar Energy Laboratory) located in Lausanne, Switzerland, considering that the building produces scientific information disseminated via services, publications, courses and students as the main output. Building lifetime was assumed to be 80 years, with two phases considered: building construction and operation. The results indicated that the most important input (from an energy point of view)

were the information brought by faculty and students, along with the inputs obtained outside the information sources. It was noted by the authors that the emergy approach was the most appropriate methodology to evaluate such system, since there was a possibility to include additional flows in evaluation, such as monetary and information flows.

Pulselli et al. (2007) performed an emergy analysis for a 10,000 m³ residential building located in Italy, considering a lifetime of 50 years and three phases: construction, operation and maintenance (corrections in building damaged structure, without the improvement of building thermal performance). The results indicated that in the case where the emergy flows were expressed on an annual basis, about 49 % of total emergy flow was caused by the building construction, while 35 % and 15 % were caused by the building maintenance and operation (respectively). Additionally, the authors noted that different scenarios for façade thermal insulation and energy system augmentation could be compared to determine potential reductions in emergy investments (and thus improvements in environmental performance).

Amponsah et al. (2012) evaluated the impact of building material recycle/reuse on selected emergy ratios (emergy yield ratio and emergy loading ratio). As a case study, a residential building located in France, with an overall net area (living space and garage) of 155 m² was studied. Since the focus of the study was on building material recycling, solely construction and recycling phases were considered. The authors found that investing in building waste management leads to lower environmental stress (that is largely dependent on the input materials from renewable, non-renewable or purchased resources), and that a good balancing of these resources would enhance the building sustainability.

Reza et al. (2013) conducted an emergy-based life-cycle assessment of a multi-apartment and single-family residential buildings in Canada, assuming a 60-year building lifetime. Four phases were considered over the building lifetime: manufacturing of the elements, building construction, maintenance and operation, and end-of-life. As the main performance indicator, total emergy over the lifetime per m² of building area was used. According to the study, multi-apartment building proved to be more resource demanding regarding non-renewable mineral and fuel consumption, while the single-family house was considerably more demanding regarding the slowly renewable natural resources (due to the further land use or the loss of soil organic matter during the construction phase). Additionally, it was found that a multi-apartment building causes higher upstream, downstream and socio-economic impacts during its lifetime. Finally, the authors suggested that the emergy-based life-cycle assessment offers a practical and suitable tool for sustainability-driven decision-making.

Sustainability evaluation of a net-zero energy building through the emergy theory application was conducted by Yi et al. (2017). As a case study, a net-zero energy residential building located in South Korea was used, and compared with the results for a similarly sized non-net zero energy building (a single-family house in the suburb of Philadelphia, United States) addressed in the previous study (Yi & Braham, 2015) of the authors. Two life-cycle phases were considered (construction and operation), but the different lifespan of each building element was considered. The authors concluded that trade-offs occur between the energy performance and material inputs – in order to reduce the energy consumption, higher amounts of materials were used. However, even with this additional material input for the net-zero energy building, the building was more sustainable on a long term basis than the non-net-zero energy building.

7.4. Preliminary conclusions from the literature survey

An overview of the studies addressed within the literature survey (of thesis Part II) that evaluated the environmental impacts of district heating systems is presented in Table 7.1. As it can be observed, all studies used the LCA approach, and most of the studies focused on the traditional two-pipe district heating systems (one supply and one return pipe). These studies however took into account potential in-variations within this network type, such as pipe placement within the insulation casing (supply and return pipe in separate or within the same insulation casing) and different pipe diameters. One study considered one of the emerging modern types of district heating systems (an ESPEX four-pipe system), but provided only a rough environmental impacts comparison of such a system with a traditional two-pipe system. Moreover, it is commonly considered that the district heating systems consist of three main elements: heat production units, distribution network and installations required to connect consumers to the network and provide heating services (building substations and heating systems within the dwelling). Most of the studies focused on the distribution side, considering only heat distribution network within the system boundaries, and partially taking into account heat production aspect by considering heat losses in the distribution network. However, one study accounted for all three major elements (production, distribution, consumer connection), but focused solely on a traditional two-pipe district heating system. Additionally, in each study, only one type of heat source was considered, and the performance of district heating systems was not compared with competitive technologies for providing heating services to urban environments (such as natural gas distribution network with individual boiler in each dwelling).

Moreover, all studies conducted an LCA analysis, and were not able to account for additional indirect inputs (such as human labor for example). Up to the conclusion of this thesis, there was no existing energy analysis of district heating systems within the bibliography (to the best knowledge of the author). Thus, it seems that the application of energy analysis on several types of district heating systems (traditional and emerging ones), that takes into account all three main elements of the system (production, distribution, consumer connection and service precision) could broaden the insight on the environmental performance of district heating systems within the urban environment. Moreover, the environmental performance of such a system should be compared with a competitive technology for providing the urban environment with heating services.

However, to fully evaluate the performance of district heating systems within the urban environment, it should be explored to which extent the heat consumed from the system affects the environmental performance of urban environment: In order to [do](#) so, the environmental performance of buildings (which are main consumers of district heat within the urban environment) over their lifetime should be evaluated. An overview of the studies that addressed building environmental performance is provided in Table 7.2. Considering that more than 2000 studies on LCA evaluation of building environmental impacts exist within the bibliography, in this literature survey the focus was on studies for which the author found to have the most similar scope in regard to the scope of thesis Part II. On the other hand, building energy analysis is nascent compared to the building LCA analysis, with significantly lower number of publications, which were also addressed in this literature survey.

As it can be observed from Table 7.2, most of the studies focused on building construction and operation phase, considering building end-of-life phase and potential envelope renovation (thermal performance improvements) outside the system boundary. While most of the studies found the building operation phase to be dominant in term of environmental impact (especially due to the energy used for heating), the potential effect of different district heating options (network type, heat production source) on building environmental performance was not explored, nor compared with other competitive systems (such as natural gas networks). Additionally, for the complete evaluation of such environmental performance, renovation and end-of-life (demolition, material sorting, landfilling and/or recycling) phases should also be considered. Evaluating the effect of building envelope renovations could be of particular interest: improving building thermal performance would reduce the heat consumption from the district heating system (and thus reduce the contribution of heat consumed from the system to the overall building environmental impact), but could increase the total building environmental

Table 7.1 Overview of the studies on the environmental impacts of district heating systems;

Study	Method	System considered	Heat production side		Network infrastructure		Consumer side	
			Heat production	Network losses	Pipes	Placement	Building subsystem	Dwelling subsystem
Fröling & Svanström (2004)	LCA	Traditional two-pipe			✓			
Fröling & Svanström, (2005)	LCA	Traditional two-pipe			✓	✓		
Persson et al. (2006)	LCA	Traditional two-pipe		✓	✓	✓		
Perzon et al. (2007)	LCA	ESPEX four-pipe		✓	✓	✓		
Oliver-Solà et al. (2009a)	LCA	Traditional two-pipe	✓	✓	✓	✓	✓	✓

Table 7.2 Overview of the studies on the building environmental performance addressed within the literature survey;

Study	Method	Building type	Case study location	Lifetime considered	Life-cycle phases considered			
					Construction	Operation & maintenance	Renovation*	End-of-life
Chang et al. (2013)	LCA	Residential	China	50	✓	✓		✓
Ortiz et al. (2009)	LCA	Residential	Spain	50	✓	✓	✓	
Bastos et al. (2014)	LCA	Residential	Portugal	75	✓	✓	✓	
Van Ooteghem & Xu (2012)	LCA	Commercial	Canada	50	✓	✓		✓
Meillaud et al. (2005)	Emergy	Educational	Switzerland	80	✓	✓		
Pulselli et al. (2007)	Emergy	Residential	Italy	50	✓	✓		
Amponsah et al. (2012)	Emergy	Residential	France	-	✓			✓
Reza et al. (2013)	Emergy	Residential	Canada	60	✓	✓		✓
Yi et al. (2017)	Emergy	Residential	S. Korea	Varies**	✓	✓		

*Without the improvements in building thermal performance; **Different lifetime for each element was considered;

impact (due to the use of additional materials and services during the renovation phase). Thus, to conclude, based on the bibliography survey conducted, there seems to be an existing need for an emergy methodology for the evaluation of environmental performance of district heating systems in urban environment, that is able to account for different types of district heating systems. Additionally, the methodology should also be able to account for the environmental performance of buildings connected to the district heating system, in order to assess to which extent the heat consumed from district heating systems contributes to the environmental performance of buildings. All phases during the building life-cycle should be taken into account (construction, operation & maintenance, renovation and end-of-life (demolition, sorting and landfilling/recycling)). Moreover, different types of district heating systems should be considered, along with competitive technologies for providing the urban environment with heating services. Several heat production options for district heating systems should also be considered, along with multiple building renovation scenarios, considering that they can vary depending on the location. For the same reason, the effect of changed heat demand on the final result should be evaluated.

CHAPTER 8: METHODOLOGY, PART II

In this chapter, the methodology developed in order to evaluate the environmental performance of district heating systems within the urban environment is presented. As mentioned in the previous chapter, in order to do so, the environmental performance of district heating systems should be primarily evaluated. Moreover, the environmental performance of such systems should be compared with competitive technologies for providing the urban environment with heating services (such as natural gas distribution network with individual boiler in each dwelling, for example). Thus, a general emergy methodology for the environmental performance evaluation of urban heating systems has been developed (that takes into account all major components of such systems: heat production units, distribution network and building and dwelling installations), and it is presented within the first part of this chapter.

Additionally, in order to fully evaluate the performance of district heating systems in urban environment, it should be estimated to which extent the heat consumed from the system affects the environmental performance of the consumer (i.e. buildings connected). Considering that the number of buildings connected to the system can vary within the district, and that by utilizing emergy analysis it is possible to express the amount of resources used per unit of service delivered (in this case, resources directly and indirectly consumed to deliver one J of heat to the customer), the impact can be evaluated on a sample of a single building connected to the system (based on the regarded building heat demand). Thus, an emergy methodology for the building environmental performance analysis was developed, that takes into account all major building life-cycle phases (construction, operation (where heating is included) and maintenance, renovation, end-of-life) , and it is presented within the second part of this chapter. However, the methodology can be also applied on a district level, by calculating the emergy footprint of each building within the district with the equations developed.

8.1 The environmental performance of urban heating systems

8.1.1 Urban heating system outline and life-cycle phases definition

In order to enable the comparison between the different systems suitable for providing the urban environment with heating services, a general system outline was adopted, with all major elements of the construction phase and processes within the operation phase presented

on Fig. 8.1, while the resource allocation is presented on the emergy diagram (Fig. 8.2). For the emergy analysis, two main phases were considered:

- **System construction** – initial construction of the system infrastructure and different elements required for its operation during the lifetime, that can be divided into:
 - ❖ **Heat source (heat production unit)** – boilers and required elements for heat distribution network connection;
 - ❖ **Network infrastructure** – network distribution pipes, additional insulation casing (for newer systems) and additional elements (surface boxes, taps, pumps etc);
 - ❖ **Building and dwelling subsystem** – installations for connection to the distribution network, substation (in the case of indirect connection), and building heating system elements (heat exchangers, measuring and safety equipment, etc.);

Transportation of the materials and human labor required for the system construction were taken into account during the system construction phase. It should be noted that the human labor is calculated for the construction phase as a whole (rather than for each subsystem).

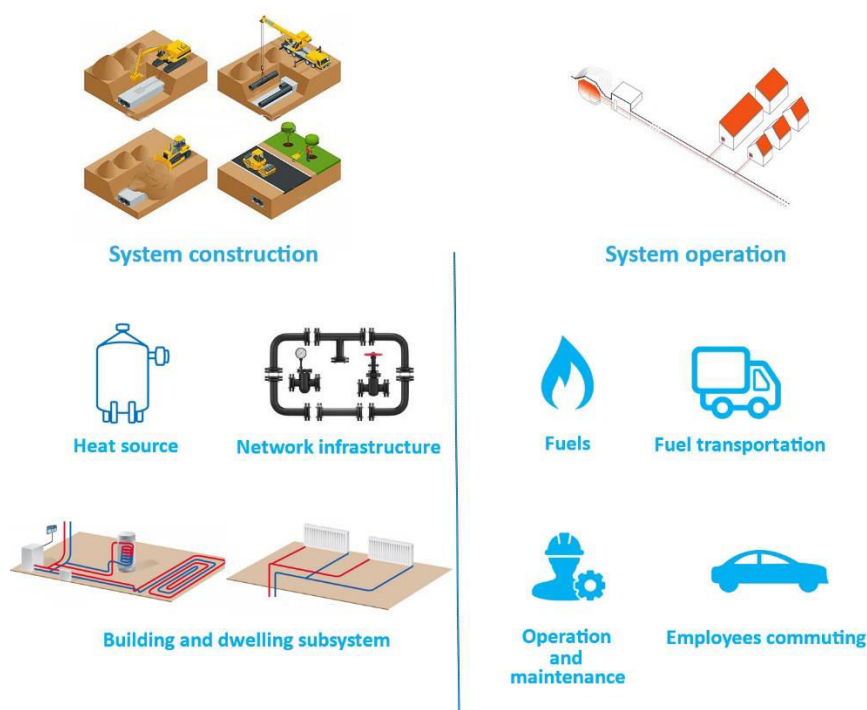


Figure 8.1 Outline of the urban heating system;

- **System operation** – this phase accounts for the use of resources and processes required for system operation over the life-cycle:

- ❖ **Fuels** - used in heat production units (fossil such as natural gas, light oil fuel, or renewable (such as biomass or solar energy in the case of the solar heat plant));
- ❖ **Fuel transportation** – transportation of the fuels combusted in heat production units (for example transportation of liquid fuels in tank trucks, or supply of natural gas via regional distribution network);
- ❖ **Human labor** - required for the system operation and maintenance (operation of the network at the control center and dispatch teams required for resolving network failures within the urban environment);
- ❖ **Employees commuting** - daily home-to-work commuting by the employees;

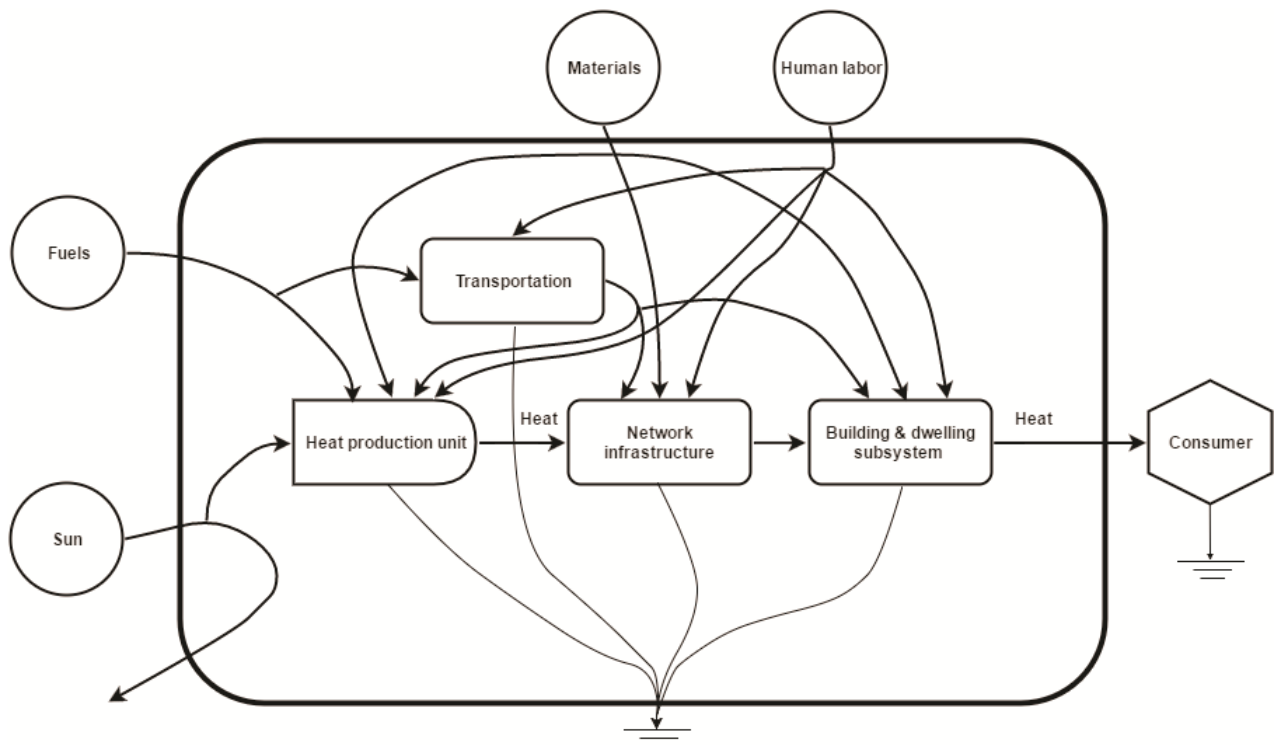


Figure 8.2 Urban heating system energy diagram;

The end-of-life phase was not considered, since there is no known case within the bibliography (to the best knowledge of the author) of such a system being dismantled, even after several decades of operation.

8.1.2 Emergy flow of urban heating system construction phase

The emergy flow of system construction can be divided into construction of three main subsystems (including materials, energy and any necessary transport) and human labor required for the construction, as shown in eq. (8.1). $E_{c,s}$ [sej] is the total emergy flow of system construction, $E_{c,hs}$ [sej] is the emergy flow of heat production unit construction, $E_{c,ni}$ [sej] is

the emergy flow of network infrastructure placement, $E_{c,bs}$ [sej] is the emergy flow of building and dwelling subsystem construction, while $E_{c,hl}$ [sej] is the emergy flow of required human labor for the construction of each system component and final assembly.

$$E_{c,s} = E_{c,hs} + E_{c,ni} + E_{c,bs} + E_{c,hl} \quad (8.1)$$

8.1.2.1 Emergy flow of heat production unit construction

The emergy flow of heat production unit construction can be calculated as:

$$E_{c,hs} = E_{hs} + E_{hs,t} \quad (8.2)$$

where E_{hs} [sej] stands for the emergy flow of heat production unit materials and assembly, while $E_{hs,t}$ [sej] accounts for the heat production unit material transportation. E_{hs} can be expressed as:

$$E_{hs} = \sum_{i=1}^n m_{hsm,i} \cdot U_{hsm,i} + \sum_{j=1}^l q_{hsr,j} \cdot U_{hsr,j} \quad (8.3)$$

where $m_{hsm,i}$ [kg] is the amount of i -th type of material (of total n number of materials) used for the heat production unit construction and $U_{hsm,i}$ [sej/kg] is the UEV of the corresponding material; $q_{hsr,j}$ [J] is the amount of j -th additional energy resource (of l total number of used energy resources - electricity for example) used for the assembly and $U_{hsr,j}$ [sej/J] is the according UEV. The emergy flow of heat production unit material transportation to the assembly location $E_{hs,t}$ [sej] is calculated through the equation developed previously in the paper of Jamali-Zghal et al. (2013):

$$E_{hs,t} = ND_{hs,t} \cdot D_{hs,t} \cdot LHV_d \cdot U_d \cdot FC_{hs,fl} \cdot (1 + \gamma_{hs}) \quad (8.4)$$

where $ND_{hs,t}$ [del.] is the number of deliveries, $D_{hs,t}$ [km] is the transportation distance during one delivery, LHV_d [J/l] is the low heating value of diesel fuel used in internal combustion engines, U_d [sej/J] is the diesel fuel UEV, $FC_{hs,fl}$ [l/km] is the truck (or other transportation vehicle considered) fuel consumption with full load while γ_{hs} [-] is the transportation vehicle fuel consumption ratio.

$$ND_{hs,t} = \frac{\sum_{i=1}^n m_{hsm,i}}{C_{hs,max}} \quad (8.5)$$

$$\gamma_{hs} = \frac{FC_{hs,wl}}{FC_{hs,fl}} \quad (8.6)$$

$C_{hs,max}$ [kg] is the transportation vehicle maximum capacity, while $FC_{hs,wl}$ [l/km] represents the transportation vehicle fuel consumption without a load.

8.1.2.2 Emergy flow of the network infrastructure placement

The main parts of network infrastructure are the pipes and additional network elements (surface boxes, markers, pumps etc.). Pipes are placed inside the excavated trench, which is later covered with certain amount of excavated ground (usually 20 %) and additional covering materials (usually sand, 80 %), as explained in the paper of Fröling et al. (2004). Concrete and pavement are commonly used as a top cover layer. Thus, the emergy flow of network infrastructure placement ($E_{c,ni}$ [sej]) is given as:

$$E_{c,ni} = E_{ni,p} + E_{ni,pl} + E_{ni,ae} \quad (8.7)$$

where $E_{ni,p}$ [sej] is the emergy flow of pipes used, $E_{ni,pl}$ [sej] is the emergy flow of pipe laying process and $E_{ni,ae}$ [sej] is the emergy flow of additional elements used. The emergy flow of pipes used consists of pipe materials emergy flow $E_{ni,pm}$ [sej] and pipe transportation emergy flow $E_{ni,pt}$ [sej]:

$$E_{ni,p} = E_{ni,pm} + E_{ni,pt} \quad (8.8)$$

$$E_{ni,pm} = \sum_{y=1}^z m_{pm,y} \cdot l_n \cdot U_{pm,y} + \sum_{a=1}^b q_{pmr,a} \cdot l_n \cdot U_{pmr,a} \quad (8.9)$$

$$E_{ni,pt} = ND_{ni,pt} \cdot D_{ni,pt} \cdot LHV_d \cdot U_d \cdot FC_{pt,fl} \cdot (1 + \gamma_{pt}) \quad (8.10)$$

The eq.(8.9) and eq.(8.10) correspond to eq.(8.3) and (8.4), with l_n [m] being the length of the network (and indexes in eq.(8.9) correspond to y -th material of total used z materials for pipe production, and a -th resource of total b resources). $ND_{ni,pt}$ [del.] represents the number of pipe deliveries, $D_{ni,pt}$ [km] is the pipe transportation distance crossed per one delivery, $FC_{pt,fl}$ [l/km] is the pipe transportation vehicle fuel consumption with full load and γ_{pt} [-] is the fuel consumption ratio of the corresponding vehicle. For the steel pipes that are transported in segments, the number of pipe deliveries is given as:

$$ND_{ni,pt} = \frac{n_{ps}}{C_{pts,max}} \quad (8.11)$$

$$n_{ps} = \frac{l_n}{l_{ps}} \quad (8.12)$$

where n_{ps} [segments] is the number of pipe segments, $C_{pts,max}$ [pipes] is the maximum capacity of pipe segments transportation vehicle and l_{ps} [m] is the length of one pipe segment. For the pipes that are made from plastic materials and usually delivered in rolls, the number of pipe deliveries is calculated as:

$$ND_{ni,pt} = \frac{n_{pr}}{C_{ptr,max}} \quad (8.13)$$

$$n_{pr} = \frac{l_n}{l_{pr}} \quad (8.14)$$

n_{pr} [rolls] is the number of required pipe rolls, $C_{ptr,max}$ [rolls] is the maximum capacity of transportation vehicle used, and l_{pr} [m] is the length of pipe in one roll. Fuel consumption ratio is calculated through the following equation:

$$\gamma_{pt} = \frac{FC_{pt,wl}}{FC_{pt,fl}} \quad (8.15)$$

where $FC_{pt,wl}$ [l/km] is the fuel consumption of pipe transportation vehicle without a load.

The energy flow of pipe laying process ($E_{ni,pl}$ [sej]) is expressed as:

$$E_{ni,pl} = E_{ni,te} + E_{ni,egt} + E_{ni,am} + E_{ni,amt} + (E_{ni,plm}) \quad (8.16)$$

$E_{ni,te}$ [sej] is the energy flow of trench excavation, $E_{ni,egt}$ [sej] is the excess ground transportation energy flow, $E_{ni,am}$ [sej] is the energy flow of the additional material for the infrastructure placement and $E_{ni,amt}$ [sej] is the energy flow of the additional material transportation. In the case of network pipes with large diameters and significant weight, additional energy flow of pipe laying process with heavy machines ($E_{ni,plm}$ [sej]) should be considered.

$$E_{ni,te} = h_{ex} \cdot LHV_d \cdot U_d \cdot FC_{ex,fl} \cdot (1 + \gamma_{ex}) \quad (8.17)$$

$$\gamma_{ex} = \frac{FC_{ex,wl}}{FC_{ex,fl}} \quad (8.18)$$

where h_{ex} [h] is the number of hours required for the trench excavation by the adequate machine, $FC_{ex,fl}$ [l/h] and $FC_{ex,wl}$ [l/h] are the hourly fuel consumptions of the excavation machine with and without the load (respectively), while γ_{ex} [-] is the fuel consumption ratio of the machine.

$$h_{ex} = n_{ex,m} \cdot h_{om} \quad (8.19)$$

$$n_{ex,m} = \frac{V_{tr}}{V_{exb}} \quad (8.20)$$

$$V_{tr} = l_{tr} \cdot w_{tr} \cdot d_{tr} \quad (8.21)$$

$n_{ex,m}$ [mov.] is the number of excavating moves, h_{om} [h] is the time of one excavating move made by the machine, V_{tr} [m³] is the trench volume to be excavated, V_{exb} [m³] is the excavating machine bucket volume and l_{tr} [m], w_{tr} [m], and d_{tr} [m] are the trench length, width and depth (respectively). V_{exb} can be found in the specification of the excavating machine and it is usually provided by the manufacturer. Energy flow of excess ground transportation is given as:

$$E_{ni,egt} = ND_{ni,egt} \cdot D_{ni,egt} \cdot LHV_d \cdot U_d \cdot FC_{egt,fl} \cdot (1 + \gamma_{egt}) \quad (8.22)$$

where $ND_{ni,egt}$ [del.] is the number of excess ground transportation deliveries, $D_{ni,egt}$ [km] is the transportation distance per one delivery, $FC_{egt,fl}$ [l/km] and γ_{egt} [-] are the transportation vehicle fuel consumption with full load and fuel consumption ratio, respectively.

$$\gamma_{egt} = \frac{FC_{egt,wl}}{FC_{egt,fl}} \quad (8.23)$$

$$ND_{ni,egt} = \frac{m_{ni,eg}}{C_{egt,max}} \quad (8.24)$$

$$m_{ni,eg} = (V_{tr} - V_{grf}) \cdot \rho_{eg} \quad (8.25)$$

$$V_{grf} = \alpha_s \cdot V_{fill} \quad (8.26)$$

$$V_{fill} = V_{tr} - V_{pp} \quad (8.27)$$

$FC_{egt,wl}$ [l/km] is the transportation vehicle fuel consumption without a load, $m_{ni,eg}$ [kg] is the amount of excess ground material to be transported to the landfill, $C_{egt,max}$ [kg] is the excess ground transportation vehicle maximum capacity, V_{grf} [m³] is the amount of excavated soil used for trench refilling, ρ_{eg} [kg/m³] is the excavated soil average density, α_s [%] is the share of soil in the mixture for trench filling and V_{pp} [m³] is the volume of pipe infrastructure placed in the trench. For the network types where the pipes are primarily placed inside an additional insulation casing (for example in the ESPEX system that is later addressed in this thesis part), pipe infrastructure volume is calculated as:

$$V_{pp} = l_{ic} \cdot w_{ic} \cdot h_{ic} \quad (8.28)$$

where l_{ic} , w_{ic} , h_{ic} [m] are the length, width and height of the insulation casing. If there is no additional casing, pipe infrastructure is calculated as:

$$V_{pp} = \sum_{g=1}^k \frac{d_{p,g}^2 \cdot \pi \cdot l_n}{2} \quad (8.29)$$

where $d_{p,g}$ [m] is the diameter of the g -th pipe type placed and k is the number of pipe types placed (for example: supply line, return line, hot water line etc.). Emergy flow of additional material for the infrastructure placement is:

$$E_{ni,am} = \sum_{x=1}^f m_{am,x} \cdot U_{am,x} \quad (8.30)$$

where $m_{am,x}$ [kg] is the amount of the x -th material used, $U_{am,x}$ [sej/kg] is the UEV of the x -th material used, and f is the number of different cover materials used. In most cases, an additional material (a mixture of sand and gravel) is used for pipe covering before filing the trench with soil, and concrete and pavement for the top covering layer. Thus, in these cases it can be assumed that the amounts of these materials are equal to:

$$m_{am} = m_{am,sd} + m_{am,tl} \quad (8.31)$$

$$m_{am,sd} = (1 - \alpha) \cdot V_{fill} \cdot \rho_{sd} \quad (8.32)$$

$$m_{am,tl} = (m_{tl,sc} + m_{tl,sp}) \cdot l_{tr} \quad (8.33)$$

where $m_{am,sd}$ [kg] is the amount of sand and gravel mixture used to cover the placed network infrastructure, ρ_{sd} [kg/m³] is the average density of sand and gravel mixture, and $m_{tl,sc}$, $m_{tl,sp}$ [kg/m] are the specific masses of required concrete and pavement per meter of the placed network infrastructure. Emergy flow of additional material transportation ($E_{ni,amt}$ [sej]) is calculated through:

$$E_{ni,amt} = ND_{ni,amt} \cdot D_{ni,amt} \cdot LHV_d \cdot U_d \cdot FC_{amt,fl} \cdot (1 + \gamma_{amt}) \quad (8.34)$$

$$ND_{ni,amt} = \frac{\sum_{x=1}^f m_{am,x}}{C_{amt,max}} \quad (8.35)$$

$$\gamma_{amt} = \frac{FC_{amt,wl}}{FC_{amt,fl}} \quad (8.36)$$

where $ND_{ni,amt}$ [del.] is the number of additional material deliveries, $D_{ni,amt}$ [km] is the

additional material transportation distance. $C_{amt,max}$ [kg] presents the maximum capacity of the vehicle used for delivery, while $FC_{amt,wl}$, $FC_{amt,fl}$ [l/km] and γ_{amt} [-] are transportation vehicle fuel consumption without a load, with full load and fuel consumption ratio (respectively).

Additionally, network infrastructure also requires additional elements for control and operation (surface boxes, taps, pumps etc.). The emergy flow of these elements ($E_{ni,ae}$ [sej]) is calculated as the sum of elements assembly ($E_{ni,aem}$ [sej]) and transportation ($E_{ni,aet}$ [sej]) emergy flows:

$$E_{ni,ae} = E_{ni,aem} + E_{ni,aet} \quad (8.37)$$

$$E_{ni,aem} = \sum_{s=1}^r m_{aem,s} \cdot U_{aem,s} + \sum_{w=1}^t q_{aemr,w} \cdot U_{aemr,w} \quad (8.38)$$

$$E_{ni,aet} = ND_{ni,aet} \cdot D_{ni,aet} \cdot LHV_d \cdot U_d \cdot FC_{aet,fl} \cdot (1 + \gamma_{aet}) \quad (8.39)$$

$$ND_{ni,aet} = \frac{\sum_{s=1}^r m_{aem,s}}{C_{aet,max}} \quad (8.40)$$

$$\gamma_{aet} = \frac{FC_{aet,wl}}{FC_{aet,fl}} \quad (8.41)$$

where $m_{aem,s}$ [kg] and $U_{aem,s}$ [sej/kg] are the mass and the UEV of the s -th material used (respectively), and r denotes the number of different materials used. $q_{aemr,w}$ [unit] is the amount of additional w -th resource used for element production and $U_{aemr,w}$ [sej/unit] is the corresponding UEV (of t additional resource used). $ND_{ni,aet}$ [del.], $D_{ni,aet}$ [km] are the number of deliveries and transportation distance for the elements transportation (respectively), while $FC_{aet,wl}$ [l/km], $FC_{aet,fl}$ [l/km] and γ_{aet} [-] are the fuel consumption without a load, with full load and fuel consumption ratio (respectively) for the transportation vehicle used. $C_{aet,max}$ [kg] stands for the additional elements vehicle transportation maximum capacity.

8.1.2.3 Emergy flow of the building subsystem construction

Building subsystem consists of heating system installations and elements that are located within the building (heat exchangers, service pipes, pumps, flow limiters, heat meters etc.) and inside the dwellings (heat exchangers, taps etc.). Emergy flow of building subsystem ($E_{c,bs}$ [sej]) consists of materials used for the subsystem elements and resources for their installation ($E_{bs,m}$ [sej]) and transportation $E_{bs,t}$ [sej]:

$$E_{c,bs}=E_{bs,m} + E_{bs,t} \quad (8.42)$$

The emergy flow of building subsystem materials and resources used for the installation ($E_{bs,m}$ [sej]) and their transportation ($E_{bs,t}$ [sej]) is given as:

$$E_{bs,m} = \sum_{v=1}^c m_{bsm,v} \cdot U_{bsm,v} \sum_{w=1}^t q_{bsmr,t} \cdot U_{bsmr,t} \quad (8.43)$$

$$E_{bs,t} = ND_{bs,t} \cdot D_{bs,t} \cdot LHV_d \cdot U_d \cdot FC_{bst,fl} \cdot (1 + \gamma_{bst}) \quad (8.44)$$

$$ND_{bst} = \frac{\sum_{v=1}^c m_{bsm,v}}{C_{bst,max}} \quad (8.45)$$

$$\gamma_{bst} = \frac{FC_{bst,wl}}{FC_{bst,fl}} \quad (8.46)$$

where $m_{bsm,v}$ [kg] is the amount of the v -th material used (of total c materials), $U_{bsm,v}$ [sej/kg] is its UEV, while $q_{bsmr,t}$ [J] and $U_{bsmr,t}$ [sej/J] are the additional amount additional of the w -th energy resource (of total t additional resources) used for the production/assembly and its UEV (respectively). $ND_{bs,t}$ [del.] and $D_{bs,t}$ [km] stand for the number of deliveries for building subsystem elements transportation and distance crossed for one delivery, while $FC_{bst,wl}$ [l/km], $FC_{bst,fl}$ [l/km], γ_{bst} [km], $C_{bst,max}$ [kg] are the transportation vehicle fuel consumptions without load, with full load, fuel consumption ratio and maximum capacity (respectively).

8.1.2.4 Emergy flow of human labor for system construction

Emergy flow of human labor for system construction $E_{c,hl}$ [sej] takes into account human labor required for construction and assembly of the whole system infrastructure along with the material transportation:

$$E_{c,hl} = n_{cd} \cdot n_{ch,d} \cdot n_{cw} \cdot U_{c,hl} \quad (8.47)$$

where n_{cd} [days] is the number of days required for the system construction and assembly, $n_{ch,d}$ [h] is the number of hours worked daily by one employee, n_{cw} [emp.] is the number of employees and $U_{c,hl}$ [sej/h] is the UEV of human labor.

8.1.3 Energy flow of urban heating system operation phase

Considering that the system operation energy flow is invested every year during the system lifetime (while the energy flow of construction is invested solely during the initial year of operation), to calculate the transformity of heat delivered to consumers (sej/J), energy flow of the operation phase should be calculated over the total lifetime of the system ($E_{o,tot}$ [sej]):

$$E_{o,tot} = E_{o,s} \cdot n_{lf} \quad (8.48)$$

where $E_{o,s}$ [sej/yr] is the annual energy flow of system operation and n_{lf} [yr] is the expected system lifetime (i.e. the amount of fuels combusted and transported, along with the human labor invested, was calculated to satisfy the heat demand during the whole lifetime of the system). Within the system operation phase on an annual level, energy flows of resources used for heat generation are considered ($E_{o,f}$ [sej/yr]), their transportation ($E_{o,ft}$ [sej/yr]), along with the human labor required to operate and maintain the system ($E_{o,hl}$ [sej/yr]) and employees' home-to-work daily commuting ($E_{o,et}$ [sej/yr]). Thus, the annual energy flow of the system operation is equal to:

$$E_{o,s} = E_{o,f} + E_{o,ft} + E_{o,hl} + E_{o,et} \quad (8.49)$$

Energy flows of resources used for heat generation and their transportation are expressed through the following equation:

$$E_{o,f} = \sum_{e=1}^o E_{f,e} \quad (8.50)$$

$$E_{f,e} = \sum_{e=1}^o q_{f,e} \cdot U_{f,e} \quad (8.51)$$

$$q_f = \sum_{e=1}^o \frac{\delta_e \cdot (H_{dm} + H_{dm} \cdot (1 - \eta_{net}))}{LHV_{f,e} \cdot \eta_{hp}} \quad (8.52)$$

where $E_{f,e}$ [sej/yr], $q_{f,e}$ [kg][m³], $U_{f,e}$ [sej/kg][sej/m³], δ_e [%] are the energy flow of the e -th fuel type combusted (of total o fuel types), amount of each fuel type combusted, its according solar UEV and share in annual heat production (respectively). H_{dm} [MJ/yr] is the annual heat demand, η_{net} [%] is the network efficiency, LHV_f [MJ/kg] (for solid fuels) or [MJ/m³] (for liquid fuels) is the low heating value of the fuel, and η_{hp} [%] is the heat production unit energy transformation efficiency. Fuel transportation energy flow ($E_{o,ft}$ [sej/yr]) is calculated as:

$$E_{o,ft} = ND_{o,ft} \cdot D_{o,ft} \cdot LHV_d \cdot U_d \cdot FC_{ft,fl} \cdot (1 + \gamma_{ft}) \quad (8.53)$$

$$ND_{o,ft} = \frac{q_f}{C_{ft,max}} \quad (8.54)$$

$$\gamma_{ft} = \frac{FC_{ft,wl}}{FC_{ft,fl}} \quad (8.55)$$

where $ND_{o,ft}$ [del.] is the number of deliveries for fuel transportation, $D_{o,ft}$ [km] is the delivery distance crossed by the delivery vehicle per each delivery, and $FC_{ft,wl}$ [l/km], $FC_{ft,fl}$ [l/km] are the fuel delivery vehicle fuel consumption without and with the load (respectively), while $C_{ft,max}$ [kg] and γ_{ft} [-] are the maximum capacity and fuel consumption ratio (respectively). Emergy flow of the human labor for network operation ($E_{o,hl}$ [sej/yr]) is given as:

$$E_{o,hl} = n_{od} \cdot n_{oh,d} \cdot n_{ow} \cdot U_{o,hl} \quad (8.56)$$

n_{od} [days], $n_{oh,d}$ [h/day/emp.] are the number of days and hours per day worked by one employee (respectively), n_{ow} [emp.] is the number of employees required for system operation and $U_{o,hl}$ [sej/h] is the UEV of human labor for network operation. Emergy flow of employees daily traveling from home to work can be calculated through the following equation:

$$E_{o,et} = n_{ow} \cdot n_{od} \cdot D_{et} \cdot LHV_d \cdot U_d \cdot FC_{c,et} \quad (8.57)$$

where D_{et} [km] is the daily distance crossed by one employee and $FC_{c,et}$ [l/km] is the average fuel consumption of the passenger cars used by the employees for commuting.

Finally, when all emergy flows are expressed on the same basis, the UEV of heat delivered to the consumer (U_{heat} [sej/J]) can be obtained through:

$$U_{heat} = \frac{E_{c,san} + E_{o,tot}}{H_{dm} \cdot \eta_c} \quad (8.58)$$

where H_{dm} [J] is the total heat demand (with losses accounted) and η_c is the Carnot efficiency of the system.

8.2 The environmental performance of building during its life-cycle

Primarily, all building life-cycle phases are defined, along with all relevant processes/systems considered in these phases. Considering the amount of different resources used during the building lifecycle, it seemed more suitable in this case to present the calculation process in order based on the resource allocation. Consequently, all required resources were defined and categorized.

8.2.1. Building system outline and life-cycle phases definition

In order to perform building energy analysis, the following phases of building life-cycle were considered with their main components outlined below and on Fig.8.3:

- **Building construction** – initial construction of the building infrastructure and different systems required for its operation during the lifetime, that can be divided into:
 - ❖ **Main infrastructure** – building envelope (walls, floors, roof, windows), inter floor constructions, basic interior, civil works and related construction operations;
 - ❖ **Water supply and sewerage** – inner (within the building itself) and outer (connections to the grids) water supply and sewerage systems and related civil works and construction operations;
 - ❖ **Heating system** – in the case that building is not connected to the district heating system (possesses individual heating system) or heating system elements were not accounted during the district heating system construction phase, construction and installation of heating system should be accounted within this phase, along with related civil works and construction operations;
 - ❖ **Electrical installations** – inner (within the building itself) and outer (grid connection) installations, elements and related civil works and construction operations;
 - ❖ **Telecommunication installations** – telephone, TV, fire and carbon-monoxide detection systems, along with video surveillance installations, elements and related construction operations;
 - ❖ **Elevator systems** – elevator shaft equipment, infrastructure and elevator system elements and installations and related construction operations;
- **Building operation** - considers the use of resources required for building operation during its assumed lifetime. The main resources considered were:
 - ❖ **Electricity** – used for lighting, space cooling (split units) and electrical appliances;
 - ❖ **Water** – tap and domestic hot water consumption;
 - ❖ **Maintenance** – labor and material for building basic maintenance over the course of its lifetime;
 - ❖ **Heat** – used for heating the premises;

- ❖ **Solar gains** – solar gains on the building envelope during the heating season that reduce the demand for space heating caused by the transmission losses through the envelope (that would otherwise be covered by purchased heat);

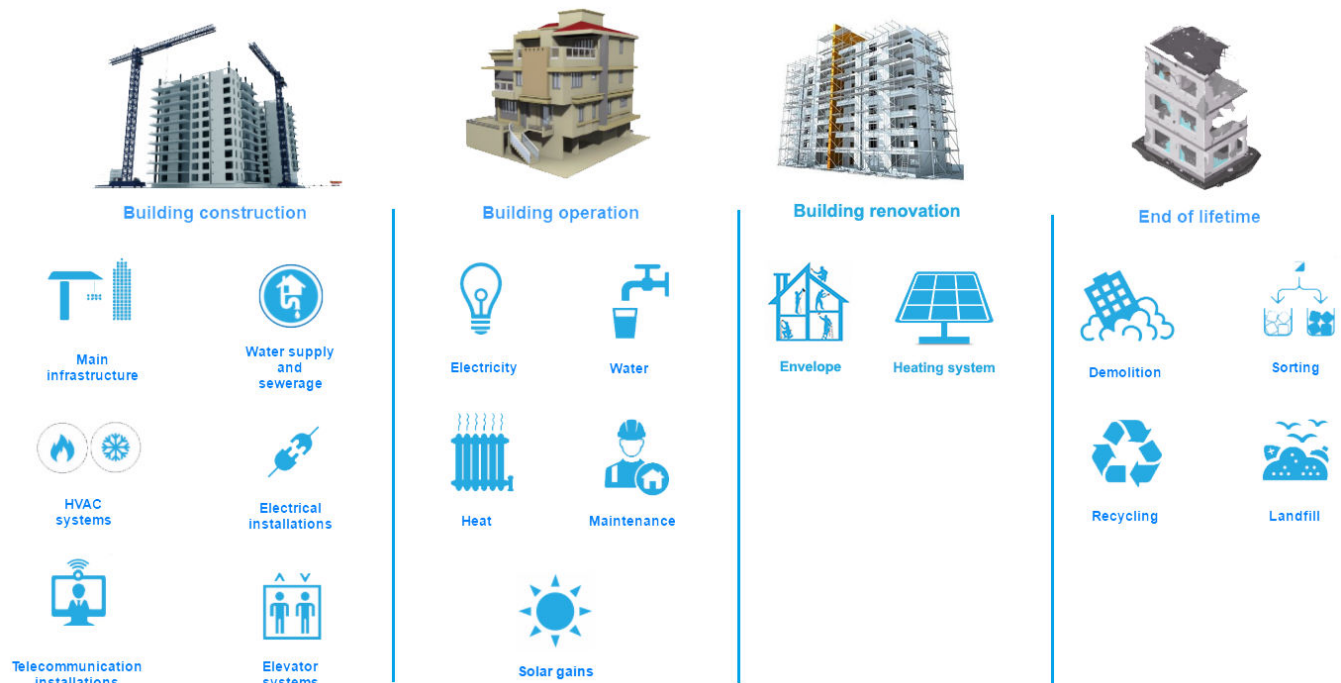


Figure 8.3 Considered phases and components of the building life-cycle;

- **Building renovation** – accounts for the improvements in building thermal performance and energy efficiency measures, such as:
 - ❖ **Envelope renovation** - improvements in thermal performance of building envelope elements (walls, roofs, floors and windows);
 - ❖ **Heating system renovation** - introduction of local renewable heat production (solar thermal collectors), as well as related construction operations;
- **End-of-life** – takes into account operations required for building dismantling, recycling and landfilling:
 - ❖ **Demolition** – building deconstruction and related use of resources;
 - ❖ **Separation** – separation of the deconstructed material to recyclable and non-recyclable materials;
 - ❖ **Recycling** – recycling of the previously separated materials and related resource use;
 - ❖ **Landfilling** – landfilling of the previously separated materials that are not suitable for recycling, and the related resource use;

8.2.2 Resource allocation and building emergy flow calculation

As mentioned at the beginning of this chapter, due to the amount of different resources used during the building life-cycle, building emergy flow calculation is presented in order based on the resource allocation. The emergy flow diagram with all required resources is given on Fig.8.4. Eight different types of resources were used as system input:

- 1) **Land use (soil erosion)** – used to evaluate the permanent loss of biocapacity in the area on which the building has been constructed. The emergy flow of soil erosion $E_{s,e}$ [sej] was calculated as (Pulselli et al. (2007)):

$$E_{s,e} = V_{\text{exs}} \cdot \rho_s \cdot f_{\text{os}} \cdot e_s \cdot U_{\text{lu}} \quad (8.59)$$

where V_{exs} [m³] is the building construction site excavated soil volume, ρ_s [kg/m³] is the average soil density, f_{os} [%] is the amount of organic substance in soil, e_s [J/kg] is the soil energy content, while U_{lu} [sej/J] is the UEV value of land use;

- 2) **Solar irradiation** – the input of solar irradiation on the construction site (as defined in the work of Pulselli et al. (2007), Amponsah et al. (2012) and Meillaud et al. (2005)) and heat gains during the building operation period. Emergy flow of solar radiation on a construction site E_{scs} [sej] (solar irradiation on a building yard during the construction process) was calculated as (Pulselli et al. (2007)):

$$E_{\text{sir}} = A_{\text{cs}} \cdot I_{\text{sr,a}} \cdot (1 - a) \cdot t_{\text{cs}} \cdot U_s \quad (8.60)$$

where A_{cs} [m²] is the building construction site surface (footprint), $I_{\text{sr,a}}$ [J/m²/yr] is the annual amount of solar radiation, a [-] is the value of ground albedo, t_{cs} [yr] is the time required for building construction and U_s [sej/J] is the UEV of solar energy. Emergy flow of solar gains on the building envelope E_{sg} [sej/yr] was calculated as:

$$E_{\text{sg}} = Q_{\text{sg}} \cdot t_{\text{op}} \cdot U_s \quad (8.61)$$

Q_{sg} [J/yr] are the annual solar gains on the envelope during the heating season and t_{op} [yr] is the total time of building operation.

- 3) **Materials** – accounts for all material input required to produce the elements used in all four stages of the building lifetime. For each subsystem (refer to Fig.8.3) during the building life-cycle phases, the emergy flow was calculated as:

$$E_{ss,i} = \sum_{j=1}^n m_{i,j} \cdot U_{i,j} \quad (8.62)$$

where $E_{ss,i}$ [sej] is the emergy flow of the i -th subsystem construction, $m_{i,j}$ [kg] is the amount of j -th material used during the subsystem construction (of total n materials) and $U_{i,j}$ [sej/kg] is the UEV of the regarded material.

4) Electricity – two sources of electricity were considered in this study: electricity produced by on-site generators powered by diesel fuel (during the construction phase) and electricity from the grid. Since diesel is considered as a separate input in this study, the emergy flow of the mobile generator use will be addressed later on. Thus, the emergy flow of electricity consumed from the grid $E_{el,o}$ [sej] during the building operation phase, is equal to:

$$E_{el,o} = W_e \cdot t_{op} \cdot U_{el} \quad (8.63)$$

where W_e [J/yr] is the annual electricity consumption and U_{el} [sej/J] is the UEV of the electricity produced for the case study location.

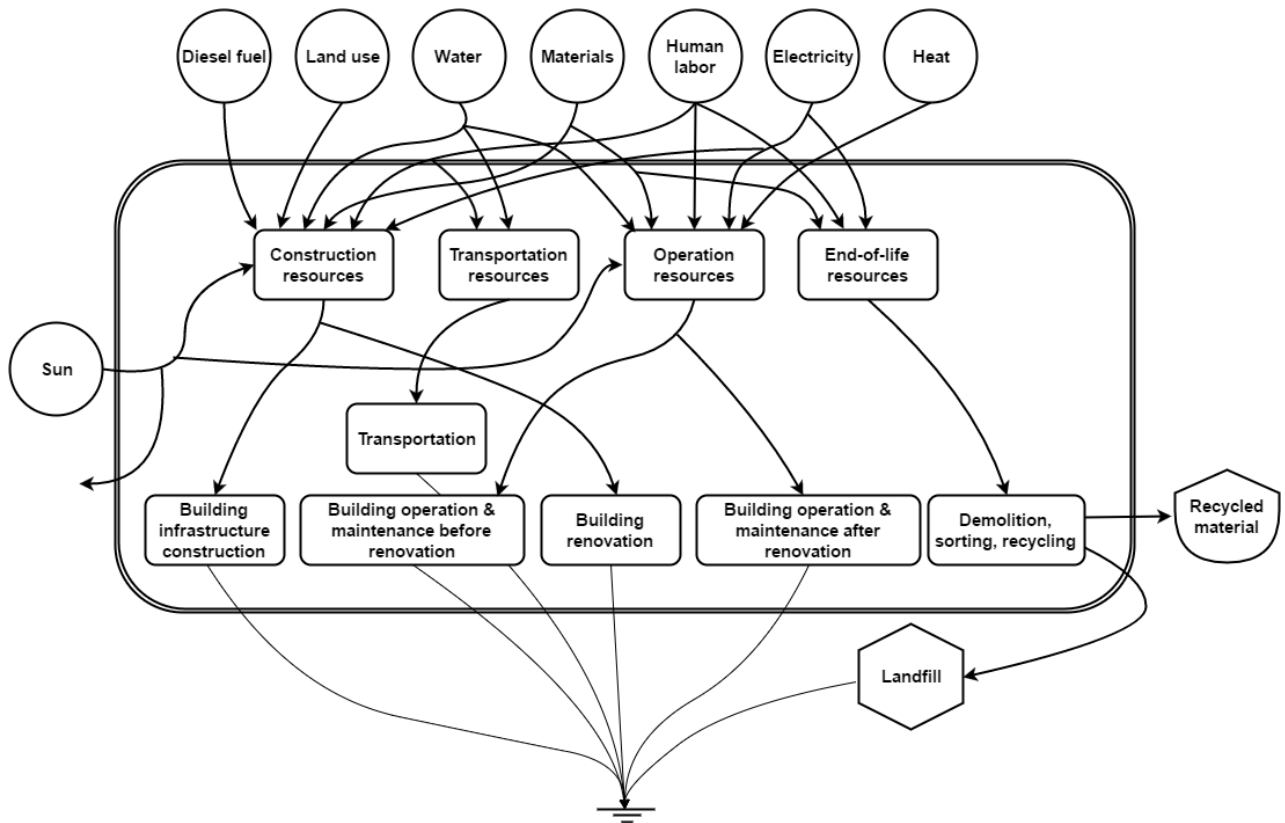


Figure 8.4 Building emergy diagram;

5) Water – the emergy flow of the water consumed during the building construction $E_{w,co}$ [sej] was calculated as:

$$E_{w,co} = V_w \cdot \rho_w \cdot U_w \quad (8.64)$$

while the emergy flow of the water consumed during the building operation $E_{w,op}$ [sej] (domestic hot water included) was calculated as:

$$E_{w,op} = \vartheta_e \cdot n_{oc} \cdot \rho_w \cdot 365 \cdot t_{op} \cdot U_w \quad (8.65)$$

where V_w [m³] is the volume of the water used during the construction phase, ρ_w [kg/m³] is the water density, U_w [sej/kg] is the water UEV, ϑ_e [m³/oc./day] is the specific daily water consumption per occupant, n_{oc} [oc.] is the number of occupants.

6) Heat – the emergy flow of heat used for heating the premises during the building lifetime E_h [sej] was calculated as:

$$E_h = Q_h \cdot t_{op} \cdot U_h \quad (8.66)$$

where Q_h [J/yr] is the amount of heat consumed annually during the heating season and U_h [sej/J] is the UEV value of heat delivered. It should be noted that within the UEV value of heat delivered, the construction of central boilers and distribution network is taken into account (please refer to the section 8.1).

7) Diesel fuel – diesel fuel is mostly used during the building construction and renovation phases for four purposes: material transportation, construction workers transportation, heavy construction machinery and on-site electricity generators. The emergy flow of transportation for each j -th material $E_{mt,j}$ [sej] was calculated analogue to the eq. (8.4)-eq.(8.6), while the emergy flow of construction workers daily commuting E_{cwt} [sej] can be expressed as:

$$E_{cwt} = n_{cw} \cdot n_{cd} \cdot D_{et} \cdot LHV_d \cdot U_d \cdot FC_{c,et} \quad (8.67)$$

where n_{cw} [c.w.] is the number of construction workers, n_{cd} [days] is the number of days required to complete the construction, D_{et} [km] is the daily distance crossed by one employee and $FC_{c,et}$ [l/km] is the passenger car average fuel consumption. The emergy flow of heavy construction machines (excavators, cranes etc.) use during the construction phase E_{cm} [sej] was expressed as:

$$E_{cm} = h_{cm,op} \cdot LHV_d \cdot U_d \cdot FC_{cm,fl} \cdot (1 + \gamma_{cm}) \quad (8.68)$$

$$\gamma_{cm} = \frac{FC_{cm,wl}}{FC_{cm,fl}} \quad (8.69)$$

where $h_{cm,op}$ [h] is the number of operating hours for the machine considered $FC_{cm,fl}$, [l/h] and $FC_{cm,wl}$ [l/h] are the hourly fuel consumptions of the machine with and without the load (respectively), while γ_{cm} [-] is the fuel consumption ratio of the machine considered. The emergy flow of the fuel used for on-site electricity generators was calculated as E_{eg} [sej]:

$$E_{eg} = \theta_{deg} \cdot A_{cs} \cdot LHV_d \cdot U_d \quad (8.70)$$

where θ_{deg} [l/m²] is the amount of fuel consumed to produce the required amount of electricity on the construction site during the construction phase (expressed per m² of the construction site). The eq.(8.67) – eq.(8.69) were also used to calculate these emergy flows during the building renovation phase.

8) Human labor – used during the construction/renovation phase ($E_{o,hl}$ [sej]) can be expressed as:

$$E_{o,hl} = n_h \cdot n_{cd} \cdot n_{cw} \cdot U_{c,hl} \quad (8.71)$$

where n_h [h/day/emp.] is the number of hours per day worked by one employee, and $U_{c,hl}$ [sej/h] is the UEV of human labor.

When emergy flows of all inputs required during the building lifetime are calculated, they can be divided into three groups in order to assess the sustainability of renovation measures: indigenous renewable (R [sej]), indigenous non-renewable (N [sej]), and purchased (F [sej]) resources outside the system boundaries. The sustainability of the measures considered was evaluated as an added value to thesis Part II, and can be evaluated through the use of the following emergy ratios:

$$EYR = \frac{R+N+F}{F} \quad (8.72)$$

$$EIR = \frac{F}{R+N} \quad (8.73)$$

$$ELR = \frac{N+F}{R} \quad (8.74)$$

EYR is the emergy yield ratio, calculated as the ratio between the sum of all inputs and purchased inputs from outside the system. Emergy investment ratio (EIR) is the ratio between the purchased inputs and indigenous renewable and nonrenewable inputs, while ELR is the

energy loading ratio, the ratio between the sum of the purchased and indigenous non-renewable inputs and the indigenous renewable inputs. The equations and indices were thoroughly explained and given in the work of Odum (1996) and Brown & Ulgiati (1997). Additionally, the UEV of the studied building $U_b[\text{sej}/\text{m}^2]$ can be used for sustainability assessment and it can be expressed as:

$$U_b = \frac{R+N+F}{A_b} \quad (8.75)$$

where $A_b [\text{m}^2]$ is the total useful building floor surface.

However, building renovation can occur in different stages of building lifetime (Fig.8.5). After the building construction phase (E_{cs}) period (t_{cs}), building has a reference thermal performance and operational flow until the renovation measures are applied ($E_{op,rf} [\text{sej}]$ for a period $t_{op,rf}$). With renovations performed, additional resources are invested increasing the energy flow ($E_{rn} [\text{sej}]$). After the renovations are performed, the operational energy flow until the end of lifetime ($t_{op,rf}$) could decrease ($E_{op,rf} [\text{sej}]$) compared to a reference case. However, due to the fact that new materials and labor were invested during the renovation, the energy flow of the end-of-life phase (recycling/landfilling) after renovations ($E_{elf,rn} [\text{sej}]$) is higher than for a reference case ($E_{elf,rf} [\text{sej}]$) without renovations. Theoretically, the total energy flow over lifetime t_{lf} for a scenario with renovations $E_{t,rn} [\text{sej}]$ should be lower than the total energy flow for a scenario without renovations $E_{t,rf} ([\text{sej}])$ for a value $\Delta_s [\text{sej}]$ due to the energy savings achieved, i.e.:

$$E_{cs} + E_{op,rf} \cdot t_{op} + E_{elf,rf} > E_{cs} + E_{op,rf} \cdot t_{op,rf} + E_{op,rn} \cdot t_{op,rn} + E_{rn} + E_{elf,rn} \quad (8.76)$$

$$\Delta_s = E_{t,rf} - E_{t,rn} > 0 \quad (8.77)$$

However, the addition of new materials and services during the renovation process and end-of-life (landfilling/recycling) could possibly result in an increase of the final energy flow rather than a decrease (i.e. $E_{t,rn} > E_{t,rf}$). Additionally, while the resource input for renovation measures remains the same no matter in which year the considered measure is applied, the overall impact of renovation measure is not the same. Namely, the sooner the renovation process is conducted, more energy may be saved over the lifetime.

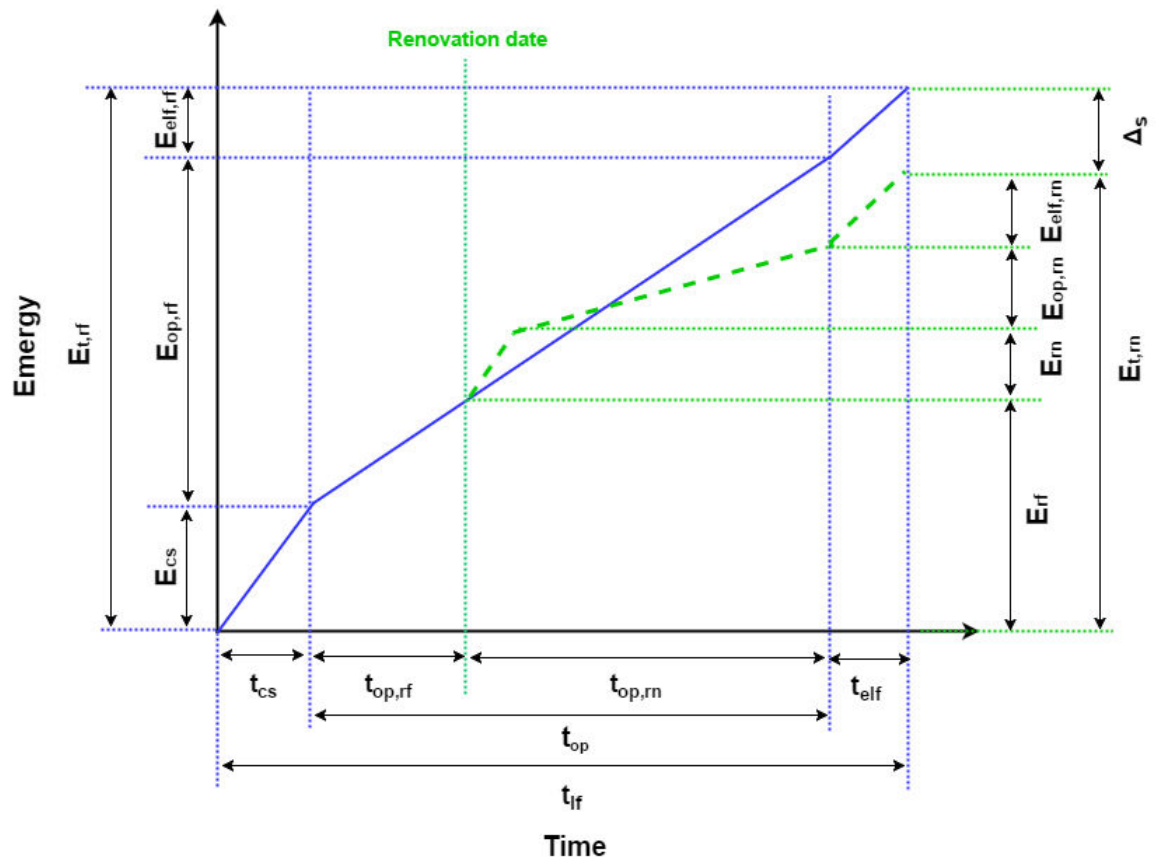


Figure 8.5 The impact of renovation measure on total building energy flow over lifetime;

CHAPTER 9: APPLICATION OF THE METHODOLOGY DEVELOPED

WITHIN THE THESIS PART II

Within this chapter, the methodology previously described is applied on case studies, in order to evaluate the environmental performance of district heating systems within the urban environment. Within the first case study, the methodology developed in order to evaluate the environmental performance of urban heating systems was applied on a district of Vråen, located in the city of Värnamo (Sweden). This particular district was selected for the case study by reason that the district has one of the modern district heating system types installed (four-pipe ESPEX network). Within the second case study, the methodology developed for building environmental performance assessment was applied on a multi-apartment building located in the city of Šabac, Serbia. The main scope of the second case study was to assess to which extent the heat consumed from the heating system (i.e. energy flow of heat consumed calculated based on the previously obtained UEVs and heat demand) affects the total building environmental performance over its lifetime. To account for possible heat consumption reduction during the building lifetime, the impact of building renovation measures and renovation timeline was addressed.

For heat demand estimations in the first part of the thesis, a dynamic RC model was developed and the calculations were conducted on an hourly basis. Hourly time step was used since the main scope was to evaluate the climate change impacts on heat demand related parameters and techno-economic parameters of district heating systems (such as the number of heating hours, peak loads etc.). However, in this (second) part of the thesis, the main scope is to evaluate the environmental performance of such systems over their lifetime by utilizing the developed energy analysis, for which the total annual heat demand is sufficient as an input (refer to the methodology chapter of this thesis part) – the difference between the hourly heat demand within the total annual demand is not of high relevance. Moreover, the difference between the total annual heat demand calculated by static simulation models and simplified dynamic models is not relevant, as proved in the paper of Murray et al. (2012) – the difference was less than 15 % for all cases studied. In addition, the difference between the total annual demands obtained by dynamic and static calculations with the RC model developed in this thesis (static calculations were achieved by removing the heat capacities of the building envelope from the model, i.e. by removing the effect of thermal inertia) was 11 % for a sample building. Thus, instead of dynamic calculations, in this thesis part, measured data was used for

the case study where it was available (buildings in the district of Vråen, Sweden). In other instance (building located in Šabac, Serbia), a static model was used due to two main reasons: local regulations for heat demand calculations were respected; complete dataset required for dynamic heat demand calculations was not available.

Finally, for all emergy calculations performed in this thesis, a recently updated global emergy baseline ($1.20\text{E}+25$ sej) calculated in the paper of Brown et al. (2016) was used. Thus, all UEVs obtained from the previous research efforts in the bibliography were updated in accordance with the new baseline. An overview of previous and updated UEVs is presented within the Appendix A of this thesis.

9.1 The environmental performance of urban heating systems

The main scope of this methodology application is to evaluate the environmental performance of different systems used for the provision of urban environment with heating services. Two district heating system types were considered, that differ in the layout of distribution network: the traditional two-pipe district heating network, and the modern four-pipe ESPEX network. Two options for heat production were considered: central boilers and thermal solar panels. Additionally, different fuels were considered for combustion in boilers. Moreover, a competitive technology was also studied for a comparison – a natural gas distribution network with individual gas boiler in each dwelling.

Primarily, for all studied systems, emergy flows of each element within the system life-cycle phase considered (construction and operation) were calculated in order to evaluate which elements have the highest environmental impact within each phase, and which phase has the highest contribution to the overall system environmental performance over the lifetime. Finally, when the amounts of resources directly and indirectly consumed in order to provide a unit of heating service from each system to the consumer (i.e., the UEV value of heat consumed by the buildings) are calculated, the environmental performance of these systems is compared on a same basis. Moreover, the impact of system parameters that could vary between different case studies (such as distribution network length and district heat demand) on the final result is explored.

9.1.1 District and system data

In order to compare different systems considered in this study on a same basis, all systems were applied on the same district. For this study, the district of Vråen (located in Värnamo, Sweden) that was described within the study of Perzon et al. (2007) was used,

considering that it is one of the rare locations with a functioning modern type of district heating network (ESPEX) in operation. The district consists of 17 buildings with 165 dwellings in total, and the required length of the district heating network is 800 m, while the district annual heat demand is equal to 4.54 TJ/yr (Perzon et al., 2007). Three different systems (Fig. 9.1) for providing urban environment with heating services are studied: a modern ESPEX four-pipe district heating network, a traditional two-pipe district heating network (both networks with connection to a central heat production unit), and a natural gas distribution network with individual dwelling in each apartment.

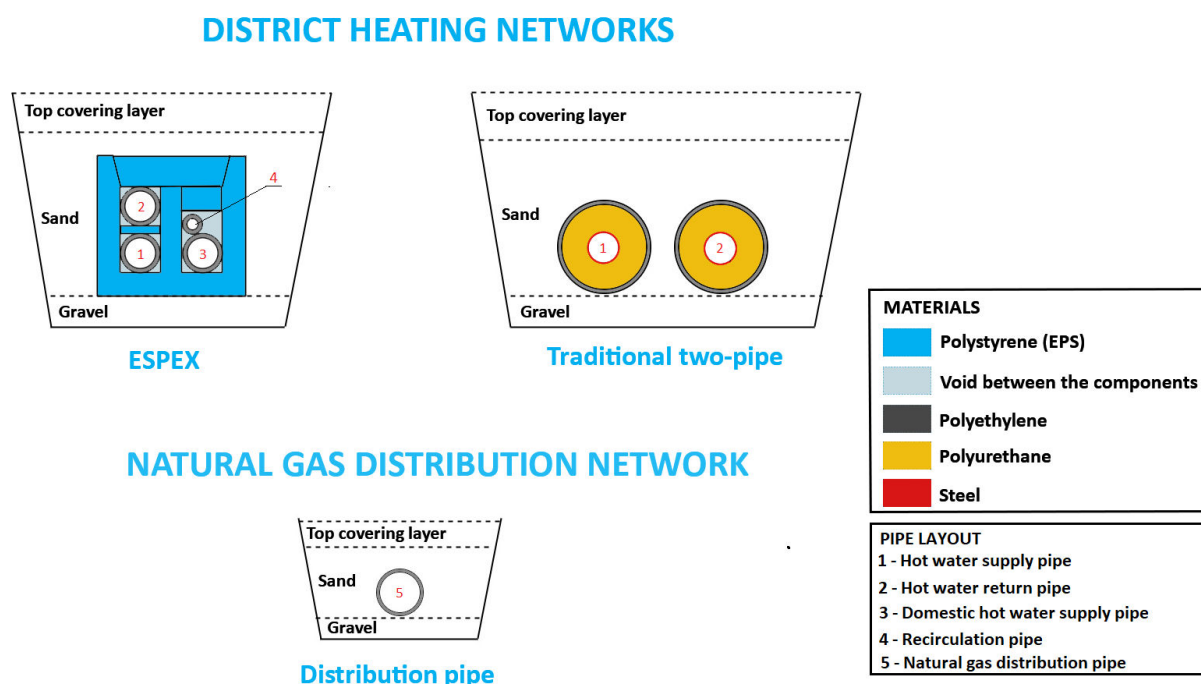


Figure 9.1 Overview of the systems considered (figures are not in scale for clearer representation);

Properties of the ESPEX network were described in detail within the work of Perzon et al. (2007). The network consists of four polyethylene pipes connected to a heat exchanger in the heat plant. The main space heating distribution pipes (supply and return line), as well as the domestic hot water distribution pipe have 40 mm diameters. The fourth, 22 mm diameter pipe, is the warm water recirculation pipe that is used for the recirculation of small amounts of water to keep the constant domestic hot water temperature at the tap. The pipes are placed within the expanded polystyrene (EPS) insulation box in order to reduce heat losses. 40 mm pipes are delivered in 50 m rolls and 22 mm pipes are delivered in 150 m rolls from the pipe factory. The authors also noted that the network was initially developed for the use in suburban areas, and that two options can be used in order to connect the network to the buildings. In the first option, hot water from the network has a direct flow into the heat exchanger units within the dwellings.

In the second option, the network is connected to a substation with heat exchanger inside each building (i.e. each building has a secondary hot water circuit, from the substation to heat exchangers inside the dwellings). Consequently, both options were considered in this study. The amounts of materials required for network construction were provided within the paper of Perzon et al. (2007).

For the second district heating network scenario, a traditional two-pipe network was considered: one pipe that serves as a supply line and another one that serves as a return line, with 100 mm pipe diameters. The inventory of such a network is provided within the work of Oliver-Solà et al. (2009a). In this scenario, building supply line (that is connected to the network main supply line) supplies heat exchangers in dwellings with hot water, where the difference in flows is controlled by flow limiters and valves. From the heat exchangers, one part of return water is used to heat the domestic hot water, while the second part is recirculated to the network main return pipe. Network properties, complete network outline and the resources required for the network construction were obtained from the study of Oliver-Solà et al. (2009a).

Finally, for the natural gas distribution network scenario, a single natural gas supply pipe network was considered. Natural gas is distributed to each dwelling, where it is combusted in small individual condensing boilers. In this study, it was assumed that the regional natural gas distribution network reaches the boundaries of the studied system - thus the construction of such network was not considered. However, the environmental costs of gas transportation through the regional network to the district network were considered. The regarded network inventory is based on the work of Oliver-Solà et al. (2009b).

In this study, the elements of building heating subsystems were considered to be the same for both district heating network types studied. The author is aware that the dimensions of these subsystems may vary from one district heating network type to another, but it was assumed that the variation in material and elements used can be neglected in comparison with the materials for the network infrastructure and heat production unit construction. However, for the building subsystem elements in the natural gas distribution network scenario, an according gas installation subsystem was considered, due to the fact that building installations significantly differ compared to district heating subsystems and elements. It should be noted that the transportation distances in this study account for both material transportation to the factory and product transportation to the system assembly location. For the building and dwelling subsystems, an estimated inventory from the paper of Oliver-Solà et al. (2009a) was used for buildings that were connected to a district heating system, and from Oliver-Solà et al.

(2009b) for the natural gas distribution with an individual boiler in each dwelling. Materials and parameters for the building subsystems (building & dwelling) were obtained from Oliver-Solà et al. (2009a) and Oliver-Solà et al. (2009b). The generic parameters (required for the energy flows calculation through eq. (8.1) – eq. (8.58)) for all systems considered and related transportation and construction works are provided within Table 9.1.

Table 9.1 Generic parameters required for the developed energy evaluation;

DISTRIBUTION NETWORKS					
Definition	Item	Unit	ESPEX	TP DHN	NGN
Network length	l_n	[m]	800 ^a	800 ^a	800 ^a
Pipe delivery distance per one delivery	$D_{ni,pt}$	[km]	500 ^b	500 ^b	500 ^b
Pipe delivery veh. fuel cons. with full load	$FC_{pt,fl}$	[l/km]	0.242 ^c	0.242 ^c	0.242 ^c
Pipe delivery veh. fuel cons. without load	$FC_{pt,wl}$	[l/km]	0.181 ^c	0.181 ^c	0.181 ^c
Pipe delivery veh. maximum capacity	$C_{pts,max}$	[rolls]	20 ^b	150 ^b	20 ^b
The length of the pipe in one roll or segment	l_{pr}	[m]	150 ^b	12 ^b	150 ^b
Trench excavator fuel. cons. with full load	$FC_{ex,fl}$	[l/km]	13.1 ^d	13.1 ^d	13.1 ^d
Trench excavator fuel. cons. without load	$FC_{ex,wl}$	[l/km]	8.9 ^d	8.9 ^d	8.9 ^d
Excavator bucket volume	V_{exb}	[m ³]	0.232 ^d	0.292 ^c	0.176 ^d
Trench length	l_{tr}	[m]	800 ^a	800 ^h	800 ⁱ
Trench width	w_{tr}	[m]	1 ^a	1.1 ^h	0.4 ⁱ
Trench depth	d_{tr}	[m]	1 ^a	0.8 ^h	0.6 ⁱ
Time for one excavating move	h_{om}	[h]	0.0125 ^e	0.0125 ^e	0.0125 ^e
Excess ground trasp. distance per one delivery	$D_{ni,egt}$	[km]	10 ^b	10 ^b	10 ^b
Excess ground transp. veh. fuel cons. with full load	$FC_{egt,fl}$	[l/km]	0.276 ^c	0.276 ^c	0.276 ^c
Excess ground transp. veh. fuel cons. without load	$FC_{egt,wl}$	[l/km]	0.207 ^c	0.207 ^c	0.207 ^c
Excess ground transp. veh. maximum capacity	$C_{egt,max}$	[kg]	10000 ^c	10000 ^c	10000 ^c
Excavated soil average density	ρ_{eg}	[kg/ m ³]	1400 ^f	1400 ^f	1400 ^f
Participation of soil in the mixture for trench filling	α	[-]	0.2 ^g	0.2	0.2 ⁱ
Placed infrastructure length	l_{ic}	[m]	800 ^a	800 ^h	0.2 ⁱ
Placed infrastructure width	w_{ic}	[m]	0.4 ^a	0.2 ^h	0.2 ⁱ
Placed infrastructure height	h_{ic}	[m]	0.4 ^a	0.1 ^h	0.2 ⁱ
Sand with gravel density	ρ_{sd}	[kg/ m ³]	1650 ^f	1650 ^f	1650 ^f
Additional mat. transp. distance per one delivery	$D_{ni,amt}$	[km]	50 ^b	50 ^b	50 ^b
Additional mat. transp. veh. maximum capacity	$C_{amt,max}$	[kg]	10000 ^c	10000 ^c	10000 ^c
Additional mat. veh. fuel cons. with full load	$FC_{amt,fl}$	[l/km]	0.207 ^c	0.207 ^c	0.207 ^c
Additional el. trasp. distance per one delivery	$D_{ni,aet}$	[km]	500 ^b	500 ^b	500 ^b

<i>Table 9.1 continued</i>					
Additional el. veh. fuel cons. without load	$FC_{aet,wl}$	[l/km]	0.276 ^c	0.276 ^c	0.276 ^c
Additional el. veh. fuel cons. with full load	$FC_{aet,fl}$	[l/km]	0.207 ^c	0.207 ^c	0.207 ^c
Additional el. transp. veh. maximum capacity	$C_{aet,max}$	[kg]	10000 ^c	10000 ^c	10000 ^c
No. of days for system construction	n_{cd}	[days]	30 ^b	30 ^b	30 ^b
No. of hours worked daily by one employee	$n_{ch,d}$	[h]	8 ^b	8 ^b	8 ^b
No. of employees	n_{cw}	[emp.]	100 ^b	100 ^b	100 ^b
Heat demand	H_{dm}	[TJ/yr]	4.54 ^a	4.54 ^a	4.54 ^a
Network efficiency	η_{net}	[-]	0.94 ^a	0.94 ^a	0.85 ^a
No. of days worked annually by one employee(op.)	n_{od}	[days/yr]	365 ^b	365 ^b	365 ^b
No. of hours worked daily by one employee(op.)	$n_{oh,d}$	[h/day]	8 ^b	8 ^b	8 ^b
No. of employees for system operation	n_{ow}	[emp.]	2 ^b	2 ^b	2 ^b
Daily distance travelled by one employee	$D_{ni,aet}$	[km/emp.]	25 ^b	25 ^b	25 ^b
Average car fuel consumption	$FC_{c,et}$	[l/km]	0.09 ^c	0.09 ^c	0.09 ^c
BUILDING & DWELLING SUBSYSTEMS					
Definition	Item	Unit	Value		
Build. subsystem el. transp. dist. per one delivery	$D_{bs,t}$	[km]	500 ^b		
Build. subsystem el. veh. transp. fuel cons. without load	$FC_{bst,wl}$	[l/km]	0.276 ^c		
Build. subsystem el. veh. transp. fuel cons. with full load	$FC_{bst,fl}$	[l/km]	0.207 ^c		
Build. subsystem el. veh. transp. max capacity	$C_{bst,max}$	[kg]	10000 ^c		

^aPerzon et al. (2007), ^bassumed, ^cJia et al. 2010, ^dCAT, (2015a), ^emeasured value, ^fEngineering Toolbox (2015a),

^gFröling & Svanström (2005), ^hOliver-Solà et al. (2009a), ⁱOliver-Solà et al. (2009b);

For the three distribution network types studied, three different options for heat production were considered. The first is the central boiler with the combustion of mixed fuels: biofuels (80 %), petroleum (15 %), light fuel oil (3 %), and landfill gas (2 %) (as given in Perzon et al. (2007)). Since the authors did not define what type of biofuels were used, in this study bioethanol was considered. It was assumed that the boiler can also combust solely natural gas due to the fact that a high-calorie fuel is typically used to start the boilers (gas in smaller units and oil derivate in large units), until the adequate temperature is reached within the combustion chamber to combust the main fuel. A central boiler with natural gas combustion was considered as a second option, while a central solar plant with flat plated solar collectors and thermal storage was considered as a third option. For the natural gas distribution network, small individual heat boilers were considered for each dwelling inside the district that cover both space heating and the domestic hot water demand. An overview of heat production options is given on Fig. 9.5, while the parameters related to boiler construction and operation are given in

Table 9.2. The properties of fuels used are provided within the Table 9.3. Finally, a complete overview of scenarios considered in this study (combinations of distribution networks and heat sources) and the abbreviations that will be used in further text are provided in Table 9.4.

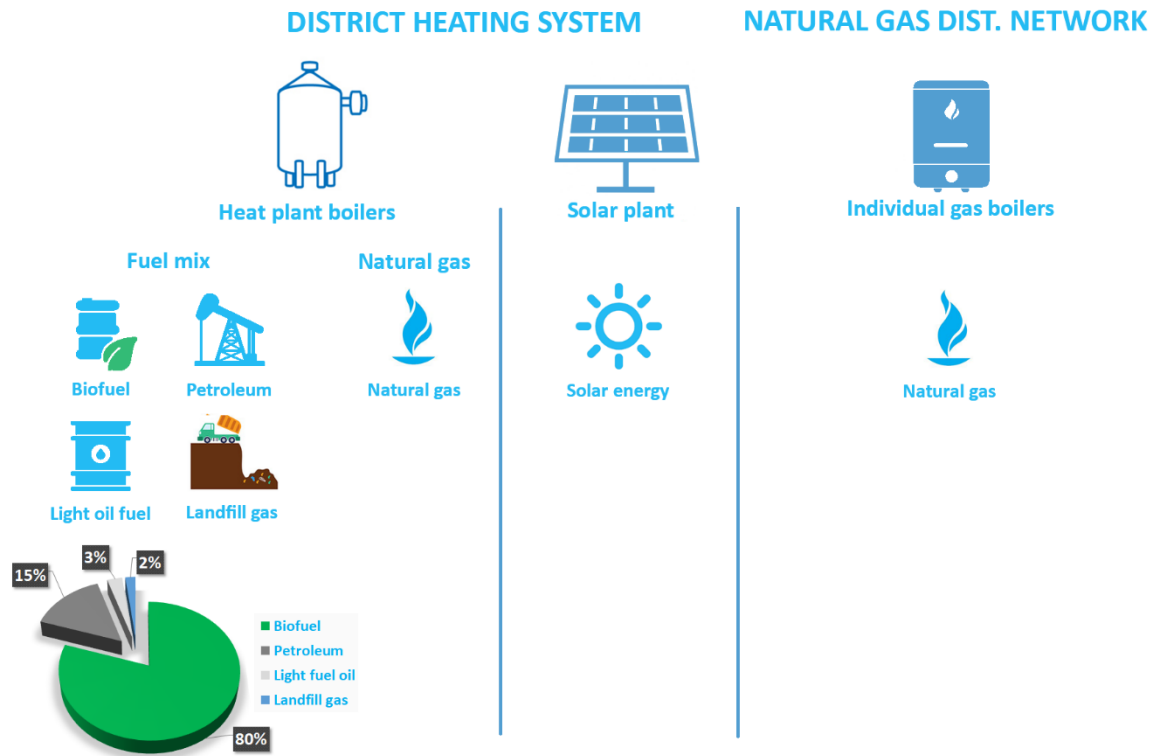


Figure 9.2 Heat production units and energy sources considered for the studied systems;

Table 9.2 Parameters of the boilers considered;

Definition	Item	Unit	Value		
			CB	IB	SP
Boiler efficiency	η	[-]	0.87 ^a	0.90 ^a	0.75 ^c
Heat production unit material transportation distance	$D_{hs,t}$	[km]	500 ^a	500 ^a	500 ^a
Heat production unit material transportation vehicle fuel consumption without load	$FC_{hs,wl}$	[l/km]	0.207 ^b	0.207 ^b	0.207 ^b
Heat production unit material transportation vehicle fuel consumption with full load	$FC_{hs,fl}$	[l/km]	0.276 ^b	0.276 ^b	0.276 ^b
Heat production unit transportation vehicle maximum capacity	$C_{hs,max}$	[kg]	10000 ^b	10000 ^b	10000 ^b

^aassumed, based on the high heating value, ^bJia et al. (2010), ^cCERTIF (2013);

As for the infrastructure placement, it was assumed that the trenches within the district are excavated with the CAT444F backhoe loader/excavator (with the backhoe bucket dimensions varying from system to system, depending on the required trench dimensions). Additionally, due to the small dimensions of the pipes, it was assumed that there is no need for the use of heavy pipe laying machinery and that human labor is sufficient for pipe laying process. Furthermore, the use of motor graders and surface compactors was not considered. All

materials and elements were assumed to be transported with trucks, with the maximum capacity varying depending on the amounts of materials to be transported. The expected lifetime of each system was assumed to be 25 years. The materials required for the central boiler construction were estimated based on the data provided within the papers of Nitkiewicz & Sekret (2014) and Ulgiati & Brown (2002), while the material requirements for individual natural gas boilers were obtained from the study of Oliver-Solà et al. (2009b). The amount of materials for solar plant and thermal storage construction were estimated based on the work of Paoli et al. (2008) and solar panels certification documents (CERTIF, 2013). In order to calculate the Carnot efficiency of the system, the supply hot water was defined as the heat source ($T_{hsr}=353$ K) and ambient air in dwellings as the heat sink ($T_{hsn}=293$ K), thus resulting in $\eta_c=0.17$.

Table 9.3 Properties of the fuels combusted;

Definition	Item	Unit	Value
Diesel fuel low heating value	LHV _d	[MJ/l]	36.5 ^a
Natural gas low heating value	LHV _{ng}	[MJ/m ³]	34 ^b
Bioethanol low heating value	LHV _{be}	[MJ/kg]	26.9 ^c
Petroleum low heating value	LHV _{pe}	[MJ/kg]	49 ^b
Light fuel oil low heating value	LHV _{lo}	[MJ/kg]	46 ^d
Landfill gas low heating value	LHV _{lg}	[MJ/m ³]	18 ^e
Proportion of the bioethanol used in heat production	δ_{be}	[-]	0.80 ^f
Proportion of the petroleum used in heat production	δ_{pe}	[-]	0.15 ^f
Proportion of the light fuel oil used in heat production	δ_{lfo}	[-]	0.03 ^f
Proportion of the landfill gas used in heat production	δ_{lfg}	[-]	0.02 ^f
Fuel transportation distance per one delivery	D _{o,ft}	[km]	500 ^g
Transportation vehicle fuel consumption without load	FC _{ft,wl}	[l/km]	0.276 ^h
Transportation vehicle fuel consumption with full load	FC _{ft,fl}	[l/km]	0.207 ^h
Maximum vehicle capacity (liquid fuels)	C _{ft,max}	[m ³]	20.7 ^g
Maximum vehicle capacity (landfill gas)	C _{ft,max}	[m ³]	15 ^g

^aJamali-Zghal et al. (2013), ^bWorld Nuclear Association (2015), ^cU.S. Department of Energy (2011), ^dStockholm Convention on POPs (2105), ^eRajaram et al. (2011), ^fPerzon et al. (2007), ^gassumed, ^hJia et al. (2010);

Table 9.4 Overview of the systems/scenarios considered;

System type	Energy source	Heat prod. unit	System/Scenario name
<i>ESPEX district heating network</i>	Fuel mix	Central boiler	ESPEX DHN, CB, FM
	Natural gas	Central boiler	ESPEX DHN, CB, NG
	Solar energy	Solar plant	ESPEX, DHN, CB, SP
<i>Two-pipe district heating network</i>	Fuel mix	Central boiler	TP DHN, CB, FM
	Natural gas	Central boiler	TP DHN, CB, NG
	Solar energy	Solar plant	TP DHN, CB, SP
<i>Natural gas distribution network</i>	Natural gas	Individual boilers	NGN, IB

9.1.2 Results and discussion

Within this section, all major emergy flows are individually addressed and discussed. Emergy flows of main phases (construction and operation) are then compared, in order to identify the highest contribution to the environmental impact of each system considered in this study. Finally, calculated UEVs of heat delivered to the consumer are observed to determine the most suitable solution (from an environmental point of view) for providing the urban environments with heating services. An overview of calculated emergy flows for the scenarios addressed in this study is presented in Table 9.5, which is further discussed in detail.

9.1.2.1 Urban heating systems construction phase

Emergy flows of heat production units construction phases are presented on Fig.9.3. It should be noted that on this figure, the human labor was not accounted, since it is calculated for the construction of the whole system (refer to the methodology section of this thesis part). For the construction of central boiler, steel and stainless steel are used as dominant materials. These materials were created through raw material extraction and transformation processes with major impacts on the environment (as explained in detail in the paper of Olmez et al. (2015), compared to the processes for the main materials used in the solar plant construction phase (glass and propylene glycol for solar panels along with copper pipes and heat exchangers for the water tank)). This assumption can be verified by referring to the UEVs of the materials provided in Tables 9.6-9.7 and within the Appendix A of this manuscript. However, due to the size of the solar plant required to cover the district heat demand, considerable amounts of construction materials are required, which will ultimately result in higher construction emergy flow than for the central boiler construction ($1.30\text{E}+17$ sej compared to $1.19\text{E}+17$ sej, respectively). Accordingly, emergy flow of the material and element transportation for solar plant construction is significantly higher ($1.39\text{E}+16$ sej compared to $6.94\text{E}+15$ sej for the central boiler), since more diesel fuel is consumed during the transportation process. On the other hand, small individual gas boilers for all dwellings required significantly less materials for construction, resulting in rather low emergy flows ($2.44\text{E}+16$ sej and $1.16\text{E}+15$ sej for construction and material/element transportation, respectively), compared to other two solutions for heat production considered in this study. Thus, it can be concluded that the construction phase of individual gas boilers for dwellings had the best environmental performance.

The impact of materials used for the regarded network types infrastructure can be observed in Table 9.6, while the total network infrastructure construction emergy flow (with

Table 9.5 An overview of the calculated emergy flows for the regarded systems;

Emergy flow	Unit	Network type						
Construction		ESPEX DHN			TP DHN			NGN
		FM	NG	SP	FM	NG	SP	IB
Emergy of pipe production material	[sej]	2.76E+16	2.76E+16	2.76E+16	5.04E+16	5.04E+16	5.04E+16	2.12E+16
Pipe transp. emergy	[sej]	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15	1.01E+15
Trench excavation emergy	[sej]	4.54E+15	4.54E+15	4.54E+15	3.18E+15	3.18E+15	3.18E+15	1.44E+15
Excess ground material transp. emergy	[sej]	2.18E+15	2.18E+15	2.18E+15	1.85E+15	1.85E+15	1.85E+15	5.32E+14
Additional netw. cov. material transp. emergy	[sej]	1.03E+16	1.03E+16	1.03E+16	1.06E+16	1.06E+16	1.06E+16	2.20E+15
Additional material for netw. pl. emergy	[sej]	1.17E+18	1.17E+18	1.17E+18	2.09E+18	2.09E+18	2.09E+18	3.12E+17
Additional material for netw. pl. transp. emergy	[sej]	5.79E+15	5.79E+15	5.79E+15	5.79E+14	5.79E+14	5.79E+14	5.79E+14
Additional elements material emergy	[sej]	5.73E+14	5.73E+14	5.73E+14	1.99E+17	1.99E+17	1.99E+17	2.46E+17
Additional elements transp. emergy	[sej]	7.04E+14	7.04E+14	7.04E+14	3.35E+16	3.35E+16	3.35E+16	2.10E+16
Emergy of human labor for netw. constr.	[sej]	1.08E+18	1.08E+18	1.08E+18	1.08E+18	1.08E+18	1.08E+18	1.08E+18
Emergy of heat production unit material	[sej]	1.19E+17	1.19E+17	1.30E+17	1.19E+17	1.19E+17	1.30E+17	2.44E+16
Emergy of heat production unit transp.	[sej]	6.94E+15	6.94E+15	1.39E+16	6.49E+15	6.94E+15	1.39E+16	1.16E+15
Building subsystem material emergy	[sej]	2.53E+17	2.53E+17	2.53E+17	2.53E+17	2.53E+17	2.53E+17	2.58E+17
Dwelling subsystem material emergy	[sej]	1.52E+17	1.52E+17	1.52E+17	1.51E+17	1.51E+17	1.51E+17	1.53E+17
Building & dwelling system transp. emergy	[sej]	5.79E+15	5.79E+15	5.79E+15	5.79E+15	5.79E+15	5.79E+15	1.16E+15
Total	[sej]	<i>2.84E+18</i>	<i>2.84E+18</i>	<i>2.86E+18</i>	<i>4.01E+18</i>	<i>4.01E+18</i>	<i>4.02E+18</i>	<i>2.12E+18</i>
Operation (during the whole lifetime)		FM	NG	SP	FM	NG	SP	IB
Emergy flow of the fuels combusted	[sej]	2.33E+19	1.85E+19	1.20E+14	2.33E+19	1.85E+19	1.20E+14	1.93E+19
Emergy flow of the fuel transp.	[sej]	1.35E+19	1.82E+18	0	1.35E+19	1.82E+18	0	1.90E+18
Emergy of human labor for boiler operation	[sej]	1.44E+19	1.44E+19	1.44E+19	1.44E+19	1.44E+19	1.44E+19	3.69E+16
Employees traveling home-to-work	[sej]	1.97E+17	1.97E+17	1.97E+17	1.97E+17	1.97E+17	1.97E+17	3.77E+15
Total	[sej]	<i>5.13E+19</i>	<i>3.49E+19</i>	<i>1.46E+19</i>	<i>5.13E+19</i>	<i>3.49E+19</i>	<i>1.46E+19</i>	<i>2.13E+19</i>

the excavation and transportation included) is illustrated on Fig. 9.4. As it can be seen, the infrastructure placement phase had the most significant energy flow for all networks considered, due to the amounts and resource types used for trench excavation (diesel fuel (for the excavator and transportation vehicles) and covering material (sand, concrete and pavement)). It should be noted that for the networks with high-volume pipes (for large districts) with considerable dimensions, heavy machinery for pipe laying process (that have a high fuel consumption levels) would have to be used, which would result in even higher impact of the network placement process.

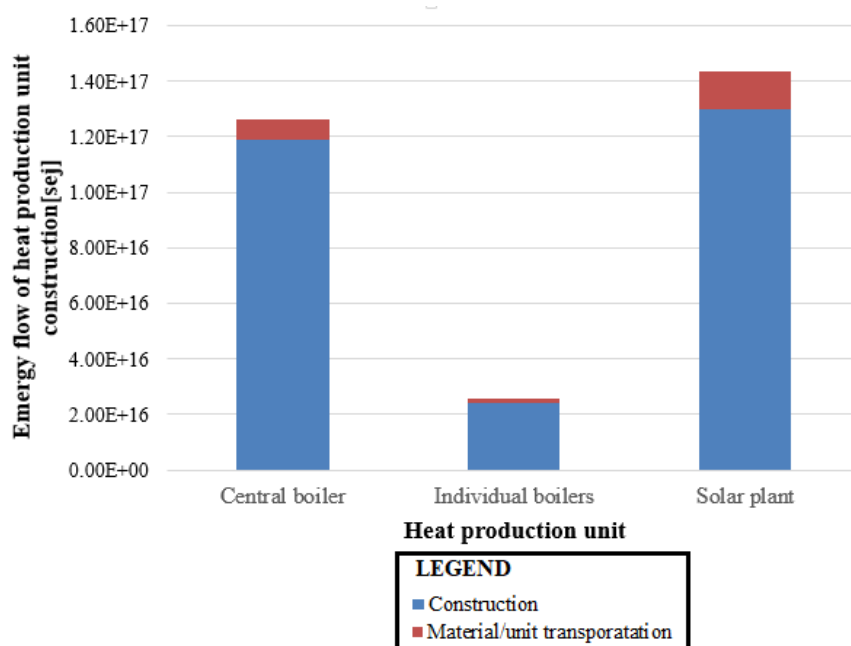


Figure 9.3 Energy flow of the heat production unit construction (without human labor);

On the other hand, the installation of additional network elements and pipe production processes had a significantly lower contributions to total energy flows, especially in the scenario of natural gas distribution networks. Natural gas distribution network is a single-pipe distribution system with compact dimensions (pipes and an additional trench infrastructure), compared to district heating networks considered in this study that consist of two and four pipes (for TP DHN and ESPEX network respectively) and have a less compact infrastructure (considering the required pipe insulation levels). These facts also explain a lower energy flow of the natural gas network pipe production process. However, the production of additional elements for natural gas network had a higher energy flow compared to TP DHN and especially ESPEX DHN, but the overall phase impact was significantly lower compared to the infrastructure placement phases for district heating networks. Consequently, it can be concluded

that the natural gas network infrastructure construction phase had the lowest pressure on the environment (out of three types of urban heat distribution systems considered in this study).

Table 9.6 Energy flows of infrastructure materials for the regarded network types;

ESPEX DHN NETWORK				
Network pipes (800m)				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Polyethylene	[g]	1.12E+06	6.70E+09	7.50E+15
Polystyrene	[kg]	3.84E+03	5.23E+12	2.01E+16
Additional material for network placement				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Polyethylene marker (bands)	[g]	9.60E+03	6.70E+09	6.43E+13
Brass (couplings)	[g]	6.40E+04	1.33E+10	8.51E+15
Galvanized steel (wedges)	[g]	4.24E+04	3.53E+09	1.50E+14
Sand	[g]	8.87E+08	1.27E+09	1.13E+18
Pavement	[kg]	1.71E+04	3.65E+12	6.24E+16
Concrete	[g]	2.57E+07	8.81E+08	2.26E+16
Additional material and resources for network elements				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Stainless steel (heat exchanger)	[g]	1.00E+05	5.25E+09	5.25E+14
Cast iron (pumps)	[g]	2.00E+04	3.37E+09	6.74E+13
Electricity	[J]	7.76E+06	1.15E+05	8.92E+11
TWO-PIPE DHN NETWORK (DN100)				
Network pipes (800m)				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Steel	[g]	1.87E+06	2.10E+09	3.93E+15
Polyurethane	[kg]	3.30E+03	6.99E+12	2.31E+16
Polyethylene	[g]	3.76E+06	6.70E+09	2.52E+16
Additional material for network placement				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Sand	[g]	9.13E+08	1.27E+09	1.16E+18
Pavement	[kg]	1.71E+04	3.65E+12	6.24E+16
Concrete	[g]	2.57E+07	8.81E+08	2.26E+16
Additional material and resources for network elements				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Sand (surface box)	[g]	3.54E+07	1.27E+09	4.50E+16
Limestone (surface box)	[g]	2.31E+06	1.27E+09	2.93E+15
Cement (surface box)	[g]	7.46E+05	2.94E+09	2.19E+15
Cast iron (surface box)	[g]	2.81E+06	3.37E+09	9.47E+15
Ceramic brick (surface box)	[kg]	3.04E+04	4.77E+12	1.45E+17
Stainless steel (pumps)	[g]	3.02E+04	5.25E+09	1.59E+14
Cast iron (pumps)	[g]	2.72E+05	3.37E+09	9.17E+14
Electricity	[J]	7.76E+06	1.15E+05	8.92E+11
NATURAL GAS DISTRIBUTION NETWORK				
Network pipes (800m)				
Item	Unit	Input	UEV [sej/unit]	Solar energy [sej]
Polyethylene	[g]	3.27E+06	6.70E+09	2.19E+16

Table 9.6 Continued

Additional material for network placement				
Sand	[g]	1.87E+08	1.27E+09	2.37E+17
Pavement	[kg]	1.71E+04	3.65E+12	6.24E+16
Concrete	[g]	2.57E+07	8.81E+08	2.26E+16
Additional material and resources for network elements				
Item	Unit	Input	UEV [sej/unit]	Solar emergy [sej]
Sand (surface box)	[g]	3.53E+07	1.27E+09	4.48E+16
Limestone (surface box)	[kg]	2.30E+03	1.27E+12	2.92E+15
Cement (surface box)	[g]	7.33E+06	1.23E+09	9.02E+15
Ceramic brick (surface box)	[kg]	3.04E+04	4.77E+12	1.45E+17
Cast iron (surface box)	[g]	2.81E+06	3.37E+09	9.47E+15
Electricity	[J]	7.76E+06	1.15E+05	8.92E+11

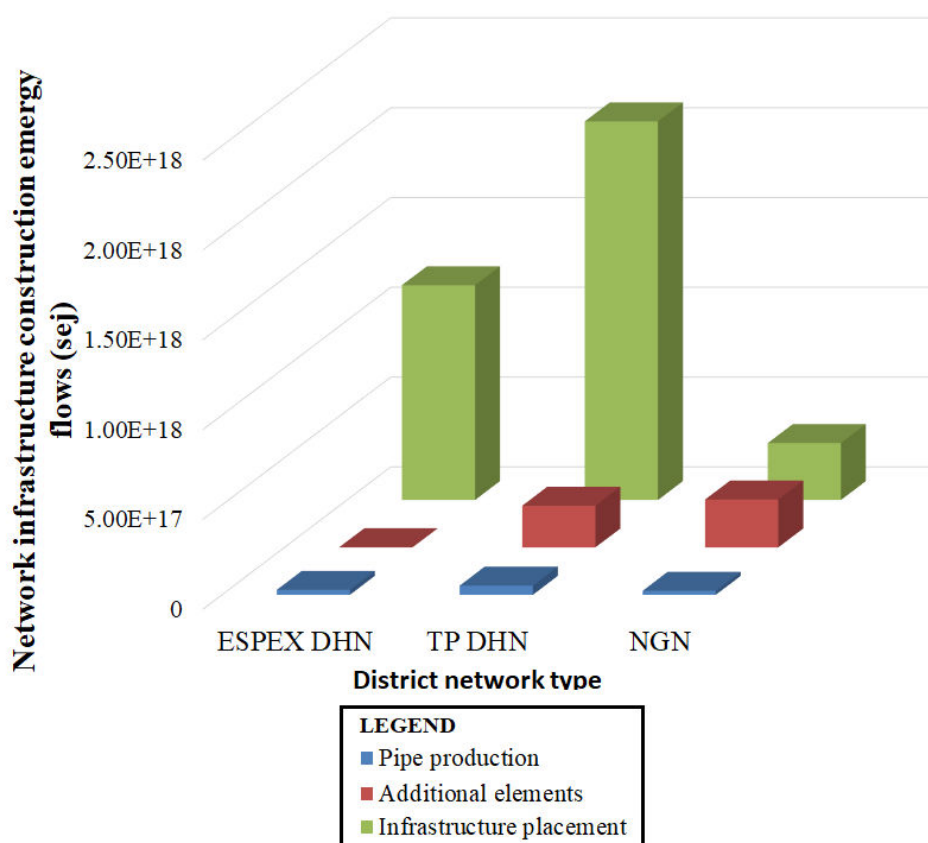


Figure 9.4 Emergy flow of the network infrastructure construction (without human labor);

Emergy flows of materials used for building subsystems considered are given in Table 9.7. Heat exchangers (radiators) in dwellings are common elements for both district heating and natural gas distribution systems, while the rest of the inventory differs due to the different physical properties of hot water and pressurized natural gas, along with additional safety requirements and elements for the natural gas infrastructure. Thus, building subsystems construction phase had a slightly lower emergy flow than the building subsystems for district heating networks ($4.11\text{E}+17$ sej compared to $4.12\text{E}+17$ sej, respectively, with transportation

energy flow for these subsystem elements accounted). However, for high-volume district heating networks, building subsystem is usually not connected directly to supply and return pipes due to the high pressure difference, and the whole system is divided into two (with district heating network being the primary circuit and building subsystem being the secondary circuit, where the heat between circuits is exchanged in substations) or even three circuits (if there is an additional circuit between the substation and building heating system, it would represent a secondary circuit while the building subsystem would be a tertiary circuit). However, comparing the emergy flows of building heating subsystem construction with emergy flows for network infrastructure placement, it is clear that the impact is quite minor (as it can be seen from comparing the values from Table 9.6 and Fig.9.4). This justifies the assumption from the previous section that the difference between the building subsystems for various district heating network types can be neglected, if the network infrastructure placement process is taken into the account.

Table 9.7 Emergy flows of the building subsystem infrastructure materials;

BUILDINGS CONNECTED TO DISTRICT HEATING NETWORKS				
Buildings subsystems				
Item	Unit	Input	UEV [sej/unit]	Solar emergy [sej]
Steel (service pipes)	[g]	2.42E+07	2.10E+09	5.08E+16
Polyurethane (service pipes)	[kg]	5.45E+03	6.99E+12	3.81E+16
Polyethylene (service pipes)	[g]	6.85E+06	6.70E+09	4.59E+16
Brass (flow limiter)	[g]	5.10E+03	1.38E+10	7.04E+13
Aluminum (heat meter)	[kg]	1.16E+02	9.65E+11	1.12E+14
PVC (heat meter)	[kg]	1.65E+01	7.49E+12	1.24E+14
Bronze (tap)	[g]	1.11E+05	1.19E+12	1.32E+17
Rubber (tap)	[kg]	1.12E+00	5.48E+12	6.14E+12
Dwelling subsystems				
Item	Unit	Input	UEV [sej/unit]	Solar emergy [sej]
Galvanized steel (heat exchanger)	[g]	3.75E+06	3.53E+09	1.32E+16
Stainless steel (heat exchanger)	[g]	4.46E+05	5.08E+09	2.27E+15
Copper (heat exchanger)	[g]	3.56E+06	5.48E+09	1.95E+16
Polyurethane (heat exchanger)	[kg]	4.46E+02	6.99E+12	3.12E+15
PVC(heat exchanger)	[kg]	7.13E+02	7.49E+12	5.34E+15
Bronze (tap)	[g]	1.11E+05	1.19E+12	1.32E+17
Rubber (tap)	[kg]	1.12E+00	5.48E+12	6.14E+12
BUILDINGS CONNECTED TO NATURAL GAS NETWORK				
Buildings subsystems				
Item	Unit	Input	UEV [sej/unit]	Solar emergy [sej]
Galvanized steel (Pe-Cu transition)	[g]	7.48E+02	3.56E+09	2.66E+12
Rubber (Pe-Cu transition)	[kg]	1.22E-01	5.48E+12	6.69E+11
Copper (Pe-Cu transition)	[g]	3.06E+02	1.52E+09	4.65E+11
Galvanized steel (service line)	[g]	1.02E+03	3.56E+09	3.63E+12
Copper (service line)	[g]	6.54E+05	5.48E+09	3.58E+15
Bronze (tap)	[g]	7.57E+04	1.19E+12	9.01E+16
Rubber (tap)	[kg]	7.65E-01	5.48E+12	4.19E+12

<i>Table 9.7 continued</i>				
Brass (gas meter)	[g]	2.95E+06	1.98E+10	5.84E+16
PVC (gas meter)	[kg]	2.67E+02	7.49E+12	2.00E+15
Cast iron (gas meter)	[g]	3.14E+05	3.37E+09	1.06E+15
Glass fiber (gas meter)	[g]	1.04E+06	2.28E+09	2.37E+15
Rubber (gas meter)	[kg]	1.12E+00	5.48E+12	6.14E+12
Bronze (gas meter)	[g]	1.11E+05	1.19E+12	1.32E+17
Galvanized steel (closet)	[g]	2.09E+06	3.56E+09	7.44E+15
Dwelling subsystems				
Item	Unit	Input	UEV [sej/unit]	Solar emery [sej]
Galvanized steel (heat exchanger)	[g]	3.75E+06	3.56E+09	1.34E+16
Stainless steel (heat exchanger)	[g]	4.46E+05	5.25E+09	2.34E+15
Copper (heat exchanger)	[g]	3.56E+06	5.48E+09	1.95E+16
Polyurethane (heat exchanger)	[kg]	4.46E+02	6.99E+12	3.12E+15
PVC(heat exchanger)	[kg]	7.13E+02	7.49E+12	5.34E+15
Steel (downpipe)	[g]	3.63E+03	2.10E+09	7.62E+12
Copper (downpipe)	[g]	1.38E+06	1.52E+09	2.10E+15
Bronze (tap)	[g]	1.11E+05	1.19E+12	1.32E+17
Rubber (tap)	[kg]	1.12E+00	5.48E+12	6.14E+12
Brass (manometer)	[g]	2.48E+04	1.38E+10	3.42E+14
PVC (manometer)	[kg]	1.65E+01	7.49E+12	1.24E+14

By comparing the total emery flows of construction phases for the systems studied (Fig.9.5, with materials, transportation and human labor accounted), it can be concluded that the construction of natural gas distribution network with individual boilers had the lowest impact on the environment (with the lowest emery flow between the studied systems, $2.12\text{E}+18$ sej), while the construction of traditional two-pipe district heating system had the highest impact (for all heat source scenarios, $4.01\text{E}+18$ sej on average). Additionally, taking into consideration results from Fig. 9.4 and Table 9.5, it is clear that the network infrastructure has the most significant contribution to the environmental performance of district systems construction phase, due to the amount of materials and additional resources required for infrastructure placement.

9.1.2.2 Urban heating systems operation phase

Regarding the operation of the systems, the use of fossil fuels (petroleum, oil fuel, natural gas) was found to be the most environmentally intensive (see Table 9.5), due to the fact that significant amounts of resources from the environment were initially used for fossil fuels creation (carbonization under high pressure and temperature) during a long time period. On the other hand, the use of solar energy for producing the same amount of heat had a notably lower emery flow ($1.20\text{E}+14$ sej compared to $1.93\text{E}+19$ sej and $2.33\text{E}+19$ sej for the natural gas and described fuel mix respectively).

As previously mentioned, emergy flows of fuels combusted during the systems operation phase were found to have a significantly higher impact on the environment than the processes during the construction phase. However, some technical aspects of heat sources considered should be taken into account before making a final decision. Barroso et al. (2010) noted that for the use of bioethanol in gasoil boilers, some aspects of boiler operation (such as gas recirculation fraction, steam cooling systems and percentage of oxygen in the exhaust gases) should be modified in order to avoid potential reductions in the capacity. Solar plant requires significantly more space for allocation (which increases proportionally with the increase of heat demand, i.e. number of solar panels required), while natural gas requires an existing regional distribution network for connection (another solution could be the use of gas reservoirs in each building, but an additional amount of diesel fuel used to transport natural gas to frequently refill these reservoirs would worsen the environmental performance of the system). While it was assumed that the employees work over the whole year to operate the boiler and the network, for the natural gas distribution network it was assumed that the employees check the installations in building systems once per year (as it was assumed that the district heating plant is within the studied system limits, while the natural gas network is connected to the regional network that is passing by the system limits - thus the gas distribution center with reservoir and pumps was considered outside the system). Consequently, emergy flows of employees commuting to work were lower for the natural gas network scenario.

With both construction and operation emergy flows calculated for the whole lifetime of the regarded systems, UEVs of heat delivered to consumers (during the considered system lifetime) can be calculated (Table 9.8) and compared on the same basis (the lower the UEV, the better the environmental performance of the system, since lower amounts and/or less environmentally intensive resources were required to produce the same amount of service - in this particular case heating). In all scenarios studied, district heating networks with solar plant as a heat production source had significantly better environmental performance than the district heating systems with centralized boiler (fueled by natural gas and proposed fuel mix) and natural gas distribution networks with individual boilers (due to the fact that the emergy flow of the fuels used has the most significant impact on the overall environmental performance of the system). However, in this case, ESPEX network coupled with solar plant proved to be more environmentally friendly than the traditional two-pipe system (with the UEVs of $9.03\text{E}+05$ sej/J compared to $9.64\text{E}+05$ sej/J, respectively). Natural gas distribution network proved to be the third best solution (with the UEV of $1.21\text{E}+06$ sej/J) from the environmental point of view, due to the less significant losses in distribution network, as well as high efficiency of small

individual gas boilers with condensing technology. Furthermore, less labor was required for system operation. The systems that used proposed fuel mix for the combustion in central boilers had the lowest environmental performance (with the UEV of $2.87\text{E}+06$ sej/J and $2.81\text{E}+06$ sej/J for two-pipe system and ESPEX network, respectively).

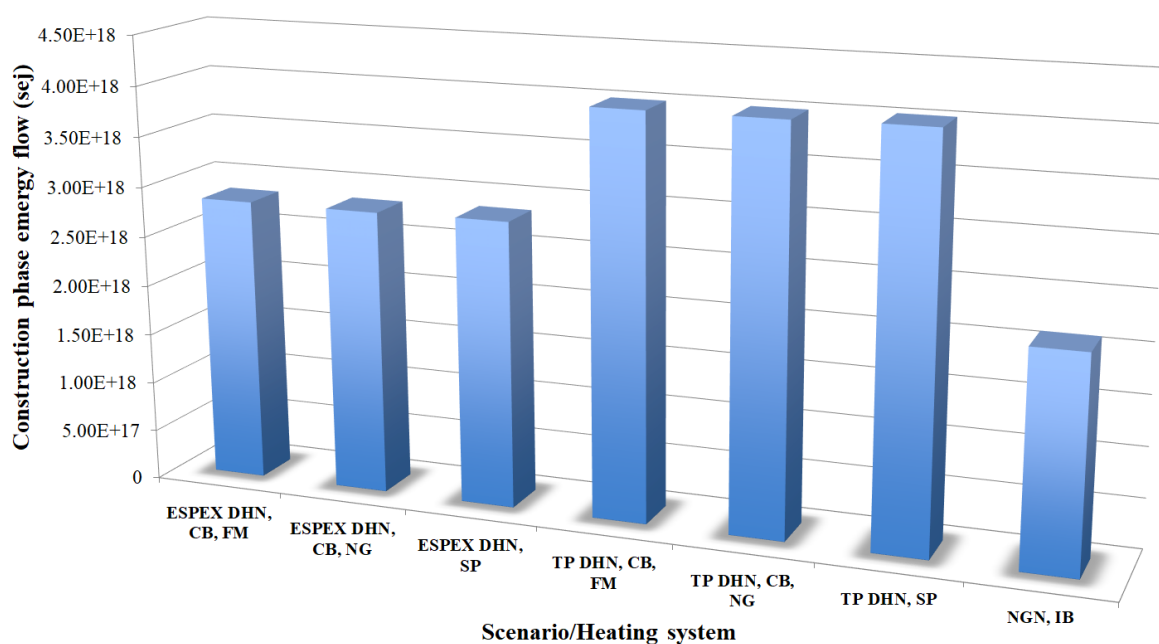


Figure 9.5 Total construction phase energy flow of the systems considered, with human labor accounted;

Table 9.8 Calculated UEVs of heat delivered to the consumer for the studied systems (construction and operation accounted);

District system scenario	UEV[sej/J]
ESPEX DHN, CB, FM	2.81E+06
ESPEX DHN, CB, NG	1.95E+06
ESPEX DHN, SP	9.03E+05
TP DHN, CB, FM	2.87E+06
TP DHN, CB, NG	2.01E+06
TP DHN, SP	9.64E+05
NGN, IB	1.21E+06

9.1.2.3 The impact of network length and heat demand density

Considering that some system parameters could vary from one location to the other, their impact on the results should be evaluated. Thus, the impact of network length (that varies depending on the size and configuration of the district) on total energy flow is evaluated (Fig.9.6). The length of the network was varied, while the total heat demand was kept constant,

to consider the districts with same heat demand, but lower heat density. The impact was the most significant for the systems with two-pipe district heating network, increasing the energy flow for an average of 6 % and 13 % (of the reference value, for each 1000 m network extension) for the scenario with central boiler and solar plant, respectively. Additionally, after the increase of network length for 2 km, the scenario with two-pipe network and solar plant had a lower environmental performance than the natural gas network scenario. This is due to the fact that heat demand was considered constant, while the network length was increased, and thus, after the increase of 2 km in length, network construction energy flow became dominant instead of the energy flow of fuels used). On the other hand, this was not the case for the ESPEX network scenario, since the construction phase energy flow is lower than for the two-pipe network (please refer to Table 9.5).

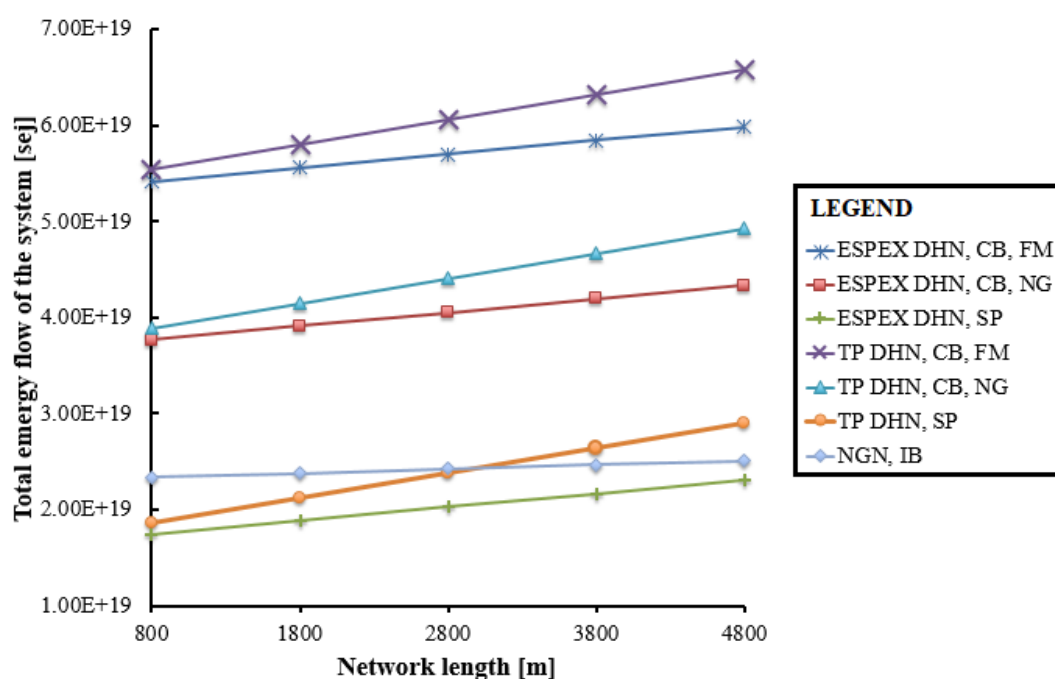


Figure 9.6 The impact of network length on total energy flow (construction and operation);

The impact of total district heat demand during the lifetime on the UEV of heat delivered to a consumer is represented on Fig.9.7 (annual heat demand was increased for 1 TJ in all instances). In this case, heat demand was varied while the network length was kept constant, to consider the districts with higher heat density. For district heating networks, the UEV decreases by an average of 6.25 % (of the reference value) with the increase in annual heat demand for 1 TJ. As for the natural gas networks, the rate of decrease is lower, being only 1 % with the increase in heat demand of 1 TJ.

As mentioned previously, in some cases of district heating networks, building installations are not directly connected to supply and return pipes. It is a common praxis in large distribution networks to construct a substation for each building (or a group of buildings) to avoid the problems with pressure differences between the network and building installations. Inside substations, heat exchangers are placed to enable heat exchange between the primary circuit (network) and secondary circuit (building installations). Required inventory for the construction of such substation in the studied district is presented in Table 9.9. The emergy flow of substations (with transportation accounted) was $3.03\text{E}+15$ sej, which changed the final result by 0.018 %.

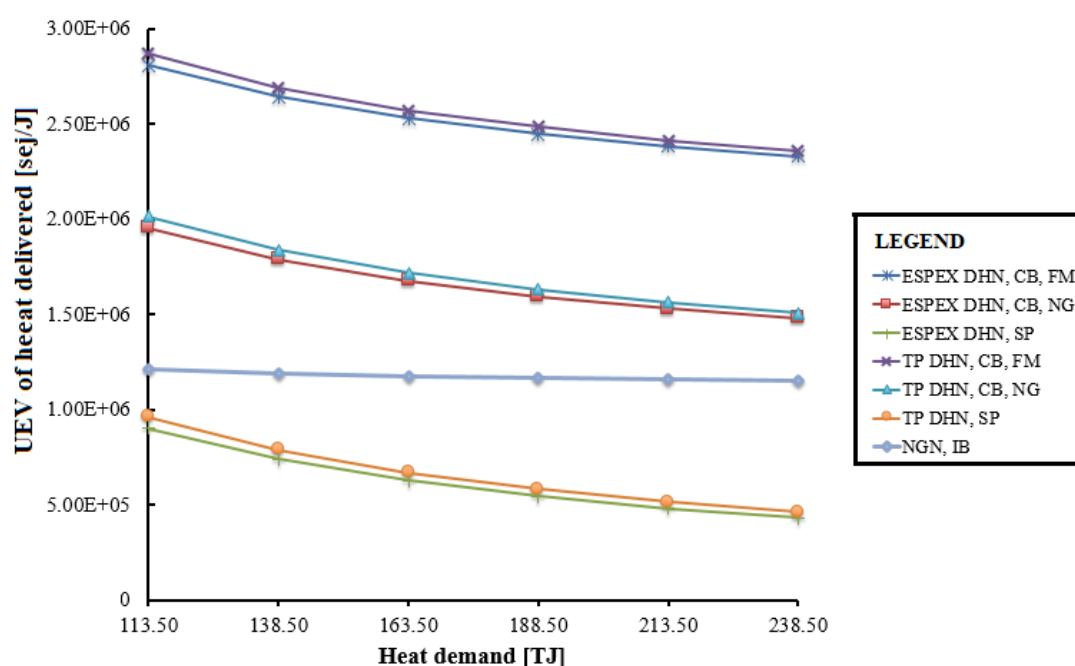


Figure 9.7 The impact of total district heat demand on the UEV of heat delivered (construction and operation);

Table 9.9 Emergy flow of substation materials;

BUILDING SUBSTATIONS (17)				
Item	Unit	Input	UEV [sej/unit]	Solar emergy [sej]
Galvanized steel	[g]	6.63E+05 ^a	3.53E+09	2.34E+15
Iron	[kg]	5.10E+01 ^a	3.15E+12	1.61E+14
Copper	[g]	2.55E+04 ^a	1.52E+09	3.88E+13
Plastics	[kg]	2.55E+01 ^a	4.37E+12	1.11E+14
Diesel for transp.	[J]	3.53E+09	1.36E+05	4.80E+14
Total				3.13E+15

^a Perzon et al. (2007);

Additionally, the influence of delivery distances is examined. From Table 9.10, it can be concluded that the delivery distances have a minor effect on the total annual energy flow (less than 1 % in all cases).

Table 9.10 The impact of delivery distances on the total annual energy flow of the systems;

	Change in the total annual energy flow [%]		
	ESPEX DHN	TP DHN	NGN
$\Delta D_{hs,t}(20\%)$	0.003	0.003	0.022
$\Delta D_{ni,pt}(20\%)$	0.001	0.001	0.003
$\Delta D_{ni,egt}(20\%)$	0.001	0.001	0.003
$\Delta D_{ni,amt}(20\%)$	0.005	0.004	0.002
$\Delta D_{ni,aet}(20\%)$	0.001	0.011	0.020
$\Delta D_{bs,t}(20\%)$	0.003	0.012	0.001
$\Delta D_{o,ft}(20\%)$	0.808	0.013	-
$\Delta D_{et}(20\%)$	0.116	0.089	0.005

9.1.3 Conclusions

The main scope of this study was an extensive comparison (from the environmental point of view) of systems suitable for providing urban environment with heating services. The methodology developed based on the energy theory proved to be suitable for the environmental performance comparison of such systems on a same basis (which is relevant considering that these systems differ in design and required resource input), and it is able to account for all resources directly and indirectly consumed in order to provide one unit of heating service to the consumer. As a case study, the district of Vråen, located in Värnamo (Sweden), was used as a case study.

Two different types of district heating systems (modern ESPEX and a traditional two-pipe network, which differ in distribution network design) with centralized heat production unit were considered. These systems were compared with a natural gas distribution network with individual boilers in each dwelling. All relevant subsystems were included in the study (heat production unit, distribution network and building installations). Furthermore, three different heat sources were considered for centralized heat production: boiler fueled by a fuel mix (bioethanol, petroleum, light fuel oil and landfill gas), central boiler fueled by natural gas and solar plant with flat-panel solar collectors.

Considering the heat production units, case study results showed that the construction phase of individual gas boilers for dwellings had the lowest contribution to the environmental degradation. Additionally, it can be noted that the network infrastructure placement had a major

impact on the environmental performance of district heating systems construction phase in all scenarios considered. On the other hand, the impact of building subsystems was minor. For all systems studied, operation phase was found to be the most important contributor to the total environmental impacts.

Based on the overall results, it can be concluded that a four-pipe ESPEX district heating network with central solar plant was the most suitable solution from the energy point of view. The second most suitable solution was the two-pipe district heating network with solar plant as the heat production unit. On the other hand, the networks with central boiler that used a fuel mixture (bioethanol and fossil fuels) and natural gas had a lower environmental performance than the natural gas distribution network with individual boilers (due to the environmental degradation caused by the use of petroleum and oil fuel in central boiler and higher efficiency of individual condensing boilers). Thus, it seemed that the fuel source used for heat production had a major role in the environmental performance of urban heating system.

However, to account for different district system configurations, a sensitivity study was conducted on network length and heat demand. Primarily, network length was increased while the heat demand was kept constant to take into account districts with low heat demand density. The results showed that after the increase in network length for 2 km, the scenario with two-pipe network and solar plant had lower environmental performance than the natural gas network scenario, indicating that the network construction phase became a dominant impact on system environmental performance. On the other hand, this was not the case for the ESPEX network scenario, since the construction phase energy flow is lower than for the two-pipe network. Additionally, to account for districts with high heat demand densities, heat demand was increased while the network length was kept constant, and the impact on UEV of heat delivered was analyzed. For district heating networks, the UEV of heat delivered during the system lifetime decreased for an average 6.25 % (of the reference value), with the increase in annual heat demand for 1 TJ, while for the natural gas networks, the rate of decrease was lower (1 % with the increase in heat demand of 1 TJ).

Finally, district heating systems can use various renewable energy sources for heat production beside the solar energy (geothermal energy, rivers, fjords and sewage treatment works outfall through the use of heat pumps). However, technical limitations of each heat production source and fuel used should be considered in order to make a final decision. Taking into account all other mentioned benefits of these systems (heat production outside municipalities, comfort level for the customers etc.), it can be concluded that the district heating

systems are the most suitable solution for providing the urban environment with sustainable heating services.

9.2 The environmental performance of urban heating systems within the urban environment

The aim of this methodology application is to assess to which extent the heat consumed from urban heating systems affects the environmental performance of the consumer (urban environment). Considering that the building ownership varies within the district (i.e. different parties own different buildings within the district), it would be of interest for building owners to be aware of the impacts solely for the building they own. Additionally, such information could be complementary to the information already existing within the building energy certificates (energy use and emission levels). Moreover, identifying the environmental performance of each building within the district would also be of interest for district heating operators and municipalities. This would enable these parties to identify for which building the heat consumed from the system affects the environmental performance the most, and act by proposing improvement measures to the building owner. Thus, in this study, the environmental performance of a single multi-apartment residential building is assessed (in order to evaluate the impact of heat consumed over building lifetime), which is the building type with highest building population in a modern urban environment. All renewable, non-renewable and purchased resources consumed during the building construction, operation (use), demolition and landfilling/recycling phases are taken into account. Furthermore, to account for possible heat demand reductions over the building lifetime, the impact of renovation measures discussed within the Part I of the thesis is taken into account (the impact of weather change was not considered, since in the Part I of the thesis it was found that this impact is minor compared to building renovation). As an added value, the impact of renovation measures on building environmental performance was assessed.

Thus, primarily, life-cycle cost of the building in its current state (without any renovation measures) is calculated and analyzed, highlighting the impact of heat consumed from the district heating system. Secondly, several renovation scenarios (refer to section 9.2.2.2) are applied in order to evaluate possible improvements in building environmental performance through the envelope and heating system renovation. Moreover, multiple time frames for the suggested renovation measures were considered. Additionally, the impact of these renovation measures on building environmental performance during the whole life-cycle is evaluated. Finally, the impact of parameters that are most likely to differ between the building types within the urban environment on the final result is evaluated.

9.2.1 Building data

A multi-apartment building located in the city of Šabac, Serbia, was used as a case study (Fig.9.8). The climate in Šabac area is continental, with cold winters, and hot, humid summers with well distributed rainfall patterns. The lowest average monthly temperatures occurs in January ($-2.3\text{ }^{\circ}\text{C}$), while the highest occurs in July and August ($27.3\text{ }^{\circ}\text{C}$). The building has a total useful surface of 4300 m^2 , and the construction was completed in 2010. The ground floor of the building is occupied by both commercial and residential premises, while the rest of the building consists of residential units (56 dwellings). The supporting structure of the building is in a form of reinforced concrete constructions and full-brick facades (insulated with polystyrene panels). The garage and heating substation are located within the underground level. The list of required materials for construction was obtained from the building project documentation with the help of engineers and architects from SET D.O.O., an engineering company which designed and completed building construction. The building is connected to a local district heating network, with heat production in natural gas boilers. Each apartment is equipped with a split unit for cooling. Additionally, building roof orientation and construction were planned in order to enable the installation of solar thermal systems in the future. For the building heat demand, the total annual heat demand was obtained from the building energy certificate (based on the Serbian legislative standards), while the annual electricity consumption was obtained from the grid operator. As mentioned previously, due to the time scale considered, the differences between the hourly energy demands over the year are not relevant in regard to this study scope, which is the reason why the total annual values are used. The suggested lifetime of buildings within the bibliography varies between 20 and 100 years. However, in this study, a 50 year lifetime was considered, due to the fact that major structural renovations were not considered. Additionally, Saynajoki et al. (2012) recommended shorter lifetimes in order to make results relevant in terms of meeting climate change mitigation goals set for the next few decades.

Considering the renovation scenarios, the date of building construction (2010) and the 50-year assumed timeline, four years were considered for the application of renovation measures: 2020, 2030, 2040, and 2050. Within the renovation scenarios, measures currently applied in Serbia described in the paper of Stefanović & Gordić (2016) were considered (i.e., the measures that have a high market penetration rate in the country of the selected case study). Furthermore, the installation of solar thermal collectors was also studied, as an improvement of the building energy system. In total, four renovation scenarios were considered:



Figure 9.8 Building used for the case study;

- **Renovation scenario A1:** Addition of 10 cm EPS (expanded polystyrene) layer on walls and triple-glazed windows;
- **Renovation scenario A2:** Addition of 15 cm EPS layer on walls and triple-glazed windows;
- **Renovation scenario B:** Installation of solar collectors without changes on the envelope;
- **Renovation scenario C:** Addition of 15 cm EPS layer on walls and triple-glazed windows, along with the installation of solar collectors;

The decrease in heat demand from the addition of EPS on the external walls and triple-glazed windows in renovation scenarios was adopted from the paper of Stefanović & Gordić (2016), who studied a similar building under the same climatic zone in Serbia. Decrease rates were adjusted proportionally to the slight difference in U-values between the buildings considered by the authors and the building addressed within this case study. The available heat output from solar collectors was calculated based on the available surface on the building rooftop, average solar irradiation values for Serbia and properties of the solar thermal collectors chosen for a case study (Jacques Giordano Industries C8 flat plated collectors). Due to the fact that solar collectors are only able to partially cover heat demand, it was considered that the rest of the demand is covered by district heating for the scenarios with solar collectors. For the recycling/landfilling process, only regional recycling potential available is considered (glass in a tile factory, glass and PVC in the windows factory, metals in the metallurgy etc.) and a local landfill.

Considering that the building renovation can occur in different periods over the building lifetime, the impact of renovation timeline on building environmental performance was assessed through the use of building UEV and emergy ratios (EYR – emergy yield ration, ELR – emergy loading ratio and EIR – energy investment ratio). As in the previous case study, for all emergy calculations performed, an updated global emergy baseline of $1.20\text{E}+25$ sej was used, calculated by Brown et al. (2016).

9.2.2 Results and discussion

Within this section, all major emergy flows of building life-cycle phases are individually addressed and discussed in order to evaluate the impact of each phase on building environmental performance (and consequently the impact of heat consumed during the building operation phase). Considering that building renovations could or could not happen over the building lifetime (depending on the owner's interest, financial status and local energy efficiency legislation), building life-cycle without renovation phase is discussed within the first part of the section, while the life-cycle with renovation phase included is addressed within the second part.

9.2.2.1 Building life-cycle without renovation phase

The outcomes of the building construction phase emergy analysis are given in Table 9.11. The construction of main building infrastructure resulted in the highest emergy flow of this phase ($2.68\text{E}+19$ sej), due to the amounts of environmentally intensive materials used for the reinforced concrete elements (especially the use of steel, $2.19\text{E}+18$ sej – which is created through raw material extraction and transformation processes with major impact on the environment (Olmez et al. (2015)). The second most environmentally intensive emergy flow in the construction phase ($5.19\text{E}+18$ sej) was caused by the additional resources and labor, due to the heavy diesel use for transportation services and the fact that 60 workers (50 construction workers + 10 engineers) were employed 8h per day over the course of 18 months (for further information about the environmental intensity of human labor based on the education level please refer to the book of Odum, (1996)).

Table 9.11 Emergy flows of building construction phase;

BUILDING CONSTRUCTION PHASE						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref. ¹	Emergy [sej]	Type
ENVIRONMENTAL INPUTS						
Land use (soil erosion)	$5.18\text{E}+12$	[J]	$9.42\text{E}+04$	Pulselli et al. (2007)	$4.88\text{E}+17$	R
Solar irradiation on the construction site	$1.16\text{E}+13$	[J]	$1.00\text{E}+00$	Odum (1996)	$1.16\text{E}+13$	R
Total					$4.88\text{E}+17$	

Table 9.11 continued

ADDITIONAL RESOURCES AND LABOR						
Diesel fuel for generators	2.98E+11	[J]	1.36E+05	Odum (1996)	4.05E+16	F
Diesel fuel for heavy machinery	3.95E+11	[J]	1.36E+05	Odum (1996)	5.36E+16	F
Diesel for employees transport	1.93E+10	[J]	1.36E+05	Odum (1996)	2.62E+15	F
Human labor	3.41E+03	[h]	2.49E+13	(calc.) ²	5.10E+18	F
Total					5.19E+18	
MAIN INFRASTRUCTURE						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Gravel	7.27E+06	[kg]	1.27E+12	Pulselli et al. (2011)	9.26E+18	R
Brick	3.09E+06	[kg]	2.79E+12	Pulselli et al. (2007)	8.63E+18	F
Cement	1.39E+06	[kg]	2.94E+12	Srinivasan et al. (2012)	4.08E+18	F
Lime	6.11E+04	[kg]	1.28E+12	Agostinho et al. (2013)	7.79E+16	F
Sand	4.01E+05	[kg]	1.27E+12	Srinivasan et al. (2012)	5.10E+17	R
Water	1.33E+06	[kg]	2.67E+09	Odum (1996)	3.54E+15	R
Iron	2.90E+05	[kg]	3.15E+12	Meillaud et al. (2005)	9.13E+17	F
Wood	5.99E+04	[kg]	6.68E+11	Meillaud et al. (2005)	4.00E+16	R
Polyester	4.31E+03	[kg]	7.34E+12	Schramski et al. (2009)	3.17E+16	F
Adhesive	1.00E+04	[kg]	7.25E+11	Schramski et al. (2009)	1.07E+16	F
Bituminous mass	3.67E+03	[kg]	2.40E+12	Mellino et al. (2015)	8.81E+15	F
Glass	1.97E+04	[kg]	1.07E+12	Pulselli et al. (2007)	2.11E+16	F
Steel	1.04E+06	[kg]	2.10E+12	Brown & Ulgiati (2002)	2.19E+18	F
Aluminum	2.03E+02	[kg]	9.65E+11	Meillaud et al. (2005)	1.96E+14	F
Galvanized steel	7.95E+03	[kg]	3.53E+12	Moss et al. (2014)	2.81E+16	F
Ceramic tile	8.36E+04	[kg]	2.43E+12	Brown & Buranakarn (2003)	2.04E+17	F
Polystyrene	5.36E+03	[kg]	5.23E+12	Meillaud et al. (2005)	2.80E+16	F
Paint	1.98E+04	[\$]	1.94E+13	Pulselli et al. (2007)	3.84E+17	F
Fly ash	3.96E+03	[kg]	1.78E+13	Srinivasan et al. (2012)	7.05E+16	F
PVC	1.26E+03	[kg]	7.49E+12	Pulselli et al. (2007)	9.45E+15	F
Roof tile	6.39E+04	[kg]	2.79E+12	Pulselli et al. (2007)	1.79E+17	F
Diesel fuel for transportation	8.74E+11	[J]	1.36E+05	Odum (1996)	1.19E+17	F
Total					2.68E+19	
WATER SUPPLY AND SEWERAGE SYSTEMS						
Building water supply and sewerage systems						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Galvanized steel	2.14E+04	[kg]	3.53E+12	Moss et al. (2014)	7.54E+16	F
PVC	1.47E+05	[kg]	7.49E+12	Pulselli et al. (2007)	1.10E+18	F
Polyethylene	9.68E+02	[kg]	6.70E+12	Pulselli et al. (2011)	6.49E+15	F
Brass	3.31E+02	[kg]	1.33E+13	Andrić et al. (2016)	4.41E+15	F
Polypropylene	2.33E+01	[kg]	7.49E+12	Moss et al. (2014)	1.74E+14	F
Cast iron	3.74E+02	[kg]	3.37E+12	Pulselli et al. (2011)	1.26E+15	F
Glass fiber	1.50E+00	[kg]	2.28E+12	Brown & Ulgiati (2002)	3.42E+12	F
Steel	2.92E+03	[kg]	2.10E+12	Brown & Ulgiati (2002)	6.15E+15	F
Iron	2.80E+01	[kg]	3.15E+12	Meillaud et al. (2005)	8.83E+13	F
Ceramic	5.79E+03	[kg]	2.43E+12	Brown & Buranakarn (2003)	1.41E+16	F
Glass	1.40E+03	[kg]	1.07E+12	Pulselli et al. (2007)	1.50E+15	F
Cement	1.85E+02	[kg]	2.94E+12	Srinivasan et al. (2012)	5.42E+14	F
Water	9.30E-01	[kg]	2.67E+09	Odum (1996)	2.48E+09	R
Gravel	1.21E+02	[kg]	1.27E+12	Pulselli et al. (2011)	1.54E+14	R
Diesel fuel for transportation	1.23E+10	[J]	1.36E+05	Odum (1996)	1.67E+15	F
Total					1.22E+18	
Water supply and sewerage grid connection						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Sand	6.73E+04	[kg]	1.27E+12	Srinivasan et al. (2012)	8.55E+16	R
Gravel	1.34E+05	[kg]	1.27E+12	Pulselli et al. (2011)	1.71E+17	R
Wood	4.91E+03	[kg]	6.68E+11	Meillaud et al. (2005)	3.28E+15	R
Polyethylene	1.17E+03	[kg]	6.70E+12	Pulselli et al. (2011)	7.82E+15	F

Table 9.11 continued

Cast iron	2.66E+02	[kg]	3.37E+12	Pulselli et al. (2011)	8.95E+14	F
PVC	1.60E+04	[kg]	7.49E+12	Pulselli et al. (2007)	1.20E+17	F
Water	7.19E+02	[kg]	2.67E+09	Odum (1996)	1.92E+12	R
Cement	1.14E+03	[kg]	2.94E+12	Srinivasan et al. (2012)	3.36E+15	F
Diesel fuel for transportation	2.76E+10	[J]	1.36E+05	Odum (1996)	3.75E+15	F
Total					3.96E+17	
HEATING AND COOLING SYSTEMS						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Steel	3.97E+03	[kg]	2.10E+12	Brown & Ulgiati (2002)	8.34E+15	F
Polyethylene	8.96E+02	[kg]	6.70E+12	Pulselli et al. (2011)	6.00E+15	F
Aluminum	3.12E+03	[kg]	9.65E+11	Meillaud et al. (2005)	3.01E+15	F
Glass wool	7.76E+02	[kg]	7.28E+12	Paoli et al. (2008)	5.66E+15	F
Brass	4.63E+02	[kg]	1.33E+13	Andrić et al. (2016)	6.17E+15	F
Stainless steel	2.88E+01	[kg]	5.25E+12	Odum (1996)	1.51E+14	F
Galvanized steel	1.19E+03	[kg]	3.53E+12	Moss et al. (2014)	4.22E+15	F
Copper	5.80E+02	[kg]	1.52E+12	Brown & Ulgiati (2002)	8.81E+14	F
Diesel fuel for transportation	3.07E+09	[J]	1.36E+05	Odum (1996)	4.16E+14	F
Total					3.48E+16	
ELECTRICAL INSTALLATIONS AND GRID CONNECTION						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Copper	3.21E+03	[kg]	1.52E+12	Brown & Ulgiati (2002)	4.87E+15	F
Aluminum sheet	4.81E+01	[kg]	1.25E+12	Almeida et al. (2010)	6.00E+13	F
Galvanized steel	4.00E+01	[kg]	3.53E+12	Moss et al. (2014)	1.41E+14	F
Steel	6.25E+03	[kg]	2.10E+12	Brown & Ulgiati (2002)	1.32E+16	F
Rubber	4.50E+01	[kg]	5.48E+12	Agostinho et al. (2013)	2.47E+14	F
Polyester	6.00E+01	[kg]	7.34E+12	Schramski et al. (2009)	4.41E+14	F
Iron	2.44E+03	[kg]	3.15E+12	Meillaud et al. (2005)	7.69E+15	F
Ceramics	2.59E+01	[kg]	2.43E+12	Brown & Buranakarn (2003)	6.30E+13	F
Plastic	4.25E+02	[kg]	4.37E+12	Meillaud et al. (2005)	1.86E+15	F
Glass	3.72E+02	[kg]	1.07E+12	Pulselli et al. (2007)	3.99E+14	F
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
Total					2.91E+16	
TELECOM. SYSTEMS AND GRID CONNECTION						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Copper	1.49E+02	[kg]	1.52E+12	Brown & Ulgiati (2002)	2.27E+14	F
PVC	3.19E+03	[kg]	7.49E+12	Pulselli et al. (2007)	2.39E+16	F
Aluminum sheet	7.14E+01	[kg]	1.25E+12	Almeida et al. (2010)	8.89E+13	F
Plastic	6.28E+03	[kg]	4.37E+12	Meillaud et al. (2005)	2.75E+16	F
Brass	4.62E+00	[kg]	1.33E+13	Andrić et al. (2016)	6.16E+13	F
Aluminum	1.32E+02	[kg]	9.65E+11	Meillaud et al. (2005)	1.28E+14	F
Glass	2.44E+00	[kg]	1.07E+12	Pulselli et al. (2007)	2.61E+12	F
Steel	3.87E+01	[kg]	2.10E+12	Brown & Ulgiati (2002)	8.15E+13	F
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
Total					5.22E+16	
ELEVATOR SYSTEMS						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Steel	1.56E+03	[kg]	2.10E+12	Pulselli et al. (2007)	3.28E+15	F
Rubber	2.00E+01	[kg]	5.48E+12	Agostinho et al. (2013)	1.10E+14	F
Iron	2.12E+03	[kg]	3.15E+12	Meillaud et al. (2005)	6.67E+15	F
Glass	1.24E+01	[kg]	1.07E+12	Pulselli et al. (2007)	1.33E+11	F
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
Total					1.03E+16	
TOTAL EMERGY FLOW OF BUILDING CONSTRUCTION						3.42E+19

¹All UEV values in this paper are updated to 1.25E+25 sej global baseline calculated by Brown et al. (2016);

²Human labor UEV was calculated based on the worker's education level and number as in the section 8.1;

Considering the operation phase (Table 9.12), heating services had the lowest environmental performance of all processes considered (with the total emergy flow of $8.20\text{E}+19$ sej). Heating services for the case study building are provided by the local district heating network, which requires significant amount of materials and labor to be deployed due to the large network infrastructure, causing significant environmental stress. Additionally, heat for the studied system was produced by combusting a fossil fuel (natural gas), generating further environmental impacts over the building lifetime. These findings are in accord with the results from the previous case study (refer to section 8.1). The second highest emergy flow ($9.25\text{E}+18$ sej) within this phase was caused by the building maintenance, considering that this process includes the use of materials, human labor, light machinery and energy.

Within the end-of-life phase (Table 9.13), the recycling processes were responsible for almost 95 % of the emergy flow ($1.06\text{E}+19$ sej compared to $5.18\text{E}+17$ sej for landfilling), due to the fact that in this particular case, maximum recycling potential was considered (85 % of the materials used were recycled and only 15 % were sent for landfilling). Additionally, recycling requires additional resources to complete the process. For example, concrete recycling (that had the lowest environmental performance) requires significant amounts of materials, energy and labor to run the concrete milling machines and pulsators, as addressed in detail in the paper of Yuan et al. (2011).

Table 9.12 Emergy flows of building operation phase;

BUILDING OPERATION (50 YEARS)						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Solar gains	$3.59\text{E}+14$	[J]	$1.00\text{E}+00$	Odum (1996)	$3.59\text{E}+14$	R
Electricity	$7.32\text{E}+12$	[J]	$6.39\text{E}+04$	Calculated ¹	$4.68\text{E}+17$	R, N ¹
Heat	$4.08\text{E}+13$	[J]	$2.01\text{E}+06$	Andrić et al. (2016)	$8.20\text{E}+19$	F
Water	$4.87\text{E}+18$	[kg]	$2.67\text{E}+09$	Odum (1996)	$4.87\text{E}+18$	R
Maintenance (labor & materials included)	$2.15\text{E}+05$	[m ²]	$4.30\text{E}+13$	Pulselli et al. (2007)	$9.25\text{E}+18$	F
Total					$9.66\text{E}+19$	
TOTAL EMERGY FLOW OF BUILDING OPERATION					$9.66\text{E}+19$	

¹UEV of the electricity from the grid was calculated based on the Serbian electricity production mix; same logic was used for electricity emergy flow division on renewable and non-renewable input;

Comparing the overall impact of life-cycle phases (Table 9.14), it can be noticed that 24 % of the total emergy flows was caused during the building construction phase, 68 % during the operation phase, while the end of life-cycle phase caused only 8 %. Thus, building operation phase had the worst environmental performance and the highest resource consumption over the life-cycle, which is in accordance with the findings from the previous studies within the bibliography (refer to literature survey section of thesis Part II). After dividing the total emergy

flow over the lifetime by the building useful surface, building UEV value of $3.30\text{E}+16$ sej/m² was obtained. Additionally, emergy indices were calculated, as previously explained within the methodology section of this article (refer to eq. (8.72) - eq. (8.74)) and are presented in Table 9.14. Suggested reference emergy indices values for comparison are taken from the paper of Brown & Ulgiati (1997). Since the EYR indicates emergy yield compared to the inputs purchased outside the system boundary, the value of 1.12 suggests that the system considered in this study is mostly dependent on purchased resources (please refer to eq.(8.72)), and has a low ability to exploit the local resources in its reference state (without any building envelope renovations considered). The EIR gives an evaluation if the process/product is a good user of invested emergy, in comparison with alternatives. The relatively high value of 7.95 obtained (considering that balanced resource use has the value of 1, refer to eq. (8.73)) indicates that the studied system is not a highly efficient user of the invested emergy. The measure of the process/product pressure on the local ecosystem, ELR, can also be considered as a measure of the ecosystem stress due to the production activity. The calculated value of 8.13 suggests that the studied system causes moderate ecosystem stress (values between 3 and 10 are considered moderate).

Table 9.13 Emergy flows of building end of life phase;

END-OF-LIFE PHASE						
RECYCLING ¹						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Glass	2.15E+04	[kg]	2.21E+11	Agostinho & Ortega (2013)	4.74E+15	F
Iron and steel	1.38E+06	[kg]	2.31E+11	Agostinho et al. (2013)	3.19E+17	F
Plastic and PVC	1.70E+05	[kg]	2.22E+11	Agostinho et al. (2013)	3.77E+16	F
Aluminum	3.58E+03	[kg]	2.21E+11	Agostinho et al. (2013)	7.89E+14	F
Bricks	3.09E+06	[kg]	2.03E+07	Buranakarn (1998)	6.28E+13	F
Concrete	8.53E+06	[kg]	1.19E+12	Yuan et al. (2011)	1.02E+19	F
Diesel for transportation	5.17E+11	[J]	1.36E+05	Andrić et al. (2016)	7.03E+16	F
Total					1.06E+19	
LANDFILLING						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
Non-recycled scrap material ²	2.39E+06	[kg]	2.10E+11	Buranakarn (1998)	5.02E+17	F
Diesel for transportation	1.15E+11	[kg]	1.36E+05	Buranakarn (1998)	1.56E+16	F
Total					5.18E+17	
TOTAL EMERGY OF END OF LIFE PHASE					1.11E+19	

¹Demolition, sorting and transformation accounted; ²Demolition accounted;

Table 9.14 Key performance indicators overview;

Emergy flow	Proportion
Building construction phase	24%
Building operation phase	68%
End of life phase	8%
Building UEV [sej/m²]	3.30E+16
Emergy indices	
Emergy yield ratio (EYR)	1.12
Emergy investment ratio (EIR)	7.95
Emergy loading ratio (ELR)	8.13

While the case study building is connected to the traditional two-pipe district heating system with heat production in natural gas fueled central boiler, similar buildings could be connected to other systems discussed within the section 8.1 of this manuscript (refer to Table 9.4). Thus, the impact of different heating systems on building environmental performance is presented in Table 9.15. It is clear that the utilization of heating services provided from the ESPEX network with renewable heat production would improve building environmental performance (indicated by lower building UEV and lower contribution of heat consumed from the system on total building emergy flow). The same conclusion can be made by observing the values of emergy indices – EYR value increase (improved building system ability to utilize local resources), while EIR and ELR values decrease (building system uses the invested resources in a more efficient manner, and has a reduced pressure on the environment (respectively)). The second best solution proved to be a traditional two-pipe network with a solar plant, while the third most optimal solution was found to be the natural gas distribution network with individual gas boilers in each dwelling, which is in accordance with findings from the previous case study (refer to section 8.1.3 of the manuscript).

Table 9.15 The impact of different systems on building environmental performance;

Heating system scenario	Building UEV[sej/m²]	EYR [-]	EIR [-]	ELR [-]	Contribution to total emergy flow [%]¹
TP DHN, CB, NG	3.30E+16	1.13	7.95	8.13	58
TP DHN, CB, FM	4.12E+16	1.10	10.16	10.38	66
TP DHN, CB, SP	2.31E+16	1.19	5.26	5.38	40
ESPEX DHN, CB, FM	4.06E+16	1.10	10.01	10.23	66
ESPEX DHN, CB, NG	3.25E+16	1.13	7.79	7.97	57
ESPEX SP	2.25E+16	1.20	5.10	5.22	38
ESPEX DHN, SP	2.54E+16	1.17	5.89	6.03	45

¹The share of emergy flow from heating services in total building emergy flow;

The same conclusion can be made by observing the impact of different heating systems on the shares of life—cycle phases in total building emergy flow (Table 9.16). Utilization of renewable heating services with modern distribution networks reduces the share of building

operation phase from 68 % (in reference case, TP DHN, CB, NG) up to 53 % (ESPEX DHN, SP). However, the results also indicate that even with the utilization of renewable heating services, building operation phase remains a dominant phase with the highest environmental impact over the building life-cycle.

Table 9.16 The impact of different heating systems on the shares of life—cycle phases in total building energy flow

Heating system scenario	Building construction phase [%] ¹	Building operation phase. [%] ¹	Building end-of-life phase [%] ¹
TP DHN, CB, NG	24	68	8
TP DHN, CB, FM	19	74	6
ESPEX DHN, SP	35	54	11
ESPEX DHN, CB, FM	20	74	6
ESPEX DHN, CB, NG	25	67	8
ESPEX DHN, SP	35	53	12
NGN, IB	31	59	10

¹Share of each phase within the building total energy flow;

9.2.2.2 Building life-cycle with renovation phase

The list of required resources for each measure considered within the renovation scenarios is given in Table 9.17. It should be noted that additional materials used within this phase are also added to the recycling/landfilling phase after the end of building lifetime. The considered heat demand reductions on an annual level after the proposed renovation measures (please refer to section 8.2.1 of this thesis part) were:

- **Renovation scenario A1:** 14.2 % reduction in annual heat demand; all heating services provided by the district heating network;
- **Renovation scenario A2:** 14.6 % reduction in annual heat demand; all heating services provided by the district heating network;
- **Renovation scenario B:** no reductions in heat demand; 30 % of the demand is covered by solar thermal collectors, 70 % covered by the district heating network;
- **Renovation scenario C:** 14.6 % reduction in annual heat demand; 30 % of the demand is covered by solar thermal collectors, 70 % covered by the district heating network;

An overview of the energy flows presented on Fig.8.5 for each scenario is provided in Table 9.18. As an example, the analogy from Fig.8.5 is illustrated for renovation scenario C (which is characterized by the highest heat demand reduction) on Fig.9.9. It is clear that the increase in total energy flow due to the building renovation was minor, along with the increase of recycling/landfilling energy flow (caused by the use of additional materials/services during the renovation phase). On the other hand, decrease in heat demand achieved by renovation

measures significantly reduced the emergy flow of building operation phase. Thus, the total emergy flow of building during its lifetime decreased.

Table 9.17 Building renovation phase emergy flows;

BUILDING RENOVATION PHASE						
MATERIAL INPUT						
Item	Raw data	Unit	UEV [sej/unit]	UEV ref.	Emergy [sej]	
EPS 10cm (Scenario A1)						
Polystyrene	3.96E+03	[kg]	5.23E+12	Meillaud et al. (2005)	2.07E+16	F
Cement	8.67E+03	[kg]	2.94E+12	Srinivasan et al. (2012)	2.54E+16	F
Water	5.41E+03	[kg]	2.67E+09	Odum (1996)	1.44E+13	R
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
EPS 12cm (Scenarios A2, B,C)						
Polystyrene	4.75E+03	[kg]	5.23E+12	Meillaud et al. (2005)	2.48E+16	F
Cement	8.67E+03	[kg]	2.94E+12	Srinivasan et al. (2012)	2.54E+16	F
Water	5.41E+03	[kg]	2.67E+09	Odum (1996)	1.44E+13	R
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
Triple glazed windows (Scenarios A1, A2, B, C)						
Glass	1.63E+04	[kg]	1.07E+12	Agostinho & Ortega (2013)	1.75E+16	F
Aluminum	1.26E+03	[kg]	9.65E+11	Agostinho et al. (2013)	1.22E+15	F
Diesel fuel for transportation	1.53E+09	[J]	1.36E+05	Odum (1996)	2.08E+14	F
Solar system (Scenarios B & C)						
<i>Solar panels</i>						
Glass	8.32E+03	[kg]	1.07E+12	Agostinho & Ortega (2013)	8.91E+15	F
Aluminum	2.89E+03	[kg]	9.65E+11	Agostinho et al. (2013)	2.79E+15	F
Copper	2.51E+03	[kg]	1.52E+12	Ulgiati & Brown, 2002	3.82E+15	F
Polyurethane	1.01E+03	[kg]	6.99E+12	Amponsah et al. (2012)	7.02E+15	F
Glass wool	8.90E+02	[kg]	7.28E+12	Paoli et al. (2008)	6.48E+15	F
Diesel fuel for transportation	4.41E+10	[J]	1.36E+05	Odum (1996)	5.98E+15	F
<i>Storage tank</i>						
Steel	4.25E+03	[kg]	2.10E+12	Pulselli et al. (2007)	8.94E+15	F
Polyurethane	2.87E+02	[kg]	6.99E+12	Amponsah et al., 2012)	2.01E+15	F
Propylene glycol	1.10E+02	[kg]	4.83E+05	(Paoli et al. (2008)	5.31E+07	F
Water	2.13E+02	[kg]	2.67E+09	Odum (1996)	5.68E+11	R
Copper	2.28E+02	[kg]	1.52E+12	Ulgiati & Brown (2002)	3.46E+14	F
Diesel fuel for transportation	8.81E+09	[J]	1.36E+05	Odum (1996)	1.20E+15	F
ADDITIONAL RESOURCES DURING THE BUILDING RENOVATION PHASE						
Solar irradiation on a construction site	8.17E+11	[J]	1.00E+00	Odum (1996)	8.17E+11	R
Electricity	5.16E+10	[J]	6.39E+04	Calc.	3.29E+15	R, N
Human labor	2.40E+02	[h]	1.36E+13	Calc.	7.98E+16	F
Diesel for employees transport	1.36E+05	[J]	1.36E+05	Odum (1996)	1.84E+14	F

Table 9.18. Overview of major emergy flows for the regarded scenarios;

	Construction emergy flow	Annual operation emergy flow (ref. state)	Annual operation emergy flow (after renovations)	Renovation emergy flow	End-of-life emergy flow (ref. state)	End-of-life emergy flow (after renovations)
Scenario	E_{cs} [sej]	$E_{op,rf}$ [sej/yr]	$E_{op,rn}$ [sej/yr]	E_{rn} [sej]	$E_{elf,rf}$ [sej]	$E_{elf,rn}$ [sej]
A1	3.42E+19	1.93E+18	1.70E+18	1.45E+17	1.11E+19	1.11E+19
A2	3.42E+19	1.93E+18	1.69E+18	1.49E+17	1.11E+19	1.12E+19
B	3.42E+19	1.93E+18	1.44E+18	3.07E+16	1.11E+19	1.12E+19
C	3.42E+19	1.93E+18	1.27E+18	1.80E+17	1.11E+19	1.12E+19

The impact of both the choice of building renovation scenario and the year of renovation on key performance indicators selected for this study (UEV and indices) is illustrated on Fig. 9.10 - Fig 9.13. From Fig 9.10., it is clear that the sooner the building renovation takes place, the better the environmental performance of the building over the lifetime (indicated by the lower UEV value). For renovation scenarios A1 and A2, the improvement in environmental performance was small, reaching 7 % if the building is renovated after the first decade of its lifetime and 4 % if the building is renovated after the fourth decade of its lifetime (2050). Thus, the average annual decrease in heat demand of 14.5 % corresponds to the decrease in building UEV value of $1.33\text{E}+15$ sej/m².

On the other hand, scenarios B and C proved to be more effective. For scenario B, building environmental performance increased by around 14 % if the solar collectors are installed after the first decade and 4 % in the case that renovations are delayed until the year 2040. As expected, the combination of heat savings with addition of renewable heat production source (scenario C) resulted in the best overall building environmental performance from all scenarios considered. If these measures are conducted after the initial 10 years of building lifetime, the overall environmental impact would be reduced by 18 %. Thus, it can be concluded that renovation measures were beneficial in all scenarios considered, and the use of additional materials and resources to conduct considered renovation measures did not have a negative impact on the building overall environmental performance. Comparing the UEVs obtained with the UEVs provided within the Table 9.15, it can be concluded that switching to renewable heat production systems would more significantly improve building environmental performance than envelope renovation (building UEV of $2.25\text{E}+16$ sej/m² obtained for the scenario with reference building state (no renovations) and ESPEX network with heat production in solar plant compared to building UEV of $2.25\text{E}+16$ sej/m²). Obviously, the combination of centralized renewable heat production, early building envelope renovation, as well as the installation of local renewable heat production units that partially cover the heat demand would

be the most optimal solution (resulting in building UEV of $2.13\text{E}+16$ seJ/m² for the case study building, in the case of ESPEX, SP heating system scenario and Renovation C scenario applied in 2020).

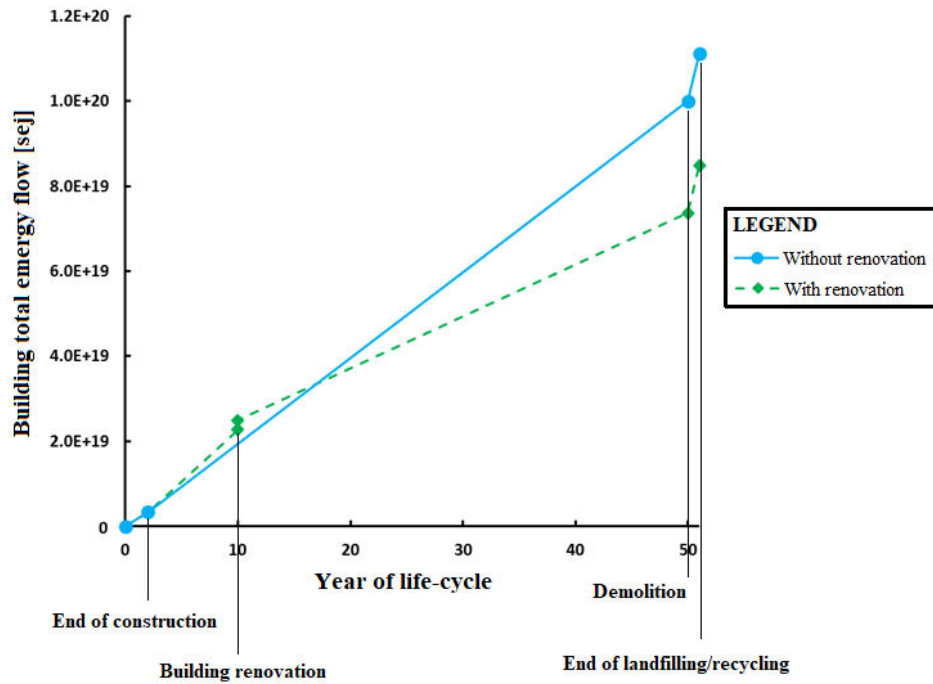


Figure 9.9 The impact of renovation measure on total building energy flow over lifetime (Scenario C);

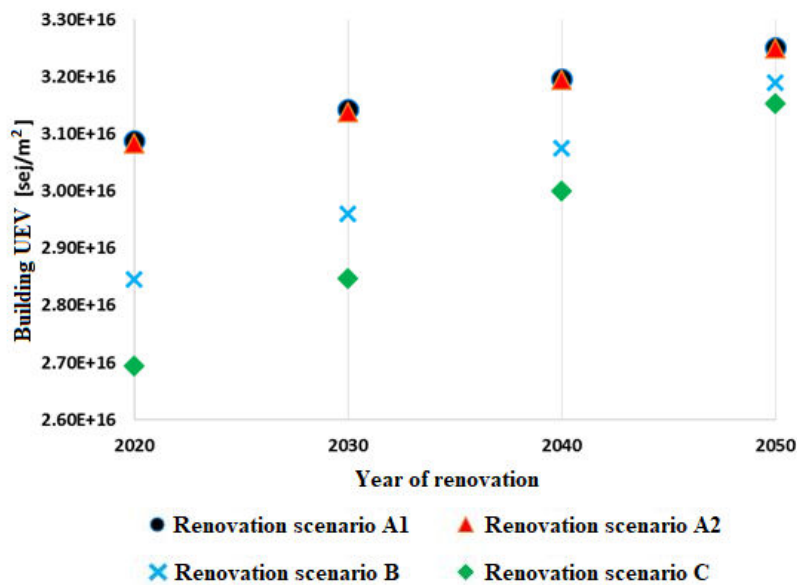


Figure 9.10 The impact of building renovation timing on building UEV (reference value $U_b=3.30\text{E}+16\text{sej/m}^2$);

The impact of building renovation on emergy yield ratio is given on Fig.9.11. The results suggest that the ability of the system to exploit local resources improves (the value of EYR increases) with building renovations, due to the fact that the amount of purchased resource with the highest emergy flow (heat, please refer to Table 9.12) decreases (please refer to eq.(8.72)). The value of the EYR was the highest (1.16) for Scenario C if the building is renovated in the year 2020 – as the amount of indigenous renewable resources used increases due to the use of solar energy for heating that partially substitutes (30 %) heat purchased from the district heating system. On the other hand, the addition of 10cm EPS layer barely changed the EYR (less than 1 % of the reference value (without renovations), even if the renovation is conducted after the first decade of the lifetime).

From Fig.9.12, it is clear that the system becomes more efficient in invested emergy use after the renovation measures (lower EIR values). For the scenarios that consider only envelope renovation (A1 and A2), the value of the EIR decreases by approximately 8 %, if early renovations are considered (2020). If the renovations are conducted in other years, the impact was found to be of less significance (less than 3 % in all cases). Finally, the impact of renovation measures on ELR is illustrated in Fig. 9.13. The addition of local renewable heat generation through the use of solar collectors accompanied by the building envelope refurbishments significantly decreases the system pressure on the local ecosystem. With this measure, the value of ELR decreases by over 20 % (in the case of 2020 renovation). Comparing the scenarios, it can be concluded that even with the partial coverage of heat demand by using renewable sources, the relief of environmental stress on local ecosystem is higher than for the simple reduction of purchased resources with the most significant emergy footprint (in this case, heating services from fossil fueled district heating system).

In order to address the data uncertainty and to account for different construction properties (that could be used in other buildings than the one addressed in the case study), the impact of parameters with the highest emergy flow on the building UEV was assessed (Table 9.19). The parameters were selected from all lifecycle phases (Table 9.11 – Table 9.13). The change in heat demand had the highest impact on the final result (building UEV), with approximately 5 % rate of building UEV decrease/increase with 10 % decrease/increase in heat demand. Other four resources considered had the impact lower than 1 % for each 10 % decrease/increase.

The observed building system has a high number of inputs (please refer to Tables 9.11-9.13), which justifies relatively low impact on the final result when a single input is modified.

The rates of increase and decrease were not linear, considering that the increase of one resource directly impacts the amount of other related materials used. For example, the increase in resources used for concrete recycling affects the amount of concrete used in the first place, its components (water, sand, gravel etc.), fuel used for transportation, human labor etc.

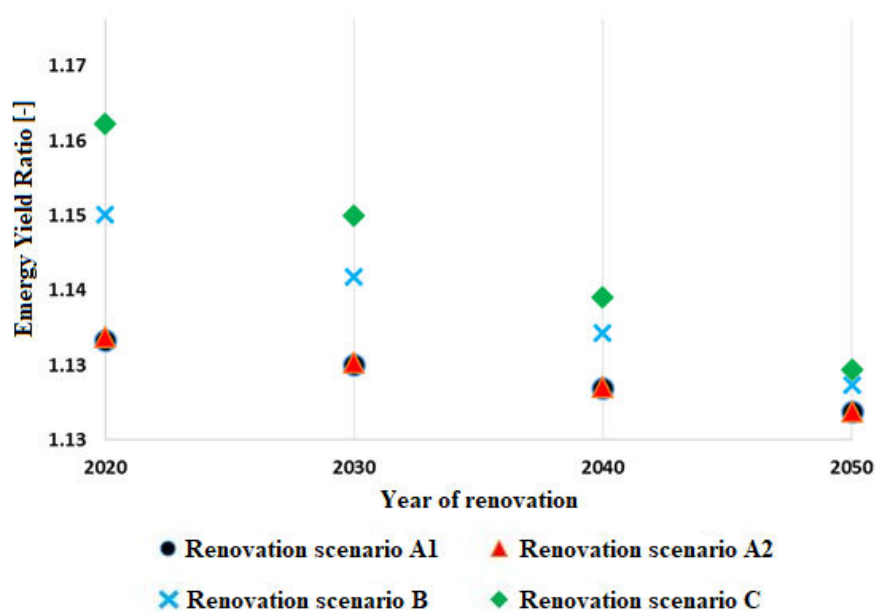


Figure 9.11 The impact of building renovation timing on EYR (reference value EYR=1.12);

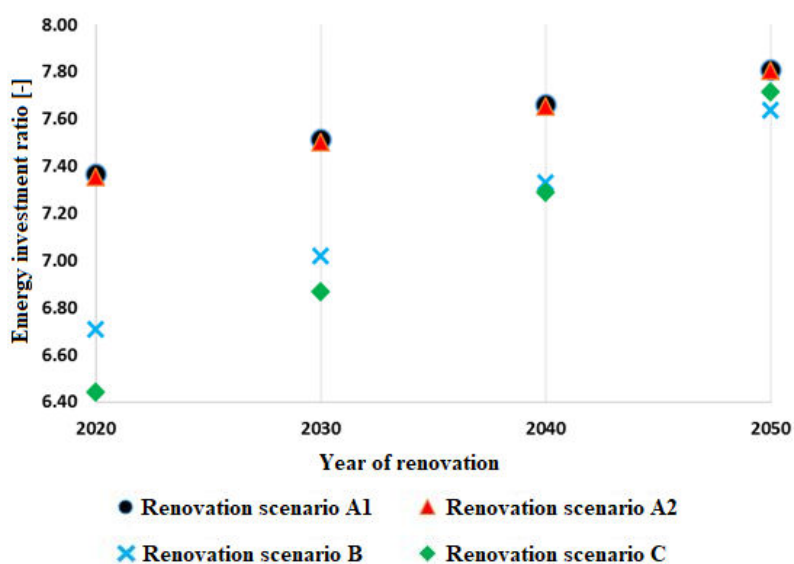


Figure 9.12 The impact of building renovation timing on EIR (reference value EIR=7.95);

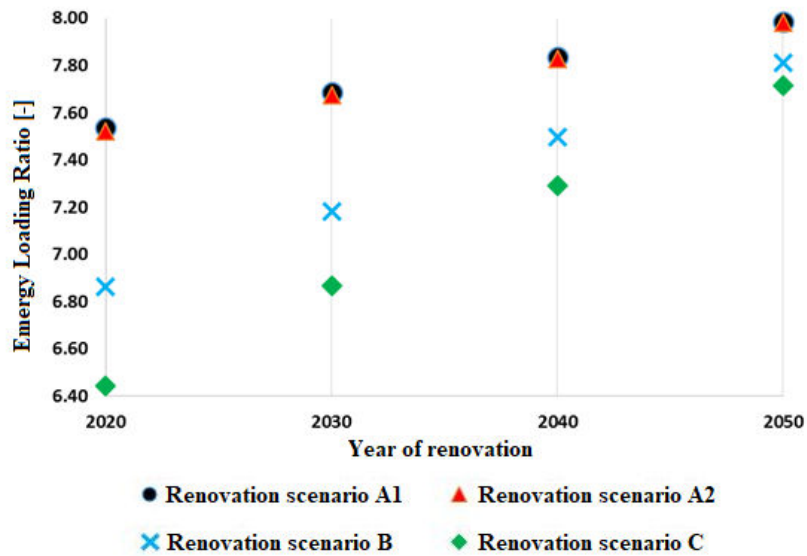


Figure 9.13 The impact of building renovation timing on ELR (reference value ELR= 8.13);

Table 9.19 Sensitivity analysis (Scenario C);

Item	Change in the building UEV [%]	
	Item decrease of 10%	Item increase of 10%
Heat demand	-4.78	+4.80
Concrete recycling	-0.88	+0.87
Gravel	-0.81	+0.78
Maintenance	-0.81	+0.77
Brick	-0.76	+0.73

9.2.3 Conclusions

The main scope of this methodology application was to assess the environmental performance of urban heating systems within the built environment. In order to do so, the environmental performance of a multi-family building was evaluated during its complete life-cycle (including the building construction, operation, renovation and end-of-life phases) to identify to which extent the heat consumed from the urban heating system contributes to overall building environmental footprint. Due to the probability of building renovation measures discussed within the Part I of this manuscript, the impact of renovation measures (that would decrease the heat demand and consequently heat consumption from the network) on building environmental performance is assessed. The methodology developed, based on the emergy theory, was applied on a case of multi-apartment building located in the city of Šabac, Serbia, and the case study data was obtained from the building contractor.

Considering that the building renovation could or could not occur during the building lifetime (depending on the economic and social conditions for the case study location, amongst

other factors), building life-cycle without renovation phase was addressed primarily. By comparing the overall impact of all life-cycle (without renovation) phases, 68 % of total emergy flow was caused during the building operation phase, 24 % during the construction phase and only 8 % during the end-of-life phase. The process with the lowest environmental performance during the operation phase in this case study was space heating, due to the fact that heat was produced from fossil fuel combustion and distributed through the use of large infrastructure (traditional two-pipe district heating system). Thus, it seems that in this case, heat consumed from the district heating system has a major contribution to the building overall environmental footprint. By analyzing the emergy indices, it can be concluded that the building system considered in its reference state (without any renovations) is heavily dependent on purchased resources and has a low ability to exploit indigenous resources (based on the EYR value obtained). Furthermore, based on the values of EIR and ELR, building system does not seem to have a high efficiency (from an emergy point of view) in exploiting the invested emergy, and produces a moderate stress on the local ecosystem.

However, as discussed within the section 8.1 of this manuscript, different energy systems could be used to provide heating services to the urban environment. Thus, the impact of different urban heating systems on building environmental performance was evaluated. As in the previous thesis chapter, the following systems were considered: ESPEX and traditional two-pipe district heating networks with various heat production units (central boiler with combustion of fuel mix or natural gas, and solar heat plant) and natural gas distribution network with individual boiler in each dwelling. The results indicated that in the case where heat is provided from the ESPEX network connected to a solar heat plant, the contribution of heat consumed to total building environmental performance reduced from 50 % to 38 % (consequently reducing the share of building operation phase from 68 % to 38 %) compared to the reference case (two-pipe network with natural gas-fueled central boiler). Moreover, by comparing the values of key performance indicators used in this study, it can be concluded that the provision of heating services from a modern type of district heating network (ESPEX) with heat production from renewable sources would improve overall building environmental performance – building UEV decreases (less intensive resources are used to produce the same amount of heat), EYR value increases (building system is more efficient in utilizing local resources), while EIR and ELR values decrease (building system uses the invested resources in a more efficient manner and has a lower pressure on the environment, respectively). The second best solution proved to be a traditional two-pipe network with heat production in solar heat plant, while the third most optimal solution was a natural gas distribution network with

individual boiler in each dwelling. These findings are in accordance with the conclusion from the previous case study (refer to chapter 8.1.3) – heat production source has the major impact on the environmental performance of large-scale heating systems within the urban environment.

When the renovation phase was included in the building life-cycle, it was found that for all renovation scenarios considered, renovation measures were beneficial from the environmental point of view and the use of additional materials and resources to conduct renovation measures considered did not have a negative impact on the building overall environmental performance. Conducting renovations after the first decade of building lifetime improved the overall building environmental performance by almost 50 % compared to same renovation measures conducted in the last decade of building lifetime, for all measures considered. The improvement in building envelope thermal performance, and the installation of local renewable heat production systems (solar thermal collectors) proved to be the most efficient renovation scenario to achieve better overall environmental performance of the system. Investing in partial heat production through the use of solar collectors (in this study, 30 % of the annual demand) resulted in a higher reduction in environmental stress than solely improving the envelope thermal performance. Finally, based on the emergy indices analysis, it can be concluded that the application of building renovation measures improves the overall building environmental performance, enables higher efficiency in indigenous resource use, and lowers the pressure on the local ecosystem. Obviously, combining the centralized heat production from renewable sources with early building renovation measures that include envelope renovation and the installation of local renewable heat production units (that partially cover existing heat demand) would significantly improve building environmental performance. In this case study, the combination of an ESPEX system connected to a solar heat plant and renovation scenario C (the addition of 15 cm EPS layer on walls and triple-glazed windows, along with the installation of solar collectors) application at the end of the first decade of building lifetime resulted in building UEV of $2.13\text{E}+16$ seJ/m² (compared to $3.30\text{E}+16$ seJ/m² in the reference case).

Within this study, only solar collectors were considered as a potential local renewable system. Further studies could consider geothermal heat production via heat pumps, or electricity production by using PV panels instead of solar thermal collectors. Additionally, it would be interesting to compare the impact of different renovation measures for different building types within the district – these buildings have been raised during different construction periods, during which different materials and construction techniques were used. However, in that case, major structural renovations would have to be considered in order to extend the building

lifetime (thus making old buildings suitable for thermal refurbishment measures instead of demolition).

CHAPTER 10: CONCLUSIONS, PART II

The main scope of thesis Part II can be defined in two points:

- Develop a suitable methodology for the evaluation of urban heating systems environmental performance within the urban environment;
- Compare the environmental performance of different urban heating systems, and draw conclusions of relevance for the scientific community, industry and governmental bodies, based on the results obtained from the series of case studies;

In order to evaluate the environmental performance of complex systems (such as urban heating systems), all resources consumed during the system lifetime should be considered. Previous research efforts within the bibliography utilised the LCA (Life-Cycle Assessment) to evaluate the environmental performance of such systems. However, LCA is a user-oriented method, which accounts solely for the resources directly consumed in order to produce a product or a service (in the case of systems studied in this thesis, a unit of heat delivered to the consumer). On the other hand, emergy analysis is a donor-oriented method that takes into account all resources directly and indirectly consumed by the system in order to provide a unit of product or a service. While there is several examples of LCA application on district heating systems within the bibliography, to the best knowledge of the author, there is no example of emergy theory application on these systems.

Additionally, in order to assess the performance of district heating systems within the urban environment, besides the environmental impact of these systems, it should be assessed to which extent the heat consumed from these systems affects the environmental performance of the consumer (i.e. buildings connected). Both LCA and emergy approaches were applied previously within the bibliography in order to evaluate building environmental performance. However, the impact of heat consumed from urban heating systems was not the main focus of these studies. Additionally, while most of the studies were focused on one or all of three phases of building lifecycle (construction, operation and demolition), the potential impact of different urban heating options (system type, heat production source) on building environmental performance during the operational phase was not explored, nor compared with other competitive systems (such as natural gas distribution networks). Moreover, in order to fully evaluate building environmental performance, all phases of building life-cycle should be taken into account (construction, operation, renovation and end-of-life (demolition, material sorting,

landfilling and/or recycling)). The effect of renovation phase could be of particular interest: by improving the building envelope thermal performance, heat consumption from the heating system would be reduced (consequently reducing the contribution of heat consumed from the system to the overall building environmental impact). However, on the other hand, it could also result in the increase of total building environmental impact (due to the use of additional materials and services during the renovation phase).

Thus, an environmental assessment methodology was developed within the Part II of this manuscript that is based on the emergy theory. The first part of the methodology addresses the environmental performance of urban heating systems, taking into account all resources directly and indirectly consumed during the system life-cycle phases: construction and operation (end-of-life phase was not considered, since there is no known case (within the bibliography, to the best knowledge of the author) of dismantling such a system, even after several decades of operation). The methodology developed can be applied on any urban heating system, which is demonstrated in this thesis by considering different system types within the case studies. The second part of the methodology addresses building environmental performance, by taking into account all direct and indirect inputs of the observed system over its life-cycle phases (building construction, operation, renovation and end-of-life). The methodology can be applied on any type of residential building, as long as the required input dataset is available. One of the main inputs, heat demand, was not calculated in this thesis part (Part II) by utilising the dynamic heat demand model developed within the Part I, due to the time scale considered. For the emergy methodology developed, total annual heat demand is required as an input. Since the difference between the hourly heat demand values within the total annual demand is not of high relevance (as previously proved within the bibliography), measured heat consumption data was used (where available) or a static model (where suggested by the local regulations).

The environmental performance of urban heating systems was evaluated on the case study of Vråen district, located in Värnamo (Sweden). This particular district was selected by reason that it has one of the modern district heating systems (ESPEX) in operation. Moreover, two additional scenarios were considered: a traditional two-pipe district heating system and a natural gas distribution network with individual gas boiler in each dwelling. Additionally, several options were considered as a heat source for district heating networks: a central boiler with fuel mix (bioethanol, petroleum, light fuel oil and landfill gas) and natural gas combustion, and a solar heat plant. The results indicated that within the construction phase, individual gas boilers had the lowest environmental impact compared to central boiler and heat plant. On the

other hand, the impact of heat production units, as well as building subsystems was significantly lower than the impact of network infrastructure placement during the system construction phase. However, for all systems considered, system operation phase had the highest contribution to the environmental degradation.

The extent of environmental degradation was mostly dependent on the design of distribution network and heat production source. Based on the case study results, it can be concluded that the four-pipe ESPEX district heating network with solar plant as heat production unit proved to be the most suitable solution for providing the urban environment with heating services (from the environmental point of view). The second most optimal solution was the system with two-pipe distribution network and heat production in solar plant. On the other hand, when both distribution network types were considered to be connected to the central boiler, fuelled by either natural gas or studied fuel mix, their environmental performance was lower compared to the environmental performance of natural gas distribution network with individual boilers (due to the environmental degradation caused by the combustion of petroleum and oil fuel in central boiler, as well as the higher efficiency of individual condensing boilers). Thus, it can be concluded that the type of fuel used for heat production has a major impact on the environmental performance of urban heating systems. However, technical limitations of each heat production source and fuel used should be considered in order to make a final judgment.

Considering that the system properties may vary depending on the case study location, the impact of two main parameters was considered: network length and annual heat demand. After an increase in network length of 2 km (for the same heat demand), the scenario with two-pipe network and solar plant had lower environmental performance than the natural gas network scenario, indicating that the network construction phase became a dominant impact on system environmental performance. On the other hand, this was not the case with the ESPEX network.

When the network length was considered to be constant, but the heat demand was varied (in order to account for districts with high heat demand densities), the UEV of heat delivered during the system lifetime decreased for an average 6.25 % (of the reference value), with the increase in annual heat demand of 1 TJ (for the case of district heating networks). On the other hand, in the case of natural gas distribution network, the decrease rate was lower (1 % with the increase in heat demand of 1 TJ).

In order to evaluate the environmental performance of urban heating systems within the urban environment (i.e. to which extent the heat consumed from these systems impacts the building environmental performance), methodology developed was applied on a multi-

apartment building located in the city of Šabac, Serbia (case study location was selected based on the suggestions from the bibliography that additional emergy applications should be conducted on case studies outside the U.S. and E.U.), which is connected to a traditional two-pipe district heating network with heat production in natural gas-fueled central boiler (addressed as the reference system in further text). Considering that the probability of building renovation depends on multiple factors (such as economic, social etc.), building environmental performance without the renovation phase is primarily discussed. The results indicated that 68 % of total emergy flow was caused during the building operation phase, 24 % during the construction phase and 8 % during the end-of-life phase. Heat consumed from the reference system had the highest contribution to the building environmental impact, due to the fact that heat was produced from fossil fuel combustion (natural gas) and distributed through the use of large infrastructure (traditional two-pipe district heating system). Thus, based on the results, it can be concluded that the heating system has a major effect on building environmental performance. The values of emergy indices (EYR, EIR and ELR) indicate that in its reference state, the observed building system is heavily dependent on purchased resources, has a low ability to exploit indigenous resources, does not have a high efficiency in utilizing the invested emergy and produces a moderate stress on the local ecosystem.

However, as discussed previously, different types of urban heating systems can be used to provide buildings with heating services. Thus, the impact of these systems is further evaluated and compared with the reference case. The results indicated that in the case that the studied building is connected to an ESPEX system with heat production in solar plant, the contribution of heat consumed to total building emergy flow would be 38 % instead of 50 % in the reference case. Consequently, the contribution of operation phase to total building emergy flow decreased from 68 % to 38 %. Moreover, by comparing the key performance parameters considered in this study (UEV and emergy indices), it can be concluded that the utilization of heating services from a modern type of district heating network (ESPEX) with heat production from renewable sources would improve overall building environmental performance. The second best solution proved to be a traditional two-pipe network with heat production in solar heat plant, while the third most optimal solution was a natural gas distribution network with individual boiler in each dwelling, which is accordance with the findings from the previous case study.

When the building renovation phase was included in the study (in order to evaluate the impact of renovation measures on building environmental performance), it was found that for all renovation scenarios studied (improvements in building envelope thermal performance and

addition of solar panels on building rooftop), these measures would reduce building environmental impact. Moreover, renovation timeline proved to be crucial: conducting renovations after the first decade of building lifetime improved the overall building environmental performance by almost 50 % compared to the same renovation measures conducted in the last decade of building lifetime. Additionally, the results indicated that by investing in partial heat production through the use of solar collectors (in this study, 30 % of the annual demand), higher reduction in environmental stress can be achieved compared to the case when only building envelope thermal performance was improved. Moreover, by analyzing the values of energy indices after the application of renovation measures, it can be concluded that these measures improve the overall building environmental performance, enable higher efficiency in indigenous resource use, and lower the pressure on the local ecosystem.

Obviously, the combination of centralized heat production from renewable sources and early building renovation with measures that include envelope improvement and the installation of local renewable heat production units (that partially cover existing heat demand) would significantly improve building overall environmental performance. In this particular case study, the combination of a modern four-pipe district heating network (ESPEX) connected to solar heat plant and renovation measure that include the addition of 15cm EPS layer on walls and triple-glazed windows, along with the installation of solar collectors (applied at the end of the first decade of the building lifetime), resulted in building UEV decrease of 34 % compared to the reference case.

Additionally, modern urban heating systems (and the ones currently in development stage) can use various renewable energy sources for heat production beside the solar energy (geothermal energy, rivers, fjords and sewage treatment works outfall through the use of heat pumps). However, technical limitations of these technologies should be considered in order to make a final judgment. The application of the methodology developed on these systems could further broaden the insight on the environmental performance of urban heating systems. Moreover, the districts are usually consisted of different building types that were erected during various historical periods and differ in both configuration and construction properties. Thus, applying the methodology developed on additional case studies would be of interest in order to provide an even deeper insight into the link between the urban heating systems and the environmental performance of urban environment.

CONCLUSION

11.1 Research motivation

Climate change is an unequivocal process, as proved by the observed air and ocean temperatures, widespread snow and ice melting along with the rise in an average sea level. The reports from intergovernmental bodies researching the causes, potential impacts and implications of climate change, suggest that it is *extremely likely* that the increased concentration of greenhouse gases caused by the anthropogenic activity is one of the main drivers of climate change. Considering that building sector is one of the major sources of greenhouse gas emissions, and taking into account a constant increase in built environment due to the population increase, migrations from rural to urban areas and the increase in the global domestic product per capita, the reduction of energy consumption and related greenhouse gas emissions from the building sector in the future present a challenging task. More specifically, considering that most of energy in buildings is typically consumed in order to maintain the comfort conditions (especially heating in countries with continental or colder climates), enabling sustainable heating services for the increasing urban environment could significantly contribute to the proposed global climate change mitigation measures.

District heating systems are commonly proposed in the literature as an environmentally friendly solution for providing heating services to the built environment. These systems have multiple benefits, such as centralized heat production located outside the city centres, large scale utilization of renewable heat sources and waste heat, overall environmental and economic efficiency, and improved comfort and security of heat supply for the consumers. Consequently, the expansion of the existing systems and the construction of new ones has been already proposed in the literature and within the official EU strategy reports that address the decarbonization of the EU energy system.

However, the construction of such systems requires significant capital costs that are returned through the heat sales throughout a long investment return period. Consequently, future reductions in heat demand could impact the feasibility of these systems by prolonging the investment return periods. Moreover, reduced heat demand and consequently changed heat demand profiles could impact the system operational parameters (required boiler capacity, heat production mix between the base load and peak load production units, frequent stops in production etc.), which would further impact the system efficiency and consequently technical

and economic feasibility of such systems. Due to the increase in outdoor air temperatures, the difference between the building internal air and external air temperature would decrease, reducing the amount of heat required to reach the internal comfort temperature. This effect can be addressed as the direct impact of climate change on building heat demand. Moreover, due to the building energy efficiency policies, directives (such as the Energy Performance of Buildings Directive, or the Directive 2010/31/EU) have been legislated in order to boost building renovation process across Europe. As a consequence of improved building envelope thermal performance, achieved by the building renovation measures, heat losses through the envelope would decrease, which would cause further reductions in heat demand. This aspect can be addressed as an indirect impact of climate change.

However, evaluating the environmental performance of a system based solely on emission levels during the system operation phase could provide misleading results - the environmental impacts associated with construction phase of such systems are frequently overlooked. Moreover, these aspects should be of interest especially for district heating systems, whose elements (high capacity heat production units, distribution networks with significant pipe diameters and connections with buildings through the use of substations or similar subsystems) are made of environmentally intensive materials (such as steel and iron for example). Consequently, in order to adequately evaluate the performance of complex systems (such as district heating systems), the impact of all resources directly and indirectly consumed during the system lifetime should be taken into account. Moreover, in order to assess the environmental performance of district heating systems within the urban environment, their performance should be compared with competitive solutions for the provision of built environment with heating services. Additionally, it should be evaluated to which extent the heat consumed from these systems affects the environmental performance of built environment (i.e. buildings connected to the system).

Thus, the scope of this thesis can be defined in two main points:

- The assessment of direct (changed weather variables) and indirect impacts (building renovation) of climate change on district heating systems;
- The environmental performance assessment of urban heating systems within the built environment, by taking into account all directly and indirectly consumed resources during the relevant life-cycle phases of the system;

11.2 Methodologies developed

Based on the literature survey on previous research efforts within the bibliography that addressed the topic of climate change impacts on building heat demand, it was concluded that there was an existing need for a dynamic building heat demand simulation tool that is able to take into account all relevant building parameters (geometrical and thermal), along with weather and building renovation scenarios, but does not require significant computing resources or time to perform the calculations. In addition, based on the previous studies that addressed simplified heat demand models, it was concluded that building energy demand models based on the thermo-electrical analogy (RC models) seem to be suitable for the suggested scope.

Thus, a model based on the thermo-electrical analogy was developed for this purpose, and used in combination with several other software and methods (CCWorldWeatherGen, ArcGIS, LiDAR) in order to develop the methodology for evaluating the climate change impacts on district heating systems. The heat demand model developed was verified through the comparison with Design Builder v4.6. (Energy Plus v.8.3) building energy demand simulation software and statistical heat demand data obtained from the national reports from governmental institutions of case study countries. The outcomes of the validation process were satisfactory, considering that the difference in calculated annual heat demand (for sample buildings) between the model developed and widely acknowledged Energy Plus software was on average 4.5 %, while when compared with the statistical heat demand data (based on the building type and construction period) from two national agencies reports, the difference was 10 % and 8 %. In both cases, the margin of error was lower than the limit for the simplified models suggested within the bibliography (20 %). Third validation step with on-situ measured heat consumption data was planned in partnership with an industrial partner. However, during the required data collection process, the industrial partner faced multiple obstacles and unpredicted costs, and was not able to provide data with guaranteed accuracy during the thesis project duration. Overall, the methodology developed proved to be suitable for the evaluation of climate change impacts on district heating systems.

Based on the literature survey on the topic of environmental performance assessment of complex systems (such as district heating systems), it was concluded that the environmental assessment approach based on emergy theory would be suitable to account for all resources directly and indirectly consumed during the system lifetime. Moreover, in order to evaluate the performance level of such systems within the urban environment, an additional methodology should be developed to assess the environmental performance of buildings connected to such

systems (in order to assess to which extent the heat consumed from such systems contributes to the overall building environmental footprint). Thus, the methodology based on the emergy theory was developed within this thesis. The first part of the methodology addresses the environmental performance of urban heating systems, taking into account all resources directly and indirectly consumed during the system life-cycle phases: construction and operation (end-of-life phase was not considered, since there is no known case (within the bibliography, to the best knowledge of the author) of dismantling such a system, even after several decades of operation). The methodology developed can be applied on any urban heating system, which is demonstrated in this thesis by considering different system types within the case studies. The second part of the methodology addresses building environmental performance, by taking into account all direct and indirect inputs of the observed building system over its life-cycle phases (building construction, operation, renovation and end-of-life). The methodology can be applied on any building, regardless of type and construction period, as long as the required input dataset is available.

11.3 Assessment of district heating potential in a context of climate change and building renovation

Considering that the results from case studies indicated that space heating has the highest impact on building environmental performance over its lifetime, it can be concluded that the district heating systems could have a significant potential for reducing the environmental impact of urban environment. However, this conclusion is valid solely for the new generation of district heating networks, which have a more compact infrastructure (compared to traditional two-pipe systems) made of less environmentally intensive materials. Moreover, it was found that heat production source has the highest impact on the environmental performance of these systems. As the results of the case studies indicated, in the case that the heat is produced from fossil fuels, natural gas networks with individual gas boiler in each dwelling, environmentally outperform district heating systems (due to the significantly more compact infrastructure and high efficiency of compact condensing boilers). Thus, it is of utter importance to provide renewable heat production in order to justify district heating systems as an environmentally efficient solution for providing the urban environment with heating services. However, several district heating systems in Europe already operate with renewable heat production from biomass, waste incineration, geothermal heat and industrial waste heat utilization and solar plants.

The results also indicated that the material input used during the building renovation phase would not increase the pressure on the environment, but rather improve the overall building environmental performance due to the reduced heat demand achieved by improved thermal performance of the building envelope. Moreover, the installation of decentralized renewable heat production sources (such as solar thermal panels considered in this study), that partially cover building heat demand, would further improve the environmental performance of the urban environment. In some scenarios studied, after the renovation measures, annual heat production from solar thermal panels surpassed building heat demand. Thus, in those cases, certain buildings could shift from the role of consumer to the role of prosumers, feeding the excess heat to the district heating system. However, on a daily and seasonal basis, hourly heat production from the collectors does not always correspond to hourly heat demand. Namely, the highest output from the solar collectors occurs during the summer months (on a seasonal level) and during the afternoon hours (on a daily level), which is the opposite from the heat demand distribution – the highest heat demand occurs during the winter season and during the night-time. Thus, in order to enable the efficient integration of decentralized solar systems in district heating networks, a sufficient heat storage should be installed as a part of the system.

On the other hand, building renovation measures and the addition of decentralized heat production systems in the future would also impact the techno-economic parameters of district heating systems, along with changed climate conditions (although the weather change impact has a lower impact compared to building envelope renovation). Reduced heat demand in buildings would consequently result in reduced district heat demand density, which is one of the main parameters on which the decision-making for district heating system feasibility is based. However, it should be noted that the value of minimal heat density for district heating feasibility is based on current district heating technologies, limitations and pricing, and could consequently change in the decades to come. Additionally, in some countries, district heating networks are currently eligible for substantial subsidies (for example, in France, the subsidies are awarded for district heating project in areas with linear heat density higher than 1.5 MWh/ml, while the threshold value usually considered is 4 MWh/ml).

Moreover, if the heat production units are designed for a reference (current) heat demand, reduced heat demand in the future would impact their operational parameters. Namely, heat production units would operate with reduced capacity, which would lower their efficiency and increase the heat production costs. Moreover, in cases where heat demand would be below the technical minimum of installed base load units, it would be covered by peak load units, which are usually boilers with fossil fuel combustion (natural gas or light oil fuel for example).

Consequently, heat production from such peak load units would increase the operation costs, as well as the levels of CO₂ emissions from heat production - this aspect is of utter importance for countries where incentives and subsidies for district heating networks projects are assigned based on the participation of renewable energy sources in heat production.

Additionally, the reduction in number of heating hours during the heating season would result in frequent starts and stops in heat production, which would further lower the efficiency and environmental performance of the heat production units. However, it should be noted that the scale of these impacts could vary between the different climates suitable for heating services. The results from one of the case studies in this thesis indicate that while in the colder climates, heat production units would run with reduced capacity but during the similar number of hours as under the reference conditions, in warmer climates, both the required capacity and number of heating hours would significantly decrease.

In addition, the results from the case studies suggest that due to the decrease in heat demand, heat prices would increase in order to retain the same investment return period. This could result in customer disconnections from the systems, considering that one of the main reasons (aside comfort) due to which customers decide to connect to district heating systems in the first place are relatively stable heat prices. The customers could decide to shift towards using competitive technologies or decentralized renewable heating systems such as heat pumps. These systems have a higher investment cost compared to district heating system connection, but the customer could recognize the long term profitability due to the lower costs of energy production.

To conclude – district heating systems could have a high potential in the future for achieving the sustainability goals set for urban environment, as long as the following aspects are taken into consideration during the system design phase:

- Heat production from renewable sources;
- The use of modern types of distribution networks, with compact infrastructure made of materials that are not environmentally intensive;
- Production capacity designed for potential future heat demand decrease caused by the direct and indirect impacts of climate change (for example, installation of two base load boilers with the equivalent joint capacity instead of one high-capacity boiler);
- The use of the least environmentally intensive fuels as possible for peak load units;
- Climate change impact differences between the climate types suitable for heating services;

- Development of an alternative business plans to avoid increase in heat prices and consequently potential disconnections of the customers;

11.4 Concluding remarks and future work

Based on the results from the case study and the conclusions drawn, several steps can be suggested for further improvements of the approach developed, in order to broaden the insight on climate change impacts on district heating systems and the environmental performance of such systems within the urban environment.

In regard to the heat demand model developed, an additional comparison with on-situ measured data should be conducted in order to further test the model precision and capabilities. Moreover, the addition of cooling and electricity demand calculations within the model would enable an in-depth evaluation of the climate change impacts on building total energy demand. Additionally, this aspect would be of relevance for further assessments of climate change impacts on the emerging combined district heating and cooling systems.

The techno-economic model developed by the industrial partner could be improved to calculate heat production costs for periods longer than 20 years, which is the limit within the current model version. Moreover, the integration of the model developed with other modelling tools could be expanded in order to include other operational district heating system models (that are able to account settings of supply and return water temperatures), as well as further integrations with GIS software. This combination of models could result in methodology for identifying future heat demand layouts and “hotspots” within the district, enabling the district heating operators an insight in future requirements for supply and return temperature regimes within different network segments.

As for the methodology developed in order to evaluate the environmental performance of urban heating systems, additional application on other types of 4th generation of district heating networks (apart from the ESPEX) system would be interesting in order to identify the most environmentally friendly option. Moreover, additional renewable energy sources for heat production beside the solar energy (geothermal energy, rivers, fjords and sewage treatment works outfall through the use of heat pumps) could be studied as heat sources for such systems. However, the technical limitations of these technologies should be considered in order to make a final judgment. The application of the methodology developed on these systems could further broaden the insight on the environmental performance of urban heating systems. Moreover, the districts are usually consisted of different building types that were erected during various

historical periods and differ in both configuration and construction properties. Thus, applying the environmental performance assessment methodology developed on additional case studies would be of interest in order to provide an even deeper insight into the link between the urban heating systems and the environmental performance of urban environment.

APPENDIX A

CHAPTER A1: UEVs USED IN THE STUDY

The UEV values used in this thesis are given a table below. The origin of each UEV is given, along with its reference and updated value (according the new baseline of $1.20\text{E}+25$ sej, calculated in the paper of Brown et al. (2016)). For the instances where additional UEV calculations were required, the equations used are provided within this chapter.

Table A1. The origin and the update value of UEVs used;

Item	UEV	UEV unit	Source	Baseline used	Updated value
Polyethylene	5.17E+12	sej/kg	(Pulselli et al., 2011)	9.26E+24	6.70E+12
Diesel fuel	1.72E+05	sej/J	(Andrić et al., 2016)	1.52E+25	1.36E+05
Polystyrene(EPS)	6.88E+12	sej/kg	(Meillaud et al., 2005)	1.58E+25	5.23E+12
Galvanized steel	4.65E+12	sej/kg	(Moss et al., 2014)	1.58E+25	3.53E+12
Stainless steel	4.13E+12	sej/kg	(Odum, 1996)	9.44E+24	5.25E+12
Cast iron	2.60E+12	sej/kg	(Pulselli et al., 2011)	9.26E+24	3.37E+12
Iron	4.15E+12	sej/kg	(Meillaud et al., 2005)	1.58E+25	3.15E+12
Copper	2.00E+12	sej/kg	(Ulgiati & Brown, 2002)	1.58E+25	1.52E+12
Plastics	5.76E+12	sej/kg	(Meillaud et al., 2005)	1.58E+25	4.37E+12
Concrete	1.81E+09	sej/g	(Pulselli et al., 2007)	1.58E+25	1.37E+09
Gravel	9.83E+11	sej/kg	(Pulselli et al., 2011)	9.26E+24	1.27E+12
Aggregates	1.00E+09	sej/g	(Srinivasan et al., 2012)	9.44E+24	1.27E+09
Bitumen	3.04E+12	sej/kg	(Mellino et al., 2015)	1.52E+25	2.40E+12
Steel	2.77E+12	sej/kg	(Ulgiati & Brown, 2002)	1.58E+25	2.10E+12
Polyurethane	8.85E+12	sej/kg	(Amponsah et al., 2012)	1.52E+25	6.99E+12
Sand	1.00E+12	sej/kg	(Srinivasan et al., 2012)	9.44E+24	1.27E+12
Limestone	1.68E+12	sej/kg	(Agostinho & Ortega, 2013)	1.58E+25	1.28E+12
Water	2.10E+09	sej/kg	(Odum, 1996)	9.44E+24	2.67E+09
Cement	2.31E+12	sej/kg	(Srinivasan et al., 2012)	9.44E+24	2.94E+12
Synthetic rubber	7.22E+12	sej/kg	(Agostinho & Ortega 2013)	1.58E+25	5.48E+12
PVC	9.86E+12	sej/kg	(Pulselli et al., 2007)	1.58E+25	7.49E+12
Wood	8.79E+11	sej/kg	(Meillaud et al., 2005)	1.58E+25	6.68E+11
Polyester	9.67E+12	sej/kg	(Schramski et al., 2009)	1.58E+25	7.34E+12
Glass fiber	3.00E+12	sej/kg	(Ulgiati & Brown, 2002)	1.58E+25	2.28E+12
Zinc	7.20E+10	sej/g	(Cohen et al., 2006)	1.58E+25	5.47E+10
Adhesive	9.54E+11	sej/\$	(Schramski et al., 2009)	1.58E+25	7.25E+11
Brass	1.69E+13	sej/kg	Calculated ^(a)	1.52E+25	1.33E+13
Tin	1.70E+12	sej/g	(Cohen et al., 2006)	1.58E+25	1.29E+12
Glass	1.41E+12	sej/kg	(Pulselli et al., 2007)	1.58E+25	1.07E+12
Lead	5.46E+12	sej/g	(Ingwersen, 2009)	1.58E+25	4.15E+12
Brick	3.68E+12	sej/kg	(Pulselli et al., 2007)	1.58E+25	2.79E+12
Bronze	1.50E+12	sej/g	Calculated ^(a)	1.52E+25	1.19E+12
Paint	2.55E+13	sej/kg	(Pulselli et al., 2007)	1.58E+25	1.94E+13
Bioethanol	2.77E+05	sej/j	(Dong et al., 2008)	1.58E+25	2.10E+05
Fly ash	1.40E+13	sej/kg	(Srinivasan et al., 2012)	9.44E+24	1.78E+13
Petroleum	5.54E+04	sej/J	(Bastianoni et al., 2009)	1.58E+25	4.21E+04
Aluminum sheet	1.64E+12	sej/kg	(Almeida et al., 2010)	1.58E+25	1.25E+12
Light oil fuel	2.66E+09	sej/g	(Bastianoni et al., 2009)	9.26E+24	3.45E+09
Aluminum	1.27E+12	sej/kg	(Meillaud et al., 2005)	1.58E+25	9.65E+11
Landfill gas	1.10E+04	sej/J	(Franzese et al., 2007)	1.58E+25	8.35E+03
Glass fiber	3.00E+12	sej/kg	(Ulgiati & Brown, 2002)	1.58E+25	2.28E+12
Human labor(plant operation)	8.01E+13	sej/h	Calculated ^(b)	9.44E+24	1.02E+14
Natural gas	1.77E+05	sej/J	(Jamali-zghal et al., 2013)	1.52E+25	1.40E+05
Human labor (plant constr.)	6.41E+13	sej/h	Calculated ^(b)	9.44E+24	8.15E+13
Glass wool	5.73E+12	sej/kg	(Paoli et al., 2008)	9.44E+24	7.28E+12

<i>Table A1. continued</i>					
Serbian electricity transformity	6.39E+04	sej/J	Calculated ^(a)	1.20E+25	6.39E+04
Ceramic brick	3.68E+12	sej/kg	(Pulselli et al., 2011)	9.26E+24	4.77E+12
Ceramic	3.06E+12	sej/kg	(Brown & Buranakarn, 2003)	1.51E+25	2.43E+12
Pavement	4.80E+12	sej/kg	(Pulselli et al., 2007)	1.58E+25	3.65E+12
Ceramic tile	3.06E+12	sej/kg	(Brown & Buranakarn, 2003)	1.51E+25	2.43E+12
Polypropylene	9.86E+12	sej/kg	(Moss et al., 2014)	1.58E+25	7.49E+12
Glass fiber	3.00E+09	sej/g	(Ulgiati & Brown, 2002)	1.58E+25	2.28E+09
Natural gas transportation	1.74E+04	sej/J	(Jamali-zghal et al., 2013)	1.52E+25	1.37E+04
Glass sorting & transformation	3.30E+10	sej/kg	(Agostinho et al., 2013)	1.58E+25	2.51E+10
Iron & steel sorting & transformation	4.71E+10	sej/kg	(Agostinho et al., 2013)	1.58E+25	3.58E+10
Plastic sorting & transformation	3.43E+10	sej/kg	(Agostinho et al., 2013)	1.58E+25	2.61E+10
Aluminum sorting & transformation	3.30E+10	sej/kg	(Agostinho et al., 2013)	1.58E+25	2.51E+10
Clay brick recycling	1.60E+07	sej/kg	(Buranakarn, 1998)	9.44E+24	2.03E+07
Concrete demolition, sorting & transformation	9.40E+11	sej/kg	(Yuan et al., 2011)	9.44E+24	1.19E+12
Demolition	1.54E+11	sej/kg	(Buranakarn, 1998)	9.44E+24	1.96E+11
Landfilling	1.11E+10	sej/kg	(Buranakarn, 1998)	9.44E+24	1.41E+10
Building maintenance	5.67E+13	sej/m ² /yr	(Pulselli et al., 2007)	1.58E+25	4.30E+13
Land use	1.24E+05	sej/j	(Pulselli et al., 2007)	1.58E+25	9.42E+04
Polyurethane	8.85E+12	sej/kg	(Amponsah et al., 2012)	1.52E+25	6.99E+12
Propylene glycol	3.80E+05	sej/kg	(Paoli et al., 2008)	9.44E+24	4.83E+05
Water for storage tank	7.30E+06	sej/g	(Paoli et al., 2008)	9.44E+24	9.28E+06
Human labor (gas network op.)	1.07E+13	sej/h	Calculated ^(b)	9.44E+24	1.36E+13
Swedish el. Transformity	1.45E+05	sej/J	Calculated ^(a)	1.52E+25	1.15E+05
Al-Cu alloy	9.98E+08	sej/g	Calculated	1.52E+25	7.88E+08
Rockwool	1.84E+09	sej/g	(Björklund et al., 2001)	9.44E+24	2.34E+09
Glass (solar collectors)	1.90E+09	sej/g	(Paoli et al., 2008)	9.44E+24	2.42E+09

^(a) For bronze, C83600 alloy was used (composed of 85 % copper, 5 % lead, 5% tin and 5 % zinc) and for brass C26000 alloy was considered (70 % copper , 30 % zinc); For the Al-Cu alloy, a ratio of 94 % aluminum and 6 % copper was used;

^(b) The UEV of human labor $U_{hl,j}$ [sej/h] for each j -th process was calculated based on the amounts of employees with high school and college education:

$$U_{hl,j} = \frac{n_{hs,j} \cdot E_{hs,j} + n_{cl,j} \cdot E_{cl,j}}{n_{hs,j} + n_{cl,j}} \cdot \frac{1}{8760} \quad (A1.1)$$

$n_{hs,j}$, $n_{cl,j}$ [emp.] are the numbers of employees with highschool and college education while $E_{hs,j}$, $E_{cl,j}$ [sej/emp/yr] are the individual emergy flows of employees with high school and college education (respectively) for the regarded j -th process, given in the book of Odum (Odum, 1996).

^(c)The UEV of electricity ($U_{el}[\text{sej/J}]$) was calculated based on the electricity production mix for the regarded country:

$$U_{el} = \sum_i^j \varepsilon_{el,i} \cdot U_{el,i} \quad (\text{A1.2})$$

where $U_{el,i} [\text{sej/J}]$ is the UEV value of i-th electricity production source and $\varepsilon_{el,i} [\%]$ its corresponding share in total electricity production.

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Thèse de Doctorat

Ivan ANDRIĆ

Evaluation du potentiel du chauffage urbain dans le contexte du changement climatique et de la renovation des batiments

The assessment of district heating potential in a context of climate change and building renovation

Résumé

Le domaine principal de cette thèse s'intéresse aux conséquences du changement climatique et des actions de rénovation dans le bâtiment sur les réseaux urbains de chaleur, ainsi qu'aux performances environnementales de ces derniers afin d'évaluer leur potentiel dans le futur. Dans ce but, deux modèles complémentaires ont été développés :

- Un modèle dynamique de prévision de la demande de chaleur d'un bâtiment. Ce modèle repose sur une analogie thermo-électrique et a comme entrées, non exclusivement, des données climatiques et des scénarii de rénovation. Les résultats de ce modèle ont été comparés avec ceux d'un logiciel de référence (Energie Plus) : les erreurs sont acceptables. Ce modèle est générique et peut être utilisé dans différentes zones géographiques à l'échelle du quartier. Il a été appliqué sur des quartiers à Nantes et Lisbonne;

- Un modèle d'évaluation environnementale (reposant sur le concept d'empreinte énergétique, éMergie) de réseau urbain de chauffage a été conçu. Ce modèle est générique et permet de tester différentes technologies de production et de distribution de chaleur. Il a été appliqué sur des applications en Suède et en Serbie;

Les résultats des différentes applications indiquent que la nouvelle génération des réseaux urbains de chaleur ayant une infrastructure compacte (utilisant des matériaux à faible impact environnemental) et une production de chaleur à base de ressources renouvelables ou assimilées pourraient être une solution porteuse d'avenir. Cependant, pour maintenir la rentabilité de tels projets, la réduction de la consommation de chaleur des clients, conséquence en direct du changement climatique et en indirect des incitations aux rénovations du bâti, devrait être considérée dès la phase de conception, et intégrée dans de nouveaux business-plan afin de maintenir des prix de vente de la chaleur attractifs.

Mots clés: Changement climatique, chauffage urbain, environnement urbain, développement durable;

Abstract

The main scope of this thesis is to assess the impacts of changed weather conditions and building renovation on district heating systems in the future, as well as the environmental performance of such systems within the urban environment, in order to evaluate the potential of district heating in the future. In order to do so, two models were developed:

- A dynamic model for heat demand forecast, based on the thermo-electrical analogy, that takes into account weather and building renovation scenarios. The model had a satisfactory precision, and it can be applied on any location for a given number of buildings, which was proved on the example of multiple case studies;

- An environmental assessment model (based on emergy theory) for the assessment of district heating systems environmental performance within the urban environment. The approach can be applied on any type of district heating systems, as well as on competitive urban heating technologies, which was proved by the application on multiple systems within the case studies considered;

The results from case studies indicate that the new generation of district heating systems with compact infrastructure (made of non-environmentally intensive materials) and renewable heat production could be a solution for providing sustainable heating services to urban environments. However, in order to maintain the feasibility of these projects, potential heat demand reductions caused by the direct and indirect impacts of climate change should be considered during the design phase, along with the development of new business plans in order to maintain relatively low prices of district heating services. Moreover, the difference between these impacts in different climate types should be considered.

Keywords: climate change, district heating, urban environment, sustainability;

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