A GIS-based Methodology for the Evaluation of Integrated Energy Systems in Urban Area

THÈSE N^{O} 5287 (2012)

PRÉSENTÉE LE 5 AVRIL 2012
À LA FACULTÉ DES SCIENCES ET TECHNIQUES DE L'INGÉNIEUR
LABORATOIRE D'ÉNERGÉTIQUE INDUSTRIELLE
PROGRAMME DOCTORAL EN ENERGIE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Luc GIRARDIN

acceptée sur proposition du jury:

Prof. M. Paolone, président du jury
Dr F. Maréchal, Prof. D. Favrat, directeurs de thèse
Prof. M. Bonvin, rapporteur
Prof. F. Golay, rapporteur
Dr O. Ouzilou, rapporteur

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE
Suisse
2012

We can't solve problems by using the same kind of thinking we used when we created them.
— Albert Einstein

The data you have for the present crisis was collected to relate to the previous one.
— Edgar Horwood

L'essentiel est sans cesse menacé par l'insignifiant.
— René Char

Knowledge speaks, but wisdom listens.
— Jimi Hendrix

Remerciements

Ils sont si nombreux celles et ceux qui, dans tous les domaines, mériteraient d'être remerciés ici. Je prie donc ceux qui ne seront pas cités nommément de bien vouloir m'excuser par avance.

Il semble loin le temps où le **Professeur Daniel Favrat**, sur la recommandation du **Dr François Maréchal**, me proposait le remplacement d'un cours "Systèmes de conversion d'énergie avancés", le lendemain de la cérémonie des diplômes; quel baptême ! Ce fut le début d'un périple riche en rencontres et projets. Qu'ils en soient donc remerciés en premier.

J'aimerais ensuite remercier tous mes collègues du Laboratoire d'Énergétique Industrielle (LENI-EPFL) pour leur aide, patience et disponibilité sans faille, ainsi que pour l'atmosphère stimulante qu'ils savent entretenir. En signe de reconnaissance, j'aimerais d'abord citer mes co-auteurs: **Dr François Maréchal**, **Prof Daniel Favrat**, **Dr Céline Weber Koppenburg**, **Dr Raffaele Bolliger**, **Nicole Calame-Darbellay**, **Matthias Dubuis**, **Helen Carla Becker**, **Jakob Rager**,
ainsi que les étudiants et diplômants qui ont contribué au foisonnement d'idées et que j'ai parfois, avec le recul, traité avec sévérité: **Ana Teresa Prata Noéme**, **Roberto Masciarelli**, **Guillaume Ridoux**, **Célien Fitoussi**, **Thorsten Helms**, **Thomas Kaminski**, **Anthony Meric**, **Magnhild Kallhovd** et **Tore Zeiner**.
Je n'oublie pas non plus l'aide précieuse de **Brigitte Fayet (Gabioud)**, **Suzanne Zahnd** et **Irène Laroche** au secrétariat ainsi que **Dave Bergomi** et **Nicolas Borboën** à l'informatique auxquels je n'ai pas manqué de poser des questions impromptues et des problèmes alambiqués.
Je remercie également ceux à qui je suis également redevable pour leurs contributions au développement des outils du groupe: **Franscesca Palazzi**, **Dr Zoé Périn-Levasseur**, **Dr Jonathan Demierre**, **Léda Gerber**, **Samira Fazlollahi**, et tous les autres.

Ma gratitude va également aux personnes et institutions ayant soutenu ou collaboré aux projets de recherche énergétique urbaine: **Prof Hans Björn Püttgen** et **Dr Massimiliano Capezzali** (Energy center-EPFL), **Prof Reto Camponovo**, **Dr Gilles Desthieux** (LEEA, HES-SO Genève), **Prof Michel Bonvin** (HES-SO Valais), **Gaëtan Cherix** (CREM), **Prof Bernard Lachal** et **Dr Pierre-Alain Viquerat** (CUEPE-UniGe), **Dr Olivier Ouzilou** et **Alexis Mayer** (Bonnard et Gardel), **Marc Spitzli** (SIG), **Dr Darren Robinson** et **Diane Perez** (LESO-PB, EPFL), **Dr Claudio Magalhaes Carneiro** et **Nicolas Lachance-Bernard** (LASIG, EPFL), **Rémy Beck** (ScanE) et **Dr Jean-Philippe Antonietti** (IMA, UNIL); sans oublier MeteoSuisse, Swisstopo, l'Office Fédéral

de la Statistique (OFS), la Commission européenne (Concerto-Tetraener) et l'Office Fédéral de l'énergie (OFEN).
Enfin, je remercie les communautés territoriales dont les études de cas constituent le point de départ de cette thèse: les villes de Nyon (**Sarah Huber**), La Chaux-de-Fonds (**Maurice Grünig**), Martigny, Neuchâtel (**Christian Trachsel**), Lausanne et la Ville et Canton de Genève.

Ceci dit, je tiens également à exprimer ma reconnaissance à tous ceux dont je suis redevable, toutes activités confondues, de la générosité désintéressée qu'ils témoignent.

Je salue mes amis du Ski Club Académique Suisse (SAS), mes coéquipiers de l'équipe Suisse universitaire, **Dr HP. Denzler**, notre coach sur les pistes de "l'Ecole Buissonière".
Je salue aussi les surfeurs, voyageurs(euses) croisé(e)s sur les routes, ceux de Monta et ceux de la Swiss Surfing Association (SSA).
Je remercie enfin les Maîtres de Budo japonais ainsi que les pratiquants inlassables qui, par l'exemple, m'ont instruit et inspiré leur enthousiasme. Au quotidien, je pense particulièrement à **Me G. Mezzo** et **Me P. Krieger** ainsi qu'à tous les membres du Shung do Kwan Budo (SDK) qui se reconnaîtront.
Qu'ils soient tous chaleureusement remerciés pour leur énergie communicative.

Je remercie aussi **Jon et Barbara** pour leur aide précieuse à la finalisation de ce document.

Habitué de la "dernière chance au dernier moment", je termine par mes remerciements à ma famille et mes parents pour leur patience et leur soutien inconditionnel.

A vous tous un grand merci !

Lausanne, Novembre 2011 L. G.

Abstract

Following the pioneering work “Tokyo Half Project” promoted by the Alliance for Global Sustainability (AGS), a geographical information system has been developed to model the energy requirements of urban areas.

The purpose of this platform is to model with sufficient details the energy services requirements of a given geographical area in order to allow the evaluation of the integration of advanced integrated energy conversion systems.

This tool is used to study the emergence of more sustainable cities that realize energy efficiency improvement measures, integrate energy efficient conversion technologies and promote the use of endogenous renewable energy. It is based on techniques at the crossroads of three domains : geographical information systems, urban energy modelling and process integration and process design techniques.

The model is illustrated with case studies for the energetic planning of urban district in Switzerland.

Keywords: Urban systems, Geographic information system, Urban energy planning, Pinch analysis, Integrated energy systems, Sustainability, Polygeneration

Résumé

Suite au projet novateur « Tokyo Half Project » porté par l'Alliance pour un développement global durable (AGS), un système d'information géographique a été développé pour modéliser les besoins énergétiques des zones urbaines.

L'objectif de cette plateforme est de décrire avec suffisamment de détails les services énergétiques requis dans une zone géographique donnée, afin d'y évaluer le potentiel d'intégration de systèmes avancés de conversion d'énergie.

Cet outil contribue à l'étude de l'émergence de cités plus durables par la mise en œuvre de mesures d'amélioration de l'efficacité énergétique, par l'intégration de systèmes de conversion d'énergie performants et par la promotion de l'utilisation de sources d'énergie renouvelables locales. Il est basé sur des techniques issues de trois domaines : les systèmes d'informations géographiques, la modélisation énergétique des zones urbaines et les techniques de dimensionnement et d'intégration des procédés industriels.

L'application du modèle est démontrée sur des études de cas de planification énergétique d'agglomérations urbaines en Suisse.

Mots-clés : Système urbain, Système d'information géographique, Planification énergétique urbaine, Analyse de pincement, Système énergétique intégré, Développement durable, Polygeneration

Contents

List of Figures

List of Tables

Nomenclature

Abreviations

BDD	Binary decision diagram
BI	Business Intelligence
BIM	Building Information Modeling
CECB	Cantonal Building Energy Certificate
CHF	Swiss franc
COP	Coefficient of performance
DBMS	Database management systems
DHN	District heating network
DSS	Decision support system
ES	Energy signature
FSO	Swiss Federal Statistical Office
GIS	Geographic Information System
GIS	Geographical information system
HHV	Higher heating value
HVAC	Heating, Ventilation, and Air Conditioning
IE	Industrial Ecology
IES	Integrated Energy Systems
LCA	Life-Cycle Analysis
M&S	Marshall & Swift installed equipment cost index
MILP	Mixed integer linear programming

$MoPEC$	Cantonal model of energy requirements
N	New buildings
$NGCC$	Natural gas combined cycle
PI	Process integration
$R\&D$	Research and development
$SFOE$	Swiss Federal Office of Energy
$swisstopo$	Swiss national mapping agency
UID	Unique identifier
WTP	Wastewater treatment plant

Functions and Operators

$\mathcal{N}(\mu,\sigma)$	Normal distribution of mean μ ans standard deviation σ
$\mathcal{U}(a,b)$	Uniform distribution between a and b
$\vee$	Logical OR
$\wedge$	Logical AND

Superscript

$boil$	boiler
chp	combined heat and power unit
cs	cooling system
dn	district network
hp	heat pump
hs	heating system
hw	hot water production
hx	heat exchangers
ref	reference
res	resource, energy source
rs	low temperature refrigeration system

Subscript

0	nominal
a	fresh air
b	building
c	category
dy	day
f	final energy/exergy
flr	floor
gnd	ground
i	interior
P	Period
r	return
ref	reference value
s	supply
t	time
tr	treshold
u	useful energy/exergy
x	exterior
yr	year
z	zone, sub-area

Units

$1\frac{Wyr}{cap\cdot yr}$	8.766 $[\frac{MJ}{kWh\cdot yr}]$
cap	capita, per capita
GWh	Energy: $3600\cdot 10^6 kJ$
ha	Surface: $10'000m^2$
km^2	Surface: $100ha$
PJ	Energy: $10^{12}kJ$

Symbols

α	thermal diffusivity	$[m^2/s]$
$\beta = -1/\rho\left(\frac{\partial\rho}{\partial T}\right)_p$	volumetric thermal expansion	$[1/K]$
ΔP_{loss}^{pipe}	Pressure drop in pipes	$[Pa/m]$
ΔT_{lm}	Log-mean temperature difference	$[°K]$
ΔT_{min}	Minimum approach temperature	$[°K]$
$\dot{Q}$	Thermal power	[kW]
$\dot{m}$	Mass flow	$[kg/s]$
$\dot{Q}_{loss}^{pipe}$	Heat losses in pipes	$[kJ]$
$\dot{S}$	Size of equipments	$[kW]$
η_{cop}	Heat pump COP efficiency	[-]
η_e	Electrical efficiency of a unit	[-]
η_{th}	Thermal efficiency of a unit	[-]
ν	Kinematic viscosity	$[m^2/s]$
$\overline{\dot{Q}_P}$	Mean thermal power during period P	[kW]
$\overline{T}_P$	Mean operating temperature during period P	$[°C]$
ρ	Density of the heat transfer fluid	$[kg/m^3]$
ρ	Mass density	$[kg/m^3]$
τ^{dn}	Annualisation factor of the DHN investment	[-]
A	Heat transfer surface area	$[m^2]$
$A_{c,z}$	Floor area of category c in zone z	$[m^2]$
c^{dn}	DHN cost per annual energy distributed in the area	[CHF/kWh]
c_p	Specific heat of the heat transfer fluid	[kJ/kg/°C]
cp	Specific heat of the heat transfer fluid	$[kJ/kg/°C]$
cp_a	Specific heat of air	$[kJ/kg/°C]$
cp_w	Specific heat of water	$[kJ/kg/°C]$
d^{dn}	DHN pipe diameter	[m]
D_P	Operating time of period P	[s]
E	Electrical energy	[kJ]
f_{CO_2}	CO_2 emissions per unit of fuel energy	$[kgCO_2/LHVfuel]$
$f_{loss,0}$	Heat loss factor for a reference supply temperature	[-]
g	Gravitational acceleration	$[m/s^2]$
h	Height	$[m]$
h_b	Height of a building	$[m]$
k	Thermal conductivity	$[(W.K)/m]$
k_1	Slope of the heating/cooling heating signature	[-]

k_2	Y-intercept of the heating/cooling signature	[-]
L	charachteristic length of the geometry	$[m]$
L^{dn}	Length of water distribution network pipe	$[m]$
$n_{b,z}$	Number of building in the area z	$[-]$
n_b	Number of buildings	[-]
n_c	Number of categories	[-]
n_P	Number of periods	[-]
n_z	Number of zone	[-]
Q	Thermal energy	[kJ]
q	Thermal specific energy	$[kJ/m^2]$
S_z	Land area of zone z	$[m^2]$
T_{gnd}	Ground temperature	$[°C]$
T_i	Room temperature	$[°C]$
T_r	Return temperature of the heat distribution system	$[°C]$
T_s	Supply temperature of the heat distribution system	$[°C]$
T_{tr}	Threshold Temperature	$[°C]$
T_x	Outdoor Temperature	$[°C]$
U	Overall heat transfer coefficient	$[W/(m^2.K)]$
v_s	Nominal flow velocity in pipe	[m/s]

nomenclature[V]$h_altAltitude$

1 Towards Design of Integrated Urban Energy Systems

1.1 Introduction

Supplying energy services in urban areas corresponds to more than 45% of the energy consumption of a country like Switzerland [Kirchner et al., 2010].
Increasing the energy efficiency in urban area is the result of the integration of five actions :

- improve the building performances
- develop distribution systems,
- integrate endogenous and renewable resources,
- increase the efficiency and the integration of energy conversion systems,
- transform the occupants behaviour.

In comparison with conventional heating solutions by individual boilers (see Figure 1.1), the design of more efficient urban energy systems requires a more detailed analysis of the energy services to be supplied, of the available resources and of the equipment integration.

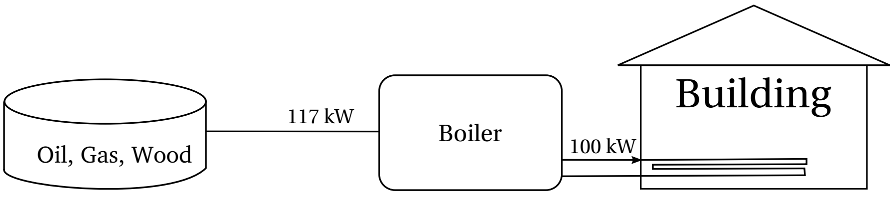


Figure 1.1: Conventional heating system.

This is particularly true when considering heat pumping or combined heat and power solutions, as shown in Figure (1.2), whose efficiencies are temperature dependent, and whose profitability strongly depends on the appropriate size of equipment and on the management strategies. This is even more the case when considering refurbishment actions and the integration of solar heat and electricity.

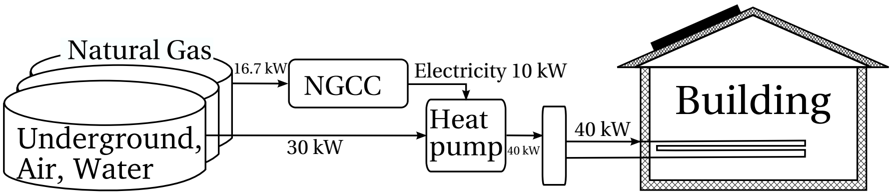


Figure 1.2: Advanced energy conversion system.

In addition, the accessibility to endogenous renewable resources (see Figure 1.3), like geothermal heat, surface water or biomass, that enter in conjunction with the scale effects of the technologies, requires the evaluation of district heating/cooling solutions.

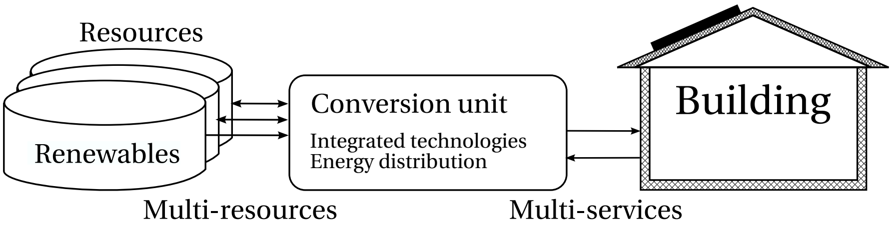


Figure 1.3: Multi-service and multi resource energy conversion in urban systems

There is therefore a need for a tool that offers a holistic energy vision of a given urban area, not only from the building perspective, but also at the district scale, considering the synergies and competitions between resources and services, via the proper integration of energy conversion technologies with district heating/cooling distribution systems.

The present work presents a methodology and tools, developed for the evaluation of integrated energy conversion systems in urban areas, using techniques at the crossroads of three domains (see Figure 1.4):

- geographical information systems (Chapter § 2, p. 31), which entails a structuring phase of the information and the design of a database management system, enabling the use of analytical and reporting tools for the generation of maps and graphs.
- urban energy systems modeling (Chapter § 3, p. 69), which aims to develop and apply model using a bottom-up approach to simulate with a sufficient level of detail the energy, cost and emissions at any given level of disaggregation.
- process integration and process design techniques (Chapter § 5, p. 109), which provide a holistic vision of the system by computing, for a set of interconnected models, the global

balance of plant resulting from the determination of the optimal size of equipment with the corresponding allocation of thermal, mechanical and material resources.

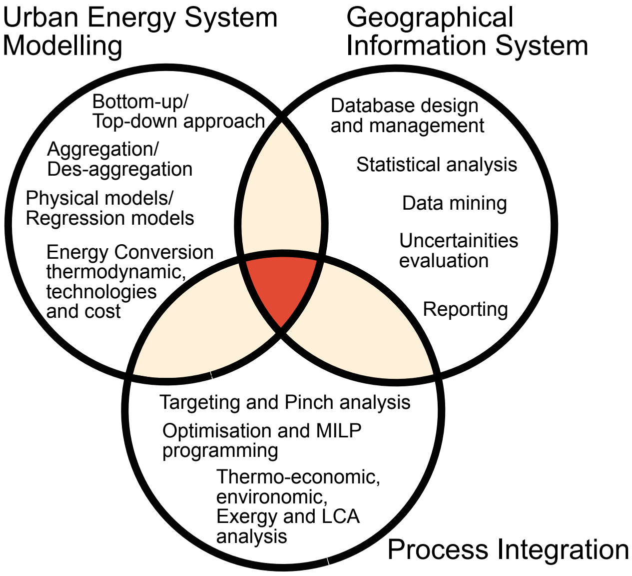


Figure 1.4: Engineering domains for the evaluation of integrated energy conversion systems in urban areas.

The combination of this technical know-how allows to present maps of energy, cost and emission indicators resulting from the evaluation of energy scenarios integrating the energy demand, resource, conversion technologies and urban infrastructure.

This provides therefore a means for the engineers to bring elements in the participatory planning processes allowing a very large number of stakeholders with different interests and agendas (e.g. developers, owners, tenants, local authorities, environmentalists, energy providers, engineers, architects, officials, people's representatives) to gather and discuss the issues of several territorial energy scenarios.

1.2 Genesis and research plan

The elaboration of a methodology (§ 1.7) based on a geographical information system started from the elaboration of a strategic thermal-energy master plan for the Canton of Geneva on horizon 2030 [Darbellay et al., 2007].

The objective of this study was to establish a method to evaluate the demand of a given geographic area to assess the need for infrastructure, particularly network development, and the performances of advanced energy conversion systems, making the best use of local resources. An energy model has then been developed based on the available information of the Geneva Territory Information System[1].

---

[1] SITG: Système d'Information du Territoire Genevois, http://etat.geneve.ch/sitg/

The present and future energy requirements as well as the resources availability have been reported on maps, drawn at the scale of urban districts (see for example Figure 1.11, p. 16). By extrapolation of the energy demand, the tool developed served as a starting point for pinch analysis that helps to determine, in geographical terms, the opportunities for the integration of energy conversion technologies, including heating distribution networks.

As the energy management of cities must take into account the coexistence of old and new housing stock, the integration of new and existing heating and cooling equipments to district network has been further studied. A multi-period energy integration procedure has been applied to evaluate the simultaneous distribution of heating and cooling services to the urban area surrounding the international organizations in Geneva[2] [Calame-Darbellay et al., 2009a; Girardin et al., 2010a]. For this purpose, not only the time scale decomposition has been refined, but also the spatial one, going down to the individual building levels. The energy model was also improved to consider scenarios for the refurbishment of the existing buildings.

Starting from the definition of a minimum set of necessary information, the method has been applied to West-Switzerland cities laying the foundation of a geo-referenced database [Girardin et al., 2010c] designed for the management of energy systems in urban areas. As the communication and synthesis of the results became an increasingly important task in the decision-making process, the geo-referenced layers, resulting from time-efficient and robust processing of the information from disparate sources, have been made available through a collaborative platform over the Internet. The graphical representation of economic, environomic and exergetic trends between competing energy integration scenarios were moreover refined [Girardin and Maréchal, 2010].

Finally, in the context of a limited time project where there is obviously no point to collect all the required measurements, statistical techniques and Monte Carlo simulation have been investigated to ensure instead that, despite the lack of information, the results are nevertheless generated with sufficient accuracy.

1.3 Motivation

Nowadays, the execution and implementation of territorial sustainable energy action plans are mostly led by local Communities engaged on a voluntary basis. Following population's demands and urban ecology motivation, an increasing number of communities are indeed adopting energy policies and sustainable energy action plans in order to promote renewable sources and rational responsible use of energy.

---

[2] European project Tetraener, www.tertaener.com

1.3.1 The “2000 Watt society”

Concerning the sustainable development, the concept of a “2000 Watt society” [Jochem et al., 2004], proposed in 1998 by the board of Swiss Federal Institutes of Technology [Maréchal et al., 2005], assumes by the middle of the 21st century a yearly per capita primary energy demand of 2000 $\frac{Wyr}{cap \cdot yr}$, corresponding to 65 $\frac{GJ}{cap \cdot yr}$, which represents the mean per capita primary energy use in the world, one third of the energy intensity in Europe and 1.78 times the energy intensity in Switzerland (2009).
At the national level, the most efficient actions in the domain of energy and building technology has been identified [Pfeiffer et al., 2005] as the adoption of Minergie-P standard for all building by 2050, in conjunction with the use of heat pumps, wood-fired boiler and solar domestic hot water system to achieve a 3-fold reduction in total gross energy use.
In summary the major recommended actions are:

- the development of holistic system design methodologies,
- the convergence towards low energy buildings through refurbishment actions,
- the improvement of the energy efficiency of large equipment, industrial plants, thermal power generation plant , as well as in material use through recycling, re-use and substitution,
- the implementation of investment policy for innovations in information technologies, power electronics and other technological equipments,
- the realization of the significant energy-saving potential in road transport, especially passenger vehicles,
- the resolution of methodological, behavioral, economical and technological bottlenecks.

The “2000W society” is currently evolving from a research concept into a long-term political agenda.

1.3.2 Greenhouse gas Emissions targets

One possible strategy of increasing the use of renewable sources of energy is to set mandatory targets for the reduction of emissions in the short term. For exemple, the “Facteur 4” [Boissieu, 2006] refers, in France, to the target set by law[3], and confirmed by the “Grenelle de l’environnement II[4]” to reduce by four, by 2050, the levels of greenhouse gas emission of

---

[3] Loi n° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique

[4] Environnement : engagement national pour l’environnement (Grenelle II), Loi n 2010-788 du 12 juillet 2010 portant engagement national pour l’environnement publiée au Journal Officiel du 13 juillet 2010

1990.
In 2009, the European Commission adopted a commitment[5] to reduce by 2020 the greenhouse gas emissions at least 30% below 1990. In 2009, a legally binding CO_2 emission reduction target, of at least 26% by 2020 and 80% by 2050, compared to 1990 levels, was set by the United Kingdom [Crown, 2009].
However, one drawback of this straightforward approach is that if it is not accompanied by commitments to specific action plans, it may be discredited as overly idealistic.

1.3.3 The European Energy Award

Another similar city network, the European Energy Award[6], counts, by the end of 2009, 590 *EU* communities engaged in a certified energy quality management system.
This certification may be seen as a preliminary step for the definition of action plans prepared under the "Covenant of Mayors".

1.3.4 The Covenant of Mayors "3×20" target

The objective of the "3×20" agreement aims to surpass the emission reduction policy, by targeting by 2020:

- a reduction of greenhouse gas emissions of at least 20% below 1990 levels,
- a coverage level of 20% of the energy consumption by renewable resources
- and the improvement of energy efficiency leading to 20% reduction in primary energy use

The Covenant of Mayors is an European movement involving local and regional authorities, voluntarily committing to the "3×20" target.
Today 2778 signatories (14-07-2011) joined the Covenant of Mayors action plan [SEAP, 2010]. The rate of involvement of 460 new members every six months since 2008 (see Figure 1.5), reflect the will of local decision-makers to progress toward sustainable development.

1.3.5 Holistic vision of Urban Energy Systems

Despite these efforts to promote best practices and increase the understanding of energy efficiencies through ambitious objective, it is thought that, at present time, the develop-

---

[5] Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020, Official Journal L 140 , 05/06/2009 P. 0136 - 0148

[6] European Energy Award® ("Cité de l'énérgie"),The European Certification and Quality Management systems for towns and cities, http://www.european-energy-award.org/

[7] http://www.eumayors.eu/about/signatories_en.html

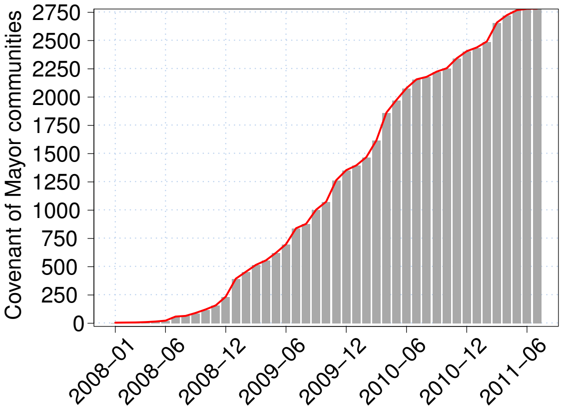


Figure 1.5: Covenant of Mayors adhesions for the period 2008-2011, source: from Covenant of Mayor web site[7].

ment of decision-making tools and planning methodologies for the efficient integration of energy systems in urban area, have fallen behind today's challenges and political commitments [Oreszczyn and Lowe, 2010]. This is explained not only by the complexity of the energy planning task, being multi-scale in its geo-spatial components, multi-period in its time breakdown and moreover stochastic, but also by its inherent multidisciplinary nature.
Among the challenges that today may catch decisions makers unprepared, we may note :

- the difficulty to have a full picture of the actual state of the real requirements of the urban energy system,
- the responsibility, to the community, for the adoption of long-term decision, shaping the future of the next thirty to sixty years,
- an inherited situation where it is likely that 90% of the building stock is existing (see Figure 1.9, p. 13),
- the growing public interest and expectation for new energy alternatives,
- the problematic fact that a global vision of the energy chain extends beyond borders, both regional and national,
- the need of a strong line of argument to find issues of common interest with the stakeholders,
- the identification of synergies between sustainable energy development and industrial development.

1.4 Previous Holistic Methodologies and Tools

In order to face the challenge of the development of sustainable urban societies, holistic methodologies [Barreiro et al., 2009; Pullen, 2009; Yamaguchi and Shimoda, 2010], tools (SUNtool [Robinson et al., 2007], CITYSIM [Robinson et al., 2009], SynCity [Keirstead et al., 2009] and platform DOME [Kraines and Wallace, 2003]) for the design and urban energy systems have recently emerged. Some of theses tools are distinguished by using Process Integration techniques to evaluate the integration of advanced energy conversion systems (ENERGIS [Girardin et al., 2010b]) and find the best mix of technologies (DESDOP [Weber, 2008; Weber and Shah, 2011]).
Unlike other bottom-up approaches working at a disaggregated level [Kavgic et al., 2010], these models rely on a multilayer energy model [Fu et al., 2009] for the description of resources, building stock, technologies and infrastructure.
Motivated by the need to optimize energy systems, genetic algorithms have been used to design district heating systems [Curti, 1998] and further developed for multi-objective optimization of a number of industrial problems [Leyland, 2002; Molyneaux, 2002], including the integration of advanced energy systems for more sustainable urban areas [Bürer, 2003]. More generally, it has been demonstrated that the combined use of an evolutionary genetic algorithm and process integration techniques [Maréchal, 1995], results in successful methods both for the preliminary design of industrial energy systems [Bolliger, 2010] and the thermo-economic optimization of industrial sites [Périn-Levasseur, 2009] and processes [Gassner, 2010].

As noted by [Manfren et al., 2011], whatever method and tool is preferred, the key points for the realization of integrated urban design tools are advanced multidisciplinary modeling, interoperability of computational models and collaborative research for the optimal integration of energy systems.

1.5 Objectives

The proposed methodology and tools aim at helping local and national communities to make decisions for the integration of more efficient and renewable energy systems, that meet thermo-economic and environomic targets, using the best local resources. Accordingly, the implementation of a geo-referenced platform, which makes best use of local available information, seeks to:

- give a representative picture of the actual thermodynamic state and performance of urban systems,
- compute indicators in order to track the evolution of the energy and environomic performances in a sustainable way,

- quantify and locate on maps the potential of energy efficiency improvement in order to implement action in the targeted areas,
- quantify and locate on maps the potential of local energy resources in order to define actions to promote the use of renewable energies,
- support the coordinated planning of the energy infrastructure (district heat, gas, electricity and water networks),
- identify the opportunities of industrial integration, like waste water treatment plant, industrial processes and data centers heat recovery,
- promote the systematic consideration of the energetic aspects in strategic urban planning and urban development projects,
- promote the set up and use of geo-referenced urban energy inventory.

1.6 Challenges and Opportunities for a Holistic Approach to Urban Energy Systems

This section presents the challenges faced by the urban planner regarding the composition of the Swiss final urban energy mix, mainly non-renewable, and the evolution of the built environment. The opportunities for the development of a bottom-up holistic methodology is then examined from a geographical, legal, and informational point of view. This should provides convincing evidence that moving over to the use of renewable energy sources is likely to require significant technological evolution, both in terms of energy conversion systems and energy planning and management tools.

1.6.1 Challenge of the Swiss final energy mix

Energy mix and intensity Figure (1.6) presents the Swiss Energy Flow Diagram [SFOE, 2009b] expressed in term of the “2000 W” society indicator[8] using Equation (1.1) [Jochem et al., 2004] which correspond to the average power used annually per person of the country.

$$E_{f,yr} = \frac{E_{f,yr}[PJ] \cdot 10^{15}}{n_{p,yr}} \cdot \frac{1}{8766[h/yr] \cdot 3600[s/yr]} \qquad [\frac{Wyr}{cap \cdot yr}] \qquad (1.1)$$

In 2009, the Swiss final consumption reached a level of 3565 $\frac{Wyr}{cap \cdot yr}$(877.6 $\frac{PJ}{yr}$) which is 1.78 times greater than the “2000W society” target. The estimation of the share of renewable energy in the consumption depends on the mix of the electricity power sources. In Switzerland, the actual electricity production mix is based on 54.8% hydroelectric, 38.1% nuclear, 4.9% fossil fuel from conventional thermal power plants, and 2.2% from other renewable (industrial

---

[8] Considering 7’801’278 capita in 2009 [FSO, 2010b]

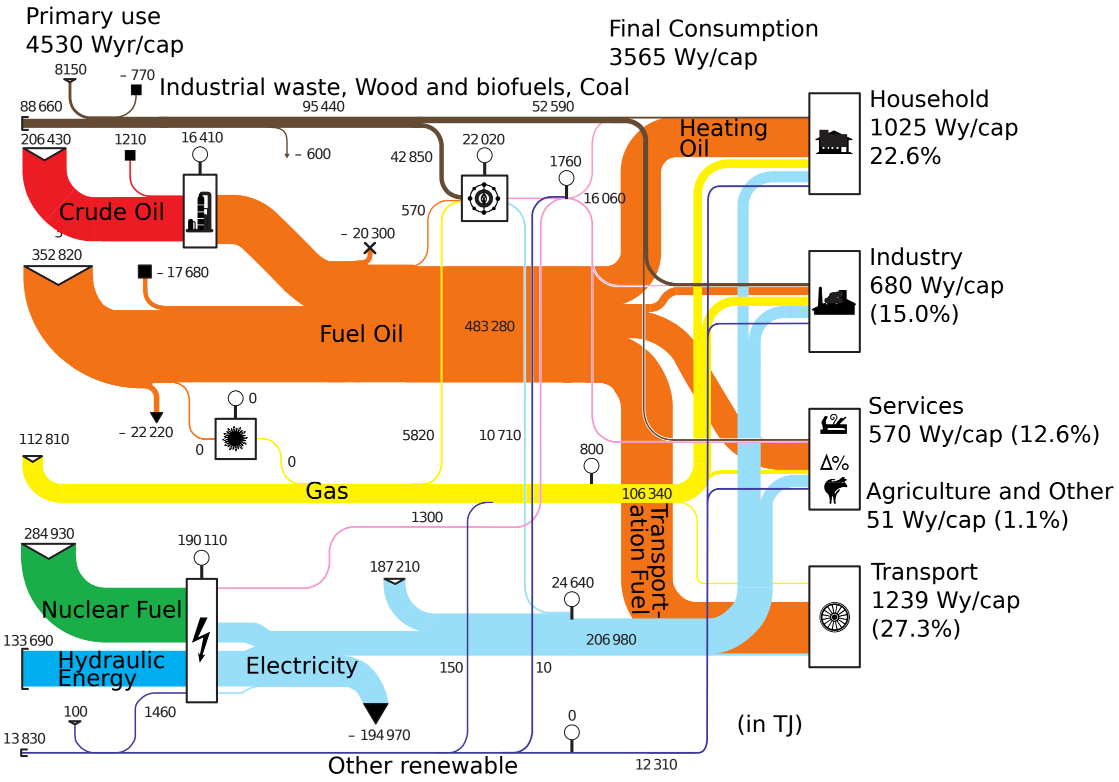


Figure 1.6: Swiss Energy flow diagram 2009 in terms of the 2000W society (Source: from [SFOE, 2009b]).

waste 1.52%, wind power 0.06%, Biomass, 0.29%, Solar 1.13% and 0.19% Biogas from WWTP plant) [SFOE, 2009a].

Urban energy systems As noticed by Pérez-Lombard et al. [2008], the building sector could legitimately aspire to form a sector beside transport, industry, services, agriculture and others. Indeed, the consumption for space heating, hot water production, cooking activities, household electrical appliances and other heat and electrical process requirements account for 47.6% of the final energy balance, as shown in pie chart (1.7). This share is even higher in Winter (60.5%) assuming 3000 heating hours per year.

However, as only buildings used for habitation are recorded in the statistics, it is not possible yet to gather information about the share of energy resource of the entire building stock. Consequently, the Swiss final consumption for the Household and Service sector are analyzed instead and referred to as “Urban energy sector”.
The value for the “Urban energy sector” are computed based on the study [Kirchner et al., 2010]) for the Household sector. For the Service sector aggregated values for heating, hot water production and process heat from [Kirchner et al., 2010]) have been dispatched between the energy sources in the same proportion known for the Household sector. The results by energy

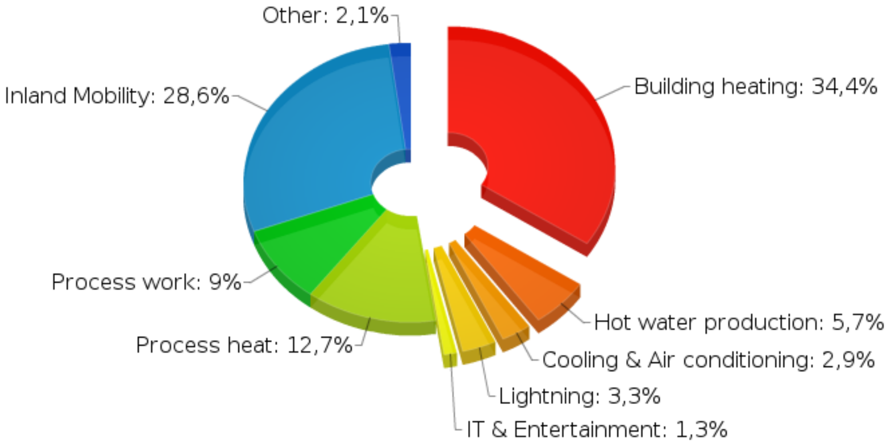


Figure 1.7: Overall Swiss final consumption by specific use, 2009 (Source: from [Kirchner et al., 2010].

sources are presented in Table (1.1) and Figure (1.8). From this point of view, the “Urban energy system” represents 45.3% of the total final energy consumption.

Table 1.1: Final consumption by energy sources in Switzerland, 2009, (Source: from [FSO, 2010a] and [Kirchner et al., 2010]).

Energy sources	Total		Urban system[a]		
	$\frac{Wyr}{cap \cdot yr}$	%	$\frac{Wyr}{cap \cdot yr}$	% Urban	% Total
Wood & biofuels	145	4.1	104	6.5	72.0
Coal	26	0.7	0.5	0.1	7.2
Industrial waste	43	1.2	0	0.0	0.0
Heating Oil	773	21.7	646	40.6	83.7
Transportation Fuel	1190	33.4	0	0.0	0.0
Gas	432	12.1	237	14.9	54.8
Electricity	841	23.6	524	32.9	62.3
District Heating	65	1.8	39	2.4	59.3
Other renewable	50	1.4	41	2.6	81.9
Total	3565 (877.6 $\frac{PJ}{yr}$)	100.0	1593 (392.2 $\frac{PJ}{yr}$)	100.0	44.7

[a] Swiss final energy demand for Household and Service.

Share of renewable It is observed that 70% of the Urban energy mix is non renewable, with a share of 57% fossil fuel and 13% of nuclear fuel, while the share of non-renewable in the total final consumption is even higher (78%), as shown in Table (1.2). The final renewable energy (Wood & biofuels, other renewable and electricity from renewable) represent 28% of the Urban mix while it reaches 19% of the total supply mix.

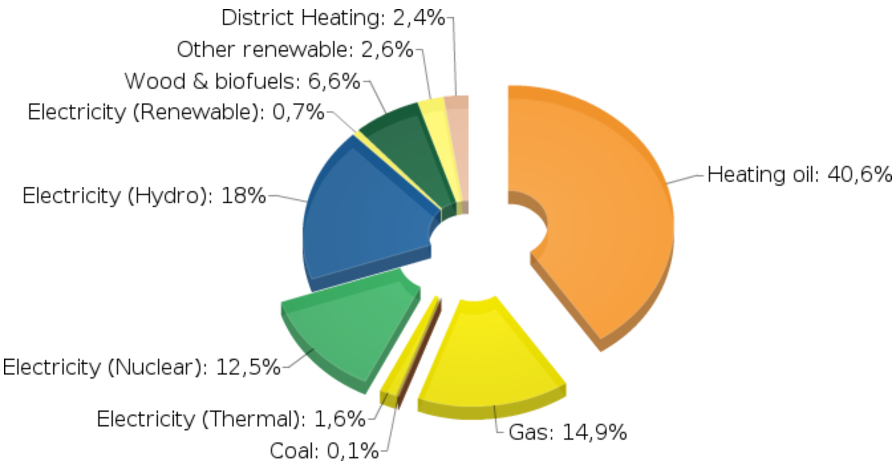


Figure 1.8: Final consumption by energy sources in Switzerland, 2009 for the Household and Service sector.

Table 1.2: Non-renewable final consumption in Switzerland, 2009.

Energy source	Total	Urban system
Fossil Fuel[a]	69.1	57.2
Nuclear Fuel[b]	9.0	12.5
District Heating & Industrial waste	3.0	2.4
Renewable[c]	18.9	27.9
Non-renewable[d]	78.0	69.7

[a] Coal, Petroleum product, Fuel, Gas, Swiss electricity production from thermal power plant.

[b] Swiss electricity production from nuclear power plant.

[c] Wood & biofuels, other renewable and electricity from renewable.

[d] Coal, Petroleum product, Fuel, Gas, Swiss electricity production from thermal and nuclear power plant.

1.6.2 Geographical opportunities

As shown in Figure (1.9), the estimated actual Swiss household floor area of 42'439 ha (see § 2.7.1, p. 45 for detailed calculation) is expected to grow at a rate of about 1.46%/yr (43'058 ha/yr) resulting in an expected increase of 30.7% (55'467 ha) by 2030 over the actual value.

At the same time, the population continues to concentrate in urban areas, as shown in map 1.10, where the gray area represents the region where the density of population is actually greater than 500 $\frac{cap}{km^2}$. The green area represents the regions where the mean resident population is decreasing since 2000. In the white areas, the population is quite stable while the red zones represents regions where the annual growth rate is positive.

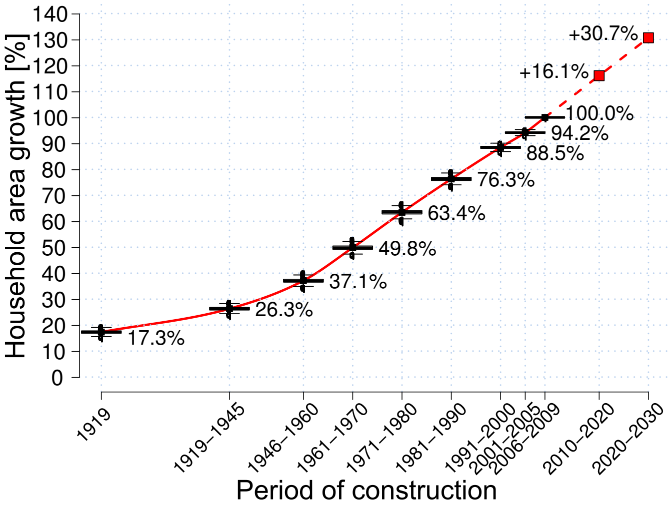


Figure 1.9: Household floor area growth in Switzerland since 1919 (Source: based on [FSO, 2011a], Table (A.1, p.160).

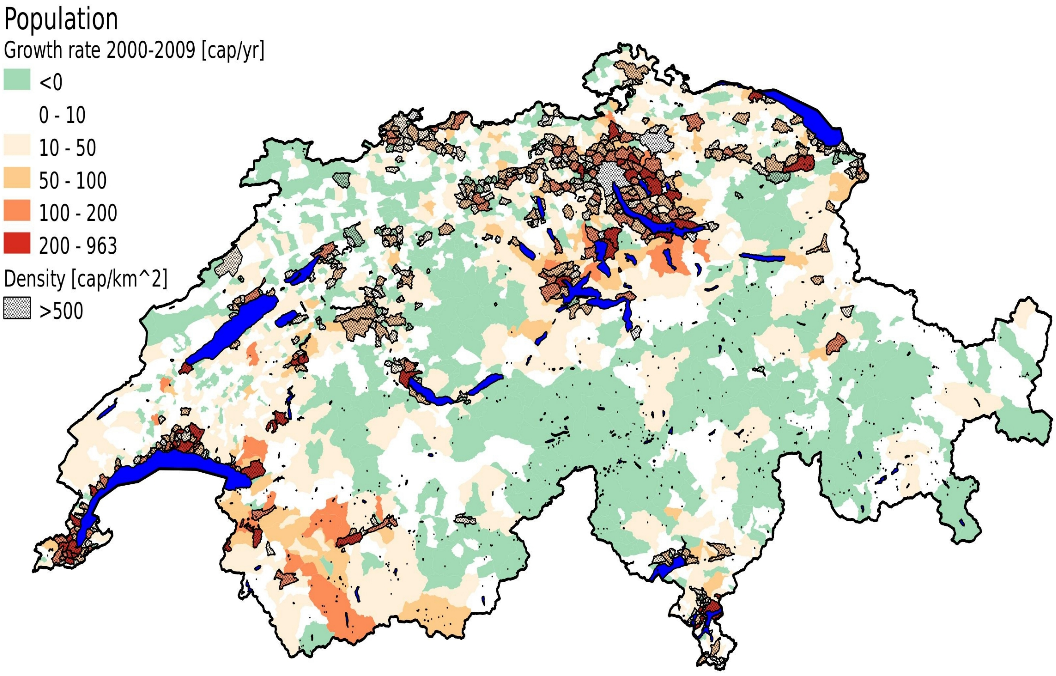


Figure 1.10: Population density growth in Swiss urban areas. Source: from [FSO, 2010b; Swisstopo, 2009]

1.6.3 State of legal binding and political will

In Switzerland, urban energy planning is not backed by national energy policies [LEne, 2011], whose objectives are rather to keep a competitive energy market, promote rational use of energy and ensure a safe and reliable energy supply chain. It therefore lies within the competence of the local states to decide on the establishment of a territorial energy master plan [Cherix et al., 2009].

For example in Switzerland since 2009, the Cantons have developed and gradually legislated a model of energy requirements (MoPEC[9]) so that the thermal energy used by new constructions is reduced by half compared to the current building stock consumption.

Concerning the existing building stock, the Cantonal Building Energy Certificate (CECB[10]) was set up to enable the comparison of the energy consumption of buildings and offers optimization measures.

Moreover, some leading states such as the Canton of Geneva, have already adopted more advanced, legally binding, frameworks. This mandates the renovation of energy wasteful buildings and the elaboration of a territorial energy concept which links the authorization of new fossil fuel supplied heating systems with the exigence of high exergy performances [Favrat et al., 2008; LEN, 2010, Art. 21].

The next coming challenge for the authorities will certainly be to set up a coherent strategy to unify and integrate the disparate energy labels and certifications, such as the ones described in section (§1.3, p. 4).

1.6.4 Source and availability of useful Information

Building and Population registers If local state authorities do have their own territorial information system, the National Statistical Office[11] is mandated by the Swiss constitution to collect general statistical information. Moreover, The Federal Statistics Act [431.01, 1992] enables researchers to use official statistics microdata for their own research projects, provided that dissemination of statistical results cannot be related to specific persons (art.18 and 19).

Thanks to the paradigm shift adopted in 2006 from a top-down to a bottom-up organizational approach driven by the principle of harmonization of local and national registries [Council, 2009], the local communities are forced, by laws such as the Federal Statistics Act [431.01, 1992] and the Federal building register prescription [Council, 2009], to collect, update and report back housing informations (§ 2.5.1, p. 35) to the National Register of Buildings and Dwellings [RegBL, 2010]. The same approach is pending for the harmonization of local and National Personal Registers, which could therefore be used to refine the estimation of the energy demand and to compute “per capita” energy indicators.

Since 2011, the Federal Statistical Office has also begun to assign a unique identification number to active firms on the territory, which suggests the upcoming opportunity to use the Business and Enterprise Register to locate industries, and to form an extensive building information system.

Cantons and the communities have access to these national registries to perform tasks attributed by law (land-use planning, urban plans developed at the lower levels, Area plans, security of electricity supply, wastewater and water treatment, waste or cleaning) or for re-

---

[9] Modèle de prescriptions énergétiques des cantons, Conférence des service cantonaux de l’énergie, http://www.endk.ch

[10] Certificat énergétique cantonal des bâtiments, http://www.cecb.ch/

[11] Bundesamt für Statistik (Office fédéral de la statistique), www.statistique.admin.ch

search, planning and statistical purposes.

Geo-reference information Another support for territorial energy mapping is provided by the Federal Geo-Information Center swisstopo[12]. In accordance with the prescription on the national mensuration [510.626, 2008] and the federal law on geoinformation [510.62, 5 October], it maintains 2D topographical maps and is entering, since 2008, into a new digital age with a 3D large-scale landscape model [O'Sullivana et al., 2008], including buildings and their roofs.

Meteorological information The Federal Office of Meteorology and Climatology[13] [MeteoSwiss, 2010] share, for educational purposes, monthly, daily and hourly measurements such as outdoor temperature, solar irradiation and wind from sixty-five automatic measurement stations across the national territory.

Energy consumption measurements The analysis of urban energy intensity from measurement of real energy consumption is however more problematic. Aside from the district of Geneva where, by means of popular vote[14], a law [REN, 2010, Art. 7] forces owners to communicate their annual energy consumption to the authority, the ability to harness information for R&D purpose dependent upon the willingness and administrative capacity of public/private owners, divided in 870 industrial services in Switzerland. Moreover, at present time, even the analysis behind energy performance certificates, often delivered by private consultants, are not automatically disclosed to public authorities and can therefore not be used for modeling.

1.6.5 Synthesis

Regarding the actual share of energy resources consumption, it is clear that the shift toward a sustainable society requires strategies across the range of urban scale [Pullen, 2009]. For example, according to Pfeiffer et al. [2005], the immediate application of the Minergie-P standard in conjunction with a balanced selection of efficient technologies could allow to achieve, by 2050, a reduction of the fossil primary energy use by a factor of 1.9–2.7. However as stated by Lowe [2007], it is possible that senior figures of local government are unaware of the scale and implications of these kind of ambitions.

The present work therefore proposes to move beyond the presentation of graphs and tables, by adopting a bottom-up approach in order to locate on maps the actual and future share and

---

[12] swisstopo, the Federal Geo-Information centre, www.swisstopo.admin.ch/

[13] http://www.meteosuisse.admin.ch

[14] Approved 7 mars 2010

use of energy resources, the possible synergies between energy demand and resource and the potential development of energy technologies and infrastructures.

1.7 Methodology overview

The goal of the method is to study the integration of energy conversion systems that realize the best matching between available resources and the energy services to be supplied in a geographic area (see Figure 1.11). The approach aims at guiding stakeholders in the definition of the energy dimension of urban planning by applying process integration techniques and energy conversion technology databases in a Geographical Information System. An overview of the method is given here before being discussed in more details in the next chapters.

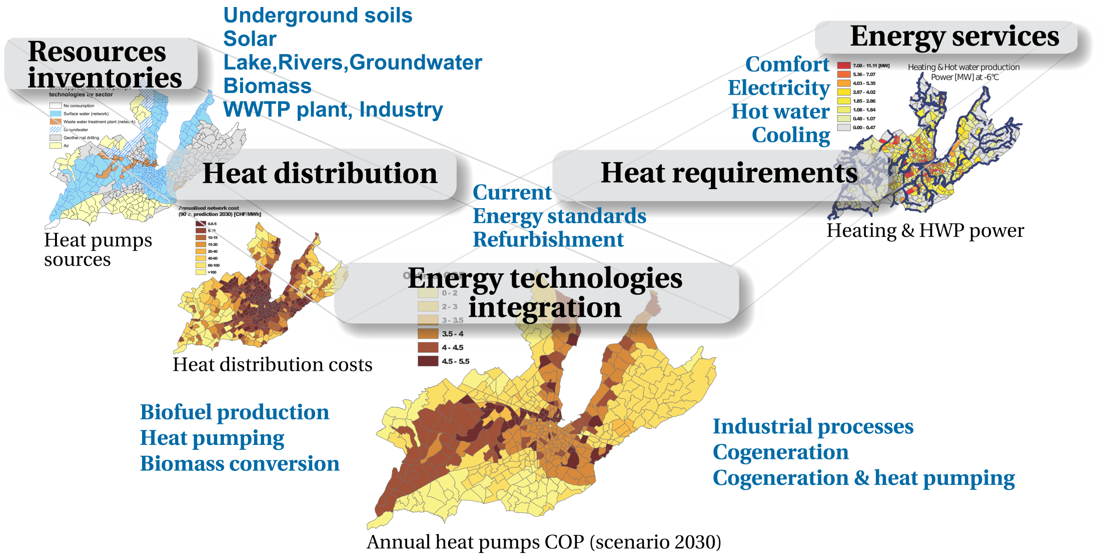


Figure 1.11: Optimal conversion of endogenous renewable resources into Energy services (Source: LENI, 2008)

1.7.1 Characterizing the demand

Considering the description of the building stock in a given area, the buildings are classified by type and range considering the years of construction or renovation.
A GIS database contains the area ($A_{c,z,yr}$) of existing and planned constructions of every category (c), in each zone (z). For each category, the annual consumption for heating, hot water production, cooling and electricity is determined from a statistical analysis of measured buildings (§ 2.7.3, p. 47). Based on these data, the building requirement model evaluates the heating and cooling loads as a function of the outdoor temperature following the signature approach [Adderley et al., 1988; Favre et al., 1983; Hammarsten, 1987; Zmeureanu, 1992] and provides the supply and return temperatures of the hydronic system as a function of the heat to be delivered (Figure 1.12).

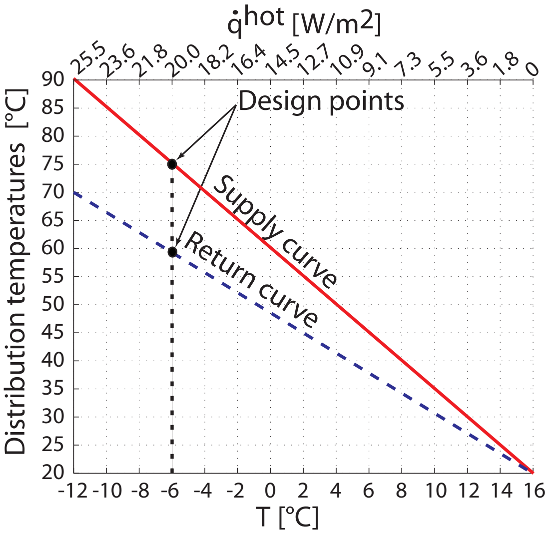


Figure 1.12: Example of heating distribution curves sized at 75/60 C for $T_{x,0}$=-6 C.

1.7.2 Characterizing the resources

The inventory of the available energy resources is also stored in the GIS data base. This gives information on the availability of endogenous resources (lake and surface water, underground water, geothermal heat) or waste heat available (waste water treatment plants or industries). Information on solar irradiation is combined with the available roof surface and their orientation to estimate the solar potential in the area. The available biomass production and the possible wind energy available is also considered.

1.7.3 Generation of centralized/decentralized options

In addition, considering the heat and power density in the different geographical areas, the cost of heat supply and distribution are estimated (see equation 4.12, p. 94). This allows one to compare centralized and decentralized polygeneration options, like the integration of combined heat and power options and/or heat pumping systems.

Considering that some of the resources have a limited availability (e.g. waste water), an aggregation method has been developed with the objective of identifying the geographical area that are suitable for district network development.

Combining requirements and resources will then allow to compute annual energy consumption and annual coefficients of performance of heat pumping systems. This calculation will take into account the temperature of the amount of heat to be delivered and the temperature of the heat source.

1.7.4 Evaluation of integrated energy systems

When applying process integration techniques (§ 5, p. 109), one can assess the integration of energy conversion technologies in a systematic manner, by computing the relevant energy efficiency indicators like exergy performance, energy and CO_2 emissions savings that will characterize the most promising energy concepts in the different zones.

1.8 Engineering elements of the method

This section gives an overview of the engineering elements required for the application of the proposed method, starting from the characterization of the demand, continuing with the generation, evaluation and analysis of integrated alternatives, and ending with the communication of graphs and maps of indicators.

1.8.1 Urban Energy System modeling

Top-down/Bottom up approach

Before thinking of solutions to convert resources into useful energy from a quality and intensity perspective, the method raises the question of means and pathways to improve the knowledge of the demand within the boundaries of territorial communities. This can be achieved following two broad classes of strategies : top-down and bottom-up approaches.
The proposed approach focuses first on the understanding of the temperature and useful energy requirements of urban areas. Starting with the final energy consumption of the energy conversion technologies, measured by consumption-meters or obtained from energy bills. This permits not only to assess, by bottom-up spatial aggregation, the final and primary demand of incremental geographic area, but also to generate, evaluate and analyze future alternatives for the energy conversion chain (Figure 1.13).
The same logic shall also apply to the identification of stakeholders, starting with local institutions and information holders, involving gradually more actors to widen the scope of actions and set more ambitious targets.

An important point is that the useful demand of the building stock is formulated not only in terms of energy, but also of temperature levels, expressed as a function of the power demand. This is particularly relevant for the modeling of existing, new and renovated buildings when considering the switch from boilers to heat pumps, from boilers to condensing boilers, from high to low temperature district network and more generally for the optimal design of district heating systems as described in Weber et al. [2006a].

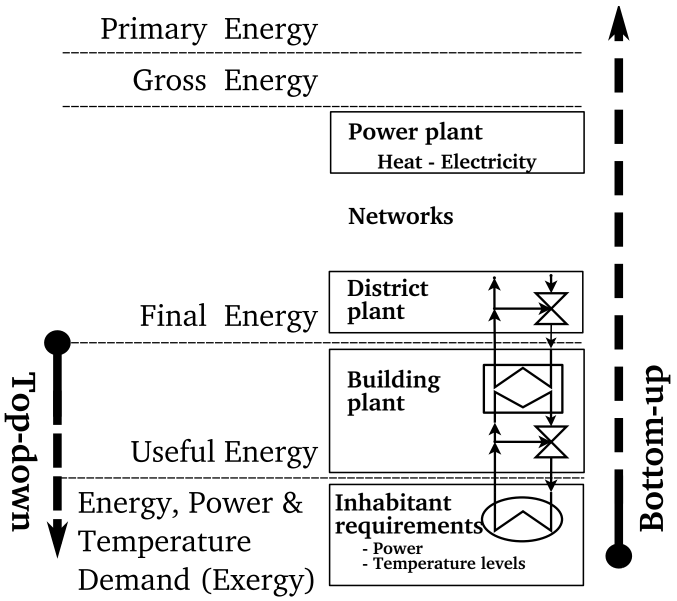


Figure 1.13: Top-down and bottom-up approaches of Urban Energy Systems.

Building energy modeling approach

The modeling of buildings performances may follow schematically three approaches.
The first one, mainly applied for building's design, relies on the proper definition of many thermo-physical parameters and geometrical dimensions and allows the prediction of the hourly behavior of the building.
The second approach uses an identification method, in order to identify the parameters of a simplified model, based on indicators like energy bills and consumption, real time measurements or even value of best practices. This kind of models fails to simulate the dynamics of the system for time periods shorter than a day. These methods often use statistical regression to perform the parameter identification.
The third approach combines the two previous ones, attempting to use experimental data in order to identify the parameters of a detailed theoretical model. These methods often use Neural Network techniques or Genetic Algorithms in order to perform the identification procedure.

Modeling strategy The proposed methodology adopts first a top-down approach starting from consumptions measurements and energy technology efficiencies in order to evaluate the requirements of the building stock. This allow to apply in a second phase a bottom-up spatial aggregation of archetypes and samples of building (see Figure 1.14). The parameters of the energy regression models are identified for each archetype based on measurements of monitored buildings.

At the scale of single buildings, the necessary information comes either from monitoring sen-

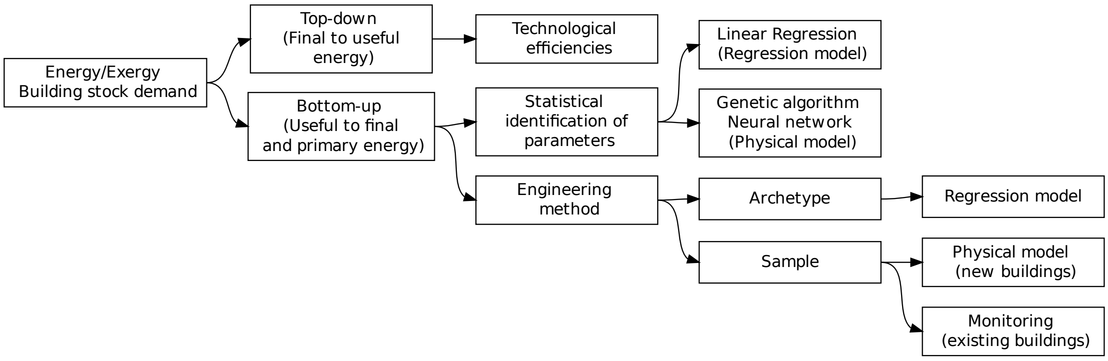


Figure 1.14: Building's energy modeling strategy (inspired by Swan and Ugursal [2009]).

sors in existing buildings or from physical simulation software for the new ones, considering that Process Integration solvers requires as input the useful electrical and thermal power with its temperature levels, the cost and availability of utilities which have to be given with the operating time of each typical period and for sizing conditions as well.

Archetype engineering method The categorization of typified surfaces permits to break away from spatial scale constraints and household architectures. Bringing the structure to this degree of abstraction permits the extension of the spatial analysis naturally to wider geographical area by aggregation of the surfaces and their usage. The attributes required to model the requirements, to compute the indicators and to perform the energy integration are attached to each surface independently of its geometrical attributes.
This classification task is performed by clustering neighboring energy requirements as a function of the period of construction/renovation, the type and the geographical location of the buildings. The initial granularity of the clusters is of course determined by the level of disaggregation of the available information (building or parcel) as well as by the available official classification.

Scale-independent aggregation

By definition. aggregation or aggregate functions combine several numerical input values into a single result. Common statistical aggregates are the count, sum, average, Max and Min, but more specifically, so far as urban energy systems are concerned, indicators such as the one listed in Table (1.5)
As shown in Figure (1.15), indicators for urban systems should apply irrespective of the magnitude of the spatial scale.

The scaling problem is addressed by the definition of an attribute-value pair model $\{(c, A_c) | c \in$

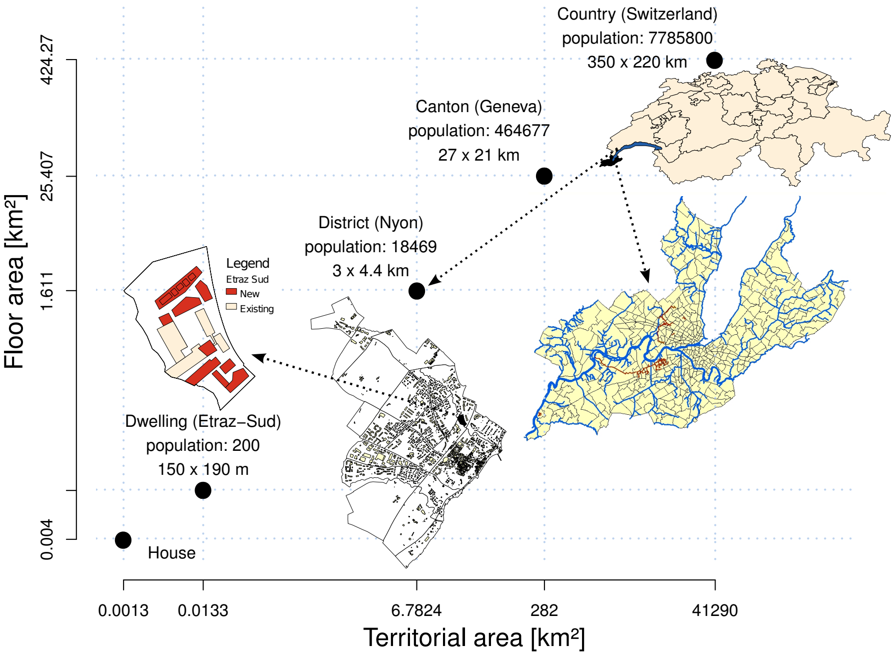


Figure 1.15: Log-log plot of the magnitude of the spatial scale to deal with in urban studies.

$C\}$, listing for each category (c) the corresponding floor area (A_c). The aggregation of a geometrical element (G_z) belonging to a geographical zone (G_Z), is achieved by summing the enclosed areas, as shown in Equation (1.2).

$$A_{c,G_Z} = \sum_{\{z \in Z | G_z \subset G_Z\}} A_{c,G_z} \tag{1.2}$$

The definition of specific values (i_c) per unit of typified area (A_c) allows to compute a global value (I_Z) for the geographical zone (Z) by summing the contribution of each category (Equation 1.3).

$$I_Z = \sum_{c \in C} i_c \cdot A_{c,G_Z} \tag{1.3}$$

Uncertainties Assessment

The Monte Carlo method emerged following the development of electronic computer between 1945-47 at Los Alamos Scientific Laboratory [Metropolis, 1987] and has been directly applied to the Manhattan Project.

This simulation method [ISO, 2004] allows to propagate the uncertainties on the input parameters to generate statistical distribution for the output results. The output error can then be delimited by confidence interval.

The procedure uses either statistical distribution or random number in intervals, such as efficiencies or floor area to model the uncertain input parameters. Simulations are then performed on each generated random sample $(X_1,\ldots,X_k)_i,\ i=1;\ldots,s_r$ repeatedly, resulting in an output sample $(Y_1,\ldots,Y_k)_i,\ i=1;\ldots,s_r$ and a distribution ($\mathscr{K}$) such as $Y \sim \mathscr{K}$, as shown in Figure (1.16). This method comes at a cost as simulation has to be repeated many times (s_r) instead of a single one, resulting in a simulation time increased for example from roughly 0.8 second to 2.5 hours for 10'000 simulations[15] performed on the city of Nyon counting 2'100 buildings.

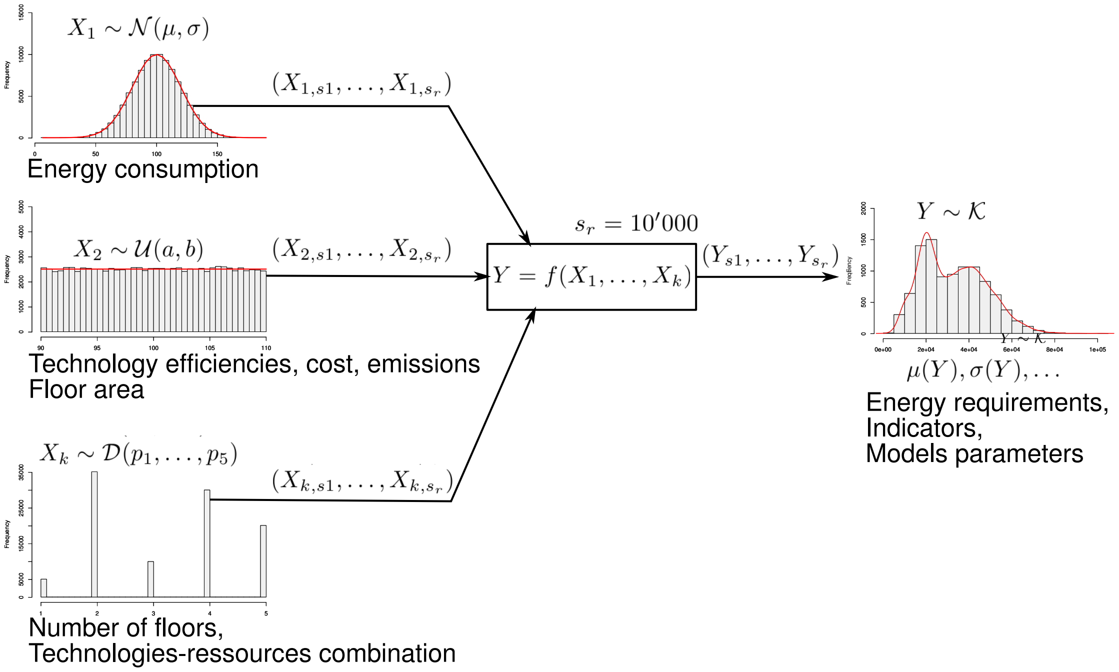


Figure 1.16: Monte-Carlo simulation techniques for the evaluation of uncertainty by propagation of statistical distributions.

1.8.2 Geographical Information System

Database management systems

When attacking a problem, analysts often prefer not to collect data, but to use existing data. They are however often forced to collect data because existing data are not usually available in forms that are usable [Dueker, 1968] or, as said by GIS pioneer Edgar Horwood (1919-1985), "the data you have for the present crisis was collected to relate to the previous one".
If the initial application of statistical values allows to compensate for the lack of data, the

---

[15] Performed on a microprocessor Intel®Core™2 Duo Processor E6600 (4M Cache, 2.40 GHz, 1066 MHz FSB)

systematic use of average values, without distinction between geographic location, may fail to accurately describe the real situation of the demand.

It is then necessary to enrich the decision support system with information collected on-site, in order to prove or challenge conventional thinking and statistical hypothesis [Isaacs et al., 2006]. Moreover, progressive introduction of measurements adds value to the database and improves the reliability of the computed indicators.

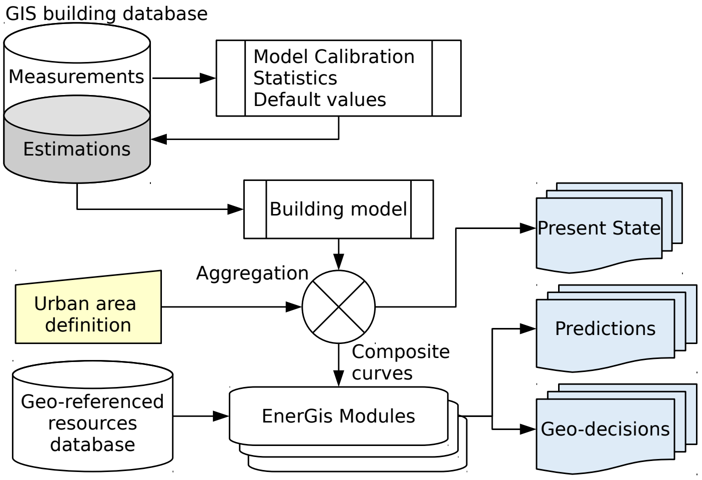


Figure 1.17: Flow of information supporting the decision-making process.

Geo-localization of energy resources and infrastructures

Mapping the material and energy resources facilitates the ability to detect limitations and opportunities for the conversion, recovery and upgrade of energy. This is particularly true when considering environmental heat sources and sinks like ground, groundwater, rainwater, ambient air, river and lake, as well as wasted heat from waste water treatment plant (WWTP), waste water and other industrial processes, where the periodic heating and cooling loads and temperature levels have a determining influence on the performance of the system [Kalz et al., 2011].

Furthermore, the setting up of an urban resource inventory permits matching the local demand with the available resources using process integration techniques applied with or without heat exchange restrictions [Becker et al., 2010] between geographical zones.

Figure (1.18) present an example of a map of energy resource and infrastructure for the district of Nyon [Darbellay et al., 2007; Girardin et al., 2010c].

A list of common resources and infrastructures is proposed in Table (1.3) and (1.4) with prime justification to seek the information.

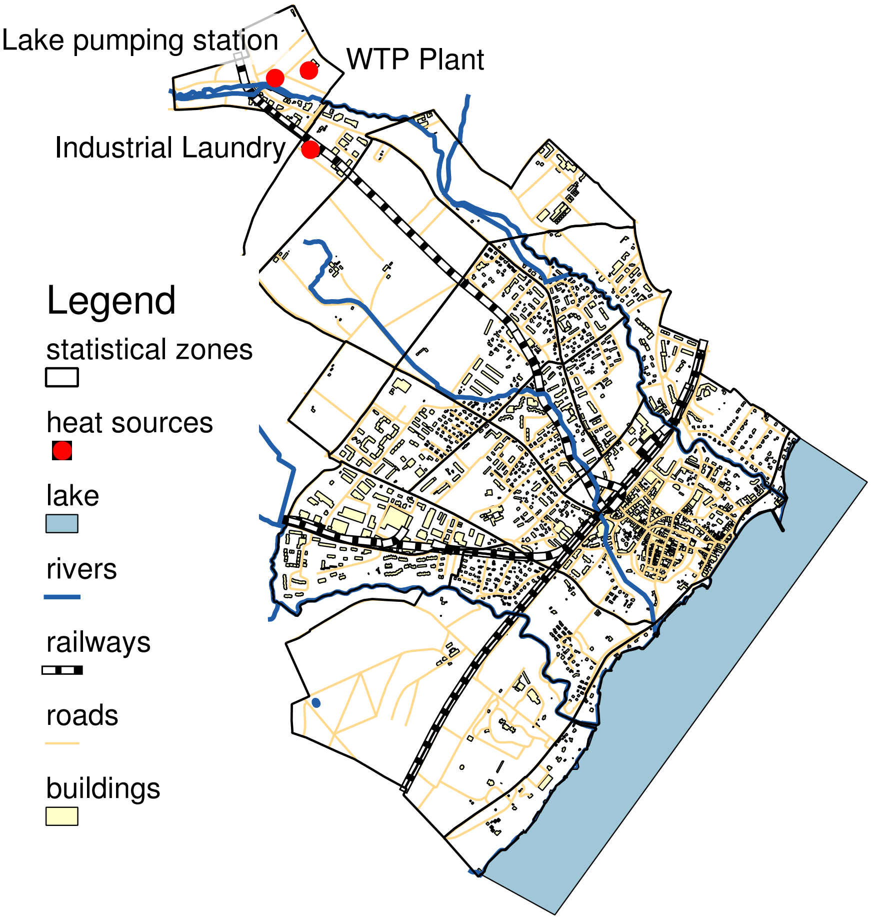


Figure 1.18: Available infrastructure inventory

Table 1.3: Main source of motivation for the geolocation of energy resources.

Energy sources	Motivations
Resources available in buildings	input of energy models
Air temperature, solar irradiation	input of energy models of heat pumps and solar technologies
Lake and rivers area	distribution of heat through networks
Undergrounds and underground aquifers	distribution of geothermal heat heat pumping and storage generation of electricity
Water collectors and WWTP plant	heat recovery
Wood and biomass	development of local, renewable energy
Industrial waste heat recovery	heat recovering/upgrading
Protected zones (drilling exclusion zone, heritage protected area, etc...)	exclusion of infeasible solutions estimation of the underlying penalty

Table 1.4: Main motivation for the geolocation of energy-related infrastructures.

Infrastructures	Motivations
Energy conversion technologies	input parameters of energy model strategic planning of centralized/decentralized energy systems
Geometry/orientation of buildings and roofs	input parameters of energy model smallest scale of the spatial disaggregation
Roads and railways, bridges	opportunity/limitation for heat distribution network fix some natural boundaries between urban zones
Heat distribution networks	information on energy consumption (monitored system) identify opportunity of extension
Industries	identify synergies and heat recovery opportunities
Power plant	integration of advanced energy system

1.8.3 Process Integration techniques

Integrated Energy Systems design using Process Integration techniques

Integrated Energy Systems (IES) combine local and centralized energy conversion and distribution technologies that transform material and thermal resources into useful energy services such as electricity, cooling, heating, ventilation, air conditioning and energy storage. Applied to district energy systems, Process Integration techniques aim to fulfill the requirements of the population with high energy/exergy efficiencies by enhancing inter-process heat exchange between the centralized/decentralized conversion technologies and power plants, the energy from the environment, the wasted heat from industrial processes and the building's heat gains and losses.

The energy integration procedure is performed by the Process Integration (PI) solver that find the optimal sizes and thermodynamic states of any kind of sub-systems (s) of a global process (S). In this approach, based on the pinch theory, the complexity of the highly non linear and multi-variable model is reduced by splitting the problem into its linear components, instead of optimizing all at once, as shown in Figure (1.19). Starting from the initial operating condition (1), every sub-system is simulated separately (2) before their thermal and mechanical streams ($\{\dot{Q}_0, T_{in}, T_{out}, C\}$), minimal temperature difference ΔT_{min} and bounds ($[\dot{Q}_{min}, \dot{Q}_{max}]$), are sent to a Mixed Integer Linear Problem (MILP) solver (3), which determines the multiplication factors (f_w) and technology selection integers (y_w), such as the cost function (1.4) is minimized under constraint (1.7-1.10), where ($\dot{E}^{el}$, $\dot{E}^{el}_{in}$, $\dot{E}^{el}_{out}$) is the electricity respectively required by the process, imported and exported.

$$\underset{f_w, Y_w, R_w, \dot{E}^{el}_{in}, \dot{E}^{el}_{out}}{\text{Minimize}} \int_{t_0}^{t} \left(\sum_{w=1}^{nw} C_w \cdot f_w + C^{el}_{w,in} \cdot \dot{E}^{el}_{w,in} + C^{el}_{out} \cdot \dot{E}^{el}_{out} \right) dt \tag{1.4}$$

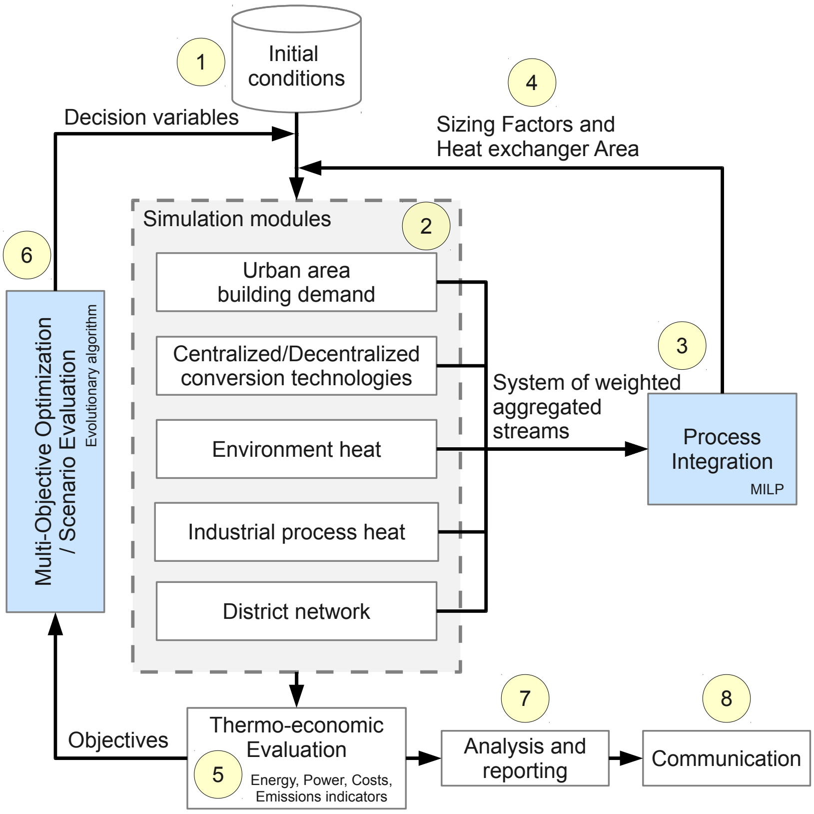


Figure 1.19: Solving procedure for the optimal integration of energy systems.

Subject to (1.5)

Technology selection $\dot{Q}_{min,k} \cdot Y_k \leq f_k \cdot \dot{Q}_{0,k} \leq \dot{Q}_{max,k} \cdot Y_k,\ Y_k \in 0,1$ (1.6)

Heat cascade balance
$$\sum_{w=1}^{nw} f_w q_{w,r} + \sum_{i=1}^{n_r} Q_{i,r} + R_{r+1} - R_r = 0,\ \forall r = 1,\ldots,n_r \tag{1.7}$$

Electricity consumption
$$\sum_{w=1}^{nw} f_w \dot{E}_{0,w} + \dot{E}_{in}^{el} - \dot{E}^{el} \tag{1.8}$$

Electricity production
$$\sum_{w=1}^{nw} f_w \dot{E}_{0,w} + \dot{E}_{in}^{el} - \dot{E}_{out}^{el} - \dot{E}^{el} \tag{1.9}$$

Feasability
$$\dot{E}_{in}^{el} \geq 0,\ \dot{E}^{el} \geq 0,\ R_1 = 0,\ R_{n_r+1} = 0,\ R_r \geq 0 \tag{1.10}$$

Moreover, this MILP problem activates the pinch point of the hot and cold streams of the heat cascade (R_w), resulting in an estimation of the total heat exchanger area.
In the context of urban system studies, the fixed streams are made of the urban area's building

demand and existing district networks, while the utilities streams, which are linked to the equipment with varying size, are composed by the energy conversion systems, part of industrial processes, new distribution networks and heat from the environment.

Once the sizing coefficients have been optimized (4), the thermodynamic state of the integrated process is obtained again by simulation (2) of the updated sub-systems size ($\dot{Q}_w = f_w \cdot \dot{Q}_{0,w}$). Based on the state of the integrated process, indicators of performance, emissions and required energy, investments and operating costs are computed (5) and finally analyzed (7) and communicated (8) .
Moreover, the variation of parameters allows to simulate predefined scenarios, or to generate promising configuration by letting a multi-objective evolutionary algorithm explore the space of the decision variables (6).

Geographic targeting indicators

The selection of quantitative indicators should be closely linked to the formulation of targets and objectives at the early stage of projects. The indicators should be designed to quantify the gap between the actual state and the targeted evolution of the urban system, such as the "3×20" target set by the Covenant of Mayors, or the one of the "per capita" $2000W$ society [Maréchal et al., 2005]. Specific indicators may be expressed per capita, per square meter of floor area or per hectare of land area. In order to deliver per capita indicators on maps, the relationship between inhabitant registry and geographic area, or even buildings, must be available. This work is currently work carried by local communities in Switzerland. An example is given by the district of Nyon [Nyon-Energie], whose development indicators have been included in the non-exhaustive list given in Table (1.5).

Table 1.5: Overview of some urban energy indicators.

Fields of practice	Indicators	Units[a]
Energy consumption	Electriciy consumption	$kWh/(unit \cdot yr)$
	Heat-energy expense index (Equation 2.8, p. 58)	$kWh/(unit \cdot yr)$
	Number of Minegie-P buildings (Table 2.9, p. 49)	–
	Number of Minergie buildings	–
Energy efficiency	Fraction of monitored buildings	%
	Energy savings on monitored buildings	%
	Gap between real and targeted energy savings	%
	Energy efficiency of water distribution system	$kWh/{m_w}^3$
	Energy efficiency of waste water treatment plants	$kWh/{m_w}^3$
Renewable Energy	Electricity generated from renewable resource	%
	Renewable energy for space heating and hot water	%
	Amout of photovoltaic electricity	$KWh/(unit \cdot yr)$
	Area of solar thermal panel	$m^2/unit$
	Electricity from cogeneration power plant	$kWh/unit$
Local Energy	Electricity generated from local resources	$kWh/unit$
	Renewable energy generated locally	kWh/yr
	Renewable thermal energy generated locally	kWh/yr
Resources and water	Water consumption	$l/(unit \cdot day)$
	Volume of water at WWTP plant	$l/(unit \cdot dy)$
CO_2 emissions	CO_2 emission index (Equation 2.10, p. 59)	$t_{CO_2}/(unit \cdot yr)$
Cost	Annual energy bill expenses (Equation 2.11, p. 61)	$CHF/(unit \cdot yr)$
	Annual subsidy for renewable energy	$CHF/(unit \cdot yr)$
	Annual investment in the energy sector	$CHF/(unit \cdot yr)$

[a] Depending on the specific definition, "$unit$" stands either for the number of inhabitant, the inhabited area [m^2] or the land area [ha]

1.9 Conclusion

In 2009 in Switzerland,the combined household and service sectors were responsible for 47.6% of the annual national energy demand. Their share reaches 59.6% in winter, due to the predominance (34.4%) of building heating. The composition of energy mix providing these energy services is mainly non-renewable (70%). This share is even higher if calculations are based on the Swiss electrical consumption mix instead of the Swiss production mix.

In the face of diminishing non-renewable energy sources, a change in the energy supply mix appears inevitable and justifies the intention to move towards the design of more integrated urban energy systems. This decision implies examining scenarios for technological evolution of the built environment.

Informed decision making demands the integration of knowledge derived from disparate domains and this in turn requires agreement on an acceptable methodology for this integration.

An holistic methodology is therefore proposed grouping urban modeling strategies and Process Integration techniques in a Geographical Information Systems (GIS) for the evaluation of integrated energy conversion systems in urban areas.

2 Specification and Methods of a GIS for Urban Energy Integration

2.1 Introduction

Despite the fact that the building and infrastructure stock is the largest physical, economic, social and cultural capital of most societies [Kohler and Yang, July 2007], the lack of structured data has hampered the development of long-term scenarios [Lomas, March 2009]. Tremendous work is indeed still involved to gather together necessary energy, building and infrastructure information required to perform regional energy assessment and strategic planning [Darbellay et al., 2007; Girardin et al., 2010c,d] going beyond the scale of individual dwelling or residential area.

This is explained by the fact that data, mainly coming from legal registers and energy bill monitoring, are often dispersed, for historical reason, among distinct administrative office and service providers. In the past,the information has moreover not necessarily been collected on purpose, making it awkward to use.

In fact, not only the worldwide scarcity of available comprehensive building energy information [Pérez-Lombard et al., 2008], but also the lack of collaborative platforms with established standards and methods, are impeding the emergence of a holistic regional approach.

Integration is therefore needed to integrate, in territorial information systems, strategy and tools in order to manage the long-term evolution of the building stock of urban areas [Kohler and Yang, July 2007], which is one the key aspects of sustainable development of our countries.

2.2 State of the art

Following the emergence of digital mapping, the development of Geographic Information Systems (GIS) in the 1960s is driven by a profound sense that decision-makers, researchers, and planners require more accessible information to support government effort in effectively planning, programming, and allocating resources to agencies performing functional tasks [Dueker, 1968]. Motivated by protection and environmental risk management, pioneer [Tomlinson and Boyle, 1981] efforts to handle natural resources inventory data lead to the implementation of a

multilayer land-use planning map of Canada's inhabited and productive land.
The production of large scale street representation and thematic maps based on digital boundary files and census variables from the U.S. Bureau of the Census required laborious development of geocoded urban planning information systems in the seventies, which become a mature technology in the 1980s with software suppliers beginning to distribute GIS packages [Morehouse, 1985].

Not linked with analytical capabilities of urban models, GIS has long been used to store and analyze land-use, land-ownership and building register information [Wegener, 1994], while at the other end of the scale the house building industry developed, in the late 1980s and early 1990s, Computed Aided Design (CAD) [Whyte et al., 1999] and in the 2000s, Building Information Modeling (BIM) [Taylor and Bernstein, 2009] tools that integrate geographic location and design parameters to enable the interoperability with software for HVAC system simulation, energy analysis, flow analysis, cost estimation and LCA analysis [Crosbie et al., 2011]. For example, a collaborative platform based on a distributed modeling environment (DOME) interconnecting data and models, has been proposed [Kraines et al., 2005] for the simulation of building designs in urban region.

The last ten years have also seen the use of energy and environmental prediction models on top of GIS platforms [Jones et al., 2001; Thuvander, 2002; Tornberg, 2005], making it possible to estimate hourly and seasonal energy consumption profiles [Heiple, 2008] and evaluate the integration of advanced energy conversion systems [Girardin et al., 2010b] at spatial scales down to the individual parcel. Methodology including application at the scale of individual buildings for Geographically-resolved airshed [Medrano et al., 2008] and spatial depiction of life cycle energy analysis [Pullen, 2009] have also been reported.
Theses methodologies use a bottom-up approach to aggregate statistical data defined on city-specific buildings archetype [Cheng and Steemers, 2011; Firth et al., 2010], classified at least by year of construction, and geo-referenced in an official land registry. However, the role played by these models in helping decision makers may be limited if the uncertainties that arise in the modeling process are not quantified [Booth et al., 2011].

2.3 Objectives

The establishment of a geo-referenced urban energy inventory constitutes the first step of the strategic planning. This task aims to achieve:

- the establishment of a minimal set of necessary information (§2.5.3) with hierarchical priorities (§2.5.3),
- the identification of the sources and owners of local information (§2.5.1),

- the centralization of existing but diffuse information structured within the data storage (§2.4),
- the production of added value out of the information gathering effort, making it available for every new study to come,
- the spatial aggregation and disaggregation of the indicators,
- the management of data import and transfer procedures (§2.9),
- the presentation of the actual balance of resource, energy, emission and cost including the corresponding indicators, composite curves and statistics, (§2.8, p. 55),
- the electronic access to geo-referenced energy data layer (§2.9.2).

The database will therefore not only be used to assess the present state of the urban system in the preliminary phase, but also support the evaluation of competing scenarios and the optimal integration of centralized and decentralised energy conversion technologies.

2.4 Overview of the Urban Energy GIS System

The proposed geo-referenced database emerged from the identification of the necessary set of data required to apply pinch analysis and process integration techniques in urban areas. Practical and methodological considerations are brought into line by the use of adequate models and solving procedures, but also by relying on standard and good practice rules instead of values that cannot be collected in a reasonable amount of time.

The elements of the urban energy database, seen in Figure (2.1), are structured in five blocks :

- the building energy inventory which geo-references building archetype, identifier, floor area, heating and cooling technologies, energy resources and consumption.
- the local resource inventory which locates environmental and industrial heat source and sink and lists their thermodynamic characteristics.
- the meteorological database, which contains local hourly measurements of outdoor temperature, solar irradiation and eventually wind speed. These data are available online [MeteoSwiss, 2010], but can also be generated with the help of dedicated software such as [Meteonorm].

- the default value for each building prototype, each energy source and conversion technology. The classification of buildings into various archetypes and the corresponding default values are determined locally by statistical analysis of the building stock. This approach results in a model incorporating both measured and unmeasured values.

- the meta-data repository which contains the data elements of the attributes of the database. Meta-data is commonly defined as being information about data. It offer description of the content, quality, condition, authorship, and any other aspects of data. The data elements of attributes contain the following meta-data fields: the physical units, the status (default, measured, precessed value), the type (character, numeric with precision, matrix, dates) and eventually the description of the uncertainty and the person responsible for issuing the value.

Added to this is a repository with general information (project name, date, author, meteorological zone, typical simulation periods) relevant to each project.

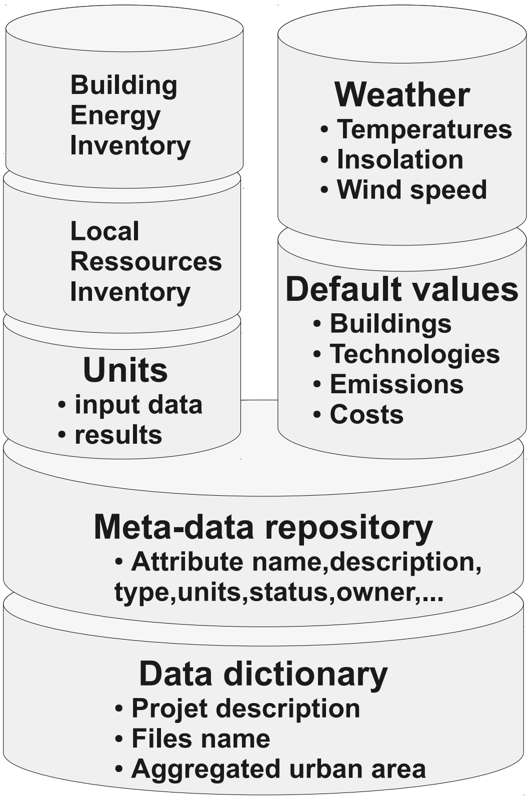


Figure 2.1: Elements of the urban energy GIS.

2.5 Building Energy Information System

The building energy inventory extends the official Cadastral map. If the Cadastral map is not accessible, an electronic topographic map with a resolution of typically 1:25000, may be used instead [Swisstopo, 2009]. Useful maps may also be downloaded from collaborative web sites offering free editable maps of the world [Ramm and Topf, 2010].

Setting up the Building Energy Information System requires identification and integration from various external sources of information. Merging and cleaning operations are then performed to obtain the desired data structure.

In order to optimize information collection and processing, different priorities are defined for the attributes of the Building Energy Inventory. The minimal set of necessary information has particularly been identified.

The hierarchical structure of the building energy inventory fields is discussed in section (§2.5.3, p. 36).

2.5.1 Integration of existing data layers

The building energy inventory is created from the integration of the information of the National Register of Buildings and Dwellings [RegBL, 2010], whose attributes are listed in Table (2.1) with their status. At national scale, residential buildings are systematically reported in the register and updated, by law, at least annually. On the contrary, the census enumeration of buildings not used for habitation is not mandatory and depends upon goodwill of the local authority processing the data.

Table 2.1: Attribute of the Swiss building register [RegBL, 2010].

Attribute name	Description	Residential building	Building partially used for habitation
EGID	Federal Identifier	**essential**	**essential**
GBAUP	Period of construction	**mandatory**	**mandatory**
GHEIZ	Space heating system	**mandatory**	**mandatory**
GENHZ	Space heating energy source	**mandatory**	**mandatory**
GWWV	HW system	**mandatory**	**mandatory**
GENWW	HW energy source	**mandatory**	**mandatory**
GKAT	Building's category	**mandatory**	**mandatory**
GASTW	Number of floors	**mandatory**	**mandatory**
GKLAS	Building's type	**mandatory**	**optional**
GAREA	Building's ground area	**optional**	**optional**
GRENP	Refurbishemnt period	**optional**	**optional**
STRNAMK1	Street identifier	**optional**	**optional**
DEINR	Entrance identifier	**optional**	**optional**

2.5.2 Data cleaning and merging

In GIS applications, there is often a need to combine diverse data sets into an integrated data set which includes all of the data points. One of the biggest challenges at the present time is the migration of geo-referenced layers with data attached to street addresses, to a layer referenced by building, more adapted to urban planning tasks. This requires merging polygons from Cadastral maps, with points from building registers, by spatial location, and then cleaning multiple points inside polygonal buildings, or badly geo-referenced points lying outside buildings, as shown in Figure (2.2).

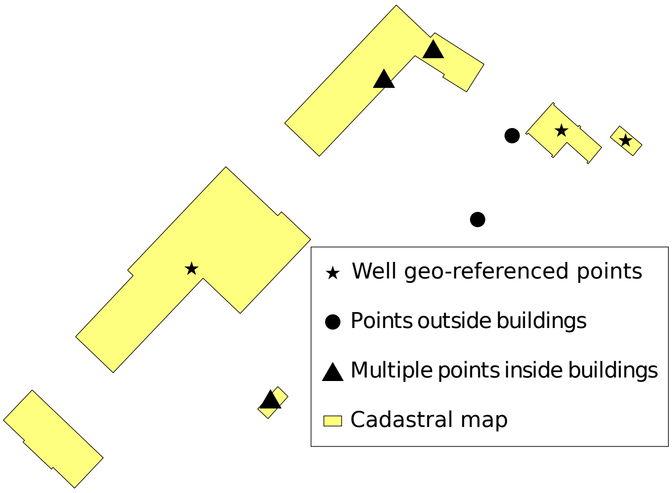


Figure 2.2: GIS View of the badly geo-referenced points to be cleaned and integrated in the [RCB, 2010] (Source: [Girardin et al., 2010c]).

The data cleaning procedure is applied systematically to each studied area and has to undergo a strict validation procedure by local authorities. Following this bottom-up approach, the national register is gradually updated and cleaned, which explains the parallel existence of local registers with most up-to-date information. For example, after data cleaning (2010), the information for the district of Nyon [Girardin et al., 2010c] is well geo-referenced for 95% of the buildings, corresponding to the covering of 99% of the estimated floor area (Table 2.2).

2.5.3 Hierarchical structure of the Building Energy Inventory

The establishment of hierarchical priorities on the information allows the improvement of the project efficiency by bringing in line the amount of required data with the level of detail expected by the analysis. This pragmatic approach emerged from a compromise between the complexity of models and the reasonable quantity of information that can initially be treated at the scale of urban zones.
For example, in the absence of energy consumption measurements, the use of statistical value nevertheless permits territorial exergy analysis, using a model of the heating and cooling

Table 2.2: Result of data merging between the [RCB, 2010] and the Cadastral map of the city of Nyon, 2010.

Source	Number of building		Ground area		Floor area	
	%	$[-]$	%	$[m^2]$	%	$[m^2]$
Land registry	100.00%	2179	100.00%	545794	100.00%	1611001
RCB,[2] well geo-referenced	83.48%	1819	68.95%	376336	66.13%	1065302
RCB, point outside buildings	5.00%	109	0.94%	5127	0.90%	14509
RCB, multiple point inside buildings	11.52%	251	30.11%	164331	32.97%	531190
Building energy inventory	**95.00%**	2070	99.06%	540667	**99.10%**	1596492

[2] Cantonal register of buildings and dwellings of the state of Vaud [RCB, 2010].

requirements (see Chapter 3). This holds provided that one has collected the minimal set of initial information, listed in Table (2.3, p. 38), which does not yet contain quantitative energy fields.

The list of prioritized sets of attributes, namely the minimal, heating, cooling, geometrical and dynamic one, are listed in Tables (2.3-2.8, pp. 38-41). The priorities, ranked on the basis of the extent of time and cost to collect the information, also reflect the increase in accuracy of the estimates while the database is enriched.

Minimal set of attributes

The minimal set of required attributes, presented in Table (2.3), allows the estimation of the exergy requirements of a given area, based solely on standards or statistical values.
The definition of a unique identifier (UID) for each building is an absolute requirement for the design of an energy inventory, as geographic, technology, demographic and energy consumption information have to be merged together from different sources and formats.

The proposed database adopts the Federal Identifier "EGID" of the National Register of Buildings and Dwellings [RegBL, 2010] as the unique identifier. This choice is consistent with the procedure of harmonization of the register of the inhabitants actually in process at the national level [LHR, 23 juin 2006], but this implies also its adoption by energy suppliers and industrial services, who historically uses multiple address identifiers for billing purposes.
The specification of buildings' categories with the corresponding heated/cooled floor areas is also central to the database. It permits the application of specific energy requirements per floor meter, as well as the computation of specific indicators afterward. Knowing the energy technology/resource combination, one may then apply typical efficiencies to compute consumption, emission and cost based on the requirements established previously.
While fairly well known by owners and tenants, the floor area is not found in official registers, contrary to ground area and number of floors (which can also be identified visually using tools such as Google Street View [Anguelov et al., 2010]). These additional fields, presented in Table

Table 2.3: Initial fields of the energy register.

Field of practice	Attribute	Units	Description
Identifiers	uid		Unique identifier
	name		Address or name of the zone
Georeference	x		X-coordinates
	y		Y-coordinates
	proj		Map projection
Archetype	aff		Building's type
	date		Construction/refurbishment year
	category		Building's category
Heating	hs_A	m^2	Heated floor space
	hs_res		Energy resource
	hs_tech		Energy conversion technology
Hot water production	hw_res		Energy resource
	hw_tech		Technology
Cooling	cs_A	m^2	Cooled floor space
	cs_res		Energy resource
	cs_tech		Energy conversion technology
Refrigeration	refr_res		Energy resource
	refr_tech		Energy conversion technology

(2.4), permit rough estimates of the inhabited floor area.

Table 2.4: Additional fields for floor area and floor occupancy.

Field of practice	Attribute	Units	Description
Building characteristics	floor_n		Number of floor
	gnd_area	m^2	Ground area
	h	m	Height
Hot water demand definition of indicators	n_p		Number of individuals

Heating consumption attributes

The accuracy of the results obtained from the minimal set of data depends on the quality of statistics that should be obtained from a large sample of categorized buildings and have acceptable standard deviation. If it makes sense to start with the proposed initial set of data for studies at the scale of cities, canton, state or country, large variations of energy consumption may be observed at the scale of neighbourhoods. It is thus, as listed in Table (2.5), a priority to gather real consumption, temperature levels of heat exchanges and measurement periods, to ensure accurate results.

Even if the measured consumption of final energy is available, the share between heating, hot water (HW) and cooling is in general not known apart from standard values. As a practical expedient, the needs of HW are guessed from typical requirements of hot water per capita or similarly from values expressed per square meter of floor area (Table 2.3, p. 38). A heating/HW ratio which is adrift from the Swiss standard (Table 2.9, p. 49), indicates an anomaly.

Table 2.5: Final consumption attributes of the database.

Field of practice	Attribute	Units	Description
Resource consumption	res_qf	KJ/yr	Final consumption by resource
	el_ec	KJ/yr	Final electricity consumption
	res_link	–	Identifier of the consumption meter
	res_pmea	–	Periods of measurements
Heating Energy signature	hs_k1	$kW/(m^2 \cdot C)$	Global heat losses coefficient
	hs_Txo	C	Nominal outdoor temperature
	hs_Tc	C	Threshold temperature
	hs_Tro	C	Nominal supply temperature
	hs_Tso	C	Nominal return temperature
	Tinto	C	Indoor temperature
Hot water production	hw_Tro	C	Nominal supply temperature
	hw_Tso	C	Nominal return temperature

An issue to tackle when treating measured consumption is the division of the information split by location of consumption meter, often referenced by street addresses for each resource (district network,gas,oil,electricity and water). To avoid overestimating the consumption levels of some buildings, an attribute points back, for each resource (res), to the unique identifier of the element containing the measurements ($D^{res}_{\{b_1,...,b_n\}}$). Such links are visible in the map of Figure (2.3).

A value for the demand ($D^{res}_{b_i}$) of building (b_i) is then attributed proportionally to the inhabited areas (A_{b_i}) using Equation (2.1).

$$D^{res}_{b_i} = D^{res}_{\{b1,...,bn\}} \cdot \frac{A_{b_i}}{\sum_{i=1}^{n} A_{b_i}} \tag{2.1}$$

Cooling system attributes

In the past thirty years, little attention has been paid to consumption for space cooling and refrigeration systems, except for big consumers, such as shopping centers or data centers. However, the effect of climate change and higher demands for comfort, is actually leading to a significant increase in sales of individual air conditioning systems, and have boosted interest

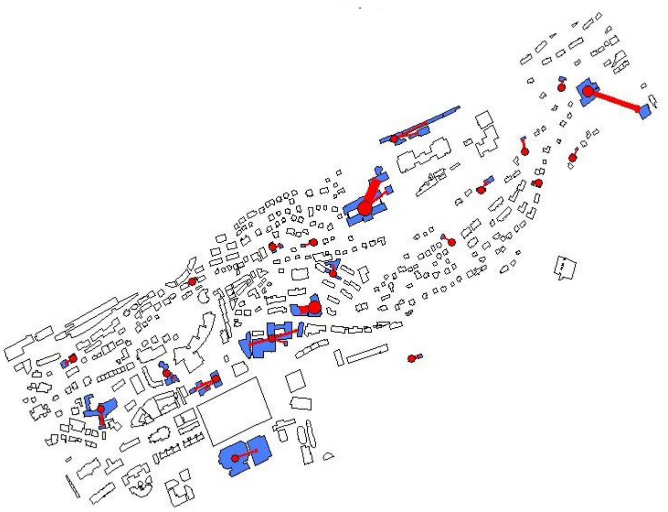


Figure 2.3: Visualisation of the link between buildings for the electricity consumption in a urban zone (Source: [Girardin et al., 2010d]).

in assessing present and future cooling requirements. Nevertheless, cooling consumption or profile recorded by monitoring systems are yet not easily available, and the estimations of the cooling and refrigeration system parameters in Table (2.6), result from detailed survey and analysis [Mermoud et al., 2008a].

Table 2.6: Cooling system attributes of the database.

Field of practice	Attribute name	Units	Description
Cooling	cs_k1	$kW/(m^2 \cdot C)$	Global heat losses coefficient
	cs_Txo	C	Nominal outdoor temperature
	hs_Tc	C	Threshold temperature
	cs_Tro	C	Nominalg supply temperature
	cs_Tso	C	Nominal return temperature
Refrigeration	rs_Tro	C	Nominal supply temperature
	rs_Tso	C	Nominal return temperature

Geometric attributes

The study of the solar energy potential and the refurbishment opportunities requires moreover at least the knowledge of the building's roof geometry, volume and window to wall ratio (Table 2.7). Roofs that cannot be covered with solar panels, due to requirements to maintain the cultural heritage features of the buildings, should be marked in the database as well.

Table 2.7: Supplementary fields of the energy database.

Field of practice	Attribute	Units	Description
Building refurbishment	geom_sbox		3D sugar-box of the buildings
	glazingRa		Window/wall ratio of surface
	volume	m^3	Building's volume
Building refurbishment	geom_3D		3D geometry of buildings and roofs
	roof_avail		Availability of the roof for solar panel

Hourly Profile

Hourly profiles, such as the one listed in Table (2.8), are used to perform dynamic simulations to ensure the feasibility of optimal designed energy conversion systems including storage tanks. However, typical profiles for hot water, electricity and refrigeration demand (D_P) are also used to estimate daily operating time ($\dot{D}_P = \frac{D_P}{\Delta T_P}$) defining the mean power over a given period, as well as the maximum to mean power ratio defining the nominal power of the equipments.

Table 2.8: Dynamic fields of the energy database.

Field of practice	Attribute	Units	
Dynamic simulation	hs_dotQ_d	kW	Daily space heating power profile
	cs_dotQ_d	kW	Daily floor cooling power profile
	hw_dotq_day	kW	Daily hot water demand profile
	rs_dotq_day	kW	Daily refrigeration demand profile
	el_dote_day	kW	Daily electricity demand profile

2.6 Energy resources inventory

2.6.1 Chemical Fuels inventory

Chemical fuels are simply described by their higher heating value and exergy values [Borel and Favrat, 2010] in each urban zones where they are available.

2.6.2 Heat source from the surrounding environment

The attribute-value pair model of the resource (r) contains, for each geographical zone (z) and each typical period (P) of the year (yr), the available mass flow ($\dot{m}_r$), specific heat capacity (c_{p_r}) and bounds of the allowed temperature variation ($T^{max}_{r,z,P}$) and ($T^{min}_{r,z,P}$). The annual thermal potential of the resource is then given by relation (2.2).

$$Q_{r,z,yr} = \sum_{P} \left[\dot{m}_{r,z} c_{p_r} \cdot \left(T_{r,z}^{max} - T_{r,z}^{min} \right) \Delta T \right]_P \tag{2.2}$$

The reference temperature ($T_{z,P}^{ref}$) is set, for each period, to the lowest logarithmic temperature difference of the heat source from the environment (Equation 2.3).

$$T_{z,P}^{ref} = \min_{r \in R} \begin{cases} \frac{T_{r,z,P}^{max} - T_{r,z,P}^{min}}{ln(T_{r,z,P}^{max} / T_{r,z,P}^{min})} & \text{if } T_{r,z,P}^{max} > T_{r,z,P}^{min} \\ T_{r,z,P}^{min} & \text{if } T_{r,z,P}^{max} = T_{r,z,P}^{min} \end{cases} \quad [K] \tag{2.3}$$

This permits to compute the Carnot factor ($1 - \frac{T_{z,P}^{ref}}{T}$) used in exergy calculation

2.6.3 Solar energy Potential

Carneiro et al. [2009] presented a method to calculate the irradiation per roof based on high quality LIDAR[1] data. A presented in Figure (2.4) The method cut each building's roof into different sub roof slices according to their monthly irradiation The method takes obstacles such as trees, chimney or shadows of different houses into account

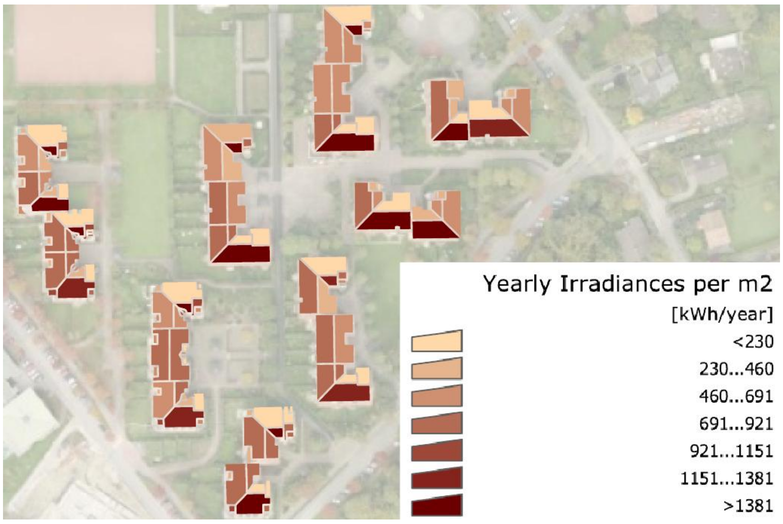


Figure 2.4: Solar map of the irradiation per roof section (Source: [Carneiro, Morello, and Desthieux, 2009])

Solar potential inventory

As each building has a roof which can be divided into different sub-roof sections A_{roof} based on their different specific irradiation, different selection strategies can be performed. On an

---

[1] LIght Detection And Ranging

urban scale two feasible strategies exist. Either, the roofs sub-cells are strictly given in the best order independent of their location, or the buildings are classified and used one after another. Both methods results in the definition of a ranked curve of solar irradiation (Equation 2.4) expressed as a function of the period (P) and roof area contained in the urban zone.

$$G_P^{solar,tot} = f(P, A_{roof}) \tag{2.4}$$

This constitute the initial point for the integration of the solar potential of the roofs of urban areas, as proposed by [Rager, Girardin, and Maréchal, 2010].

2.7 Evaluation of the Annual Energy Demand in Urban areas

This section presents the algorithm developed to compute the estimations of floor areas and annual demand for district hot water production (DHW), electricity and space heating/cooling in urban areas.

General algorithm During the computation phase of the energy requirements, the solver access non-homogeneous and geographically distributed information and measurements. A strategy has thus been adopted, based on successive visits to the Binary Decision Diagram (BDD [Akers, 1978]), to estimate floor areas (§2.7.1) and compute the requirements for hot water production (§2.7.3), space heating and cooling (§2.7.5).
The conceptual algorithm is presented in Figure (2.5). Before computation, each empty-valued attribute is replaced, if possible, by existing default value and the corresponding status is updated. Then, starting from an initial vector of status, the algorithm visits the decision diagram, computes new values of attributes, updates the state of the vector of status and continues until no more status changes is observed. At this point, the status of the desired value are either marked as computed or found unpredictable. in which case the user is asked to resolve the gap in information where it has been localized.

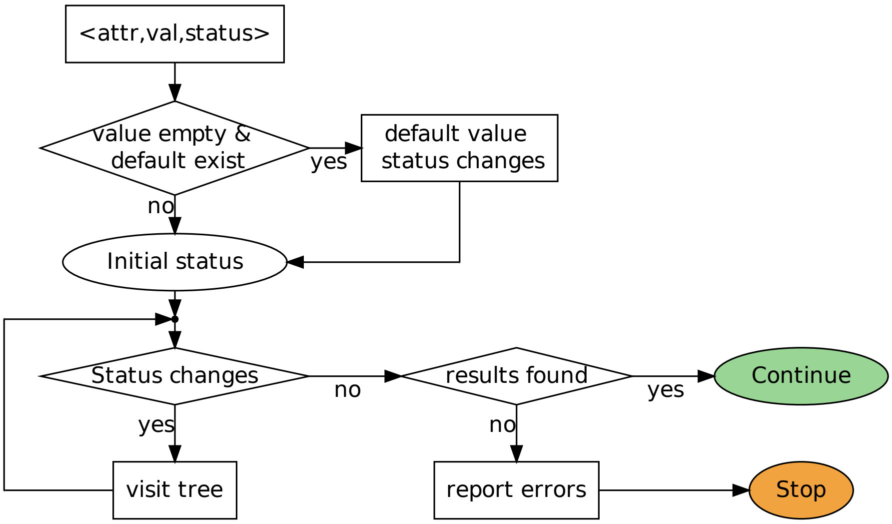


Figure 2.5: Flow chart of the algorithm.

Overcoming uncertainties As the quantity of information increases, it make sense to compute statistical indicators from the measurements in order to refine the default value of the database. By assessing the statistical distribution of measured and computed values, it is possible to evaluate inherent uncertainties and to overcome the lack of necessary data using typified mean default value instead. Statistical distributions of data can be represented by Box-Whisker-Plot McGill et al. [1978], shown in figure 2.6, where half of the data lies in the box and outliers are placed outside the limit (interquartile range, IQR) located as far away from the median as 1.5 times the width of the box .

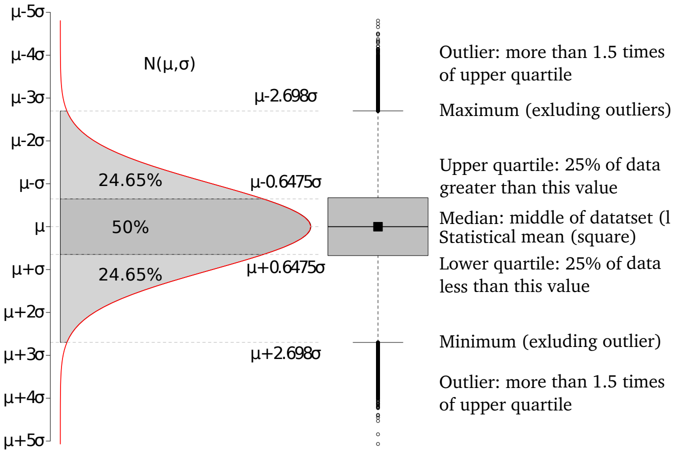


Figure 2.6: Meaning of the boxplot representation and interpretation in relation to the normal distribution.

2.7.1 Estimation of the Floor Area

Single building strategy

When not directly available at the desired scale, typified floor space is computed by aggregation of floor area stored with a highest granularity. At the smallest scale, when the floor area of a building (A_b) is unknown, it is automatically estimated from the geometric coordinates (x_b, y_b) defining the ground area ($A_{b,gnd}$), provided that either the berber of floors ($n_{b,flr}$) or the total height (h_b) and floor's height ($h_{b,flr}$) is known, as detailed in the binary decision diagram of Figure (2.7).

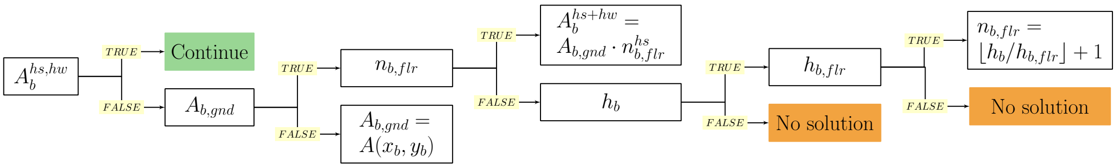


Figure 2.7: Decision diagram to compute the floor area.

Overcoming uncertainties

When the typified floor area is unknown, bounded interval $[A_{min}, A_{max}]$ are defined based on ground areas and the number of floors determined approximately either by the analysis of 3D numeric models and/or using panoramic views [Anguelov et al., 2010] and/or using known value of similar buildings of the neighborhood.

The distribution of typified floor area (A_c) is estimated using a frequency table containing, for each interval $[A_{min,c}, A_{max,c}]$, the number of buildings (n_c) belonging to category (c).

Application at national level For Swiss dwellings in 2009, the frequency Table (A.1, p. 160) from the Swiss Federal Statistical Office [FSO, 2011a] allows the computation of the distribution of Swiss household floor area. The mean value[2] (for 2009), reported in Figure (2.8), is estimated at 38'125 $[ha]$ or 48.8 m^2/cap, while the Swiss Federal Statistical Office gives a slightly different value of 44 m^2/cap (for 2000)[3]) which rather corresponds to the lower boundary of the distribution.
Figure (2.9) reports the history of the growth of floor area by type households in Switzerland since 1920, with a linear extrapolation up to 2030. Table (A.2, p.A.2) gives the corresponding detailed mean values.

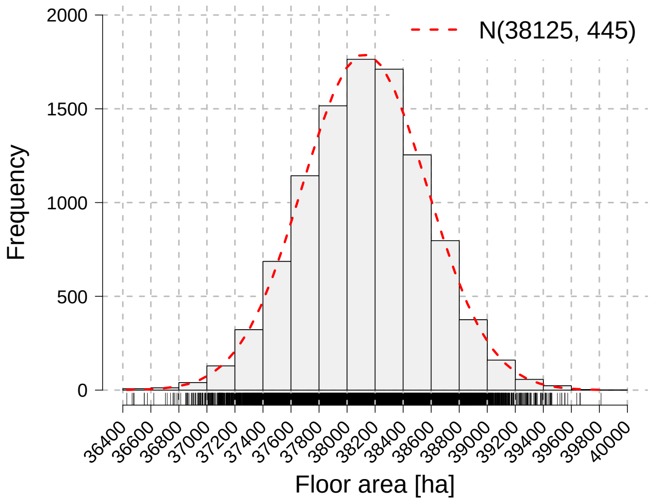


Figure 2.8: Estimation of the household floor area in Switzerland for 2009.

2.7.2 Estimation of the Energy conversion mix

Single building By definition, energy conversion efficiencies make the link between final and useful energy ($\eta_{yr} = \frac{E_{u,yr}}{E_{f,yr}}$). If the combination of energy source/technology is known, annual energy conversion efficiencies from the Swiss norms SIA 380/1 [2009] are applied. When this is not the case, a value is set based on statistical values from the surrounding buildings with the same usage.

---

[2] Considering 7'801'278 capita in 2009 [FSO, 2010b]

[3] OFS, Construction et logement - Les principaux chiffres, http://www.bfs.admin.ch/bfs/portal/fr/index/themen/09/01/key.html

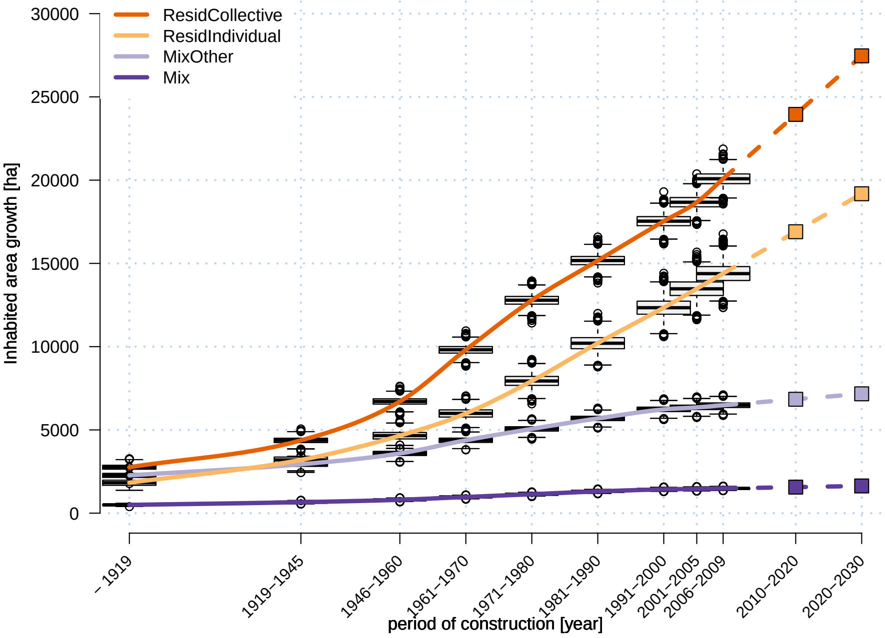


Figure 2.9: Household area growth per affectation in Switzerland

Overcoming uncertainties In order to simulate the share of heating and DHW technologies in proportion of the floor area, a sample is generated based on a frequency table, such as the one presented in Tables (A.4-A.7, pp. 161-166) for Switzerland. The corresponding discrete probability distribution $p_k = n(\omega_k) / \sum_{\omega \in \Omega} n(\omega)$ is defined by the unique combination (ω_k) of energy source/technology.

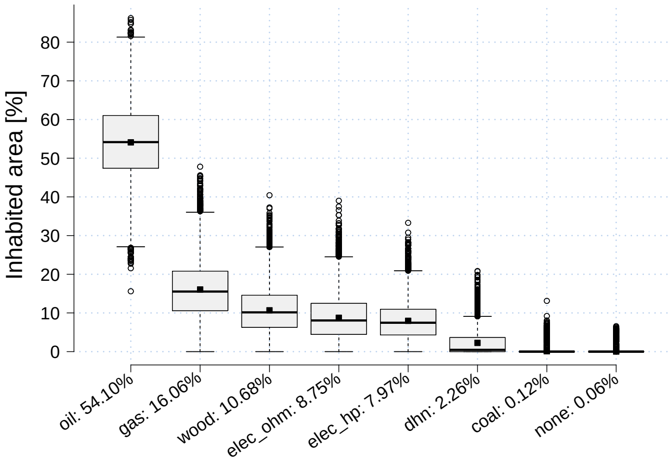
Application at national level The results for Switzerland are presented in Figure (2.10.1) and Table (A.4.1) for space heating technologies, and in Figure (2.10.1) and Table (A.4.2) for DHW technologies.

Fuel oil(54.1%) and gas(16%) boiler together provide building heating services for 70% of the national floor area, while heat pumps supply heat to 8% of the surface. For hot water production, oil(39.8%) and electrical boiler(35.8%) dominate, while about 2% of the floor area has access to a district heating network.

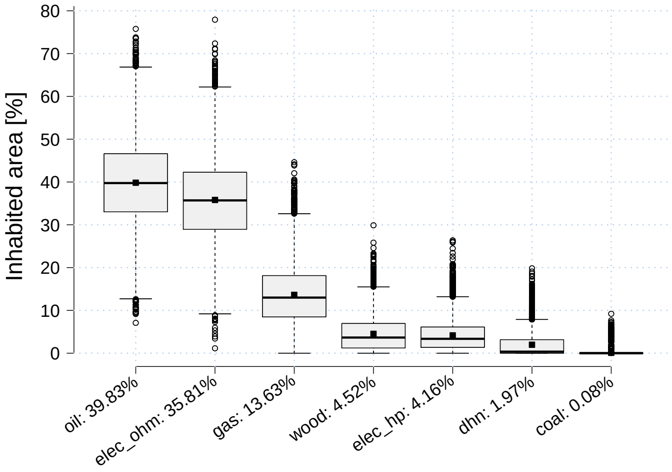
2.7.3 Domestic Hot Water Annual Requirements

Single building strategy

Annual useful heat for domestic hot water production (HW) is, as far as possible, computed hot water mass flow $(\dot{M}_b^{hw})$ using Equation (2.5) . Unfortunately this value is rarely recorded.



2.10.1: Space heating technologies



2.10.2: Domestic hot water technologies

Figure 2.10: Boxplot of the share of heating and dhw technologies ([%]) in proportion to the inhabited area of Switzerland, 2009.

Even if the flow rate of domestic water ($\dot{M}_b^{w}$) is known, it is useless when the share ($f_b^{\dot{M}^{hw}}$) between the two is unknown. Therefore, the algorithm instead uses the specific mass flow consumption per capita ($\dot{m}_b^{hw,pers}$), typically around 50-70 [$\frac{l}{cap\cdot dy}$], or the specific DHW requirements ($\dot{q}_b^{hw}$). This strategy, summarized in the binary decision diagram of Figure (2.11), holds if either the number of urban dwellers (n_b^{cap}) or the floor area ($A_b^{hs,hw}$) is known.

$$
\begin{aligned}
Q_{b,yr}^{hw} &= M_{b,yr}^{hw} \cdot c_{p_w} \cdot \left(T_{s,b}^{hw} - T_{r,b}^{hw} \right) \quad [kW] \\
\text{with } c_{p_w} &= 4.18 \frac{kJ}{kg \cdot K}
\end{aligned}
\tag{2.5}
$$

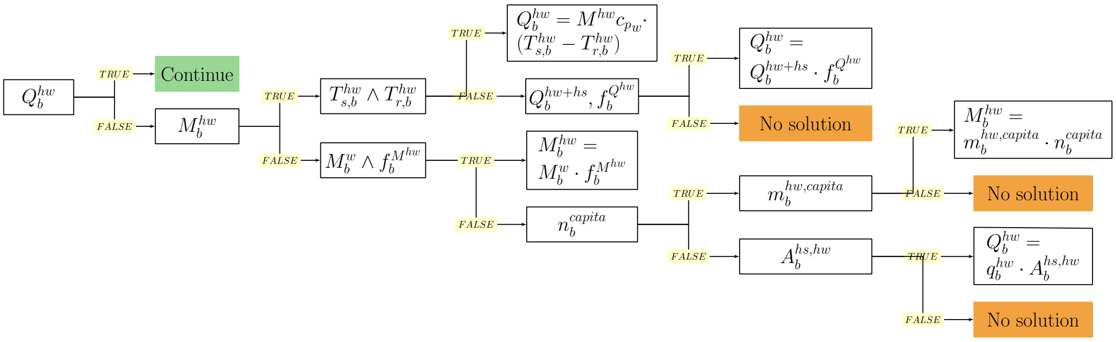


Figure 2.11: Decision diagram for the domestic hot water energy requirements.

When only the floor area ($A_b^{hs,hw}$) is available, typical values from the norms of the Swiss society of Architect and Engineers [SIA 380/1, 2009] of Table (2.9) are adopted and the space heating to hot water production ratio ($\frac{q^{hw}}{q^{hw+hs}}$) is used as a benchmark indicator to detect inconsistency problems.

Table 2.9: Room heating and hot-water systems useful energy requirements according to the Swiss standards norm SIA 380/1 [2009].

Type	SIA 2009				Minergie		Minergie-P <2000		Minergie-P >2000	
	q_u^{hw}	q_u^{hs}	e_u^{el}	$\frac{q_u^{hw}}{q_u^{hw+hs}}$	q_u^{hs}	$\frac{q_u^{hw}}{q_u^{hw+hs}}$	q_u^{hs}	$\frac{q_u^{hw}}{q_u^{hw+hs}}$	q_u^{hs}	$\frac{q_u^{hw}}{q_u^{hw+hs}}$
		$\frac{MJ}{m^2 \cdot yr}$		%	$\frac{MJ}{m^2 \cdot yr}$	%	$\frac{MJ}{m^2 \cdot yr}$	%	$\frac{MJ}{m^2 \cdot yr}$	%
Collective house	75	120	100	38.5	108.0	41.0	96.0	43.9	72.0	51.0
Individual houses	50	130	80	27.8	117.0	29.9	104.0	32.5	78.0	39.1
Administration	25	150	80	14.3	135.0	15.6	120.0	17.2	90.0	21.7
Schools	25	140	40	15.2	126.0	16.6	112.0	18.2	84.0	22.9
Shopping areas	25	115	120	17.9	103.5	19.5	92.0	21.4	69.0	26.6
Catering	200	170	120	54.1	153.0	56.7	136.0	59.5	102.0	66.2
Gathering places	50	170	60	22.7	153.0	24.6	136.0	26.9	102.0	32.9
Hospitals	100	160	100	38.5	144.0	41.0	128.0	43.9	96.0	51.0
Industry	25	130	60	16.1	117.0	17.6	104.0	19.4	78.0	24.3
Depots	5	130	20	3.7	117.0	4.1	104.0	4.6	78.0	6.0
Sports facilities	300	145	20	67.4	130.5	69.7	116.0	72.1	87.0	77.5

2.7.4 Annual Electricity Demand

Without access to real measurements or energy bills, the annual electricity demand is estimated using standard value annual electricity demand per floor area (e_u^{el}) given in Table (2.9).

2.7.5 Annual space Heating/Cooling Demand

Single building strategy

As only the total final heat consumption is likely to be measured, standard values for DHW needs ($Q^{hw}_{u,yr}$) are often used to estimate the space heating requirements with the help of Equation (2.6) using mean annual efficiencies, given in Table (2.10), for heating (η^{hs}_{yr}) and hot water (η^{hw}_{yr}) systems efficiencies.

$$\dot{Q}^{hs}_{u,yr} = \eta^{hs}_{yr} \cdot (Q^{hs+hw}_{f} - \frac{Q^{hw}_{u,yr}}{\eta^{hw}_{yr}}) \tag{2.6}$$

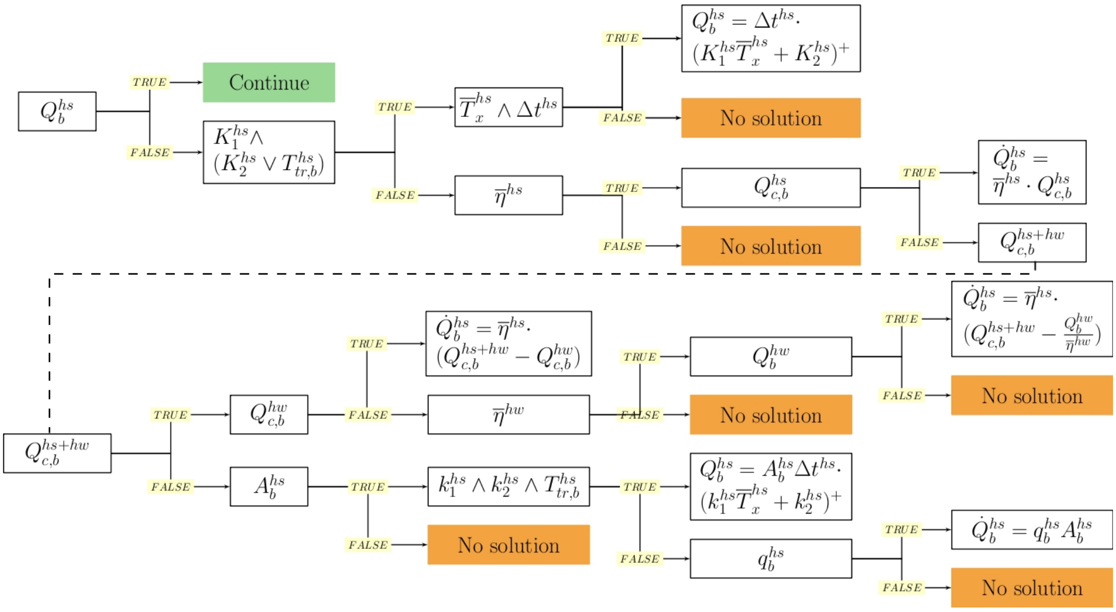


Figure 2.12: Decision diagram for the space heating energy requirements.

Table 2.10: Probability distribution applied for the simulation of the space heating requirement (value from [SIA 380/1, 2009]).

Attribute	Categories	Distribution	units
η^{hs}_{yr}	All	$\mathcal{U}[0.725, 0.925]$	–
η^{hw}_{yr}		$\mathcal{U}[0.436, 0.636]$	
$q^{hw}_{u,yr}$	Individual homes	$\mathcal{N}(50, 15)$	$\frac{MJ}{m^2 \cdot yr}$
$q^{hw}_{u,yr}$	Building with several households	$\mathcal{N}(75, 22.5)$	
$q^{hw}_{u,yr}$	Other buildings	$\mathcal{U}(10, 90)$	
$q^{hs+hw}_{f,yr}$	Table (A.8, p. A.8)	$\mathcal{N}(\mu, \sigma)$	

The cooling requirements are computed symmetrically to the heating one, with domestic hot water replaced by refrigeration requirements. Moreover, if the cooled area (A_b^{cs}) is unknown, the heated floor area (A_b^{hs}) is taken instead.

Overcoming uncertainties

Starting from fuel consumption measurements, the statistical distribution of final heating and DHW consumption are first evaluated. The missing mean value and standard deviation are then interpolated and extrapolated for each category of building. Statistical values for space heating requirements are then computed using Monte-Carlo techniques on Equation (2.6) using the distribution of Table (2.10).
The resulting mean and standard deviation are presented in Tables (A.10, p. 174).

Application at Urban scale (Geneva Canton) Thanks to the Office of Energy of Geneva (ScanE[4]), more than 56'200 gas and oil yearly consumptions have been collected in the Geneva area between 1990 and 2006 on 5'453 monitored buildings with known floor area. The number of measurements is summarized by categories in Table (A.3, p. 161).
At the scale of Geneva Canton, buildings have been classified into 8 different types (Residential, Administrative, Commercial, Industrial, Education, Healthcare, Tourism and Others) with ten ranges for the years of construction or renovation, leading to a set of 80 building categories.
At the National level, the typification of the RegBL [2010][5] is taken with periods steps of ten years and a division in four types of buildings: individual homes, building with several households, building partially used for habitation (store, workshops, farms, etc.) and housing with other end-use (factories, schools, hotel, hospital, old people's home, administrative and other buildings including living rooms).

Final Heating and DHW Consumption The final heat-energy consumption per floor area (A^{hs}) is obtained from the annual fuel consumption ($M_{F,yr}$) by Equation (2.7) using a higher heating value of $HHV_{oil} = 37.6[MJ/l]$ for fuel oil and $HHV_{ng} = 40.3[MJ/m^3]$ for natural gas.

$$q_{f,yr}^{hs+hw} = \frac{HHV_F \cdot M_{F,yr}}{A^{hs}} \tag{2.7}$$

The annual heat-energy final consumptions per floor area (q_f^{hs+hw}) is reported in Figure (2.13) as a function of the construction/renovation periods. One observes that the housing stock reached a peak of consumption around the 1970s. The distribution of final heat-energy consumption as a function of building type, is given in Figure (2.14).
The corresponding value underlined in Table (A.8, p.172), represents the typified mean and

---

[4] République et canton de Genève, Service Cantonal de l'énergie, http://www.ge.ch/scane/

[5] The National Register of Buildings and Dwellings (Registre fédéral des bâtiments et des logements)

standard deviations for a reference meteorological year (Y_{ref}) in Geneva between 1990 and 2006.

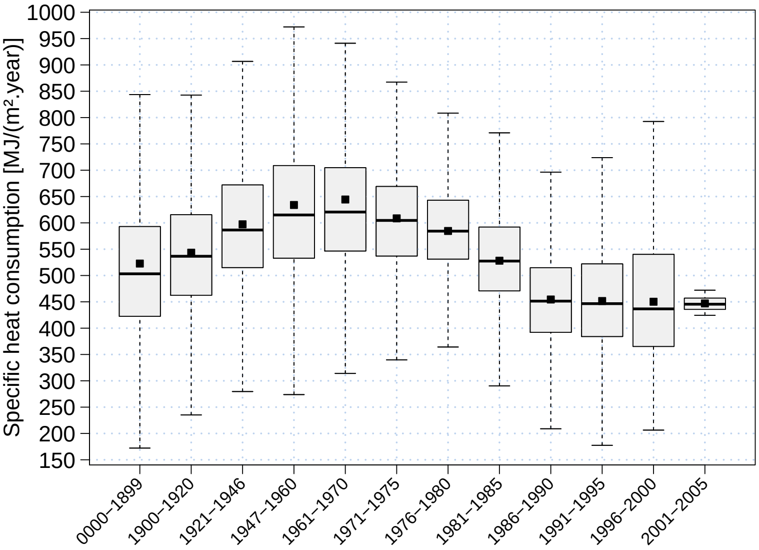


Figure 2.13: Annual specific consumption per period of construction/renovation in Geneva (outliers are excluded from the picture).

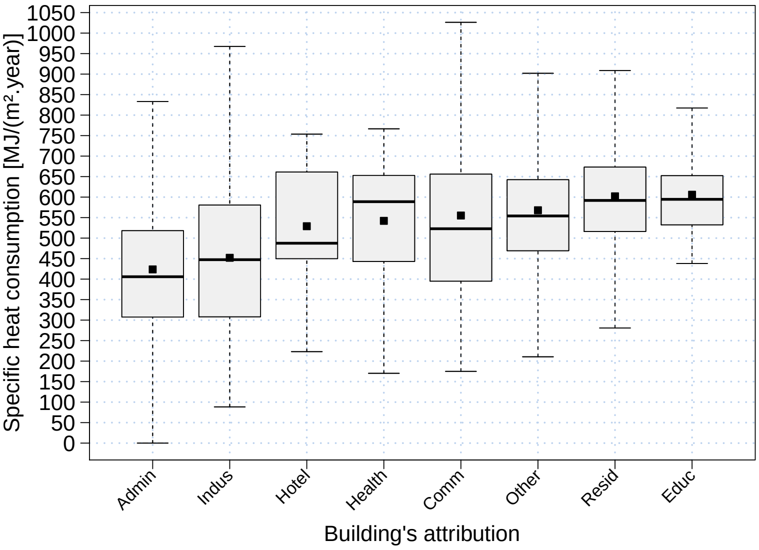
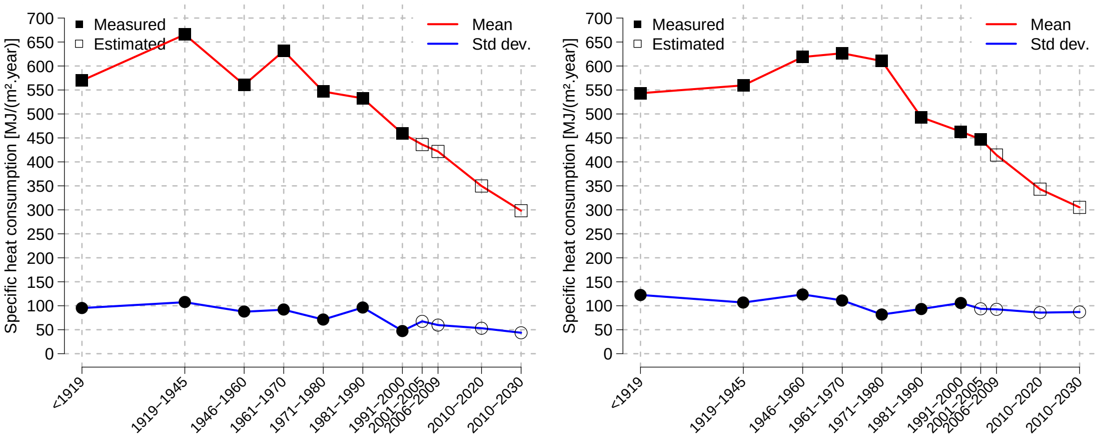


Figure 2.14: Annual heat-energy final consumption per building type.

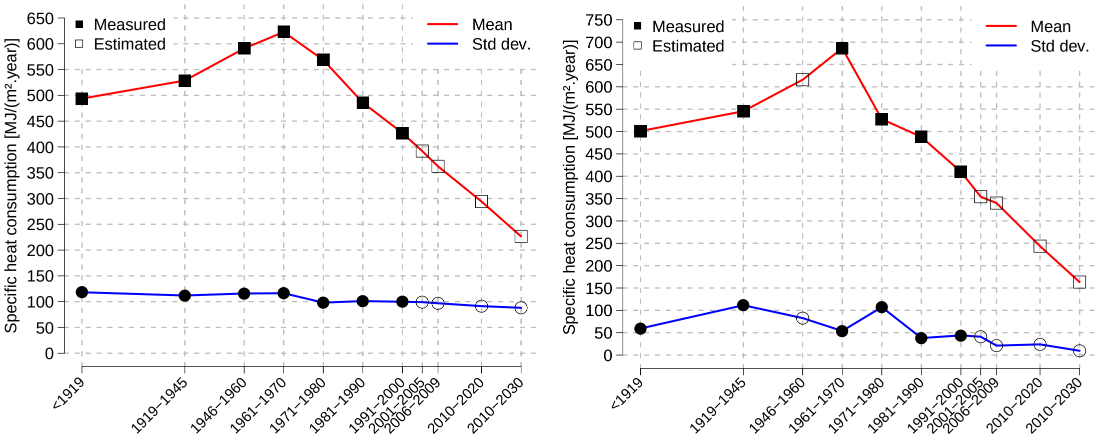
Final Energy Interpolation and extrapolation The histograms of the final heat-energy consumption, which includes building heating and domestic hot water production, are reported for each Swiss National category from the RegBL [2010] in Figures (A.1-A.4, pp. 168-171).

As there is a lack of measurements for some categories, the unknown mean and standard deviation of the sample are first interpolated and then extrapolated up to 2030, based on the sample of each category. The resulting consumption for a typical year in Geneva, composed of 2659 ($18/12°C$) heating degree-days, are reported in Table (A.8, p. 172) and plotted with filled dots in Figure (2.15).



2.15.1: Individual homes (ResidIndividual)

2.15.2: Building with several households (ResidCollective)



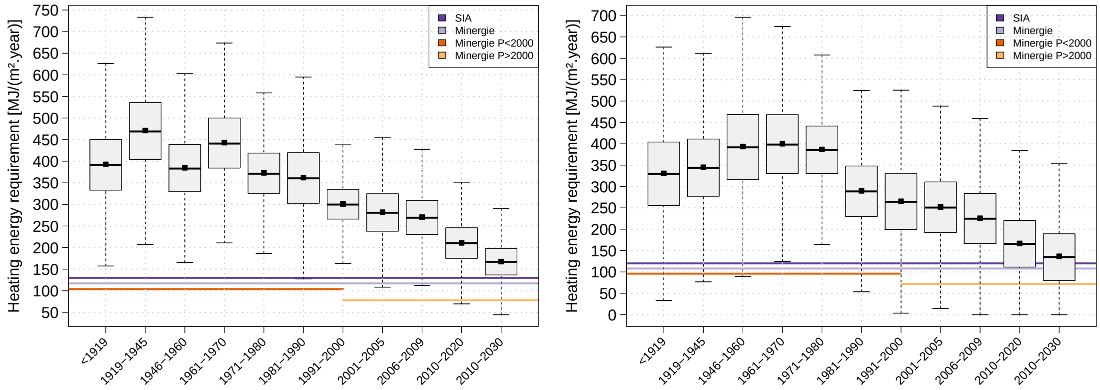
2.15.3: Building partially used for habitation (Mix)

2.15.4: Housing with other end-use (MixOther)

Figure 2.15: Measured and estimated specific heat consumption for the Geneva area between 1990 and 2006).

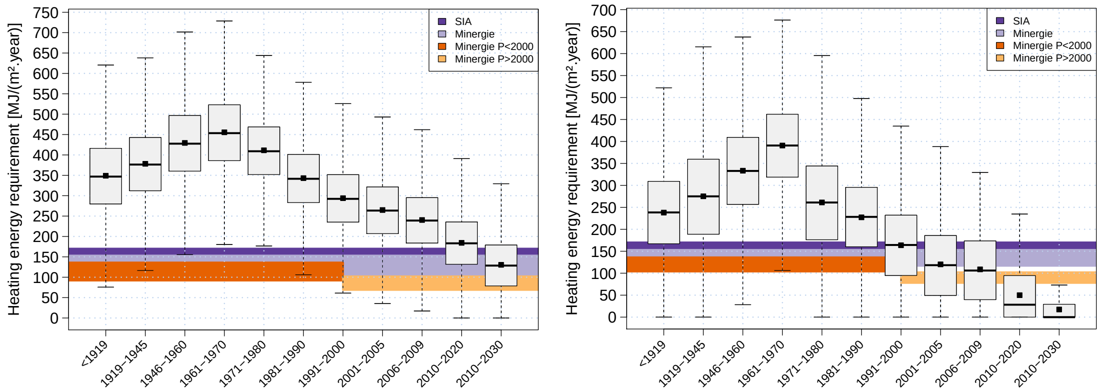
Useful space heating requirements The specific space heating requirements are estimated using Equation (2.6, p. 50) on which Monte Carlo experiments are performed with technology efficiencies and DHW requirements uniformly distributed around the recognized value [SIA 380/1, 2009] listed in Table (2.10).

Figure (2.16) shows the resulting space heating requirements computed with random samples having $n = 100'000$ elements for each category. Table (A.10,p. 174) lists the corresponding mean and standard deviations obtained in this way. The horizontal colour strip represents the Min. and Max. value of the Swiss SIA and Minergie standards across all the type of buildings.



2.16.1: Individual homes

2.16.2: Building with several households



2.16.3: Building partially used for habitation

2.16.4: Housing with other end-use

Figure 2.16: Specific Heating requirement for the official categorization of Switzerland's households.

2.8 Straightforward strategic applications

Before speaking about a deeper characterization of the energy requirements in urban areas, the use of annual energy consumption in specific meteorological and geographical location is demonstrated with energy, cost and emission indicators reported on flow diagrams and maps. Moreover, coupling the energy needs with a classification algorithm allows the definition of pathways meeting global targets at minimal efforts and costs.

> For the following example, attention must be paid to the fact that the results do not incorporate real consumption data but only assume typical statistical consumption.

The method is demonstrated on a case study applied on the Nyon area. The main assumptions concerning the floor area (A^{hs}), the annual heating ($q^{hs}_{u,yr}$), DWH ($q^{hw}_{u,yr}$) and electricity ($e^{el}_{u,yr}$) useful requirements are presented in Table (2.11).

Table 2.11: Assumption for the energy intensities of the building stock for a typical year in Nyon.

Category	Date	A^{hs}	$q^{hs}_{u,yr}$	$q^{hw}_{u,yr}$	$e^{el}_{u,yr}$
-	-	m^2	$\frac{MJ}{m^2 \cdot yr}$	$\frac{MJ}{m^2 \cdot yr}$	$\frac{MJ}{m^2 \cdot yr}$
Residential	< 1920	12881	340	71	100
Residential	1920-1970	1254174	378	71	100
Residential	1970-1980	23678	392	71	100
Residential	1980-2005	80028	286	71	100
Residential	2005-2020	11800	157	71	100
Administrative	2005-2020	6545	129	25	80
Commercial	1980-2005	17173	176	50	120
Industrial	1970-1980	1661	370	25	60
Hospital	< 1920	537	302	95	100
Other	< 1920	10255	276	66	100
Other	1920-1970	51127	352	66	100
Other	1970-1980	7704	369	66	100
Other	1980-2005	129537	264	66	100
Other	2005-2020	3901	144	66	100

The corresponding energy, emissions and operating costs results are presented in Table (2.12). The numer of building (n_b) in the database equal 2179 and the total floor area (A^{hs}] is estimated at 161.1 [ha].

2.8.1 Final energy flow diagram

The final energy consumption is obtained, for each energy technology/resource visible in Figure (2.17), from the useful energy ($Q_{u,c} = q_{u,c} \cdot A_c$) and the technology efficiency (η^{tech}) for each energy service. Moreover, a solar utilization factor ($f^{solar} = Q^{solar}/Q_{u,c}$) allows

Table 2.12: Energy, emissions and operating costs for heating, cooling and domestic electrical appliances (Simulation, Nyon).

Sector	A^{hs}	n_b	Q_u^{hs}	Q_u^{hw}	$\dot{Q}_u^{hs+hw}$	Q_u^{el}	CO_2	Cost
-	m^2	$-$	$\frac{MWh}{yr}$		kW	$\frac{MWh}{yr}$	t/yr	$\frac{MCH}{yr}$
Chantemerle	94056	90	9069	1838	4032	2613	2597	984
Piscine	19750	46	1794	377	788	549	655	171
Rive	6208	22	622	122	277	172	227	57
Plantaz	41428	96	4276	817	1906	1151	1594	369
Le Viez	11036	20	1086	214	479	307	365	97
La Biolatte	1195	5	121	24	54	33	46	10
L'Asse	36944	35	2717	683	1179	1026	788	306
La Vuarpillière	39783	21	3477	758	1530	1105	1191	337
Changins	51848	33	5380	1019	2391	1440	1932	461
En Oie	118719	140	12219	2348	5459	3298	4611	1050
Le Reposoir	99746	186	10332	1973	4616	2771	3859	893
Prélaz	44036	79	4422	869	1976	1223	1276	468
Cossy	88324	92	9273	1743	4129	2453	3534	782
Marans	117856	159	12216	2300	5440	3274	4678	1025
Bois - Bougy	8397	13	821	155	346	233	33	68
Colovray - Métairie	31143	26	3117	606	1371	865	1093	283
Clémenty	25004	90	2406	490	1075	695	846	228
Vieux - Bourg	391343	624	38349	7529	17117	10930	14314	3386
Martinet et Morâche	34868	28	3664	690	1636	969	1415	305
Rive bis	5230	13	537	102	238	145	174	62
Sadex	4029	13	413	79	184	112	119	42
La Banderolle	35571	81	3221	688	1430	988	1189	296
Champ-Colin	195364	64	19426	3802	8635	5408	7427	1660
Les Tines-Ouest	81100	71	8202	1605	3672	2253	3155	694
Les Tines-Est	28022	132	2832	553	1267	778	1037	254
Total	1611001	2179	159992	31384	71227	44791	58156	14290

consideration of the use of thermal solar panels on the roofs of urban areas.

The resulting balance between final and useful energy and energy losses is represented in the energy flow diagram[6] of figure (2.18) by type of energy source.

2.8.2 Energy, Emissions and Cost mapping

The maps are generated based on statistical annual values and assumptions on purchase cost, CO_2 emissions and primary energy factor ($f_{prim}^{res} = \frac{\dot{D}_p}{\dot{D}_f^{res}}$) reported in Table 2.13).

---

[6] Implementation James SPELLING, KTH-EGI-EKV,02.11.2009

©2009 Google, Image ©2010 IGN-France

Figure 2.17: 3D visualisation of the GIS buildings resource/technology layer. The buildings are colored by their heating energy source. (Source: [RegBL, 2010; Swisstopo, 2009].

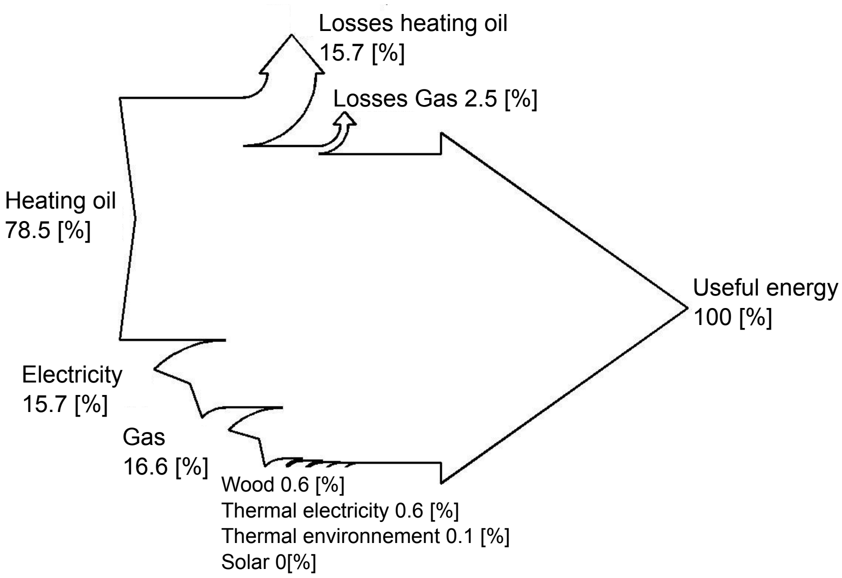


Figure 2.18: Annual final energy balance by energy source.

Useful Heat-energy indicator

The useful heat-energy expense indicator ($\dot{q}_{u,b}^{hs+hw}$) represents the sum of the useful heat-energy ($Q_{u,b}^{hs+hw}$) per square meter consumed in the building (b) for heating and domestic hot water production during a typical year. This indicator (2.8) is computed for each building (b) by dividing the useful heat-energy demand of a typical year by the floor area (A_b).

Table 2.13: Default operating cost, CO_2 emission and primary energy factor of energy source for room heating and hot water systems

Energy source	Operating Cost (C_O) $[cts_{CHF}/KWh]$	Emission CO_2 $[g/MJ]$	Primary energy factor [Crown, 2011] $[-]$
Natural gas	9	67 [SIA 380/1, 2009]	1.02
Heating oil	7	82 [SIA 380/1, 2009]	1.06
Wood logs	6	2.2 [Crown, 2011]	1.05
Wood pellets	6	7.7 [Crown, 2011]	1.2
Wood chips	6	2.5 [Crown, 2011]	1.07
House coal	85	83.6 [Crown, 2011]	1.02
Electricity	18	45 [SIA 380/1, 2009]	2.94 [SIA 2032, 2010]

$$q_{u,b}^{hs+hw} = \frac{Q_{u,b}^{hs+hw}}{A_b} \qquad [MJ/(m^2.an)] \tag{2.8}$$

Figure (2.20) present the useful heat-energy expense indicator of each building represented by bars proportional to the floor area. The area under the curve thus represents the annual useful heat-energy required in the urban zone.

$$q_{u,z}^{hs+hw} = \frac{\sum\limits_{b \in z} Q_{u,b}^{hs+hw}}{\sum\limits_{b \in Z} A_b} \qquad [MJ/(m^2 \cdot yr)] \tag{2.9a}$$

$$q_{f,z}^{hs+hw} = \frac{\sum\limits_{b \in z} Q_{f,b}^{hs+hw}}{\sum\limits_{b \in Z} A_b} \qquad [MJ/(m^2 \cdot yr)] \tag{2.9b}$$

The mean indicator (2.9a) of 427 $MJ/(m^2 \cdot yr)$, representing the annual expense of 191 GWh/yr for the zone, is drawn with a black dotted line in figure 2.20. In order to minimize the impact on privacy, the indicators are averaged by zone, instead of being represented for each buildings, as shown on the map (2.20).

Emission indicator

In the same way as for the energy expense indicator (2.9b), a specific CO_2 emission indicator (2.10), is linked to the annual consumption of fuel and electricity for space heating and hot water production.

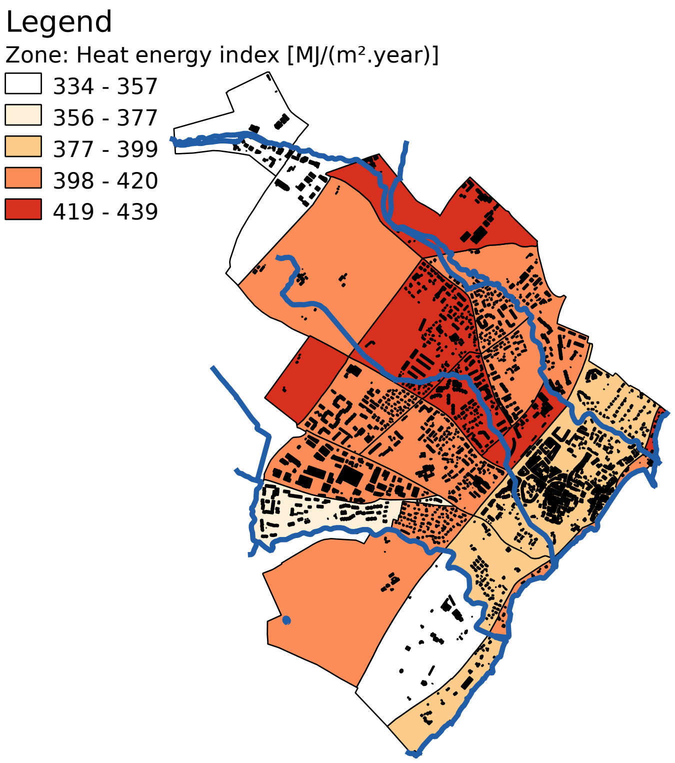


Figure 2.19: Annual final heat-energy demand by zone.

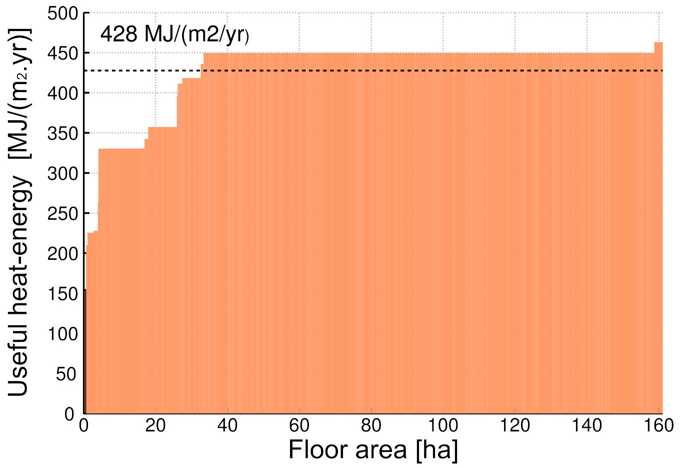


Figure 2.20: Ranked annual useful heat-energy demand.

$$m_{CO_2,z} = \frac{\sum\limits_{\substack{b \in Z \\ res \in R}} Q_{f,b}^{hs+hw,res} \cdot m_{CO_2}^{res} + E_{f,b}^{el} \cdot m_{CO_2}^{elmix}}{\sum\limits_{b \in Z} A_b} \qquad [t_{CO_2}/(m^2 \cdot yr)] \qquad (2.10)$$

The estimated indicator, computed from the assumption of Table (2.13) for the zone shown in Figure (2.21), is visible in the Figure (2.22).
The mean specific emission indicator of the zone is 36 $kg_{CO_2}/(m^2 \cdot yr)$, representing an annual total of 58 t/an.

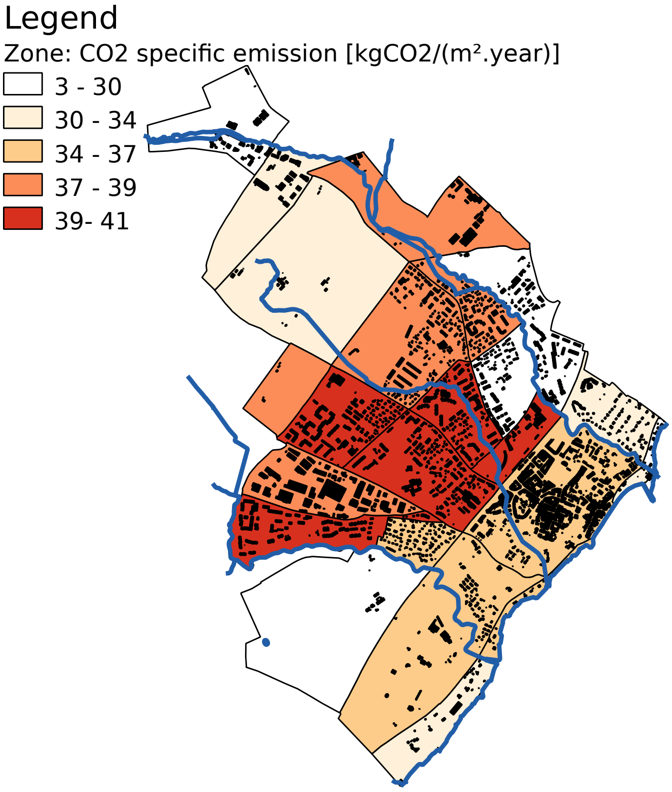


Figure 2.21: Annual CO_2 emission by zone.

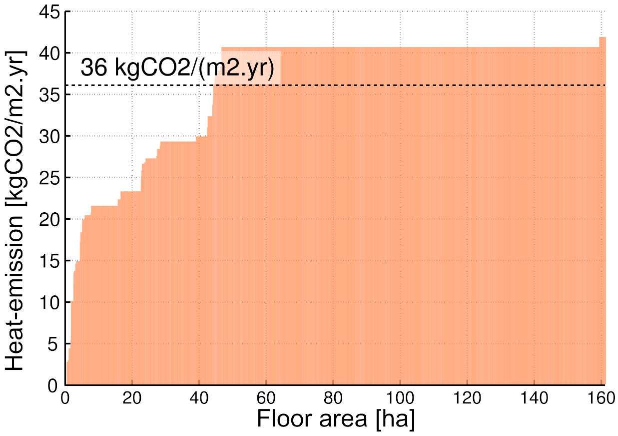


Figure 2.22: Ranked annual CO_2 emission

Cost expense indicator

The operating costs indicator (2.11) of the fuel and electricity consumption is computed based on the assumption of Table (2.13).

$$C_{O,z} = \frac{\sum\limits_{\substack{b \in Z \\ res \in R}} Q_{f,b}^{hs+hw,res} \cdot C_O^{res} + E_{f,b}^{el} \cdot C_O^{el}}{\sum\limits_{b \in Z} A_b} \qquad [CHF/(m^2 \cdot yr)] \tag{2.11}$$

This indicator represents the willingness of the inhabitant of the zone to pay for the energy services. For example, this amount is estimated at 9.22 $CHF/(m^2 \cdot yr)$, representing an annual bill of 14.76 $MioCHF/yr$ for the zone shown in the map (2.23).

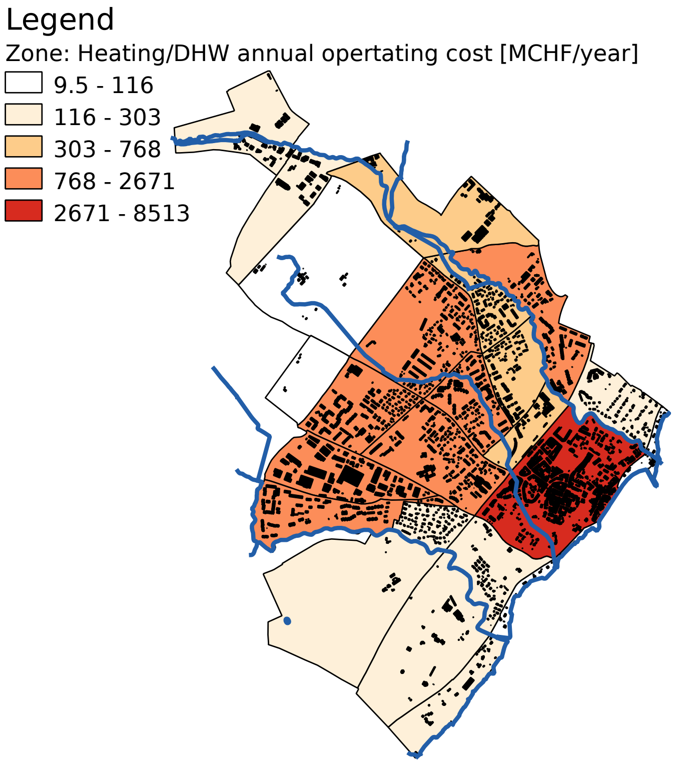


Figure 2.23: Annual heating and hot water production operating cost by zone.

2.8.3 Identification of the most significant consumers

In order to achieve actions with greater effectiveness, the "80/20" principle, stating that roughly 80% of the effects come from 20% of the causes, is challenged in order to identify groups and numbers of buildings to address as a priority issue. The buildings or zones are ordered by increasing heat consumption, and the cumulated sum is compared with the total heat energy consumption. This results in a ranked curve, such as the one shown in Figure (2.24).

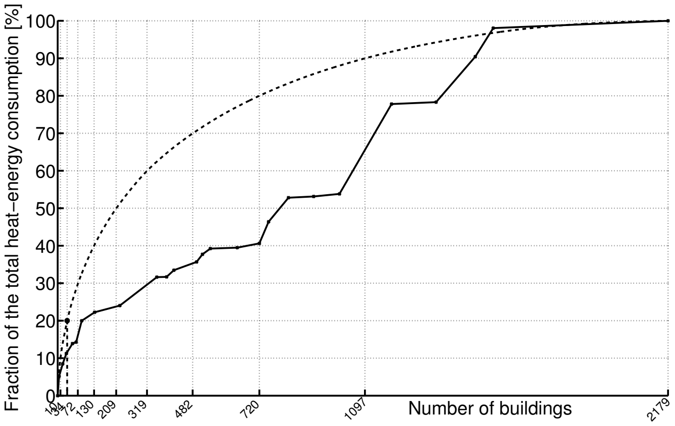


Figure 2.24: Identification of the most significant consumers.

For this particular case, we observe that 34 buildings consume 20% of the heat-energy distributed in the area and that 33% of them consume 80% of the actual heat-energy. These buildings or urban area, identified on the maps, significantly impact the system and are consequently the ones to monitor first.

2.8.4 Potential for building's envelope improvement

Similarly, the curve of Figure (2.25) shows the heating energy savings if all buildings are refurbished to Minergie-P standard of Table (2.9, p. 49). The preferred choice of candidates for envelope improvement action is given here by order of increasing economy. For the particular case study [Girardin et al., 2010c], one observes in Figure (2.25) that 140 refurbished buildings will generate 20% energy savings, and that large scale envelope improvement will reduce the actual consumption by a factor of two.

The detection of zones with the greatest impact involved by buildings envelope improvement is achieved by comparing the simulation at the horizon 2030 with the situation where all buildings build before 2005 are supposed to be refurbished.
For example, applied in the Geneva Canton, the map of Figure (2.26) permits the identification of zones with the greatest potential for savings ($\Delta Q^{hs+hw}_{2030,z}$) between the two scenarios.

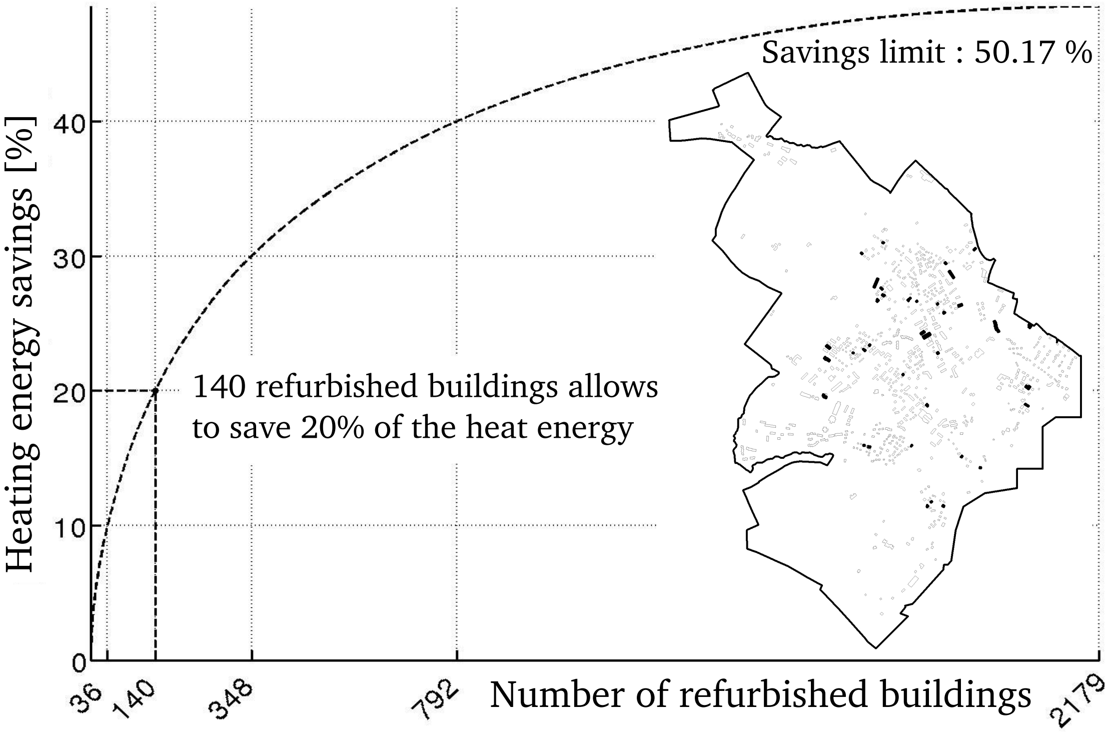


Figure 2.25: Evolutionary curve of the potential of building's improvement actions.

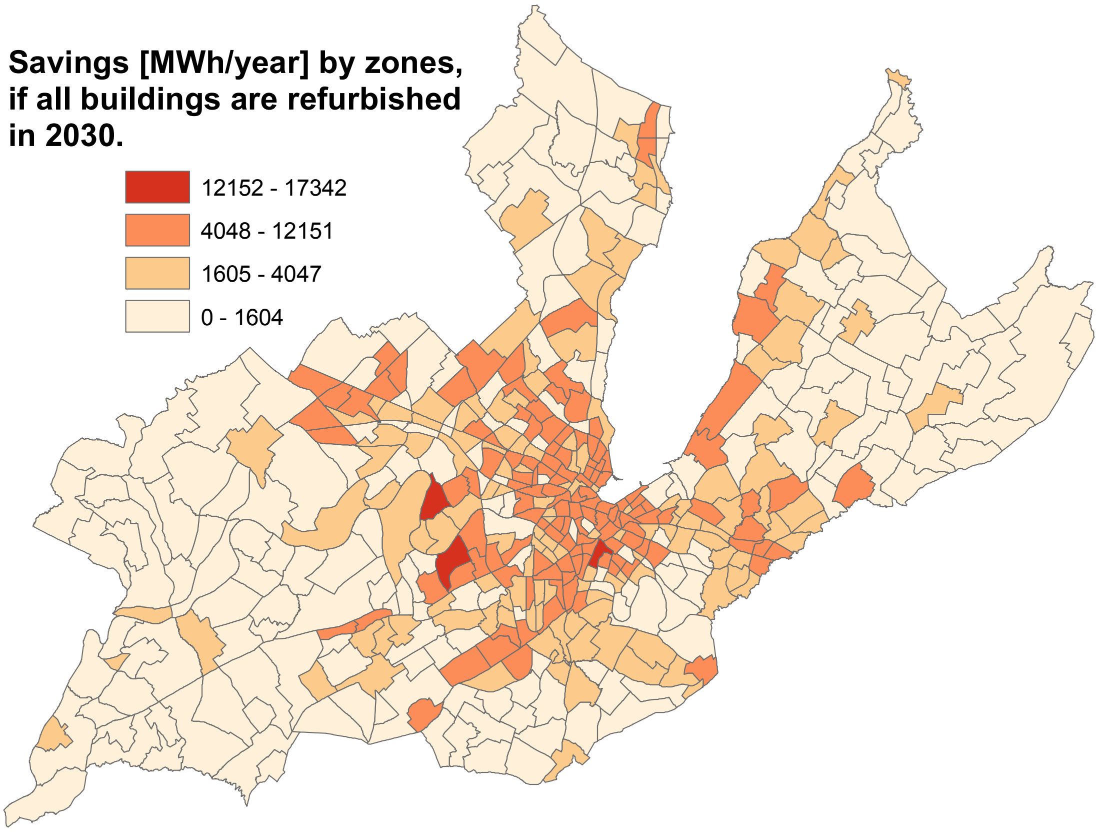


Figure 2.26: Savings by zones at the horizon 2030 if all buildings build before 2005 are refurbished (Geneva Canton, Source: [Girardin et al., 2010b]).

2.9 Implementation of the Geographical Information System

GIS database systems aim at storing, displaying, editing, sharing, and analyzing geographic information for territorial decision making. The implementation of an online database led to effective dissemination at minimal cost of the urban energy inventory, including maps of the computed indicators.
Nowadays, relational database systems can be spatially extended with modules for the description of geographic objects (Point,Curve,Surface) [Herring, 2010], the definition of their Spatial Reference System, and the implementation of methods on geometric object (reprojection, polygon overlay, buffering, measure of distances/areas, data reduction and smoothing, shortest path algorithm,etc.). Compatibility between GIS systems are driven by publicly available interface standards such as the Open Geospatial Consortium [OGC, 2011].

2.9.1 Practical implementation

The Urban Energy database is based on the open source database PostgreSQL [PostgreSQL, 2010] extended with the PostGIS [PostGIS, 2011] spatial database extension.
The information is first imported manually in the PostgreSQL database from various formats, such as text CSV format and geospatial vector data (ESRI-Shapefile [ESRI, 2011]).
Cleaning and merging operations are performed and the results are exported in Shapefile or stored in the database for further use.

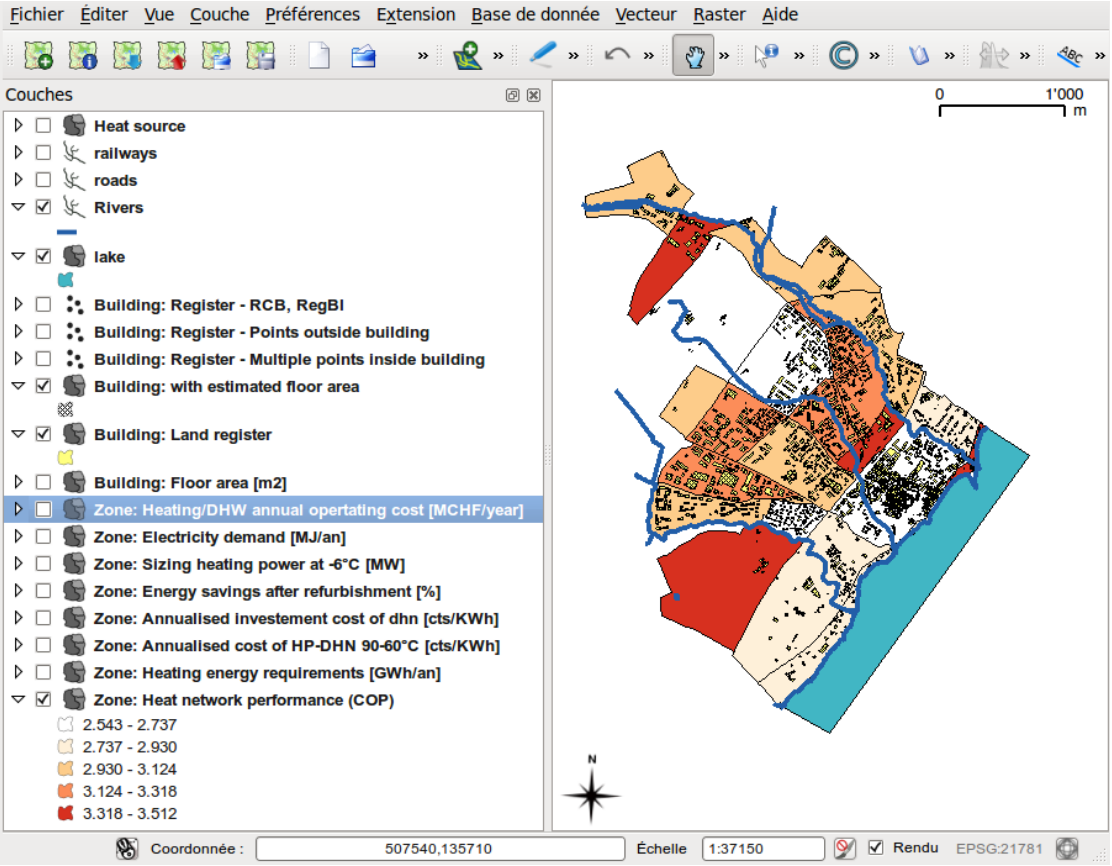
The core algorithm is implemented in the MATLAB language [MathWorks, Inc., 2010], while statistical analysis are performed using the R Language [R, 2011]. The code make use of the MATLAB Mapping Toolbox [MathWorks, Inc., 2011b] and Database Toolbox [MathWorks, Inc., 2011a].
Optimization and process integration are performed using the FORTRAN program EASY [Maréchal, 1995], OSMOSE [Palazzi et al., 2010] and the Linear programming language GLPK [Makhorin, 2011].

The results are stored in a MATLAB structure, exported in Shapefile layers and stored in the PostgreSQL database for online access.

2.9.2 GIS Remote Access

The client software accesses the information stored on a server in order to modify, download, print or simply view geo-referenced layers. On the server side, the database is protected by a password and the connection is restricted to computers identified by their Internet Protocol address (IP).

The open source client QGIS [QGIS, 2009] is used to demonstrate the access to layers of the geo-referenced urban energy inventory but the uses of other clients (ArcGIS, Manifold, Grass GIS, uDig,etc) would give a similar picture. As shown in Figure (2.27), the user can generate its own custom layer and symbology from pre- and post-processing remote attributes, combining them and saving the layout locally for further use.



Coordonnée : 507540,135710

Échelle 1:37150

Figure 2.27: Client access to an Energy inventory for the Commune of Nyon [Girardin et al., 2010c].

2.10 Conclusion

The study presented in this Chapter demonstrates that the built environment in Switzerland is growing at an annual rate of 1.46% and will be 30% greater in 2030 than it is today. This increase is concentrated in urban areas, often in proximity to rivers or lakes (Geneva, Lausanne, Bern, Zürich, Basel, Four-Canton Lake area).

This situation motivates interest in characterizing the present state of the energy needs of urban zones and assessing its evolution. This requires not only the treatment of information from disparate sources and formats, but also ensuring that this information is archived and kept as a valuable resource for future use.

The specification of a Building Information System has therefore been proposed which integrates the building requirements together with layers of energy resources. Applied as a Geographical information System, the platform becomes the cornerstone for the evaluation of energy integrated systems in urban areas.

To overcome uncertainties resulting from a lack of data, statistical methods have been applied to the platform to constitute a set of localized default values that can be used to calibrate a more advanced model such as the Energy Signature presented in Chapter 3.

Strategic applications have been demonstrated for the establishment of priorities, geo-localized at the desired level of granularity, where the results indicate high potential for annual savings in terms of energy, monetary cost and emissions.

A platform has moreover been implemented to demonstrate the practical potential of the methodology and tools.

Finally, by identifying, consolidating, organizing and presenting relevant data from disparate sources, this platform enables decision makers to take the measure of the needs, the possibilities and the constraints of a given area.

3 Characterization of Heating and Cooling requirements in Urban areas

3.1 Introduction

The vision of integrated energy systems in urban area requires the implementation of models of the building's energy demand, which can be linked to a process integration solver in order to evaluate the integration of building stock, energy conversion technologies, energy distribution infrastructure and energy resources, in order to assess the performance of new design and retrofit solutions for urban systems.

Depending on meteorological areas, the proposed model shall estimate, for large urban areas, the mean heat power-temperature profile and operating time for typical periods, as well as for extreme conditions defining the size of the installed energy conversion technologies. It shall moreover consider the effect of refurbishment actions and give the estimation of annual energy, costs and emissions satisfying the needs of urban regions.

For existing buildings, the models are defined by a minimal set of parameters identified either from consumption measurements, energy bills or statistical values, whereas for new buildings they are ideally taken from value obtained from building permits, recognized construction standards, or obtained from the simulation of thermodynamic models.

3.2 State of the art

Building's energy modelling has been a subject of research since the 1910's, resulting in a plethora of Building Energy Software Tools among them four hundred are referenced by the U.S. Department of Energy [DOE, 2011].

State of the art physics based building energy simulation programs [Crawley et al., 2008], like ESP-r [Clarke et al., 2007], EnergyPlus [Crawley et al., 2001], BREDEM [Anderson et al., 1985] are currently applied to predict the energy performance either in the design phase of individual buildings, or to propose energy improvement action for existing buildings. However, they require extensive physical and geometrical parameters. This affects modeling and solving time depending on the levels of detail of the building information models [Leite et al., 2011]. This leads to the adoption of disaggregated approaches using predefined typical values when used at urban scale [D. and Dunster, 1997; Hamilton et al., 2010; Johnston et al., 2005]. While in wide use, most of these tools still suffer a lack of transparency of both data sources [Hand et al., 2008] and model structures [Kavgic et al., 2010] and rarely offer access to the core calculation code.

On the other hand, linear regression techniques have been applied since the early fifties for research on energy consumptions in buildings [Hammarsten, 1987]. The use of these models, based either on data from energy audits, energy bills or from measurement campaigns, shows that the energy consumption may be predicted within 90% confidence interval only with the outdoor temperature as explanatory variable [Dong et al., 2005; Jiménez and Heras, 2005; Zmeureanu et al., 1999].
In the 1980's, refurbishment and maintenance strategies of existing buildings received a regain of interest [Kohler, 2002] and statistical methods based on the Energy Signature (ES), like PRISM [Fels, 1986], have been proposed to predict the energy performance of building [Ghiaus, 2006; Rabl and Rialhe, 1992], giving an estimate of the total heat loss coefficient [Sjögren et al., 2009; Sjögren et al., 2007] and of the cost of energy-saving actions [Adderley et al., 1988].

Recently, the (ES) models have been extended to handle simultaneously both heating and cooling aspects [Bauer and Scartezzini, 1998] as well as to address a wider range of regression parameters contributing to the variation of energy consumptions [Caldera et al., 2008; Catalina et al., 2008; Chua and Chou, 2011]. The development of polynomial meta-models, using Design of Experiments for the design of low energy buildings, has also been reported [Chlela et al., 2009].

Although multiple regression models have been applied to domestic building stock to estimate energy performance and operating costs [Summerfield et al., 2010], their potential to model nominal loads, capital cost and temperature requirements [Girardin et al., 2010b] is still underexploited. Moreover, application at the level of neighborhoods and cities are still relatively rare.

3.3 Steady State modeling of the Building stock thermal requirements

The biggest problem for the energy analysis of large urban areas is the scarcity of energy consumption measurements. Actually, one may expect at best to have access to annual consumptions, even if for public buildings or those connected to district heating networks, monthly reports may be available. On the other hand, the great number of parameters needed to perform building's physical simulation would require disproportionate investment of time when applied to wide urban areas, while a high level of detail is not necessary for the targeting and preliminary design phase at least.

The present work is inspired by audits methods and tools like the Energy Signature (ES), commonly used since the eighties to check the design performance against real data. The proposal therefore is to identify the parameters of the simplest quasi-steady state energy-balance models and to simulate the performance of buildings for monthly or yearly periods. However, nothing prevents the use of advanced regression models or correlations [Catalina et al., 2008] when more measurements are available, nor to perform physical simulation, especially for new buildings, starting from overall construction plans.

3.3.1 The Energy Signature model

The general form of the thermal balance of buildings can be split in terms of Equation (3.1), where k_1 is the slope of the energy signature comprising conduction and air renewal loss of the building, C is the thermal capacitance that affect the response time of the internal temperature and $\dot{Q}_0$ stands for the other power loss or gain, such as heat from persons, electrical facilities heat gain, solar heat gain, heat gain from other zones, short time-constants effects (internal air, furniture and radiator system), energy losses to the ground and energy used for heating the cold water entering the house.

$$\dot{Q} = \dot{Q}_0 + k_1 \cdot (T_i - T_x) + C \cdot dT_i/dt \tag{3.1}$$

For a time-period decomposition greater than a day with small differences between initial and final conditions, the quasi-static Equations (3.2-3.3) of the useful hot ($\dot{Q}^{hs+hw}$), respectively cold ($\dot{Q}^{cs+rw}$) power requirements, neglect the building's thermal mass dynamic. Moreover it considers only heat losses through exposed surfaces above ground level and infiltration losses and/or heat required to warm outdoor air used for ventilation.

The heating ($\dot{Q}^{hs}$) and cooling requirements ($\dot{Q}^{cs}$), where $(\bullet)^+$ represents the positive part of the expression, depends on the meteorological conditions and are therefore modeled separately from the domestic hot water ($\dot{Q}^{hw}$) and refrigeration demand ($\dot{Q}^{rs}$), defined independently. Terms and units of these quasi-static thermal balances are given in Table (3.1).

$$\dot{Q}^{hs+hw} = \underbrace{\left(-\left[\sum_{i}^{n_{bc}^{hs}} U_i A_i + \frac{n_a}{3600} \cdot V_b^{hs} \cdot (\rho_a c_{p_a})\right] \cdot (T_x - T_i) - (\dot{Q}_s + \dot{Q}_p + \dot{Q}_e)\right)^+}_{\dot{Q}^{hs}} + \dot{Q}^{hw} \tag{3.2}$$

Table 3.1: Description of the terms of steady state thermal balance of buildings

symbol	description	units
$\dot{Q}^{hs}$	Useful space heating power	kW
$\dot{Q}^{cs}$	Useful space cooling power	kW
$\dot{Q}_b^{hw}$	Useful hot water production power	kW
$\dot{Q}_b^{rs}$	Useful controlled refrigerating at constant temperature	kW
U_i	Heat transfer coefficient of the buildings component	$kW/(m^2.C)$
A_i	Area of the buildings component i	m^2
n_{bc}^{hs}, n_{bc}^{cs}	Number of buildings component	–
n_a	Air change rates	$1/hour$
$\rho_a c_{p_a}$	Heat capacity of the air	$kJ/(m^3.C)$
V_b^{hs}, V_b^{cs}	Heated/cooled volume	m^3
T_x	Outdoor temperature	C
T_i	Uniform internal temperature	C
h_{alt}	Building altitude	m
$\dot{Q}_s$	Solar heat gain	kW
$\dot{Q}_p$	Heat gain from people	kW
$\dot{Q}_e$	Heat gain from electrical appliances	kW
h_{alt}	Altitude above see level	m

$$\dot{Q}^{cs+rs} = \underbrace{\left(\left[\sum_i^{n_{bc}^{cs}} U_i A_i + \frac{n_a}{3600} \cdot V_b^{cs} \cdot (\rho_a c_{p_a})\right] \cdot (T_x - T_i) + (\dot{Q}_s + \dot{Q}_p + \dot{Q}_e)\right)^+}_{\dot{Q}^{cs}} + \dot{Q}^{rs} \tag{3.3}$$

The specific global heat loss coefficient of a building (k_1), including heat losses by transmission ($\sum_i^{n_{bc}^{hs}} U_i A_i$) and air renewal ($\frac{n_a}{3600} \cdot V_b^{hs} \cdot (\rho_a c_{p_a})$), is given in Equation (3.4)[1]. For multifamily buildings, it has been observed by Sjögren et al. [2009] that for the periods of the year when the solar irradiation yields a minor contribution to heating, the estimated values of k_1 based on monthly data are fairly insensitive (±5%) to whether internal gain and indoor temperature are taken as constant or not, to whether solar gains are included or not and to whether measurements for one or multiple years are used.

$$\begin{aligned} k_1 &= \frac{-\left[\sum_i^{n_{bc}^{hs}} U_i A_i + \frac{n_a}{3600} \cdot V_b^{hs} \cdot (\rho_a c_{p_a})\right]}{A_{fl}} && [kW/(m^2 \cdot C)] \\ \text{with } \rho_a c_{p_a} &= 1220 - 0.14 \cdot h_{alt} && [kJ/(m^3 \cdot C)] \end{aligned} \tag{3.4}$$

---

[1] $(\rho_a c_{p_a})$ correlation from [SIA 380/1, 2009]

Considering constant air change rates and averaged internal gains from people and appliances ($\dot{Q}_i = \dot{Q}_p + \dot{Q}_e$), the general formulation (3.2) can be expressed per square meter of floor area (A_{fl}) by Equation (3.5), where i_s $[kW/m^2]$ is a measure of the solar irradiation and s is the solar gain factor such as ($\dot{q}_s = s \cdot i_s$).

$$\dot{q}^{hs} = \left(k_1^{hs} \cdot (T_x - T_i) - s \cdot i_s - \dot{q}_i\right)^+ \qquad [kW/m^2] \tag{3.5}$$

According to Hammarsten [1987], this three-parameter static model may be used if more than ten observations are available for time periods greater than 24 hours. Otherwise, the most effective model is a linear model of the outdoor temperature(3.6), considering the terms $k_2 = -k_1 \cdot T_i + \dot{q}_s + \dot{q}_p + \dot{q}_e$ as constant.

$$\dot{q}^s(T_x) = \begin{cases} k_1^s \cdot T_x + k_2^s & \text{if } T_x < T_{tr}^{hs} \text{ and } s := hs \\ & \text{if } T_x > T_{tr}^{cs} \text{ and } s := cs \\ 0 & \text{otherwise} \end{cases} \tag{3.6}$$

The heating threshold $T_{tr}^{hs} = -k_2/k_1$ (respectively cooling threshold T_{tr}^{cs}) temperatures are the ones above (respectively under) which heating (respectively cooling) services are not required any more.

3.3.2 Identification of the Energy Signature parameters

When the heating/cooling loads are not available from measurements, they are computed for a given threshold temperature in such a way that the specific annual useful energy requirements $q_{u,yr}$ are conserved (Equation 3.7).

$$q_{u,yr} = \int_{yr} \dot{q}(t)dt \qquad [kJ/m^2] \tag{3.7}$$

When threshold temperatures (T_{tr}) and/or annual energy requirement are not known, the values are obtained from the typical building database (see Table (B.1, p.176 and B.4, p.179). The heating and cooling signatures, computed by Equations (3.8), are presented in Figure (3.1) for each of the 80 building categories. The value of the corresponding signature parameters are presented in Table (B.2, p. 177).

$$k_1^{hs} = \frac{q^{hs}_{u,yr}}{\int_{yr:T_x<T^{hs}_{tr}} T_x(t)\,dt - \int_{yr:T_x<T^{hs}_{tr}} T^{hs}_{tr}\,dt} \qquad [\frac{kW}{m^2\cdot C}] \tag{3.8a}$$

$$k_1^{cs} = \frac{q^{cs}_{u,yr}}{\int_{yr:T_x>T^{cs}_{tr}} T_x(t)\,dt - \int_{yr:T_x>T^{cs}_{tr}} T^{cs}_{tr}\,dt} \qquad [\frac{kW}{m^2\cdot C}] \tag{3.8b}$$

$$k_2 = -k_1 \cdot T_{tr} \qquad [\frac{kW}{m^2}] \tag{3.8c}$$

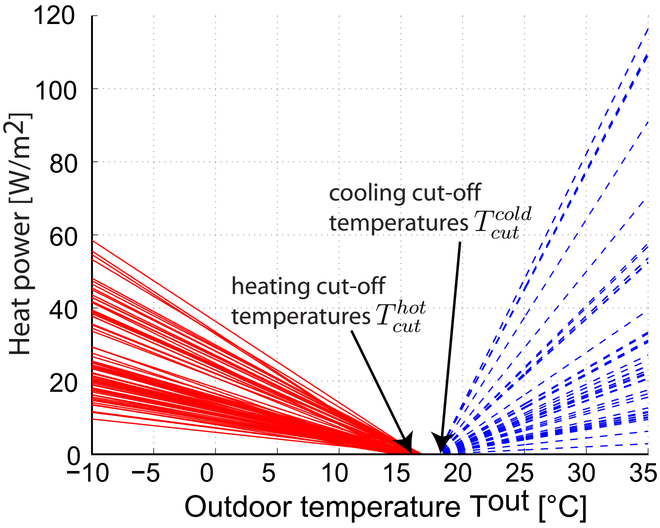


Figure 3.1: Heating Signature for every categories of buildings defined in the Geneva area (see also Table (B.2, p. 177).

When many heat-energy consumption measurements are available, the equation system (3.9) is solved to find both the parameters of the Energy Signature model (k_1, k_2) and the mean hot water production load, provided that the measurements are taken at different periods of the years (summer and winter), such that the system does not become singular.

$$\begin{bmatrix} \int_{t\in P_1:T_x<T^{hs}_{tr}} T_x(t)\,dt & \int_{t\in P_1:T_x<T^{hs}_{tr}} dt & \frac{\int_{t\in P_1} dt}{\int_t dt} \\ \vdots & \vdots & \vdots \\ \int_{t\in P_m:T_x<T^{hs}_{tr}} T_x(t)\,dt & \int_{t\in P_m:T_x<T^{hs}_{tr}} dt & \frac{\int_{t\in P_m} dt}{\int_t dt} \end{bmatrix} \cdot \begin{bmatrix} k_{1,b} \\ k_{2,b} \\ q^{hw} \end{bmatrix} = \begin{bmatrix} \eta^{hs+hw}_{P_1}\cdot q^{hs+hw}_{f,P_1} \\ \vdots \\ \eta^{hs+hw}_{P_1}\cdot q^{hs+hw}_{f,P_m} \end{bmatrix} \tag{3.9}$$

Figure (3.2) shows the results of the regression (Equation 3.9) for a building located in the city of Neuchâtel [Girardin et al., 2010d], and connected to a district network with monthly measurements.

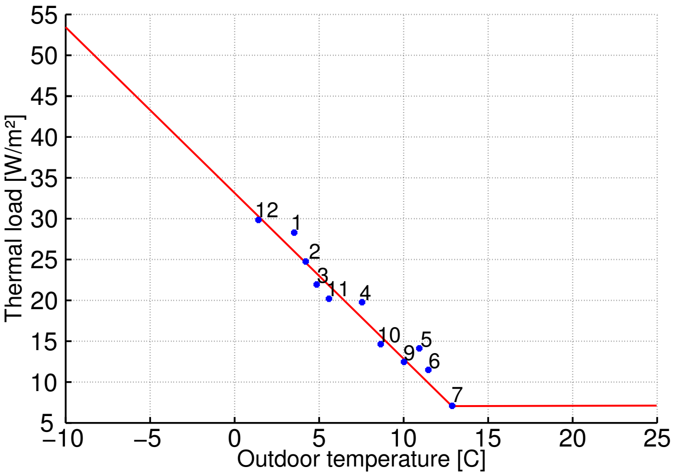


Figure 3.2: Regression of the signature model (Equation 3.9) applied with 12 monthly heat-energy measurements from a building in Neuchâtel (Source: [Girardin et al., 2010d]).

3.4 Domestic Hydronic System Modeling

The supply (T_s^{hs}) and return (T_r^{hs}) temperatures of the domestic hydronic system are derived from a heat exchange model for buildings (Figure 3.3) described by the set of Equations (3.10), where U $[\frac{W}{m^2 \cdot K}]$ is the overall heat transfer and A $[m]$ the heat exchange area. The model assumes a given indoor comfort temperature ($T_{i,0}$) and two nominal supply ($T_{s,0}^{hs}$) and return ($T_{r,0}^{hs}$) temperatures depending on the building category.

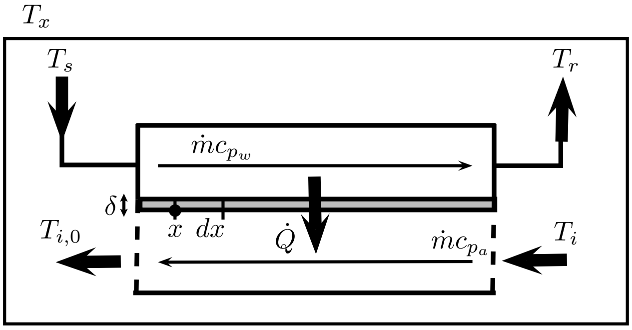


Figure 3.3: Heat exchanger model of the domestic hydronic system.

$$\dot{Q} = UA \cdot \frac{(T_s - T_{i,0}) - (T_r - T_i)}{\ln\left(\frac{T_s - T_{i,0}}{T_r - T_i}\right)} \tag{3.10a}$$

$$\dot{Q} = \dot{m}c_{p_w} \cdot (T_s - T_r) \tag{3.10b}$$

The determination of the heat transfer fluid flow rate ($\dot{m}c_{p_w}$) depends on the adopted control strategy that may be further optimized (§3.4.3, p. 78). In the case of a constant mass flow strategy, the value of ($\dot{m}c_{p_w}$) is defined by the design condition of Equation (3.11).

$$\dot{m}_0 c_{p_w} = \frac{\dot{Q}_0}{T^{hs}_{s,0} - T^{hs}_{r,0}} \tag{3.11}$$

By doing so, it is possible to model the temperature of the building heat delivery system as a function of the heat to be delivered (Equation 3.12b-3.12a), therefore representing the temperature benefit when the building envelope is refurbished.

$$T_r = T_i + \frac{\dot{Q}\cdot(\frac{1}{\dot{m}c_{p_w}} - \frac{1}{\dot{m}c_{p_a}})}{1 - exp\left[UA\cdot(\frac{1}{\dot{m}c_{p_w}} - \frac{1}{\dot{m}c_{p_a}}\right]} \tag{3.12a}$$

$$T_s = T_r + \frac{\dot{Q}}{\dot{m}c_{p_w}} \tag{3.12b}$$

3.4.1 Free convection distribution systems

When the convector surfaces are in contact with the ambient air of the rooms, natural convection occurs. In this situation, the flow of air ($\dot{m}c_{p_a} = 0$) is negligible and the indoor temperature is stable ($T_i = T_{i,0}$). This permits to simplify Equation (3.12b) into Equation (3.13).

$$T_r = T_i + \frac{\dot{Q}\cdot\frac{1}{\dot{m}c_{p_w}}}{1 - \exp\left[UA\cdot\frac{1}{\dot{m}c_{p_w}}\right]} \tag{3.13}$$

The overall heat transfer coefficient (U) of the heat exchanger is obtained from connection in series of conductive and convective terms of Equation 3.14. wall thickness and conductivity of the material (W/mK)

$$\frac{1}{U} = \frac{1}{h_w} + \frac{\delta}{\lambda} + \frac{1}{h_{air}} \tag{3.14}$$

The conductive term (δ $[\frac{W}{m\cdot K}]$) of the wall (thickness δ $[m]$) and the convective term (h_w) on the water side, being between 100 to 15000 $W/(m^2.K)$, may be neglected.
On the air side, the convection heat transfer coefficient (h_{air}) is between 10 to 100 $W/(m^2.K)$.

It may be obtained from the relation of Equation (3.15a) and with the help of an empirical correlations for the Nusselt number (Nu) for external free convection flows [Incropera et al., 2006], reported in Equation (3.15b).

$$\overline{\mathrm{Nu}_L} = \frac{h_a L}{k} \tag{3.15a}$$

$$\mathrm{Nu}_L(x) = C \cdot \mathrm{Ra}_L(x)^n \tag{3.15b}$$

$$\text{with } \mathrm{Ra}_L = \frac{g\beta\,(T_m - T_i)\,L^3}{\alpha\nu} \text{ and } T_m = \frac{T_s + T_r}{2} \tag{3.15c}$$

Typical values for the Rayleigh exponent are $n = 1/4$ for laminar flows and $n = 1/3$ for turbulent flows [Incropera et al., 2006, p. 551].

It follows from the development of Equations (3.14-3.15) that $\frac{U}{U_0} = \left(\frac{T_m}{T_{m,0}}\right)^n$ and $\frac{Q}{Q_0} = \left(\frac{T_m}{T_{m,0}}\right)^{n+1}$. The variation of the global heat exchange coefficient may then be expressed as a function of the nominal exchange coefficient and the distribution temperatures according to the Equation (3.16).

$$UA = (UA)_0 \cdot \left(\frac{T_m}{T_{m,0}}\right)^n \tag{3.16}$$

Standard emission coefficients(n) according to the swiss norm [SIA 384/2, 1984] are reported in Table (3.2) for typical hydronic systems.

Table 3.2: Emission coefficient (source [SIA 384/2, 1984]).

distribution system	emission coefficient [−]
radiators element and panel Radiators	0.33
heating coils or finned tubes	0.25
miscellaneous convector,	0.25 to 0.4
water underfloor Heating	0.24
ceiling heat	0.22

3.4.2 Heating/cooling curves

The substitution in Equation (3.12a) of the supply temperature of Equation (3.12b) and of the global heat exchange coefficient of Equation (3.16), leads to the implicit Equation (3.17), solved to find the return temperatures ($T_r(\dot{Q}, \dot{m}c_{p_w})$) of the hydronic distribution systems. The supply temperature curves ($T_s(\dot{Q}, \dot{m}c_{p_w})$) are then obtained from Equation (3.12b).

$$f(T_r, \dot{m}c_{p_w}) = 0 \tag{3.17}$$

Example of heating curves, for typical hydronic distribution systems of Table (3.2), are plotted in Figure (3.4) considering a constant flow rate strategy ($\dot{m}c_{p_w} = \dot{m}_0 c_{p_w}$).
For $h = 0$, the heat distribution temperature follows the straight line of Equation (3.12a) with constant relation $(UA) = (UA)_0$.

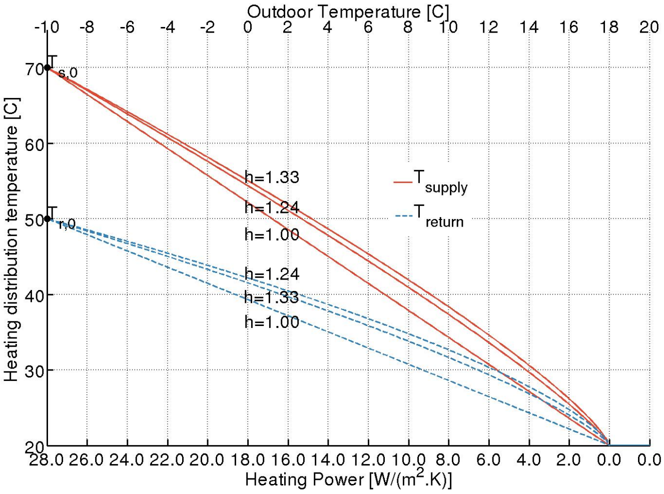


Figure 3.4: Example of heating curves for a building with Energy Signature slope ($k_1^{hs} = 1\ \frac{W}{m^2 \cdot C}$) and heating threshold temperature ($T_{tr}^{hs} = 18°C$).

3.4.3 Hydronic system mass flow

Various control strategies may be adopted to model the mass flow of the hydronic distribution system, such as constant mass flow (see Figure 3.4) or mass flow proportional to the required power. If the constant mass flow assumption (§3.4.1) allows to model large scale urban area with sufficient details, it is worthwhile to consider optimal mass flow strategies in order to evaluate retrofit actions and/or integration of new energy conversion systems.
In this situation, the mass flow is optimized by maximizing the performance of the whole integrated heating/cooling system, thus introducing to Equations (3.10a-3.10b) a new one of the form of Equation (3.18) expressing the link between the control of the hydronic distribution system and the operating conditions of the energy conversion technologies.

$$\dot{m}c_{p_w}(\dot{Q}) = \max_{\dot{m}c_{p_w}} f\left(\dot{m}c_{p_w}, T_s, T_r\right) \tag{3.18}$$

3.5 Period dependent requirements using Q-T composites

The knowledge of the load curve of Figure (3.5) allows to size boilers supplying heat at temperatures levels far above 800-1000 $°C$. On the contrary, the performances of energy systems delivering heat at temperatures close to the heating 30-70$°C$ and/or hot water production 55-70$°C$ requirements, are much more sensitive to heat exchange restrictions and to the de-

pendence of the distribution temperatures to the operating conditions.
It is therefore necessary to use a representation that expresses the inter-dependence between heat-power and temperature.

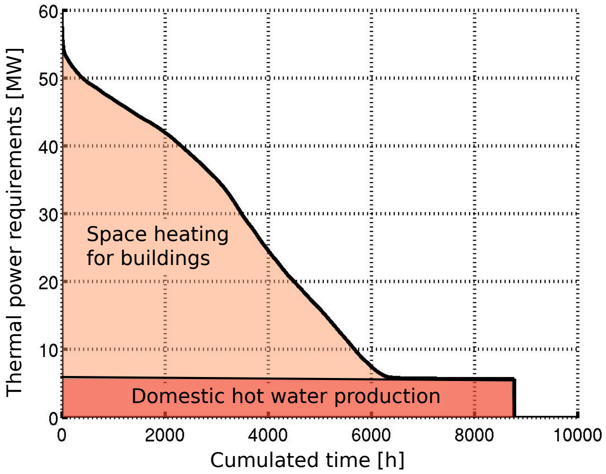


Figure 3.5: Exemple of Load-duration curve (Source: Energy concept for the Nyon Area [Girardin et al., 2010c]).

3.6 Composite Curves in Urban areas

The composite curves represent graphically the sum of the streams defined by a heat flow and two corresponding temperature levels. For every selected building, this summation is performed for floor heating and hot water production streams, as shown in Figure (3.6). Furthermore, for cooled buildings or those having refrigeration equipment, the cooling and refrigeration streams are integrated similarly.

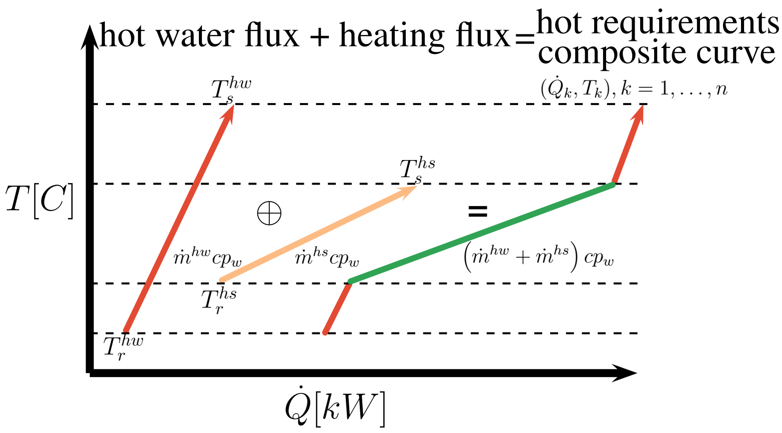


Figure 3.6: Construction of the heating composite curve.

The composite curve represents the heat cascade defining the constraint of the Mixed Integer Linear Problem (MILP) solved during the Process Integration phase.

The time scale is first decomposed into a limited number of representative periods (P). The definition of the periods depends on the design problem to be solved. In the case of urban planning, the variation of temperatures may be compensated by the uncertainties of the data and a multi-period analysis is made with many individual steady state periods, as shown in Figure (3.7). When a more detailed model is needed, for example for the design of district network, the integration of solar heat or when storage tanks have to be designed, a higher number of periods like typical days representation [Weber et al., 2006b] should be applied. The building model being defined as a function of the outdoor and room temperature, any time discretization may be applied as long as the building model remains valid, e.g. the building structure inertia is not relevant. Considering the building dependent threshold temperatures, a typical mean temperature $\overline{T}^{hs}_{ext,P,c}$ is associated with each building/category. This is done for each period using equation (3.19), and similarly for the cold requirement.

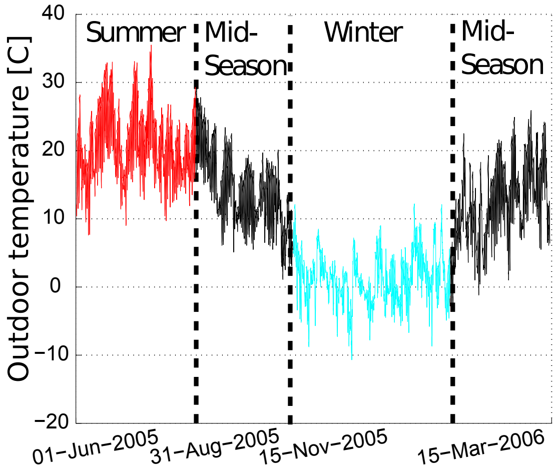


Figure 3.7: Outdoor temperature in Geneva (2005) and definition of the periods.

$$T^{hs}_{x,P,c} = min\left(\frac{\int\limits_{t\in P:T_x<T^{hs}_{tr,c}} T_x(t)dt}{\int\limits_{t\in P:T_x<T^{hs}_{tr,c}} dt}, T^{hs}_{tr,c}\right) \tag{3.19}$$

Using the heating signature, the hot/cold mean power ($\overline{\dot{Q}}^{j}_{P,z}$) is computed for each period (P) by Equations (3.20-3.21) (see Table B.3, p. 178). The sum over the different types of building defines the required power of a given area. The equivalent operating time (D_P) of the period for the area is defined as the energy/power ratio (3.22).

$$\dot{Q}^{hs+hw}_{P,z} = \sum_{c=1}^{n_c} ({k_1}_c^{hs} \cdot T^{hs}_{x,P,c} + {k_2}_c^{hs} + \dot{q}_c^{hw}) \cdot A_{c,z} \tag{3.20}$$

$$\dot{Q}^{cs+rs}_{P,z} = \sum_{c=1}^{n_c} ({k_1}_c^{cs} \cdot T^{cs}_{x,P,c} + {k_2}_c^{cs} + \dot{q}_c^{rs}) \cdot A_{c,z} \tag{3.21}$$

$$D_P = \frac{Q_P}{\bar{\dot{Q}}_P}, \tag{3.22}$$

Considering the list of buildings in a given area and applying process integration techniques [Maréchal and Kalitventzeff, 1998], it is possible to compute the heat-temperature composite curves $((\dot{Q}_k, T_k)_P, k = 1, ..., n_k + 1)_z$, that defines in each zone the net hot/cold services to be delivered in a typical period. The heat cascade integrates the hot water production, the heating and the cooling requirements of all the buildings in the area. Such representation allows to quantify the possible heat recovery between hot and cold streams. The heat enthalpy curves also allows to compute the overall exergy required in a given period [Maréchal and Favrat, 2005].

Figure 3.8 shows such composite curves for the district of Geneva. The dotted curves correspond to the targeted heat demand at the horizon of 2030, based on a given refurbishment and urban development scenario. It includes the increase of the built area and the increase of the building efficiency and its corresponding decrease of the temperature at which the heat will need to be supplied. For the new buildings, we considered the application of the most recent standards. It is shown that the overall heat load is going to change less than 7% in the area, but its temperature levels are expected to decrease.

Knowing the composite curves, the process integration techniques may be used to estimate the optimal integration of the energy conversion technologies. This is particularly useful when the integration of combined heat and power, heat pumping or polygeneration systems are considered. Together with the resources database, the calculation of the composite curves of an area in each period will correspond to the structuring phase of the optimal design of district heating systems as proposed by Weber et al. [2006a].

3.6.1 Mathematical implementation

Mathematically, the curve represents the heat cascade of the system and is obtained by Equation (3.23) applied for each temperature T_k encountered in the list of hot and cold

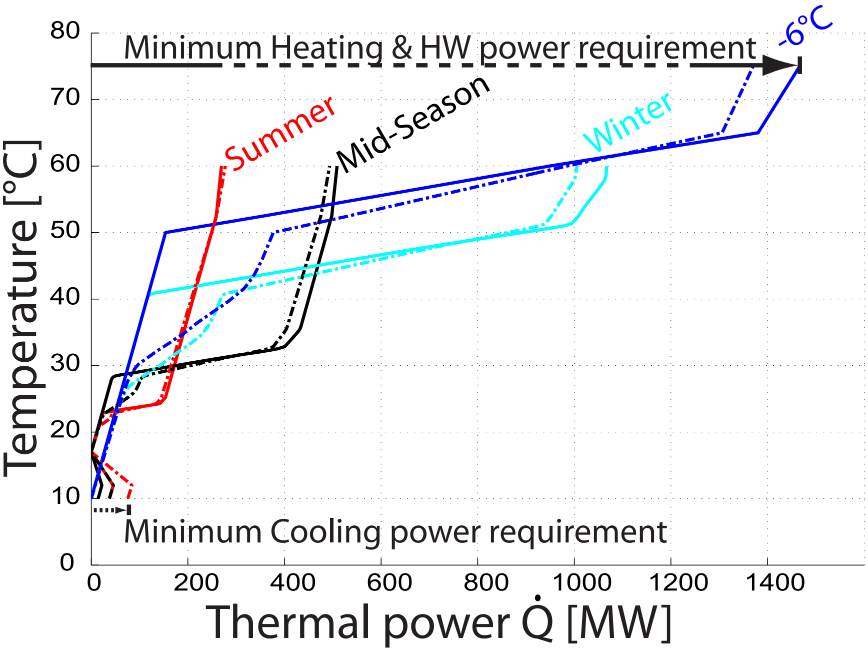


Figure 3.8: Composite curves of the Geneva area: Actual states and 2030 predictions. (Source [Girardin et al., 2010b])

streams of the system.

$$\dot{Q}_k = \sum_{i=1}^{\#\text{ hot flux}} \dot{Q}_i / \left|T_{s,i} - T_{r,i}\right| \cdot \left(max(T^*_{k,i}, T^*_{s,i}) - max(T^*_{k,i}, T^*_{r,i})\right)$$
$$- \sum_{j=1}^{\#\text{ cold flux}} \dot{Q}_j / \left|T_{s,j} - T_{r,j}\right| \cdot \left(max(T^*_{k,j}, T^*_{r,j}) - max(T^*_{k,j}, T^*_{s,j})\right) \tag{3.23}$$

with $T^*_i = T_i - \Delta(T_{min})_i/2$ for hot flux

and $T^*_j = T_j + \Delta(T_{min})_i/2$ for cold flux

The contribution of the hot and cold building's requirements to the minimum temperature difference in the heat exchangers ($\Delta(T_{min})_i/2$) is fixed to 5 $°C$.

3.7 Synthesis

The simplest thermal requirement model expresses heating and cooling loads and temperatures of the domestic heat distribution system, as a function of the outdoor temperature. This thermal model may be defined with a minimal set of seven (heating and hot water production only) to thirteen parameters for each building :

- the annual energy requirements (q_Y^{hs}, q_Y^{cs}),
- the threshold heating and cooling temperatures $(T_{tr}^{hs}, T_{tr}^{cs})$,
- the indoor comfort temperature (T_i),
- the nominal temperatures of the domestic heating system$(T_{supply,0}^{hs}, T_{return,0}^{hs})$,
- the nominal temperatures of the domestic hot water system $(T_{supply,0}^{hw}, T_{return,0}^{hw})$,
- the nominal temperatures of the domestic cooling system $(T_{supply,0}^{cs}, T_{return,0}^{cs})$,
- the nominal temperatures of refrigeration system $(T_{supply,0}^{rs}, T_{return,0}^{rs})$.

When these values are unknown, they are estimated based on norms [SIA 380/1, 2009] or good practice rules.

For new buildings designed as passive buildings, the outdoor temperature has a weaker influence compared to solar gain and occupant behavior. In this situation, a solar heat gain factor must therefore be identified in order to properly estimate the nominal loads.

3.8 Straightforward strategic applications

The characterization in a GIS system of the demand of urban zones in terms of power and temperature level, and not only in terms of annual energy intensity, opens the door to straightforward strategic applications. It makes for example possible to determine geographically the zone of influence of heat source and sink based on the knowledge of the nominal power requirements of urban sectors.
This allows moreover to define rigorously the thermodynamic performance of urban energy systems, leading to the identification, on maps, of the priority areas for allocating subsidies and investing in infrastructure and equipments.

3.8.1 Heating/cooling density Power map

The map of Figure (3.9) shows the values of heating and domestic hot power requirements ($\dot{Q}^{hs+hw}_{0,z}$) computed, for each zone z of the Canton of Geneva, by Equation (3.24) for an outdoor temperature of ($T_{out,0} = -6°C$), which corresponds to the nominal temperature for heating devices.

$$\dot{Q}^{hs+hw}_{-6,z} = \sum_{c \in C} (\dot{q}^{hs}_{-6,c} + \dot{q}^{hw}_{c}) \cdot A^{hs}_{c,z}, \forall z \in Z \tag{3.24}$$

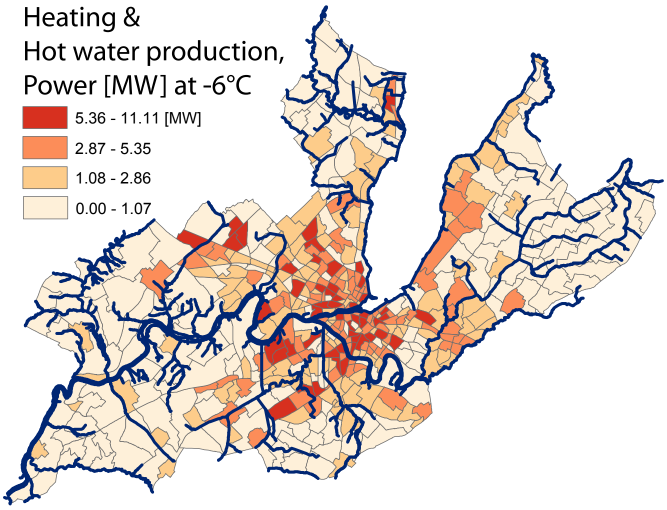


Figure 3.9: Heat and hot water power requirements by zones for an outdoor temperature of $-6°C$ (Source [Girardin et al., 2010b]).

Figure (3.10) shows the values of cooling and refrigeration requirements ($\dot{Q}^{cs}_{0,z}$) computed, for each zone z of the Canton of Geneva, by Equation (3.24) for an outdoor temperature of ($T_{out,0} = 21°C$).

Theses maps allow to identify high energy density areas and attractive energy market place.

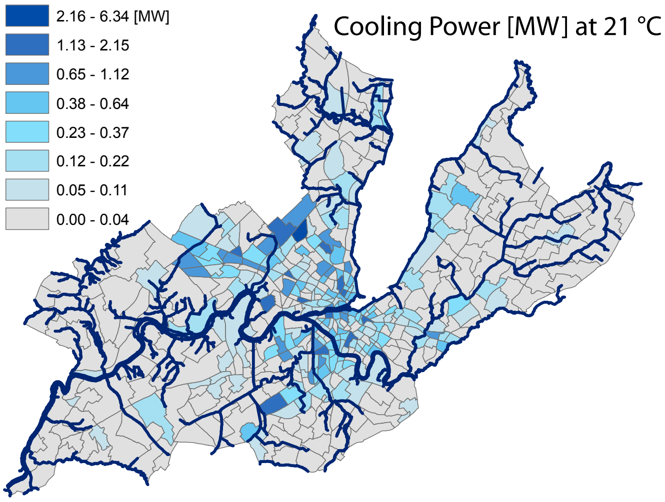


Figure 3.10: Cooling and refrigeration power requirements by zones for an outdoor temperature of $21°C$ (Source [Girardin et al., 2010b]).

Moreover it constitute the basis for the determination of influence zones of Urban Heat sources (Waste Water Treatment plant, lake, river, Water collector, Industries, ...) using spatial aggregation procedures (§4.2.5, p. 95).

3.8.2 Evaluation of the Exergy performance of Urban Areas

The exergy balance (Equation 3.25) of a system corresponds to the expression of the ideal conversion, into mechanical work, of the three forms of energy found in the exergy balance [Borel and Favrat, 2010]: work-exergy ($\dot{E}$), heat-exergy ($\dot{E}_q$) and enthalpy-transformation exergy ($\dot{E}_y$), the latter being considered as fuel exergy in urban systems.

$$\dot{L} = \dot{E} + \dot{E}_y + \dot{E}_q \geq 0 \tag{3.25}$$

In order to achieve the theoretical thermodynamic conversion of heat-exergy (Equation 3.26) and fuel exergy value (Equation 3.27) into mechanical work, a reference temperature ($T_{ref,z,p}$) is defined as the lowest temperature of the environment for each period (p) and location(z).

$$\dot{E}_q = \int \Theta \delta \dot{Q} = \int (1 - \frac{T_{ref}}{T}) \delta \dot{Q} \tag{3.26}$$

$$\dot{E}_y = \dot{M}_F \Delta k^0 = \dot{M}_F \cdot EXV_f \tag{3.27}$$

Exergy efficiency

The performance of the conversion of energy resources into useful energy services can rigorously be expressed, in terms of both quantity and quality, by an exergy indicator [Favrat et al., 2008]. The exergy efficiency, always lower than 100%, is defined by the ratio (3.28) of the useful exergy service arising from the inhabitant needs to the exergy delivered in the form of energy sources consumed on the spot.

$$\eta_x = \frac{Ex_u}{Ex_f} \tag{3.28}$$

Useful Exergy in Urban Areas

The useful exergy of Equation (3.29) expresses, in each zone (z), the sum over all categories of buildings (c) and periods (p) of the useful heating $(\dot{Q}^{hs}_{p,c})$, DHW $(\dot{Q}^{hw}_{p,c})$ and electrical $(\dot{E}^{el}_{p,c})$ exergy required, given the corresponding reference temperature of the environment $(T_{ref,p})$ and the comfort temperature inside the building (T_i).
The reference temperature of the environment $(T_{ref,p})$ is set by default to the periodic mean outdoor temperature and the indoor temperatures (T_i) are fixed according to the Swiss norm [SIA 380/1, 2009].

$$Ex_{u,z} = \sum_{\substack{c\in C\\ p\in P}} \dot{Q}^{hs}_{p,c} \cdot \left(1 - \frac{T_{ref,p}}{T_i}\right) \cdot \Delta t^{hs}_{p,c} + \dot{Q}^{hw}_{p,c} \cdot \left(1 - \frac{T_{ref,p}}{T^{hw}_{ln}}\right) \cdot \Delta t^{hw}_{p,c} + \dot{E}^{el}_{p,c} \cdot \Delta t^{el}_{p,c} \tag{3.29}$$

$$\text{with } T^{hw}_{ln} = \frac{T^{hw}_s - T^{hw}_r}{ln\left(\frac{T^{hw}_s}{T^{hw}_r}\right)} \; [K] \tag{3.30}$$

Final Exergy in Urban Areas

The annual final exergy of Equation (3.31) expresses, in each zone (z), the sum over all categories of buildings (c) and periods (p) of the amount of combusted Fuel $(M^F_{c,yr}\ kg)$, global solar radiation $(G^{solar}_{i,yr})$ and electrical $(\dot{E}^{el}_{p,c})$ exergy supplied. The exergy value of $(EXV^{gaz} = 49563.1\ kJ/kg)$ for natural gas and $(EXV^{wood} = 20939\ kJ/kg)$ for the wood [Gassner and Maréchal, 2009] are applied by default. These final exergy values do not take account of the supply chain, but consider only the import consumed on the spot.

$$Ex_{f,z} = \sum_{\substack{c \in C \\ p \in P}} (\sum_{Fuels} M^F_{c,yr} \cdot EXV^F) + G^{solar}_{i,yr} \cdot \Theta_s + E^{el,in}_{yr} \tag{3.31}$$

The solar exergy [Candau, 2003] is obtained through equation 3.32 with a temperature of solar radiation of $T_s = 5800\ K$.

$$\Theta_s = 1 + 1/3 \cdot \left(\frac{T_{ref}}{T_s} \right)^4 - 4/3 \cdot \frac{T_{ref}}{T_s} \tag{3.32}$$

3.9 Conclusion

For the design of advanced energy conversion systems, building stock must be characterized in terms of its heat-power and temperature requirements. A multi-period steady-state model aggregating the energy demand of urban zones has therefore been proposed.

This 1D model is inspired by state of the art use of Energy Signature for energy audit of buildings. It is calibrated on real measurements whenever possible. When these are unavailable, the statistical database of typified buildings developed in Chapter 2 provides the necessary values for extrapolation. This makes it possible to extend the application from individual building to urban scale. The advantage of this approach is that it is based on a minimal set of required physical parameters. While it is applicable to the vast majority of existing building stock, totaling 90% of the built environment, the new high performance buildings require the use of higher resolution models incorporating solar gain and inhabitant behavior, which in turn requires more measurement data. The implementation of large scale systems such as the one proposed in Chapter 2 shall contribute to more accurate modeling of the new urban environment.

The specificity of the modeling approach is that it links heat-power requirements with a model of the heating and cooling domestic hydronic distribution system, thus representing the temperature requirements as a function of the heat-power requirements. This enables modeling of the effect of refurbishment actions not only in terms of energy savings but also in terms of temperature lowering.

Furthermore, it defines the hot and cold streams comprising the composite curve of the requirements, aggregated independently of the spatial scale of the study characterizing the heat requirements of urban areas in different periods and scenarios.

4 Integration of centralized and decentralized urban energy systems

The part of the thesis describing the Design of Advanced energy conversion system was presented at the ECOS Conference, held in Kraków (Poland) in June 2008 [Girardin et al., 2008] and published in the journal Energy [Girardin et al., 2010b].

4.1 Introduction

The establishment of a strategic energy development planning to meet the thermal energy requirements of urban area requires the analysis of synergies between conversion and distribution technologies, linking energy resources and requirements for energy services.

The performance of advanced energy conversion systems using the best local resources are assessed starting from the definition of the energy services required in a geographic area. The integration of cogeneration technologies of different sizes and the use of heat pump technology is evaluated using a pinch analysis approach. Emphasis is also placed on the use of high and low temperatures district network.
The aim is to highlight the potential savings associated with the use of alternative technologies instead of conventional boilers. Combined heat and power cogeneration plant offer a possible alternative to distribute thermal energy for heating while supplying electricity including for heat pumps or air conditioning units. Compensation measures for the additional CO_2 emissions from electricity generation are also analysed.

The developed model forms the basis of a strategy for the identification of the best way to integrate energy conversion technologies in urban areas. Moreover, the tool follows a prospective approach by analysing also the future situation based on an extrapolation of the energy demand.

4.2 District heat distribution system

Considering the access to local resources like lake water or waste water, it is necessary to compare centralized and decentralized solutions. For centralized solutions, one has to evaluate the integration of the district network (dn) and therefore estimate the cost of the system. This requires the evaluation of the temperature levels at which the heat will be distributed as well as its return temperature.

4.2.1 Network flow rate

Given the composite curve characterizing the thermal demand for typical periods and scenarios of urban areas, the integration of a district network begin with the definition of a supply temperature (T_s^{dn}), a minimum temperature difference (ΔT_{min}^{dn}) in the heat exchanger and a minimum allowed return temperature ($T_{r,min}^{dn}$). When the supply temperature is given, the heat loads $\dot{Q}_{n_k+1} - \dot{Q}_k$ are given by the composite curve data, and the return temperature is computed by Equation (4.2) in order to minimize the flow in the system (4.1).

$$\begin{aligned} \dot{m}^{dn} &= \max_{k=1,\dots,n_k} \left[\frac{\dot{Q}_{n_k+1} - \dot{Q}_k}{c_p \cdot (T_s^{dn} - T^*)} \right] \\ \text{with } T^* &= \max\left(T_{r,min}^{dn}, T_k + \Delta T_{min}^{dn} \right) \end{aligned} \tag{4.1}$$

4.2.2 Network return temperature

Given the supply temperature (T_s^{dn}) and having computed the flow rate activating the demand pinch point, the corresponding return temperature (T_r^{dn}) is obtained for each period by Equation (4.2).

$$T_r^{dn} = T_s^{dn} - \frac{\dot{Q}(T_s^{dn})}{\dot{m}^{dn} \cdot c_p} \tag{4.2}$$

4.2.3 Heat exchangers area

The heat exchanger area, given by Equation (4.3), is obtained by summing, for each vertical enthalpy interval ($\Delta \dot{Q}_k = \dot{Q}_{k+1} - \dot{Q}_k$), the heat-exchange matches between the network and the requirements composite curve.

$$A^{dn,hx} = \sum_{i=1}^{n_k^*} A_k = \sum_{i=1}^{n_k^*} \frac{\dot{Q}_k}{U_k \cdot (\Delta T_{ln})_k} \tag{4.3}$$

For the special case of district network water/water heat exchange, the global heat exchange coefficient (U_k) is taken constant with $U_k = 560\ W/(m \cdot K)$.
Knowing the heat exchanger area required to distribute heat in buildings (b), it is possible to assign an exchange area to each building proportionally to their marginal contribution at the nominal load ($\dot{Q}_{b,0}$) to the total demand (Equation 4.5).

$$A_b^{dn,hx} = \frac{\dot{Q}_{b,0}}{\sum\limits_b \dot{Q}_{b,0}} \cdot A^{dn,hx} \tag{4.4}$$

The investment cost of heat exchangers installed in buildings are then estimated by Equation (4.5) Bolliger et al. [2005].

$$C_I^{dn,hx} = \sum_b \frac{M\&S}{1069.9} \cdot 7038 \cdot A_b^{dn,hx^{0.7948}} \tag{4.5}$$

4.2.4 Preliminary Investments Estimation

Network length The length of the network (L^{dn}) is computed by correlation (4.6), considering the land area (S_z), the number of buildings (n_b) and a topological factor (K). The value $K = 0.23$ has been identified from an existing network in Geneva.

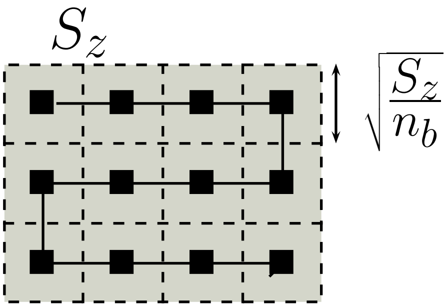


Figure 4.1: Geometric network length correlation in urban zones.

$$L^{dn} \simeq 2(n_b - 1)K\sqrt{\frac{S_z}{n_b}} \tag{4.6}$$

Heat losses An approximation of the heat loss $\dot{Q}_{loss}^{dn} = f_{loss}^{dn} \cdot \dot{Q}^{dn}$ is obtained considering a heat loss factor ($f_{loss,0}^{dn}$) of 10% for a given reference supply temperature ($T_{s,0}^{dn}$) of $100°C$ and a mean ground temperature (T_{gnd}). The heat loss factor (f_{loss}^{dn}) is considered proportionnal to the supply and ground temperature difference, as defined in Equation (4.7).

$$f_{loss}^{dn} = f_{loss,0} \cdot \frac{T_s^{dn} - T_{gnd}}{T_{s,0}^{dn} - T_{gnd}} \tag{4.7}$$

Heat load This allow to compute the corrected district heat load (4.8) and its corresponding supply temperature (4.9).

$$\dot{Q}^{*dn} = \dot{Q}^{dn} + \dot{Q}_{loss}^{dn} \tag{4.8}$$

$$T_s^{*dn} = T_r^{*dn} + \frac{\dot{Q}^{*dn}}{\dot{m}^{dn} \cdot c_p} \tag{4.9}$$

Pipe diameter The pipe diameter (d^{dn}) is computed by (4.10) assuming a nominal velocity (v_s) of 3 m/s.

$$d^{dn} = \sqrt{\frac{4 \cdot \dot{m}^{dn}}{\pi \cdot v_s \cdot \rho}} \tag{4.10}$$

Investments The investment cost correlation (4.11) includes material costs, proportional to the pipe diameters and fixed costs of civil engineering works. The values of the corresponding coefficient $c_1 = 7047\ CHF/m^2$ and $c_2 = 752.8\ CHF/m$ have been calibrated on data from Table (4.1).

$$I_C{}^{dn} = \left(c_1 \cdot d^{dn} + c_2\right) \cdot L^{dn} \qquad \text{[CHF]} \tag{4.11}$$

Table 4.1: Typical cost of network pipes, for diameters between 25mm and 300mm.

Parameters	values											
pipe diameter [mm]	25	32	40	50	65	80	100	125	150	200	250	300
pipe cost [CHF/m]	950	950	1000	1200	1250	1350	1470	1600	1750	2000	2500	3000

The specific cost of the heat distribution (Ic^{dn}), shown in Figure (4.2), is computed by Equation (4.12), typically considering 60 years lifetime for the annualisation factor of the district network investment (τ^{dn}).

$$I_c{}^{dn} = \frac{\left(c_1 \cdot d^{dn} + c_2\right) \cdot L^{dn} \frac{1}{\tau^{dn}}}{Q_{yr}^{dn}} \qquad \text{[CHF/kWh]} \tag{4.12}$$

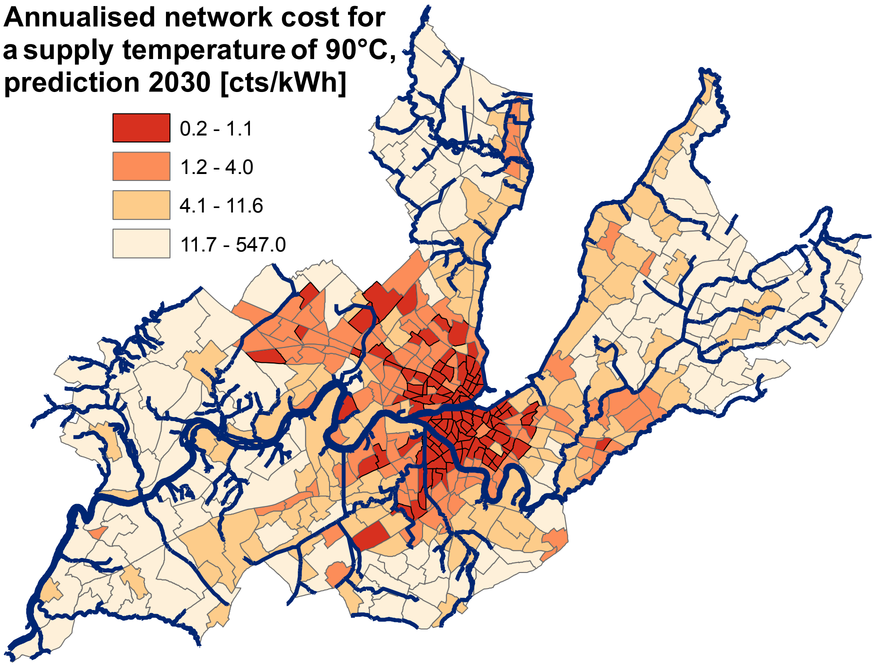


Figure 4.2: Cost of DHN by zones for a distribution temperature of 90° and the heat requirement expected for 2030 (Source: Girardin et al. [2010b]).

4.2.5 Resource-limited geographical aggregation

District heating is typically interesting when it allows one to access to endogenous resources, or when it allows to profit from scale effects of the investment and the efficiency of the technologies. In both cases, the available capacity ($\dot{Q}^{max}$) of the resource or of the technology requires the calculation of the area covered by a given technology or a given resource.
A MILP aggregation mechanism has therefore been developed in order to evaluate the best zone to be covered by a district heating system that has access to a given resource.
The integer variables of the problem are the existence $N_{z_1,z_2} = 1$ or not $N_{z_1,z_2} = 0$ of a network between neighboring zones (z_1, z_2) and the existence $X_z = 1$ or not $X_z = 0$ of a network in a zone.
The application of such algorithm is illustrated by targeting the area covered by the heat $\dot{Q}^{max} \geq \sum_{z=1}^{n_z} (X_z \cdot \dot{Q}_{0,z}^{dn})$ available from waste water treatment plants (WWTP) (figure 4.3). The area is increased from a given resource location X_{start} by the selection of neighboring zones that minimize the DHN's specific costs $\sum_{z=1}^{n_z} (X_z \cdot c_z^{dn})$.

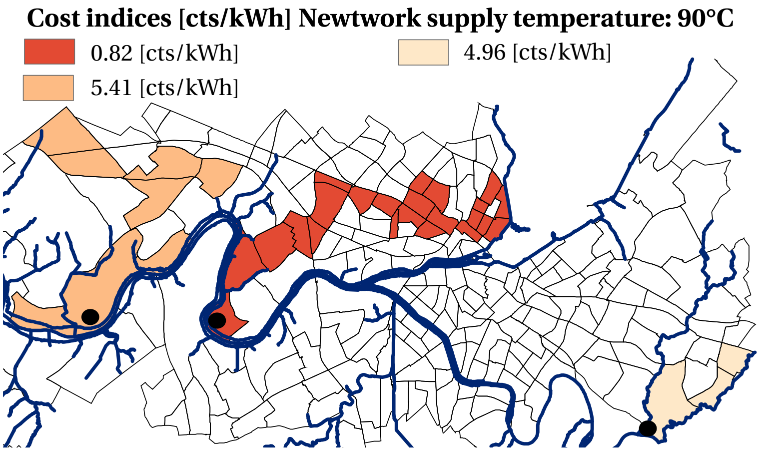


Figure 4.3: Areas covered at minimal cost by the heat available from WWTP plants (Source [Girardin et al., 2010b]).

4.2.6 Network design using MILP formulation

In order to estimate more precisely the length of the network, a Mixed Integer Linear programming (MILP) is proposed. Starting from a set of nodes n and roads $((i,j))$, the algorithm determines the existence$(Y_{i,j} = 1)$ or not $(Y_{i,j} = 0)$ of a connection between two nodes. Each node belonging to the network can be part $(X_i = 1)$ or not $(X_i = 0)$ to the network.

The algorithm minimizes the cost function of Equation (4.13) where $(L_{i,j})$ is the length between two nodes, (c_1) and (c_2) are the proportional and fixed cost of the pipes, (IC_n^{dn}) is the fixed cost of a node (n) and $(\tilde{d}_{i,j})$ is a linear approximation of the pipe's diameter between two nodes. The constraints of the problem ensure that the energy and mass balance holds (Equations C.2, p. 181) and define a tree structure (Equations C.1, p. 181) such as the one visible in Figure (4.4).

$$\tilde{I_C}^{dn} = \sum_{(i,j)\in P} \left(c_1 \cdot \tilde{d}_{i,j} \cdot 2L_{i,j} + c_2 \cdot L_{i,j}\right) + \sum_{n\in N} IC_n^{dn} \cdot X_n \qquad \text{[CHF]} \tag{4.13}$$

Being a non linear function of the heat load $(Q_{i,j})$, the diameter is linearized as shown in Equation (4.14) and Figure (4.5).

$$S_{i,j} = \frac{\dot{Q}_{i,j}}{c_p \cdot \left(T_{s,0} - T_{r,0}\right) \cdot \rho \cdot v_0} \tag{4.14}$$

$$\tilde{d}_{i,j} = d1 \cdot S_{i,j} + d2 \tag{4.15}$$

The networks computed for each zone of the application of Chapter (§2.8, p. 55) are visible in

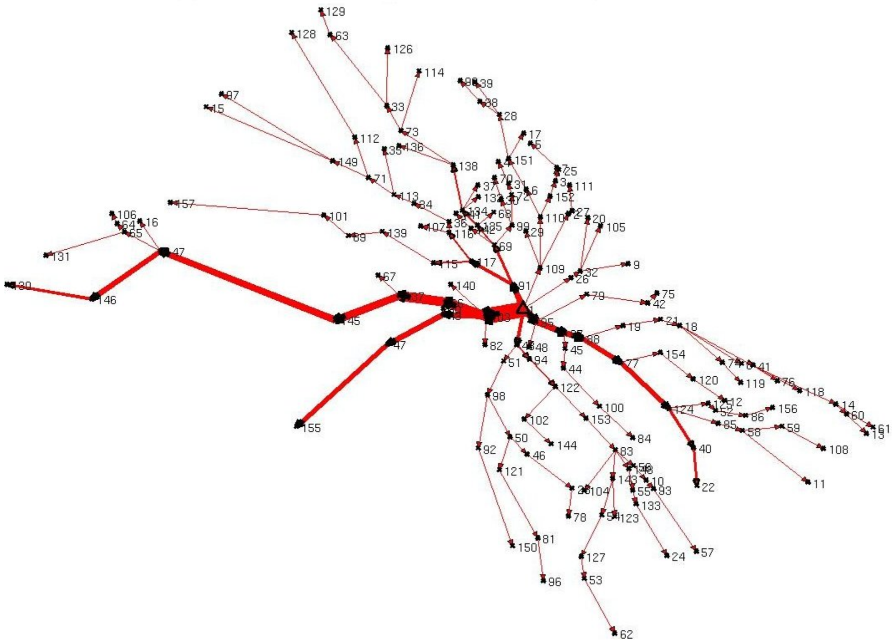


Figure 4.4: Structure of the network (Sector “Marans”, see Table (4.2, p.99)).

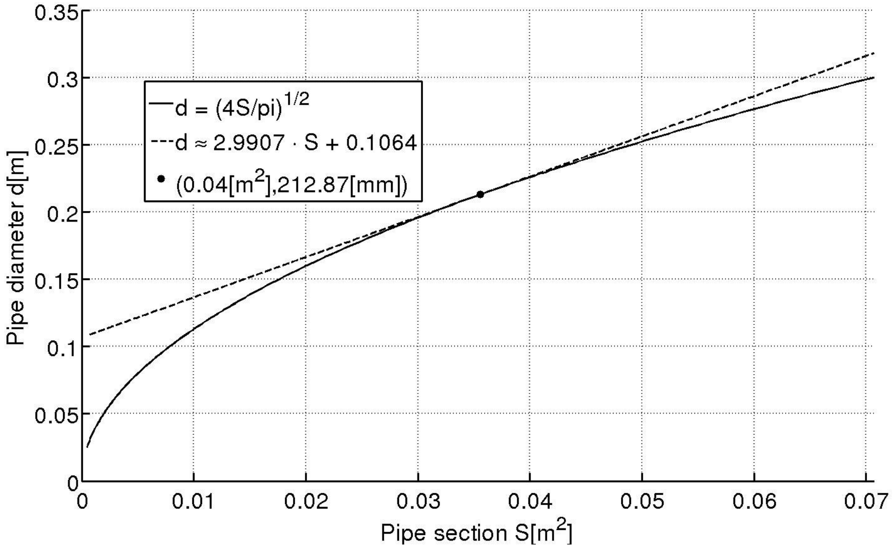


Figure 4.5: Linear approximation of the pipe diameter to solve the MILP problem.

Figure (4.6) and the corresponding results are presented in Table (4.2).

Figure 4.6: Overall view of the network design.

Table 4.2: Value for the network of the case study of Chapter (§2.8, p.55)

Sector	n_b		Length	Investment
	-	s	m	$MCHF$
La Biolatte	5	0.8	464	401
Bois - Bougy	13	0.0	666	628
Rive bis	13	0.0	552	516
Sadex	13	0.0	732	659
Le Viez	20	0.0	2296	2186
La Vuarpillière	21	0.1	1317	1454
Rive	22	0.1	1554	1455
Colovray - Métairie	26	0.1	2854	2813
Martinet et Morâche	28	0.1	1504	1634
Changins	33	0.1	3620	4007
L'Asse	35	0.1	2595	2511
Piscine	46	0.1	2662	2605
Champ-Colin	64	0.1	4541	5753
Les Tines-Ouest	71	0.2	5036	5855
Prélaz	79	0.2	2986	3142
La Banderolle	81	0.2	3514	3509
Chantemerle	90	0.2	5875	6458
Clémenty	90	0.2	3138	3015
Cossy	92	0.2	3980	4444
Plantaz	96	0.2	3433	3419
Les Tines-Est	132	0.4	3577	3375
En Oie	140	0.4	5216	5921
Marans	159	0.5	6832	7594
Le Reposoir	186	0.6	7440	7851
Vieux - Bourg	624	6.1	16575	19065

4.3 Empiric Model for the energy conversion technologies

A short-cut model has been developed to model energy conversion systems at the appropriate level of complexity required for the preliminary design and retrofit of urban energy systems. The useful models for the following studies, are conventional boiler, heat pumps, cogeneration engine, photovoltaic and thermal solar collector.

4.3.1 Conventional Boiler

The thermal load of a boiler burning different fuels (F), characterised by their Higher Heating Value (HHV) and flow rate ($\dot{m}_F$), is linked to the combustion heat load ($\dot{Q}_F = \dot{m}_F \cdot HHV_F$) by (Equation 4.16).

$$\dot{Q}^{boil} = \eta^{boil} \cdot \dot{Q}_F \tag{4.16}$$

The boiler efficiency (η^{boil}) depends strongly on the operating condition, particularly when the load falls below 20 to 10% of the nominal load, as studied by Ottin [1986]. For periods greater than a day, transient are averaged and a constant mean efficiency is applied.

4.3.2 Heat pumps

The coefficient of performance of heat pumps ($COP = \frac{Q_{hp}}{E^{hp}}$) describes the ratio of useful heat supplied (Q_{hp}) to work input (E^{hp}). The centralized/decentralized heat pumps are computed on the basis of a COP efficiency factor η_{COP} defined by (Equation 4.18) linking the theoretical COP_{th} (Equation 4.18) with the real observed COP.

$$COP = \eta_{COP} \cdot COP_{th} \tag{4.17}$$

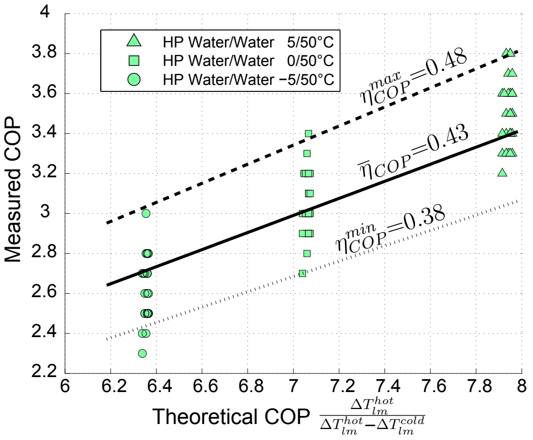
$$\begin{aligned} COP_{th} &= \frac{T^{hot}_{lm}}{T^{hot}_{lm} - T^{cold}_{lm}} \\ \Delta T_{lm} &= \frac{T_1 - T_2}{ln(\frac{T_1}{T_2})} \end{aligned} \tag{4.18}$$

The results of the linear identification from the data of heat pump certification center [WPZ, 2009][1] are shown in Figure (4.7.1) for decentralized Water/Water heat pumps and Figure (4.7.2)

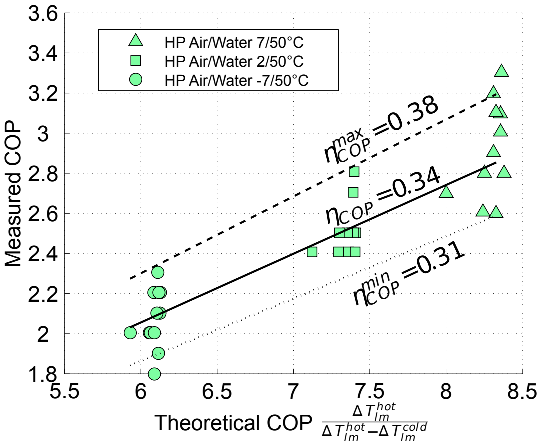
---

[1] Wärmepumpen-Testzentrum WPZ, Interstaatliche Hochschule für Technik (NTB), Buchs SG

for Air/Water heat pumps.



4.7.1: COP efficiencies $\eta_{COP} = COP/COP_{th}$ for local Water/Water heat pump.



4.7.2: COP efficiencies $\eta_{COP} = COP/COP_{th}$ for local Air/Water heat pump.

The COP efficiency η_{COP} is a function of the resource and therefore of the technology. Table (4.3) summarizes the mean efficiency factor adopted for each type of natural resource.

Table 4.3: Theorical COP efficiency factors.

Type	Size	T_{lm}^{cold}	η_{COP}(2005)	η_{COP}(2030)
Air/water	local	$T_x - 5$	0.34	0.38
Ground/water	local	2	0.43	0.48
Water/water	local	3	0.43	0.48
Geostructure/water	local	6	0.43	0.48
Surface water/water	centralized	6	0.55	0.60
WTP/water	centralized	12	0.55	0.60

4.3.3 Cogeneration plant

Thermal (Q_{th}^{chp}) and electrical (E_{el}^{chp}) power outputs of a combined heat and power cogeneration plant (chp) are given by (Equation 4.19).

$$\dot{Q}_{th}^{chp} = \eta_{th} \cdot \dot{Q}_F \dot{E}_{el}^{chp} = \eta_{el} \cdot \dot{Q}_F \tag{4.19}$$

The thermal (η_{th}) and electrical η_{el}) efficiencies depend on the type, size and operating condition of the technologies. Typical starting value of $\eta_{el} = 0.4$ and $\eta_{th} = 0.45$ are applied by default.

4.4 Design of Advanced energy conversion system

The interest of the model is to allow for evaluating the integration of advanced energy conversion systems, like combined heat and power or heat pumping systems. Such conversion systems have an efficiency that depend on the temperature level of the heat requirement and of the resource. One could also imagine district heating systems where the preheating is first done by a heat pump, the rest being supplied by a cogeneration unit whose electricity is used to drive the heat pump.

4.4.1 Heat pumping resources and performances

The list of possible resources for heat pumping has been first established. This analysis considers the accessibility of the resource (for example some area are not accessible for the geothermal drill due to the presence of potable water resources). Each area is therefore attributed a heat pumping resource (Figure 4.7).

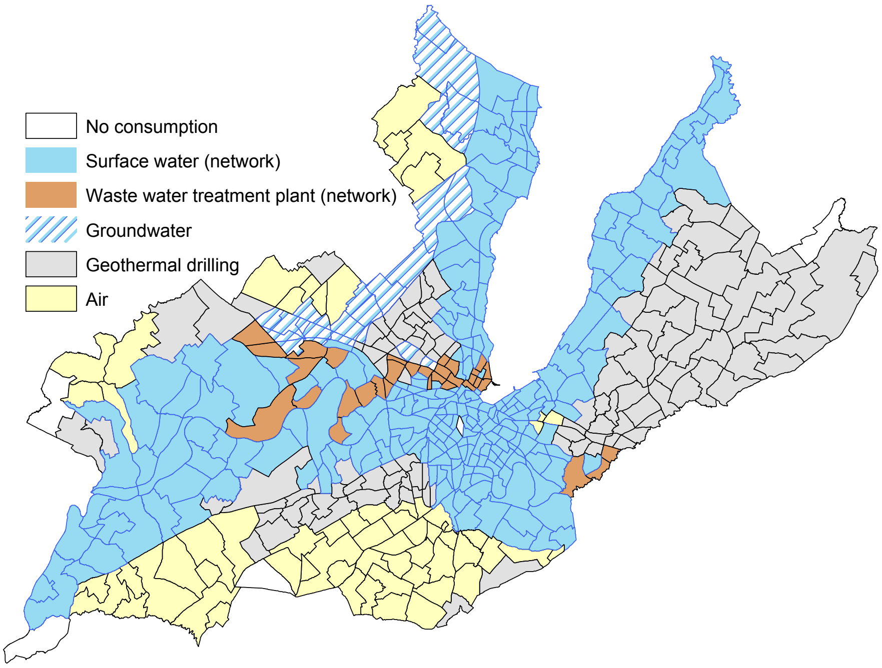


Figure 4.7: Inventory of the available energy sources

The electrical consumption of the heat pumps is computed from the composite curves by summing for each segment $[T_k, T_{k+1}]$ of the composite curve (Equation 4.20).

$$\dot{E}^{HP} = \sum_{k=1}^{n_{k-1}} \frac{\dot{Q}_{k+1}-\dot{Q}_k}{COP_k} = \sum_{k=1}^{n_{k-1}} \frac{\dot{Q}_{k+1}-\dot{Q}_k}{\eta_{COP}/(1-\frac{T^{cold}_{lm,k+1,k}}{T^{hot}_{lm,k+1,k}})} \tag{4.20}$$

4.4.2 Distribution temperature evaluation

The composite curves allows to compute the optimal supply temperatures for the district heating system. In order to maximize the efficiency of the system and avoid having to size the network to only satisfy the highest temperature in a zone, we consider that decentralized heat pumps may be used to locally upgrade the temperature level of the distributed heat, as illustrated in Figure (4.8).

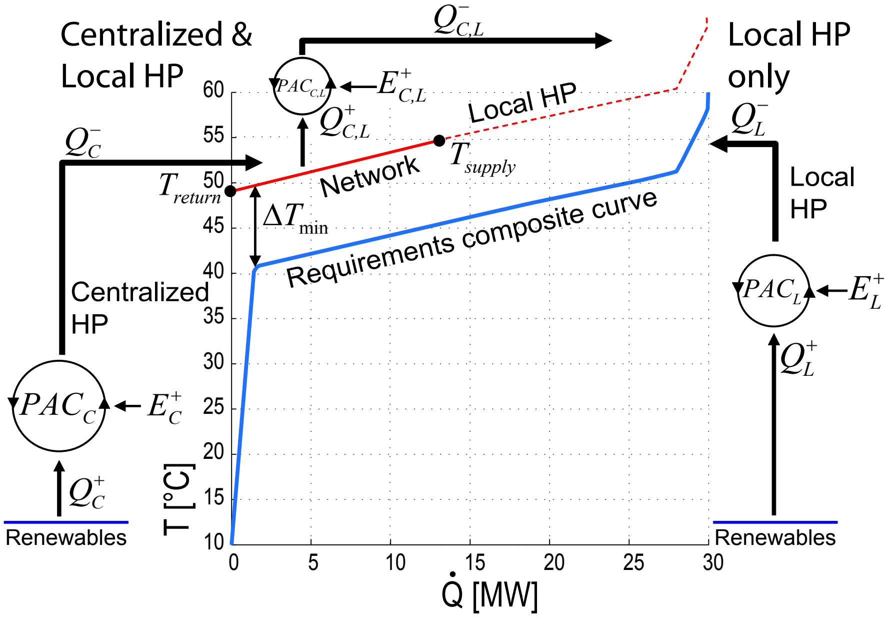


Figure 4.8: Centralised and decentralized options.

The annual COP_z of heat pumping in a zone, defined by the ratio of the required heat $Q^{hot}_{Y,z}$ by the electricity $E_{Y,z}$, is computed by Equation (4.21). If one removes the conflicting technological option at territorial level, a list of COP corresponding to technological scenarios can be reported for each region.

$$COP_z = \frac{\sum\limits_{P=1}^{n_P} D_P(\sum\limits_{c=1}^{n_c}(\dot{Q}_{P,c,z})}{\sum\limits_{P=1}^{n_P} D_P\left(\sum\limits_{c=1}^{n_c}(\sum\limits_{HP=1}^{n_{HP}}\dot{E}^{HP}_{P,c,z})\right)} \tag{4.21}$$

Each points and lines in Figure (4.9) represents annual COP_z values for a urban zone.

When considering the combination of centralized and decentralized heat pumps, the optimal heat distribution temperature may be assessed. For example, Figure (4.9) shows the value of the COP in the different geographical areas drawn as a function of the supply temperature for the district heating solutions.

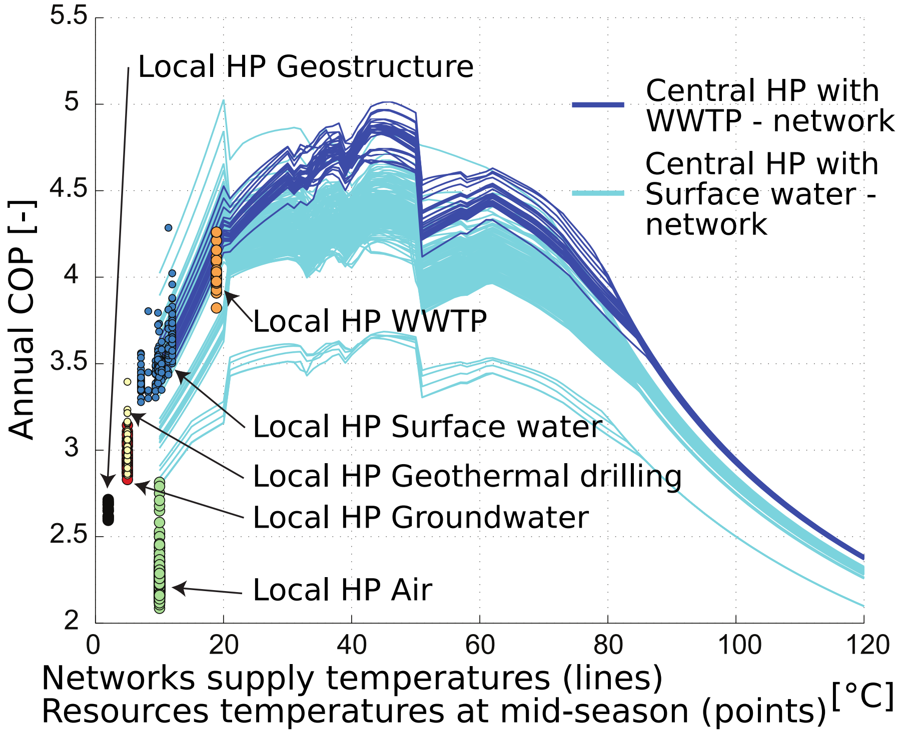


Figure 4.9: Dependence between COP and resources/networks supply temperatures.

The map of the predicted optimal HP annual COP for 2030 is given in Figure (4.10).

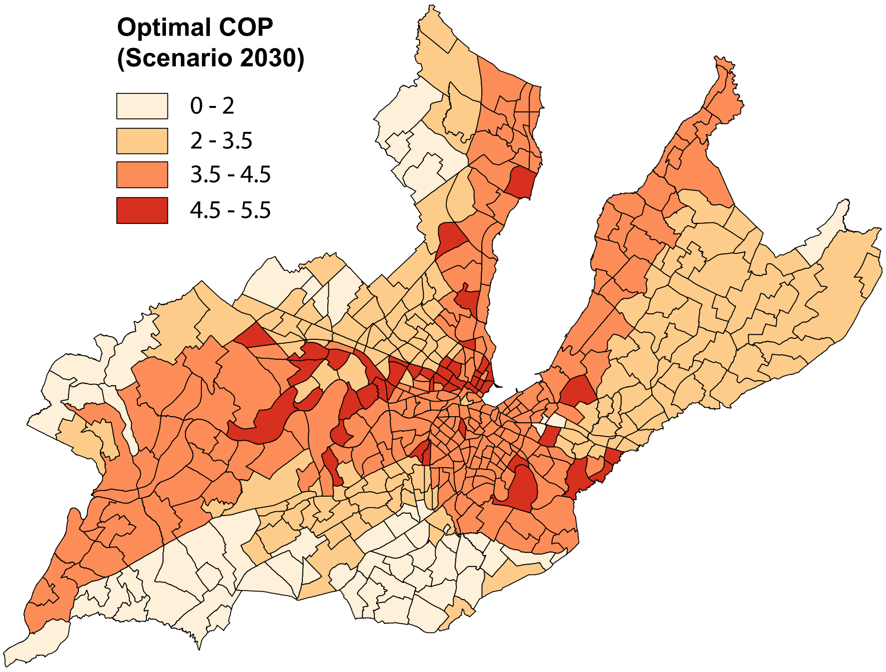


Figure 4.10: COP map considering the available resources for heat pumping in 2030.

4.4.3 CO_2 neutral electricity production

When considering the boiler substitution by the integration of combined heat and power units, the electricity produced is attributed an amount of CO_2 emissions that corresponds to the extra amount of natural gas used in the cogeneration unit. This calculation accounts for the efficiency of the conventional boilers (η_{th}^{boil}) and the CO_2 factor of the fuel used in the boiler ($f_{CO_2}^{boil}$). Applying the same principle, one may compute the CO_2 savings that relates to the use of electricity in a heat pump. Combining heat pumping and combined heat and power production can therefore be done by using the electrical network as an energy carrier between the equipments in the system. Considering the amount of electricity used in a heat pump to compensate the extra amount of CO_2 emitted by the cogeneration, on may compute the net electricity produced while compensating the CO_2 emissions. In our system, the aggregation method is first used to compute the area that can be supplied by a natural gas combined cycle (NGCC) delivering both heat and electricity. The remaining area is determined by ranking the decentralized HP COP_z to aggregate zones in such a way that the cumulated heat load of the area compensates the emissions $\sum_z^{n_z} \dot{m}_{CO_2,z}^{boil} = \dot{m}_{CO_2}^{chp}$.

The GIS model also identifies the priority zones for installing the heat pumps and the combined cycle. This is done by applying the aggregation mechanism first to the centralized system. The candidate areas for the heat pumping systems are then identified among the remaining areas (Figure 4.11).

The fraction of electricity needed to run the heat pumps while compensating the CO_2 emissions is computed by Equation (4.22). If the electricity used in heat pumping systems in the area is higher than $\dot{E}_{CO_2,0}^{HP}$, the polygeneration system that includes heat pumps and the combined cycle system will correspond to an overall reduction of CO_2 even in areas where the electricity is already produced without CO_2 emissions. In this formula, the $COP(Q)$ refers to the overall COP of the area corresponding to the heat load of the CO_2 compensation, the value will have to be computed considering a map of COP that will be expressed as a function of the heat and electricity supplied by the cogeneration unit.

$$\dot{E}_{CO_2,0}^{HP} = \dot{E}^{chp} \cdot \frac{\eta_{th}^{boil} \frac{f_{CO_2}^{chp}}{f_{CO_2}^{boil}} - \eta_{th}^{chp}}{\eta_e^{chp} COP(Q)} \tag{4.22}$$

Finally, the remaining CO_2 neutral electricity ($\dot{E}_{CO_2,0}^{chp}$) that can be exported out of the system is obtained by Equation (4.23).

$$\dot{E}_{CO_2,0}^{chp} = \dot{E}^{chp} - \dot{E}_{CO_2,0}^{HP} \tag{4.23}$$

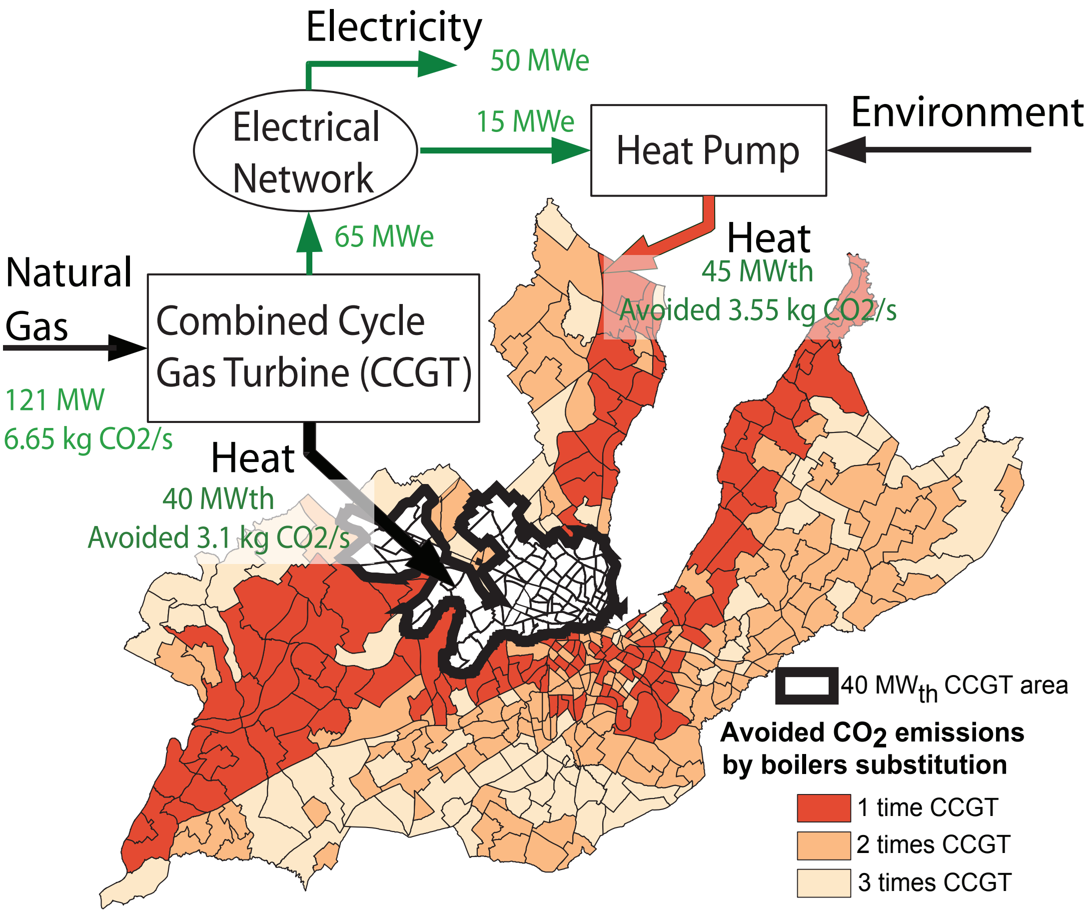


Figure 4.11: Combined heat pumping and combined cycle option in the district.

4.5 Conclusion

A method has been presented for the integration of centralized and decentralized energy conversion equipments, satisfying the heating energy demand of a given urban area. For a given network nominal supply temperature, the proposed algorithm minimizes the network mass flow and gives the corresponding share of local and central load. This permits the evaluation of the size and performance of a predefined mix of centralized and decentralized technologies. When data from a Geographical Information System are embedded in the proposed algorithm, this permits evaluation of the integration of advanced energy conversion and comparison of the performance of urban zones having access to different local energy resources.

A second algorithm has been proposed to determine the best locations, around a given central area, for the extension of district networks under the constraint of a limited distributed heat power. This allows, for example, the estimation of the zone of influence of a cogeneration power plant supplying heat in its neighborhood.

The combined use of these two algorithms offers a wide range of applications. For example, it is possible from this work to use a genetic algorithm to optimize the network distribution temperature, the location of the centralized energy conversion system and the zone of the district network [Masciarelli, Girardin, and Maréchal, 2009]. This pinpoints the most promising urban zones for the development of energy infrastructure, promoting efficient use of energy and local resources.

While the integration algorithm permits the resolution, with comparative ease, of problems falling under its general structure, its rigid format does not enable, without extra programming, the introduction of novel variables. These variables are required for the design of more complex configurations, for example the design of low-temperature district networks supplying heating and cooling services to urban areas. This scenario is treated in the following Chapter.

5 Methodology for the Integration of Low Temperature District Network in Urban Areas

The part of the Thesis related to the Integration of Low Temperature District Network was presented at the 5^{th} Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik (Croatia) in September 2009 [Calame-Darbellay, Girardin, and Maréchal, 2009b]. It is also greatly inspired by two Technical reports of the European project Tetraener[1] [Calame-Darbellay, Girardin, Dubuis, and Maréchal, 2009a; Girardin, Kallhovd, and Maréchal, 2010a].

5.1 Introduction

Starting from audits realized on single buildings, a method using process integration techniques, has been developed to evaluate the retrofitting options and their impacts on the integration of cooling system in buildings connected to a low temperature district network using lake water as cold source. As good control strategy is just as important to make the most of the energy savings potential, the impact of building's envelope refurbishment has been studied in parallel.

The proposed method is first demonstrated on a single building and then applied to evaluate the impact of the optimal integration of cooling and heating systems at the scale of the Geneva Lake Nation (GLN) Urban area. The analysis also considers the benefits of retrofitting the heating systems in order to take the best advantage of the low temperature distribution network. The integrated solution is compared to a conventional configuration of local gas boilers/refrigeration cycle systems in terms of cost and CO_2 emissions

---

[1] TETRAENER: "creating residential and administrative communities where external energy dependency is reduced by optimising the supply/demand balance", http://www.tetraener.com/

5.2 Overview

When assessing the retrofit of the energy conversion system, one has first to assess the possible building retrofit scenarios that will affect both the heat/cold demand but also the temperatures. Such actions should be then modeled in order to represent the impact of these actions on the energy system configuration and its efficiency.
For the heating/cooling requirements, the retrofit of a building envelope (better insulation, new windows, cold bridges diminution) lowers the energy needed and leads to a less demanding temperature level in the building heat distribution loop hence allowing a lower heating temperature and/or a higher cooling temperature. Beside modifying the building structure (passive measures) or the way it is used (active measures like changing the comfort temperature or changing the control strategies), actions can also be taken on the energy conversion system. Therefore, it is important to consider all possible actions as a whole trying to make the most appropriate choice that maximizes the profit of the system.
In the case of the low temperature district network, such analysis is of prime importance since the goal is first to maximize the direct use of the distributed cold water. It is therefore important to study the possibility that a building has to increase the temperature level of the cold requirement. For the requirement below the cold water distribution a HVAC system will be needed, and again its efficiency will be highly related not only to the cold delivery but also to its temperature level. The system configuration has to be optimized in order to maximize the cold water usage, i.e. maximize the temperature lift realized in the unit so that the flow of cold water will be minimized. Consequently more clients could be connected with the same pumping capacity.

The proposed method implement a superstructure integrating the requirements of the buildings, the energy conversion technologies, the district network and the lake resource. It uses Process Integration techniques to meet the challenges of connecting both existing and new building to the same low temperature resource. Process Integration techniques allows to propose design and simulation results for equipments supplying both heating and cooling services for steady operation and multi-period scenarios and to characterize the performance of the integrated system (size of equipment, investments and operating costs, efficiencies and emissions) at a scale starting from individual building up to district area, without going into the detailed calculation of the heat exchanger configurations.

5.3 Building Model

5.3.1 Heating and cooling load

The model of heating and cooling energy signature (§3.3.1, p.71) is applied to assess the multi-period energy and power requirements. The parameters of the energy signature are either identified from energy audits [Mermoud et al., 2008a,b] or estimated based on the annual building energy consumption.

5.3.2 Heat distribution system

The supply and return temperatures of the domestic hydronic heating system are derived from the heat exchange model presented in Chapter 3 (§3.4.1, p. 76). It assumes a constant mass flow ($\dot{M}_0 c_p$) and considers the maximum heat exchange area available ($UA = U_0 A_0$). The model is determined when the indoor comfort temperature (T_i) and the two nominal temperatures ($T_{s,0}$) and ($T_{r,0}$) are fixed.

Temperature dependence to the cooling loop mass flow Following the same methodology as for the heating system (Chapter 3, §3.4, p.75), the supply (T_s) and return (T_r) temperatures of the cooling system are calculated by the set of Equations (5.1), considering fresh air (a) pulsed into the rooms at the target temperature (T_a).

$$\dot{Q} = UA\left(\frac{T_i - \Delta T_a - T_s - (T_i - T_r)}{\ln\left(\frac{T_i - \Delta T_a - T_s}{T_i - T_r}\right)}\right) \tag{5.1a}$$

$$\dot{Q} = \dot{M}c_p\,(T_r - T_s) \tag{5.1b}$$

$$\dot{Q} = \dot{M}c_{p_a}\,(\Delta T_a) \tag{5.1c}$$

$$\text{with } \Delta T_a = T_i - T_a \tag{5.1d}$$

Substituting (5.1b) and (5.1c) into (5.1a) gives Equation (5.2).

$$\frac{T_i - \Delta T_a - T_s}{T_i - T_r} = \exp\left[UA\left(\frac{1}{\dot{M}c_p} - \frac{1}{\dot{M}c_{p_a}}\right)\right] \tag{5.2}$$

Equation (5.2) permits the calculation of T_s and T_r as a functions of the cooling load to be supplied $\dot{Q}$ (Equation 5.3).

$$T_r(\dot{Q}) = T_i + \frac{\dot{Q}\left(\frac{1}{\dot{M}c_p} - \frac{1}{\dot{M}c_{pa}}\right)}{(1 - \exp\left[UA\left(\frac{1}{\dot{M}c_p} - \frac{1}{\dot{M}c_{pa}}\right)\right]} \tag{5.3}$$

$$T_s(\dot{Q}) = T_r(\dot{Q}) - \frac{\dot{Q}}{\dot{M}c_p} \tag{5.4}$$

By assumption, the flow (5.5) and (5.6) are considered constant, as well as the (UA) parameter that represents the available heat transfer area. The value of the (UA) parameter is identified using Equation (5.7), knowing the nominal temperatures $(T_{s,0} = 6°C,\ T_{r,0} = 12°C)$ and the nominal cooling power $(\dot{Q}_0)$. In order to account for the fact that part of the heat exchange area is not available, a factor of availability $(\phi = 50\%)$ is applied.

$$\dot{M}c_p = \frac{\dot{Q}_0}{T_{r,0} - T_{s,0}} \tag{5.5}$$

$$\dot{M}c_{p_a} = \frac{\dot{Q}_0}{\Delta T_{a,0}} \tag{5.6}$$

$$UA = \phi \cdot \frac{\dot{Q}_0}{\frac{T_{r,0} - T_{s,0}}{\ln\left(\frac{T_i - T_{s,0}}{T_i - T_{r,0}}\right)}} \tag{5.7}$$

Direct cooling Reducing the flow and, consequently, rising the temperature difference between supply and return temperature, permits to lower the pumping power. On the other hand, increasing the flow permits to increase the use of direct cooling. There is therefore an optimal water distribution flow that realizes the trade off between the pumping energy and the cooling energy.

The heat load being exchanged directly with the lake water is computed assuming a minimum temperature difference $(\Delta T_{lake} = 4°C)$ between the hot stream and the lake water. The minimum temperature (T_s^*) at which the water can leave the direct heat exchange is given by Equation (5.8).

$$T_s^* = max(T_s, T_{lake} + \Delta T_{min,lake}) \tag{5.8}$$

In direct cooling mode, (T_s^*) represents the supply temperature of the cooling loop. If more cooling power is needed, it represents the highest temperature of the hot source (cooled down) of the cooling machine (Figure 5.1).

Refrigeration equipment The electrical power supplied to the cooling machine is estimated considering the theoretical $COP_{th} = \frac{T_c}{T_h - T_c}$ and a Carnot efficiency $(COP = \eta_{COP} \cdot COP_{th})$ of 0.35, as reported in [Girardin et al., 2008]). The theoretical COP is computed based on the hot (h) and cold (c) temperature given in Equation (5.9).

$$T_h = \frac{T_{lake,max} - (T_s^* + \Delta T_{lake,min})}{\ln\left(\frac{T_{lake,max}}{T_s^* + \Delta T_{lake,min}}\right)} \tag{5.9}$$

$$T_c = T_s(T_{ext}) \tag{5.10}$$

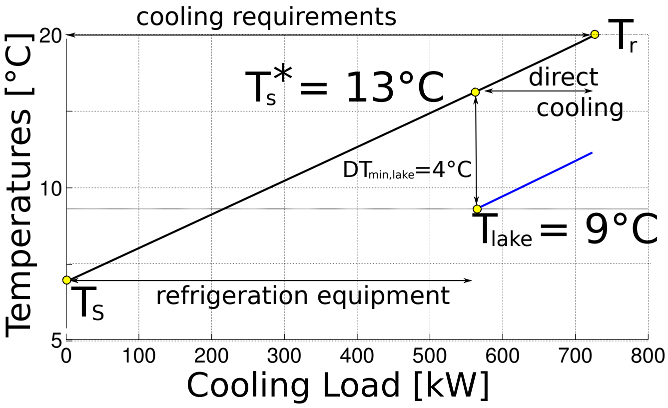


Figure 5.1: Integration of a direct cooling system.

The electrical power of the cooling system is therefore given by Equation (5.11).

$$\dot{E}(\dot{M}c_p) = \dot{M}c_p(T_s^* - T_s) * (\frac{T_{lake,max} - T_s}{T_s}) * \frac{1}{\eta_{cop}} \tag{5.11}$$

with	T_s^*	The pinch point of the cooling system
	$T_{lake,max}$	The maximum allowed temperature of the lake water at the exit of the building
	T_{lake}	The temperature of the lake water
	η_{COP}	The efficiency factor of the theoretical COP_{th}

Cooling distribution pumping Equation (5.12) is used to compute the electrical consumption of the circulating pumps.

$$\dot{E}_{pump}(\dot{M}c_p) = \dot{E}^0_{pump}(\frac{\dot{M}}{\dot{M}^0})^3 \tag{5.12}$$

Optimal mass flow The cooling power consumption is therefore calculated by Equation (5.13).

$$\dot{E}_{tot}(\dot{M}c_p) = \dot{E}(\dot{M}c_p) + \dot{E}_{pump}(\dot{M}c_p) \tag{5.13}$$

The efficiency of the cooling load production is calculated by Equation (5.14)

$$COP_{cooling}(\dot{M}c_p) = \frac{\dot{M}c_p(T_r - T_s)}{\dot{E}(\dot{M}c_p) + \dot{E}_{pump}(\dot{M}c_p)} \tag{5.14}$$

The best value of the mass flow is therefore calculated by an optimization procedure that maximizes the $COP_{cooling}(\dot{M}c_p)$, that is solved using a conventional 1D optimization approach.

As expected the optimal flow corresponds to the minimum possible flow that allows one to maximize the direct cooling, which means that the flow is adapted to reach temperatures that are high enough to profit at least in part of the direct cooling.

When the overall heat load can be satisfied by the lake water, then an additional amount of cooling duty is realized using the refrigeration cycle that is using the cold water as a cold source.

The flow rate is optimized by minimizing the use of electricity compared to the cooling supplied (Equation 5.13) or equivalently, by maximizing the COP of equation (5.15).

The proposed control strategy aims at optimizing the mass flow of the distribution system ($\dot{M}(T_x)$) in order to maximise the use of the lake resource.

$$\max_{\dot{M}c_p}\left[COP_{cooling}(\dot{M}c_p)=\frac{\dot{M}c_p(T_r-T_s)}{\dot{E}(\dot{M}c_p)+\dot{E}_{pump}(\dot{M}c_p)}\right] \tag{5.15}$$

5.4 Process integration

Having defined the optimal flows, one can define the enthalpy temperature profiles that will define the heat transfer requirement of the cooling system (i.e. a hot stream to be cooled). A thermodynamic model of the refrigeration cycle has then been developed. This model defines as a function of the evaporation and condensation temperatures, the hot and cold streams to be considered in the problem. The calculations require the definition of the refrigerant as well as the definition of the isentropic efficiency of the compressor (typically 70%). The flowsheet model defines the hot stream and the cold stream of the refrigeration cycle considering the desuperheating and under cooling of the device. The optimal flow in the cycle is then computed considering as well the optimal integration of the lake water. The problem is solved by applying process integration techniques and is solved as a linear programming problem. The details of the process integration model can be found in [Maréchal et al., 2002].

The process integration model is applied systematically for different values of the external temperature in order to obtain the annual energy consumption of the cooling system. As the operating conditions are changing with time, the optimal operating conditions of the refrigeration cycle have to be determined as well.

The interest of the approach is that it allows to compute the optimal flow rates in the system as a function of the demand and to redesign the heat exchanger system.

Table 5.1: Data for the building “R” calibration

Parameters	as usual	refurbished	units
Available installed cooling power	$[kW]$	1140.0	1140.0
Available installed (UA)	$[kW]$	82.8	93.9
Installed maximum flow	$[m^3/h]$	207.334	207.334
Nominal temperatures “building” cool loop	$[C]$	6/12	6/12
Nominal temperatures “info” cool loop	$[C]$	12/16	12/16
Installed pumping power	$[kW]$	11.40	11.40
Comfort air temperature	$[C]$	26	28
Sizing air temperature	$[C]$	26	26
Sizing cooled air target temperature	$[C]$	16	16
Cooling signature			
Constant power	$[kW]$	40.0	36.0
Signature slope	$[kW/C]$	40.0	36.0
Cooling threshold temperature	$[C]$	18	20
Available (UA) for retrofit	$[kW/C]$	111.50	111.50

Table 5.2: Lake conditions

Lake temperature	9	$[C]$
Maximum allowed lake temperature	20	$[C]$
Minimum approach temperature for lake direct heat exchange	4	$[C]$

In the proposed approach, we considered that the refrigeration cycle may be reused since it will work in less demanding situations.
Using the results of the process integration approach, the new design of the system is set-up and the final configuration is evaluated.

5.5 Application of the Retrofit Strategy on a single Building

5.5.1 Heat load requirements from measurements

The building heat loads are defined by calibrating building heating/cooling signatures using the requirements data given in Table (5.1) and the condition of the Lake water of Table (5.2). The scenario “without refurbishment” is based on the results of an energy audit [Mermoud et al., 2008a]. The scenario with refurbishment considers a cooling load reduction of 10% based on the slope of the signature, with an increase of the threshold temperature of $2^\circ C$ and an increase of the comfort temperature of $2^\circ C$ obtained by changing the behavior of the people.

The cooling signatures of the two scenarios are plotted in Figure (5.2) and the corresponding cooling duration curve is presented in Figure (5.3). The scenarios “without refurbishment” is plotted as a plain line and the scenario “with refurbishment” as a dotted line.

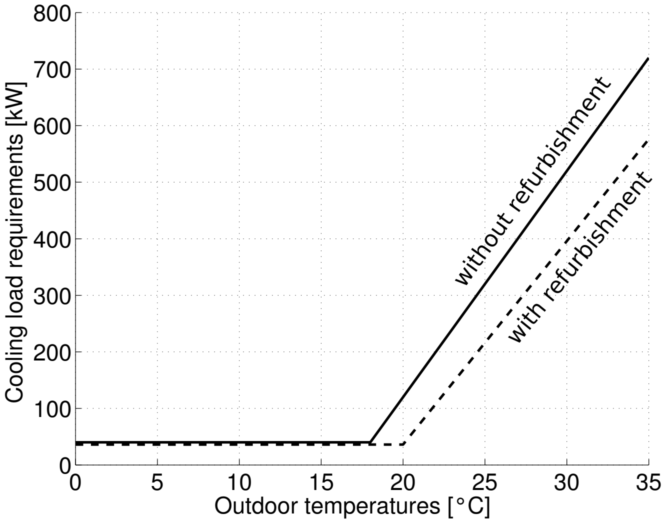


Figure 5.2: Building Energy cold Signature

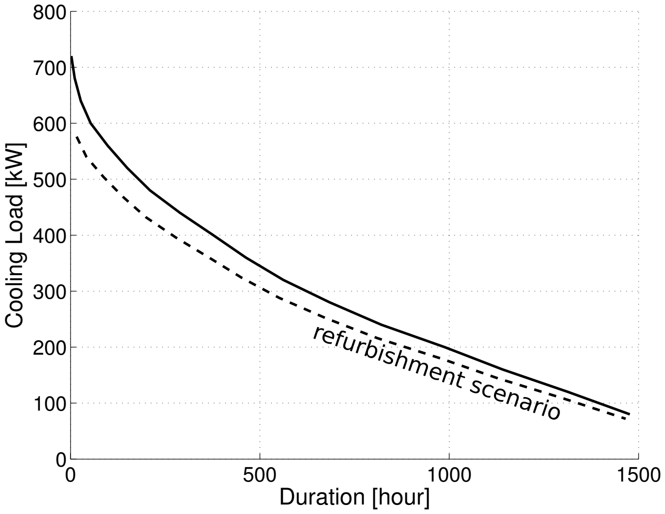


Figure 5.3: Duration Curve (0700-1900)

5.5.2 Optimal set points in the distribution system

The water distribution flow calculated as a function of the cooling load is given in Table (D.1, p.184) and presented in Figure (5.4).
The definition of the terms found in Table (D.1, p.184) is given here.

The optimal supply and return temperatures of the distribution system is given in Figures (5.5) as a function of the cooling load requirements.

Description of the terms in Table (D.1) and (D.2)

Duration	Number of operating hours where the temperature is between T_x and $T_x - 1$. For this calculation we considered only the operating hours between 6:00 and 19:00.
Distr. Flow	Optimal water flow distribution
Supply T	Calculated supply temperature in the distribution system. This temperature is calculated from the results of the optimal flow calculation and the available heat transfer area.
Return T	Calculated return temperature in optimal operating conditions.
Target T	Calculated set point for the air temperature in the cooling blocks.

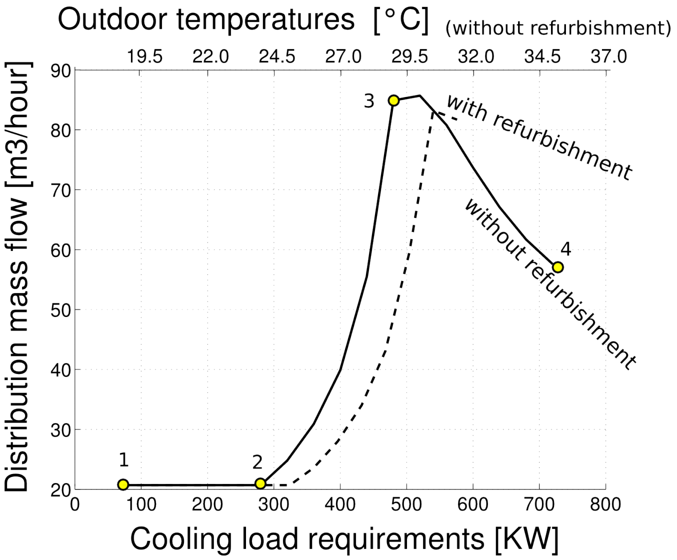


Figure 5.4: Optimal flow rate control.

Three sections are observed for the optimal control of the hydronic cooling system mass flow :

(1)-(2) At the low cooling loads, the flowrate is maintained at its minimum value and the return temperature is progressively decreasing.

(2) At a given cooling load, about 290 kW of cooling power, the flow of distributed water is increased in order to maintain the supply temperature above the lake water temperature . It should be noted that in our model, the temperature is 4°C above the supply temperature but, in reality, since the heat exchange area is fixed, this temperature difference will be lower and therefore the assumption is still optimistic.

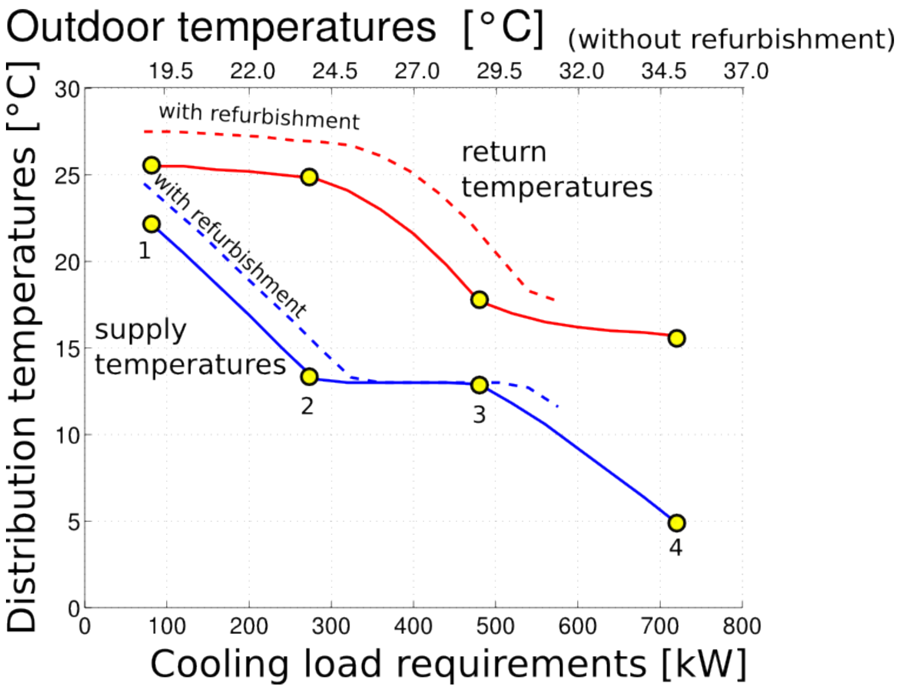


Figure 5.5: Optimal Temperature control.

(2)-(3) Above a cooling of 290 kW, the flowrate of distributed water is considered to increase proportionally to the cooling load. The relationship is not linear but in this section the rule is to maintain the supply temperature above the lake supply temperature in order to maximize the use of direct cooling.

(3) When the cooling load reaches 480 kW, the heat exchange no longer allows to realize the direct cooling using the water of the lake. Above this temperature, the cooling load will be done partially with the cooling cycle. In this case, the cooling load is first supplied by direct cooling and the rest is supplied by the refrigeration cycle. The refrigeration cycle uses the lake water as the cold source which allows to still have very good efficiencies.

(3)-(4) Above 480 kW, the cold water distribution flowrate will decrease in order to maintain the return temperature as high as possible. This allows to optimise the amount of direct cooling that is used in this case.

5.5.3 Power load distribution in the integrated system

The result of the process integration procedure are given in Table (D.2, p. 185) for different outdoor temperatures (T_x).
The definition of the terms found in Table (D.2, p. 185) are given here.

Description of the terms in Table (D.1) and (D.2)

T_x	Outlet temperature
Load	Cooling load required according to the signature
Estim.	Electricity consumption estimated by the Carnot factor using η_{COP}=0.4 %.
Electricity	Electricity consumed in the integrated solution (results of the optimal integration solution
Flow	Lake Water flow consumed in the integrated solution
Temp	Temperature of the Lake water at the outlet of the building
Direct Cooling	Cooling load of the direct exchange with the lake water
COP	Calculated COP = $\frac{Load}{Cooling}$

The flowsheet of the cooling system including the lake water integration is given on Figure (5.6) for the scenarios with and without refurbishment. It considers the reuse of the two cooling cycles that are now connected on the lake water network. The values are given for the extreme conditions at $T_x = 35°\text{C}$.

Figure (5.8) presents, for the scenario without refurbishment, the cooling and electrical loads to supply the cooling load as a function of the cooling power distributed.

Figure (5.9) shows the hot and cold composite curves of the system (scenario without refurbishment).

Figure (5.10) shows the integrated composite curves of the requirement corresponding to Figure (5.9). The dotted line corresponds to the cooling load required (hot stream), while the plain line corresponds to the system used to provide the cooling service. One can visualize the contribution of the cooling cycle and of the direct heat exchange with the lake water. Above the requirement, the condensation of the cycle is represented and defines a new hot stream that is cooled using the lake water.

5.5.4 Overall Performance of the Integrated system

Based on operation time of each period, the overall operating cost and the energy savings are computed, taking into consideration that the cooling requirement is supplied with an annual $COP_{initial}$ of 2.79 with an initial energy demand $E_{initial}$ of 145’379 kWh/yr.
After retrofit, the annual COP is given by Equation (5.16) and the savings (ΔE) by Equation (5.17).

$$COP = \frac{Q_{req}}{E_{retrofit}} \tag{5.16}$$

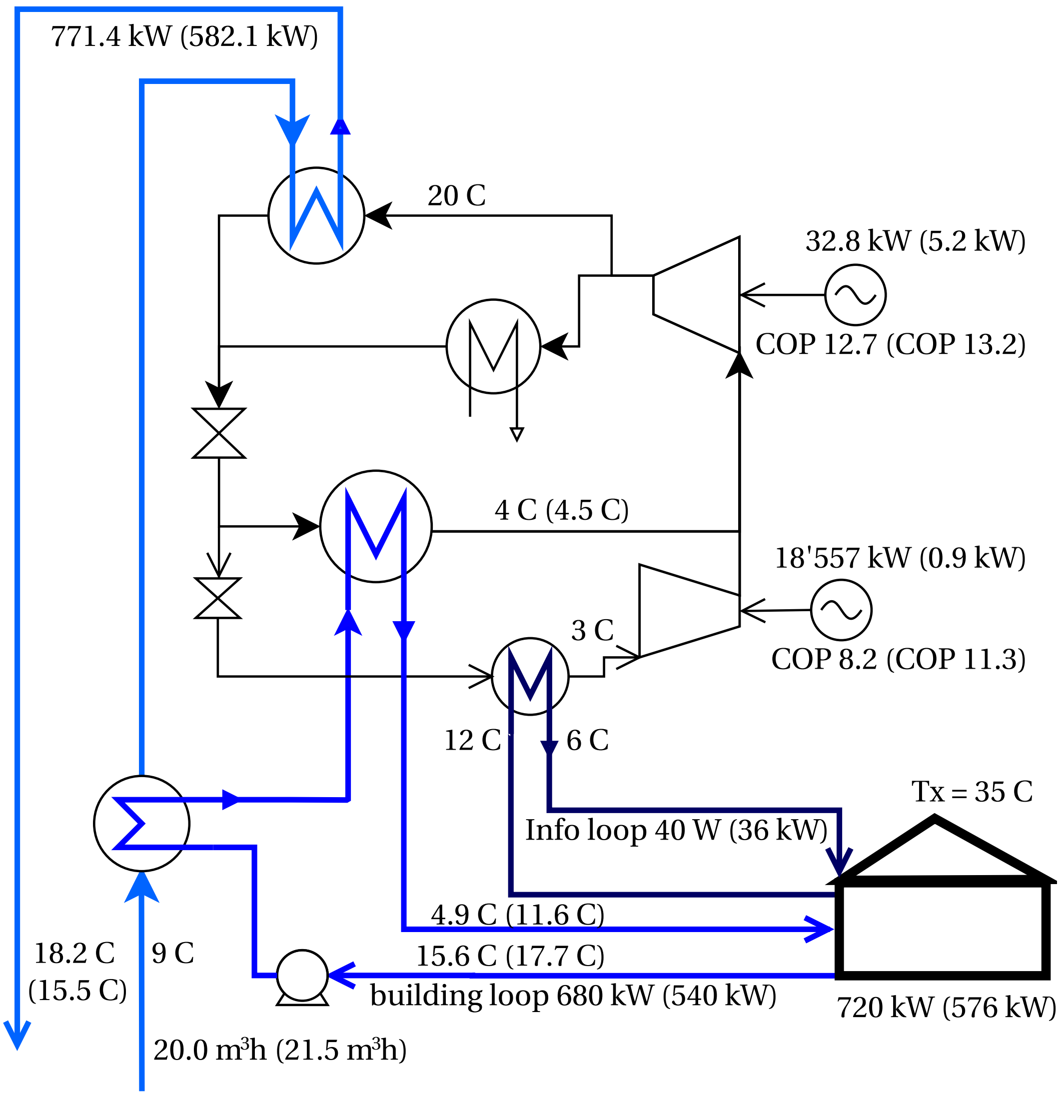


Figure 5.6: Flowsheet of the cooling system with values estimated at $T_x = 35°\text{C}$ without (and with) refurbishment.

$$\Delta E = \frac{E_{initial} - E_{retrofit}}{E_{initial}} \tag{5.17}$$

The overall performances of the integrated system are summarized in Table (5.3).

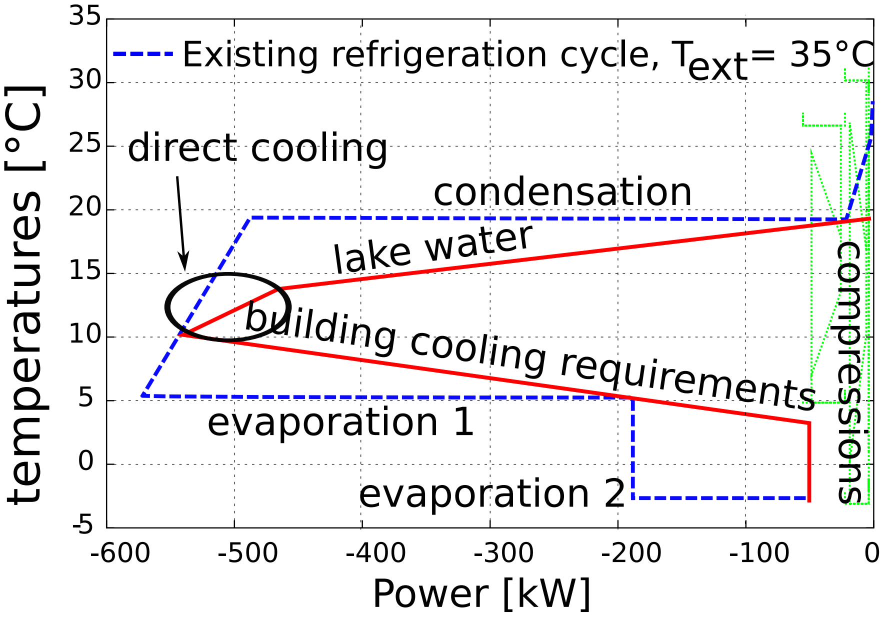


Figure 5.7: Grand composite curve of the integrated district cooling system (scenario without refurbishment).

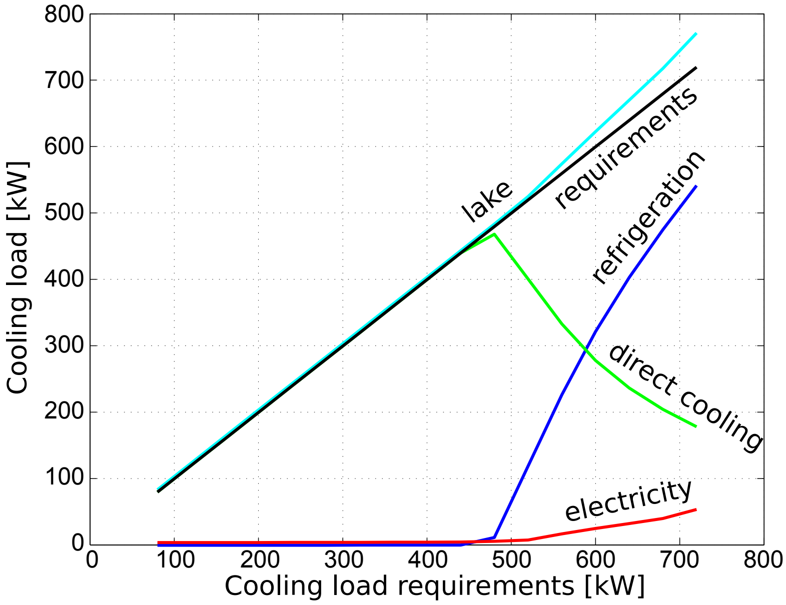


Figure 5.8: Repartition of the Power requirements (scenario without refurbishment).

5.5.5 Synthesis

The results after retrofit show energy savings surpassing 90%. This is explained by use of direct cooling and use of cold water instead of air as the cold source of the refrigeration cycle. Refurbishment permits to increase the period during which the direct cooling is feasible and therefore reduces the use of the refrigeration cycle. The operating time of the refrigeration

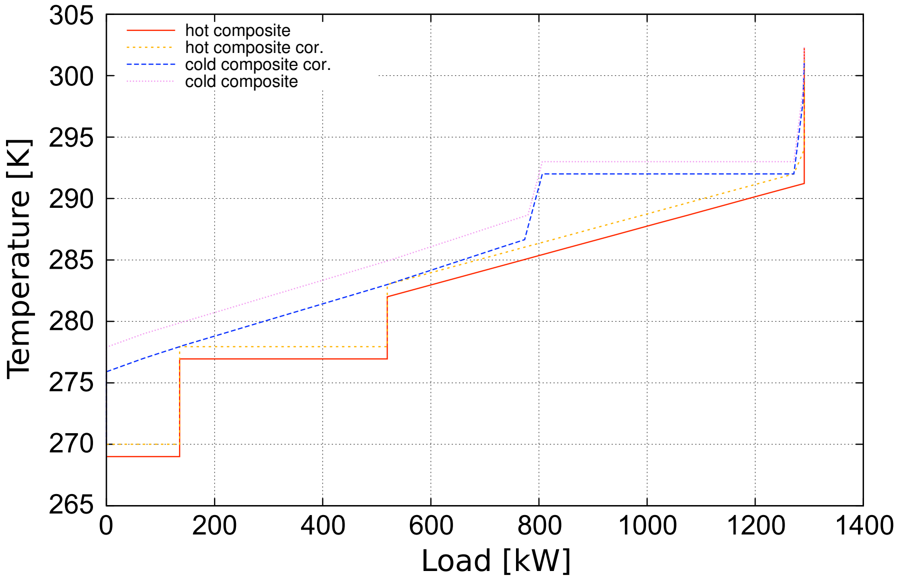


Figure 5.9: Curves of the integrated hot and cold composite curves of the flowsheet (5.6) at ($T_x = 35°C$)

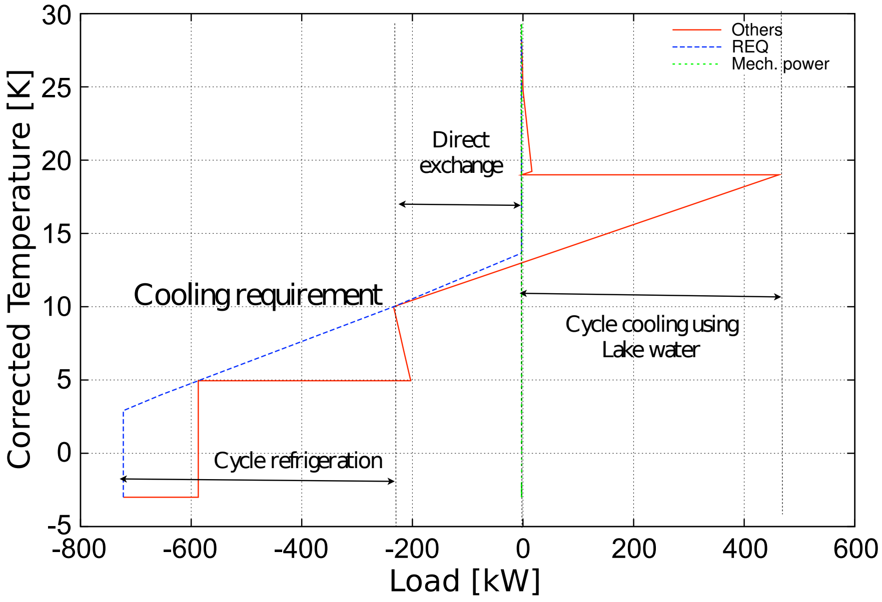


Figure 5.10: Integrated composite curves of the flowsheet (5.6) at ($T_x = 35°C$)

cycle is reduced by 23%, while the electricity consumption is reduced by 49%.

Table 5.3: Benefits from the connection to the lake water

symbols	units	descriptions	without refurbishment	with refurbishment
Q_{req}	$[kWh/year]$	Overall Cooling requirement	405’760	252’612
Q_{lake}	$[kWh/year]$	Lake Water supply	413’045	256’361
$E_{retrofit}$	$[kWh/year]$	Overall Electricity	8’432	4’284
COP	$[-]$	Annual COP	48.1	58.9
ΔE	[%]	Overall Savings	94.2	98.9

5.6 Application to the Geneva-Lake-Nation (GLN) Urban district

5.6.1 Method

The geographic information system database contains the location and annual consumption of the considered buildings.

Starting from these measurements, Energy Signature models are calibrated and the demand is aggregated to provide the actual thermal power and temperature requirements of the connected buildings.

5.6.2 Assumptions

The known values for the heating and cooling system of the buildings selected for the study are presented in Table (5.4). They include the Floor area (A^{hs}), the space heating efficiencies (η^{hs}). the annual space heating (Q^{hs}), the hot water production consumption (Q^{hw}), the space cooling (Q^{cs}), the cooling threshold temperature (T^{cs}_{tr}) and the cooling nominal temperature levels ($T^{cs}_{s,0}$/$T^{cs}_{r,0}$), that have been collected thanks to the work of the UNIGE-CUEPE [Viquerat et al., 2008], the ScanE [Mayer and Beck, Feb. 3rd 2009, Geneva] and SIG [SIG, 2010].

Table 5.4: Annual consumption of the buildings considered in the “GLN” area.

acronym	A^{hs}	η^{hs}	Q^{hs}_{2008}	Q^{hw}_{2008}	Q^{cs}_{2008}	T^{cs}_{tresh}	$T^{cs}_{s,0}/T^{cs}_{r,0}$	T_i
	$[m^2]$	$[-]$	$[MWh]$	$[MWh]$			$[C]$	
A	26’069	0.95	6’300	-	-	-	-	-
B	172’848	0.95	7’225	-	2’700	-	-	-
C	38’909	0.95	6’295	-	900	-	-	-
D	154’246	0.8	18’500	-	2’580	17	7/13	-
E	28’308	0.95	5’568		1’300	-	-	-
F	24’300	0.95	5’000		-	-	-	-
G	26’069	0.95	2’520		1’700	-	-	-
H	51’000	1	2’448	357	-	-	-	-
I	15’433	1	687	216	0	-	-	-
J	62’315	0.95	4’300		1’400	-		-
K	21’153	0.95	4’000		801	18	6/12	26
L	28’100	0.8	5’950		1’311	-		-

The missing values are replaced considering the assumptions of Table (5.5).

5.7 Results

The energy requirements and the optimal control strategy of the network flow rate are examined first. The thermo-economic performance of the integrated solution is then presented

Table 5.5: Default value for the buildings

Variable	Description	Value
P	Year of measurement	2008
T_{tr}^{cs}	Threshold cooling temperature	18°C
T_{tr}^{hs}	Threshold heating temperature	16°C
$T_{s,0}^{cs} / T_{r,0}^{cs}$	Nominal temperature of the cooling system	6/12°C
T_i	indoor temperature	23°C
c	Building category	Administrative building, 1980-2005
A^{cs}	Cooling area (SRC)	Equal to heating area (A^{hs})

.

5.7.1 Energy requirements

The sum of the building energy requirement for each temperature interval, obtained by multiplication of the mean power by the operating time, is shown in Figure (5.11).

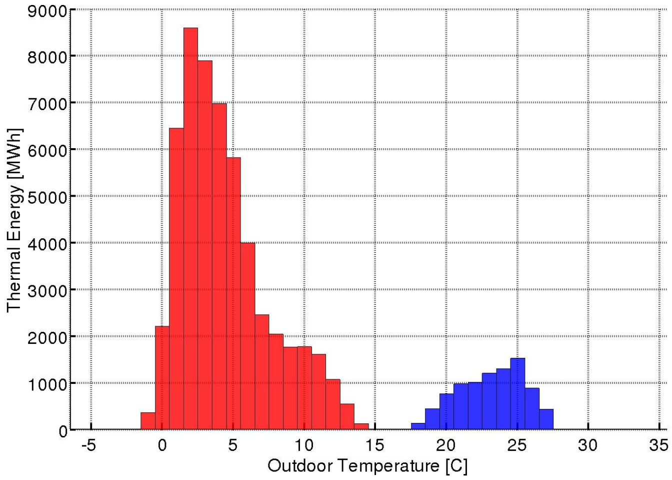


Figure 5.11: Heating (red) and cooling (blue) energy required for the periods defined by the outdoor temperatures intervals.

The total heating requirement for a typical year is 60’920 $\frac{MWh}{yr}$ while the total cooling demand is 8’746 $\frac{MWh}{yr}$. This total energy demand has been plotted in Figure (5.12) throughout the whole year. It can be seen that the energy demand is largely dominated by the heating demand.

The power requirements (see Figure 5.13) for heating and cooling seem to follow approximately the same slope. The dimensioning requirement for the cooling is almost the double of what is required during a typical year.

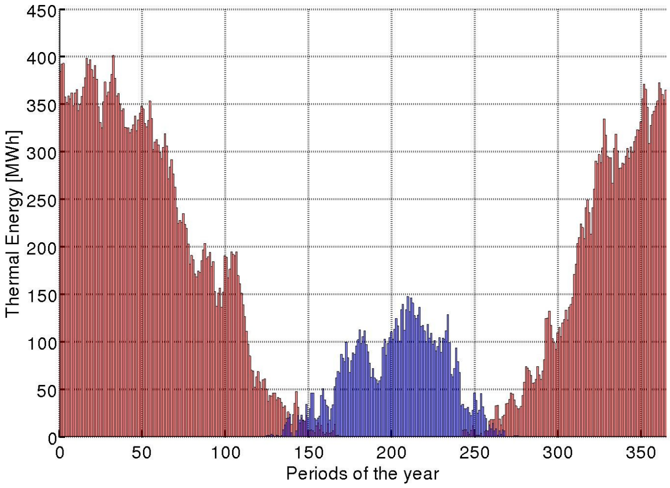


Figure 5.12: Heating and cooling requirement during a typical year.

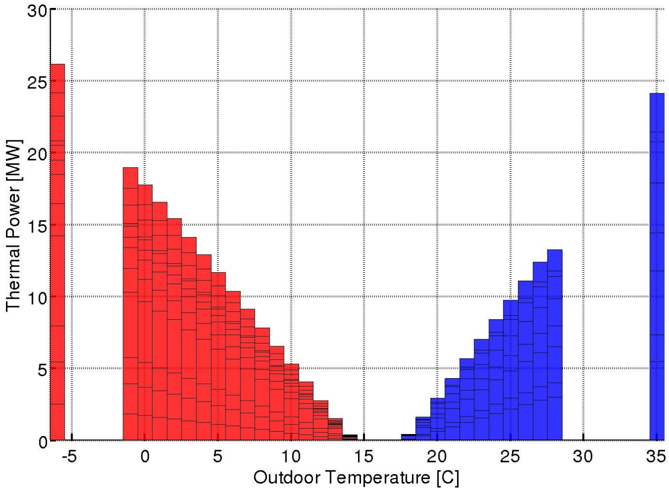


Figure 5.13: Heating(red) and Cooling(blue) power required for the periods defined by the outdoors temperatures intervals and nominal requirement at -6°C.

5.7.2 Optimal cooling mass flow

The mass flow is optimized by maximizing the COP of the total cooling system (Equation 5.15, p.114). Figure (5.14) shows the overall mass flows of all buildings.

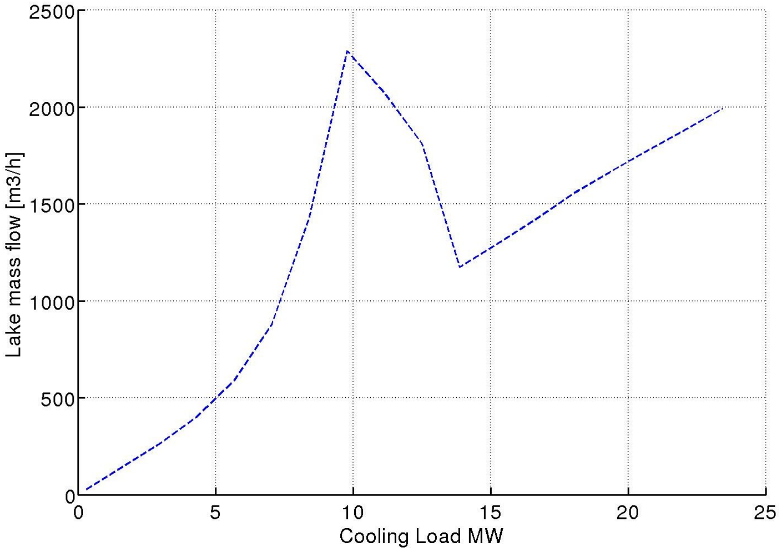


Figure 5.14: Network/Lake mass flow

5.7.3 Integration of the network and cooling cycles

Figure (5.15) represents the hot and cold composite curves resulting from the integration for the nominal outdoor temperature of 35°C. The condensation is observed at 4°C in the refrigeration cycle while the lake is at 15°C. This optimal integration procedure has been performed for each temperature interval ranging from -6°C to 35°C.

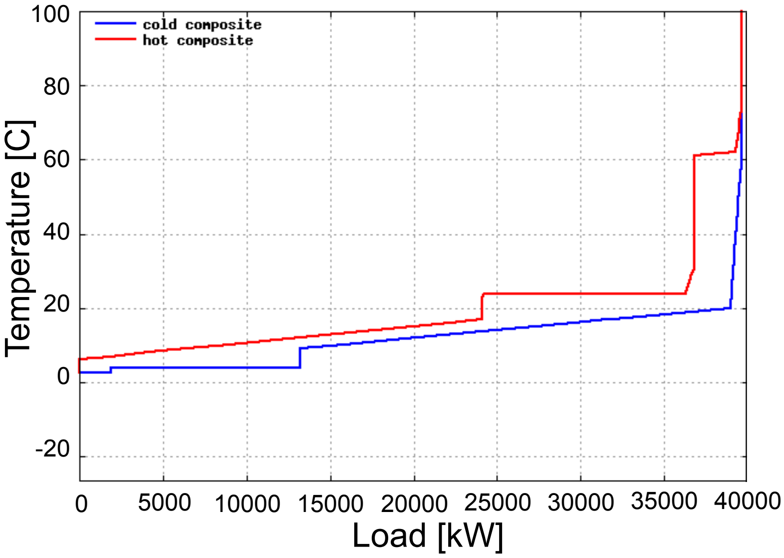


Figure 5.15: Integrated hot (red) and cold (blue) composite curves GLN area-network-cooling cycles for an outdoor temperature of $T_x = 35°C$.

Figure (5.16) is another representation of the integration, where the streams obtained by the thermodynamic simulation of the cooling cycles (blue) is separated from the rest of the system (water network and GLN area requirements).

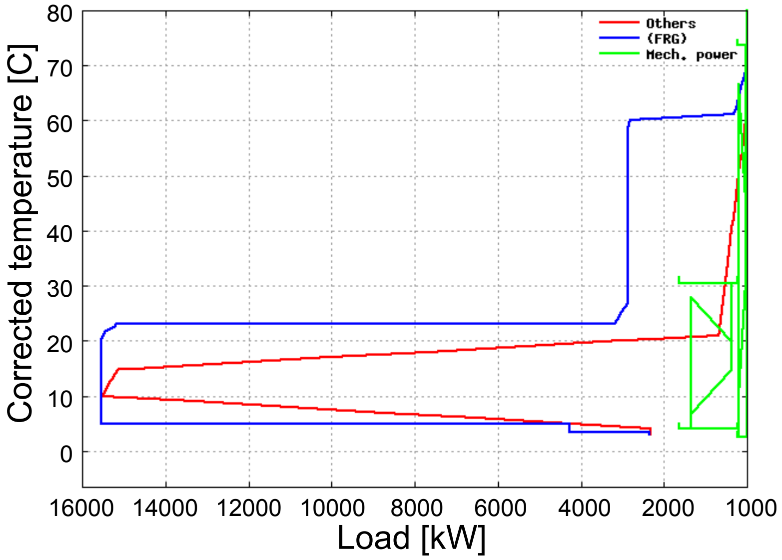


Figure 5.16: Integrated composite curves of the GLN area-network (red) and cooling cycles (blue) for an outdoor temperature of $T_x = 35°C$.

The result of the integration of the cooling system for a typical year is presented in Figure (5.17).The refrigeration cycle (on the top) is used to cover the peaks of the cooling demand during summer time. During the rest of the time, the cooling requirements could be satisfied by direct cooling (blue) from the lake water.

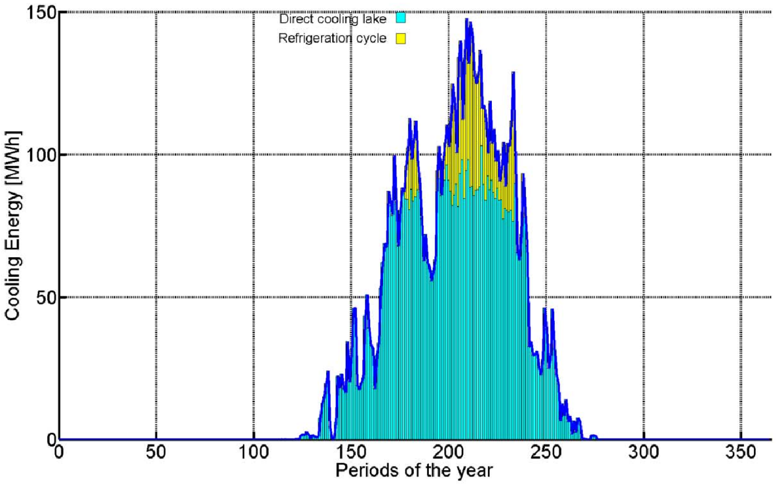


Figure 5.17: Results of the optimal integration of the network and cooling cycle for a typical year.

The overall performance coefficients, defined in Equation (5.15, p. 114), have been obtained by the optimal integration of direct cooling and refrigeration cycles including pumping power.

These coefficients are presented in Table (5.6).

Table 5.6: Results after mass flow optimisation

Total electricity consumption	110’600	kWh
Electricity consumption refrigeration cycle	92’240	kWh
COP refrigeration cycle	13.4	-
COP cooling, whole system	79.0	-
COP cooling, whole system with lake pumping	67.8	-

5.7.4 Integration of the network with heat pumps

5.7.5 Assumptions

The scenario without heat pumps and the one with heat pump integration are compared with regards to the energy bill and the CO_2 emissions. The assumption on energy prices and CO_2 emissions are listed in Table (5.7).

Table 5.7: Energy prices and CO_2 emissions

Energy carrier	Cost $[CHF/kWh]$	Emissions $[g_{CO_2}/kWh]$
Natural gas	0.09	234 [SSIGE, 2007]
Swiss Electricity production Mix	0.18	24 [FOEN]
Swiss Electricity Consumption Mix	0.18	143 [FOEN]

5.7.6 Additional Heat pump integration

Figure (5.18) represents the hot and cold composite curves resulting from system integration at the nominal outdoor temperature of -6°C.

In the alternative representation of Figure (5.19), the streams obtained by simulation of the heat pump cycle (blue) are separated from the rest of the system (red).

5.7.7 Annual energy bill and CO_2 savings

The heating requirements (60’920 MWh) are actually covered by a natural gas boiler. Considering efficiencies of 95% for gas boilers, the total use of natural gas equal (64’126 $[MWh]$). The estimated electricity consumption are presented in Table (5.8). For the pumping power of the lake, one obtains an electricity consumption of 129 $\frac{MWh}{yr}$.

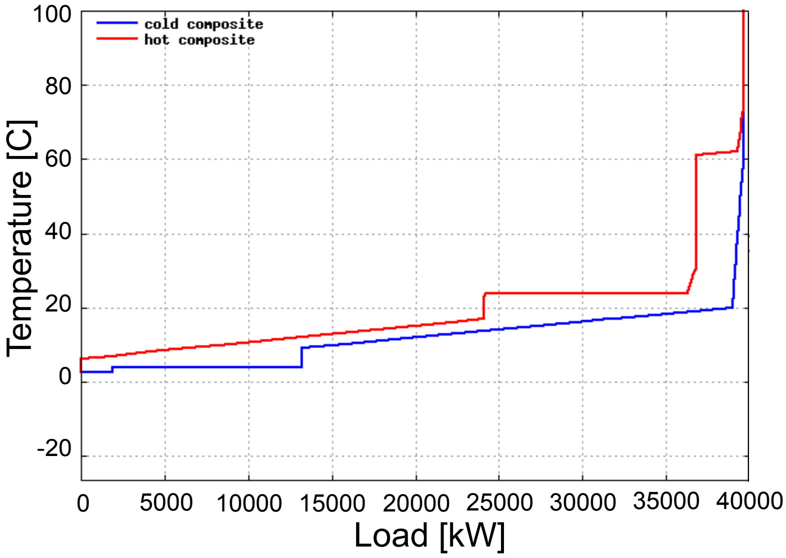


Figure 5.18: Integrated hot (red) and cold (blue) composite curves of the GLN area-network-heat pumps for an outdoor temperature of $T_x = -6$°C.

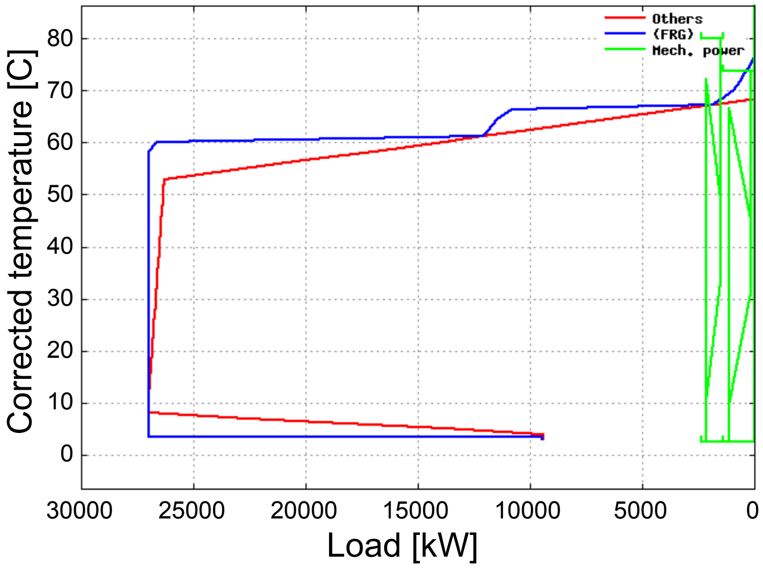


Figure 5.19: Integration of direct cooling and cooling cycles -6°C

Table 5.8: Final energy consumptions for the integrated low temperature district network.

Heating technology	Gas Boilers	Heat pumps
	$[MWh]$	
Gas consumption	64’126	0
Electricity consumption	129	21’828

The energy cost presented in Table (5.9), are computed based on the assumptions of Table (5.7) and the electricity consumption of Table (5.8)
The corresponding CO_2 emissions are given in Table (5.10).

Table 5.9: Energy expenses for the integrated low temperature district network.

Heating technology	Gas Boilers	Heat pumps
	$[MCHF/yr]$	
Gas costs	5'771	0
Electricity costs	23	3'929
Total costs	5'795	3'929

Table 5.10: CO_2 emissions for the integrated low temperature district network.

Heating technology	Gas Boilers	Heat pumps
	$[t_{CO_2}/yr]$	
Emissions from natural gas	15'005	0
El emissions, Swiss production Mix	3	524
El emissions, Swiss Consumption mix	18	3'100
Total emissions, Swiss production Mix	15'008	524
Total emissions, Swiss consumption Mix	15'023	3'100

5.7.8 Synthesis of the results

The savings obtained are given in Table (5.11). The CO_2 emission reduction is about 80% and even more when considering the Swiss production electricity (96%). The monetary value the energy saved is estimated at 1'865'500 $CHF/year$.

Table 5.11: Costs and emissions savings from the heating technology shift.

	Savings	
Reduced CO_2 emissions, Swiss Production mix	14'484 $[tCO_2/yr]$	96.5%
Reduced CO_2 emissions, Actual Swiss consumption Mix	11'923 $[tCO_2/yr]$	79.4%
Energy bill savings	1'865.5 $MCHF/yr$	32.2%

Considering a discount rate (i) of 8% and the life time of the equipments (n) of 20 years, the net present value (NPV) of a savings (S) for the coming 20 years computed with Equation (5.18), release an actual investment of 18.3 $[MioCHF]$. It is worthwhile to mention that this evaluation is based on the assumption of a constant gas and electricity prices for the coming 20 years.

$$NPV = \frac{S}{r} \cdot \left(1 - \frac{1}{(1+i)^n}\right) \tag{5.18}$$

5.8 Conclusion

The GIS-based methodology simulates the buildings' temperature and energy requirements and realizes the optimal integration of energy conversion systems using Process Integration techniques. Process Integration techniques have been used for decades to improve the energy performance of industrial processes.

Applied to territorial energy planning, this permits the design and simulation of equipment supplying both heating and cooling services, for steady state operation and multi-period scenarios. This can be done at a scale starting from individual building up to district areas, without going into detailed calculation of the heat exchanger network configurations, but giving the size of the equipment and the performances of the integrated system. The investment and operating costs, as well as the effficiencies and emissions can then be calculated.

Applied to the design of a low temperature district network, the proposed methodology enables the identification of an optimal strategy that maximizes the use of direct heat exchange. It also enables the evaluation of the impact of buildings' envelope refurbishment.

The results give evidence that optimal integration of endogenous renewable energy resources with heating and cooling equipment can achieve considerable ecological benefits and savings. This is particulerly suited for areas, like many in Switzerland, where population and industries centers are situated near large bodies of water.

This method could be further extended to integrate heat storage equipment as well. A further developement might be to compute the optimal developement sequence for a given temporal horizon.

6 Conclusion

Nowadays, urban energy planners and designers, like site managers in the industry, are asked to meet new environmental standards. They are required to improve the efficiency of their systems and propose sustainable designs that satisfy the energy requirements with an increasing share of renewable energy sources. For example in the European Union, more than a thousand cities signed the climate action and renewable energy package, known as the “Covenant of Mayors” [SEAP, 2010], that targets by 2020 the reduction by 20% of the CO_2 emissions, the increase by 20% of the energy efficiency and an increase by 20% of renewable energy utilized. Furthermore, urban energy planners are confronted with multi-scaled systems: ranging geographically from individual buildings to districts, cities and agglomerations and temporally from a single to a multi-period model.

To face these challenges a methodology has been proposed that is applied in three stages:

Starting with the identification of disparate information, a Geographical Information System (GIS) has been prototyped to assess the possible integration of available resources and energy requirements of urban areas. This permits an assessment of the situation by identifying and localizing the energy needs, resources and infrastructures in urban areas. This includes for example specificities such as the geological layers, the land use, the existing building stock, the heat district networks, the gas and electricity networks and typical meteorological conditions. The geographical energy needs are estimated using primarily real data and secondarily, when necessary, statistical values resulting from a local analysis. The future energy requirements are then estimated based on the urban development prediction.

In the second stage the potential of the available energy resources are characterized. These include among others geothermal resources, lakes and rivers, solar irradiation, waste water, industrial wasted heat. Moreover the infrastructures such as energy distribution networks, roads, railways are identified.

In the third stage, once the energy needs, the potential of resources and the infrastructure have been assessed, the optimal energy integration subject to limited resource availability and temperature levels compatibility is assessed. Thus for example, one may find that the replacement of decentralized gas boilers by a centralized co-generation plant is beneficial: distributing heat through a heat district network and electricity to some optimally-situated decentralized heat pumps would produce extra electricity with a CO_2-neutral balance.
Moreover, this allows to outline on a comprehensive map the optimal correlation of each urban zone with its optimal energy sources.
A further example is the determination of the size of centralized and decentralized equipment that permits to supply heat and cooling services using lake water as a resource in a substantially more efficient manner then that which is actually done with decentralized gas boilers and refrigeration cycles.

Application of the methodology was done as follows :

A data model has been proposed to homogenize and prioritize the information coming from disparate origins.
A statistical approach has been proposed to supply the crucial data which may be missing, such as used built area and energy consumptions.
A spatial aggregation model has been developed in order to enlarge or refine the perspective at different scale factors.
As the efficiency of advanced energy conversion systems depends on the required loads and temperature levels, a model characterizing the heat requirements, where the temperature is given as a function of the heat load, has been proposed. This permits computing, for each geographical area, the so called “heat-temperature composite” curve.

A GIS database has been adapted as an analytic tool which permits the identification of territorial opportunities and constraints linking energy resources and demands.
As certain energy resources are accessible only through distribution networks, an algorithm has been developed to integrate energy conversion technologies of decentralized, partially centralized or completely centralized configurations. This enables, for example, an assessment of the efficiency of centralized/decentralized combination of heat pumps for different heat distribution temperatures. Moreover, an aggregation algorithm has been developed to target economically promising zones.

In order to optimally correlate energy demand and offer while privileging endogenous renewable resources, Process Integration techniques, borrowed from industrial process engineering, have been applied.
I suggest this GIS-based approach, ignoring the details of the heat exchangers configurations,

is well suited for large scale urban applications: when solutions are materialized by visually comprehensible cartographic maps, optimal decision making is facilitated.

Bibliography

SR 431.01. Federal Statistics Act (FSA) of 1992 (SR 431.01), October 1992. URL http://www.admin.ch/ch/e/rs/431_01/index.html.

RS 510.62. Federal Act of 5 October 2007 on Geoinformation (Geoinformation Act, GeoIA), RS 510.62, 2007 5 October. URL http://www.admin.ch/ch/e/rs/c510_62.html.

RS 510.626. RS 510.626, Ordonnance du 21 mai 2008 sur la mensuration nationale (OMN, RS 510.626)., 21 mai 2008. URL http://www.admin.ch/ch/f/rs/510_626/a1.html.

A. E. Adderley, P. W. O'Callaghan, and S.D. Probert. Energy-saving options. *Applied Energy*, 30(4):269 – 279, 1988. ISSN 0306-2619. doi: DOI:10.1016/0306-2619(88)90014-1. URL http://www.sciencedirect.com/science/article/B6V1T-49803G9-2P/2/f2c97f4b787406c01c783cc796d7414e.

S. B. Akers. Binary decision diagrams. *Computers, IEEE Transactions on*, C-27(6):509 –516, june 1978. ISSN 0018-9340. doi: 10.1109/TC.1978.1675141.

B. R. Anderson, A. J. Clark, R. Baldwin, and N. O. Milbank. *BREDEM - BRE Domestic Energy Model: background, philosophy and description*. Building Research Establishment report. Building Research Establishment, 1985. ISBN 9780851253510. URL http://books.google.com/books?id=e1WzOQAACAAJ.

D. Anguelov, C. Dulong, D. Filip, C. Frueh, S. Lafon, R. Lyon, A. Ogale, L. Vincent, and J. Weaver. Google street view: Capturing the world at street level. *Computer*, 43(6):32 –38, june 2010. ISSN 0018-9162. doi: 10.1109/MC.2010.170.

E. Barreiro, J. Belausteguigoitia, E. Perea, R. Rodríguez, A. Romero, and E. Turienzo. City planning and energy efficiency: Towards an integrated urban design and planning process. volume 120, pages 43–51, 2009. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-71749087487&partnerID=40&md5=3b321708cb0f6bfebcd1105c3ac17308.

M. Bauer and J.-L. Scartezzini. A simplified correlation method accounting for heating and cooling loads in energy-efficient buildings. *Energy and Buildings*, 27(2):147 – 154, 1998. ISSN 0378-7788. doi: DOI:10.1016/S0378-7788(97)00035-2. URL http://www.sciencedirect.com/science/article/B6V2V-3SYYRFM-4/2/b6da1dcd1e83e6e97aeb27f4addfc6a7.

H. Becker, L. Girardin, and F. Maréchal. Energy integration of industrial sites with heat exchange restrictions. 28:1141–1146, 2010. URL http://www.aidic.it/escape20/.

C. Boissieu. *Rapport du groupe de travail « Division par quatre des émissions de gaz à effet de serre de la France à l'horizon 2050 »*. La Documentation française, Paris, octobre 2006.

R. Bolliger. *Méthodologie de la synthèse des systèmes énergétiques industriels*. PhD thesis, Lausanne, 2010. URL http://library.epfl.ch/theses/?nr=4867,http://library.epfl.ch/theses/?nr=4867.

R. Bolliger, D. Favrat, and F. Maréchal. Advanced Power Plant Design Methodology using Process Integration and Multi-Objective Thermo-Economic Optimisation. In *ECOS 2005, 18th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, volume 2, pages 777–784, Trondheim, Norway, 2005.

A. T. Booth, R. Choudhary, and D. J. Spiegelhalter. Handling uncertainty in housing stock models. *Building and Environment*, 48(1):35–47, 2011. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-80052594887&partnerID=40&md5=38d54eed593aba4d18f93b0405408a75.

L. Borel and D. Favrat. *Thermodynamics and Energy Systems Analysis; From Energy to Exergy*. Presses Polytechniques et Universitaires Romandes PPUR, Lausanne, 2010. ISBN 978-2-940222-45-2.

M. Bürer. *Multi-Criteria Optimization and Project-Based Analysis of Integrated Energy Systems for More Sustainable Urban Areas*. PhD thesis, EPFL, LENI - IS - STI, Laboratoire d'énergétique industrielle, CH-1015 Lausanne, Switzerland, 2003.

N. Calame-Darbellay, L. Girardin, M. Dubuis, and F. Maréchal. Monitoring and adaptation of existing buildings to a hydraulic network Impact of the retrofit of buildings and heat distribution systems on the system performance. Technical report, 2009a.

N. Calame-Darbellay, L. Girardin, and F. Maréchal. Methodology for the integration of low temperature district network in urban area. In Zvonimir Guzović, Neven Duić, and Marko Ban, editors, *CD PROCEEDINGS*, 2009b. URL http://www.sdewes.fsb.hr/.

M. Caldera, S. P. Corgnati, and M. Filippi. Energy demand for space heating through a statistical approach: application to residential buildings. *Energy and Buildings*, 40(10):1972–1983, 2008. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-48949115046&partnerID=40&md5=539c579f429f6e976dcd9631fbc8bf48.

Y. Candau. On the exergy of radiation. *Solar Energy*, 75(3):241 – 247, 2003. ISSN 0038-092X. doi: DOI:10.1016/j.solener.2003.07.012. URL http://www.sciencedirect.com/science/article/B6V50-49DMTP0-1/2/4fc0f1c43da899c3b7e3de2b93aa7c7c.

C. Carneiro, E. Morello, and G. Desthieux. Assessment of solar irradiance on the urban fabric for the production of renewable energy using lidar data and image processing techniques. pages 83–112, 2009.

T. Catalina, J. Virgone, and E. Blanco. Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy and Buildings*, 40(10):1825 – 1832, 2008. ISSN 0378-7788. doi: DOI:10.1016/j.enbuild.2008.04.001. URL http://www.sciencedirect.com/science/article/B6V2V-4SBHX2P-1/2/32485bae1127ff269629529c173a09ee.

V. Cheng and K. Steemers. Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. *Environmental Modelling & Software*, 26(10):1186 – 1198, 2011. ISSN 1364-8152. doi: 10.1016/j.envsoft.2011.04.005. URL http://www.sciencedirect.com/science/article/pii/S1364815211001034.

G. Cherix, M. Finger, M. Capezzali, H.-B. Püttgen, A. Chapuis, and A. Nour. Action and influence of the multiple decision levels over the whole energy chain. In *5th Conference on Sustainable Development of Energy, Water, Environment Systems*, 2009.

F. Chlela, A. Husaunndee, C. Inard, and P. Riederer. A new methodology for the design of low energy buildings. *Energy and Buildings*, 41(9):982 – 990, 2009. ISSN 0378-7788. doi: 10.1016/j.enbuild.2009.05.001. URL http://www.sciencedirect.com/science/article/pii/S0378778809000954.

K. J. Chua and S. K. Chou. A performance-based method for energy efficiency improvement of buildings. *Energy Conversion and Management*, 52(4):1829–1839, 2011. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-78650785889&partnerID=40&md5=82db3b7cdf3132d4d236b7d33c63c254.

J. A. Clarke, N. J. Kelly, and D. Tang. A review of esp-r's flexible solution approach and its application to prospective technical domain developments. *Advances in Building Energy Research*, 1(1):227–247, 2007. doi: 10.1080/17512549.2007.9687277. URL http://www.tandfonline.com/doi/abs/10.1080/17512549.2007.9687277.

The Swiss Federal Council. Ordonnance sur l'harmonisation de registres (431.021), February 2009. URL http://www.admin.ch/ch/f/rs/431_021/index.html.

D. B. Crawley, L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, Y. J. Huang, C. O. Pedersen, R. K. Strand, R. J. Liesen, D. E. Fisher, M. J. Witte, and J. Glazer. Energyplus: creating a new-generation building energy simulation program. *Energy and Buildings*, 33 (4):319 – 331, 2001. ISSN 0378-7788. doi: 10.1016/S0378-7788(00)00114-6. URL http://www.sciencedirect.com/science/article/pii/S0378778800001146. <ce:title>Special Issue: BUILDING SIMULATION'99</ce:title>.

D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43(4):661–673, 2008. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-36549076471&partnerID=40&md5=74f87f5d5b68d037d40783fef229c17f.

T. Crosbie, N. Dawood, and S. Dawood. Improving the energy performance of the built environment: The potential of virtual collaborative life cycle tools. *Automation in Construction*, 20(2):205–216, 2011. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-79551687730&partnerID=40&md5=d4f2d9466b0c97918eaceaa52f6d0cb4.

Crown. Climate change act 2009 (uk: The stationary office limited) chapter 27. *The Climate Change Act 2008 (2020 Target, Credit Limit and Definitions) Order 2009 No. 1258*, 2009. URL http://www.legislation.gov.uk/ukpga/2009/27/pdfs/ukpga_20090027_en.pdf.

Crown. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2009 edition incorporating RdSAP 2009*. Building Research Establishment (BRE), 2011. URL www.bre.co.uk/sap2009. rev October 2010, RdSAP 2009 added March 2011.

V. Curti. *Modélisation et optimisation environomiques de systèmes de chauffage urbain alimentés par pompes à chaleur*. PhD thesis, Lausanne, 1998. URL http://library.epfl.ch/theses/?nr=1776,http://library.epfl.ch/theses/?nr=1776.

Shorrock L. D. and J. E. Dunster. The physically-based model brehomes and its use in deriving scenarios for the energy use and carbon dioxide emissions of the uk housing stock. *Energy Policy*, 25(12):1027 – 1037, 1997. ISSN 0301-4215. doi: 10.1016/S0301-4215(97)00130-4. URL http://www.sciencedirect.com/science/article/pii/S0301421597001304.

N. Darbellay, C. Weber, L. Girardin, M. Dubuis, F. Maréchal, and D. Favrat. Stratégie thermique pour le canton de Genève: réseau de distribution de chaleur et climatisation. Technical report, 2007.

DOE. Building energy software tools directory. world wide web site: http://apps1.eere.energy.gov/buildings/tools_directory/, us department of energy,washington, dc., (the on-line version has been updated extensively since first published in 1998.), 2011.

B. Dong, S. E. Lee, and M. H. Sapar. A holistic utility bill analysis method for baselining whole commercial building energy consumption in singapore. *Energy and Buildings*, 37(2):167–174, 2005. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-6344278502&partnerID=40&md5=23c68107c992797fdc8de37bd0b41d16.

K. J. Dueker. A look at state and local information system efforts. In *Proceedings of the 1968 23rd ACM national conference*, ACM '68, pages 133–142, New York, NY, USA, 1968. ACM. doi: http://doi.acm.org/10.1145/800186.810575. URL http://doi.acm.org/10.1145/800186.810575.

ESRI. Esri shapefile technical description, http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf, 2011.

D. Favrat, F. Maréchal, and O. Epelly. The challenge of introducing an exergy indicator in a local law on energy. *Energy*, 33(2):130 – 136, 2008. ISSN 0360-5442. doi: 10.1016/j.energy.2007.10.012. URL http://www.sciencedirect.com/science/article/pii/S0360544207001892. <ce:title>19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impactof Energy Systems</ce:title> <ce:subtitle>ECOS 2006</ce:subtitle>.

P. Favre, O. Barde, C. Weinmann, and C. Trachsel. La signature energétique - outil du diagnostic thermique d'un bâtiment. *Annales de l'Institut technique du bâtiment et des travaux publics*, pages 35–59, 1983.

M. F. Fels. PRISM: an introduction. *Energy and buildings*, 9(1-2):5–18, 1986. ISSN 0378-7788. URL http://cat.inist.fr/?aModele=afficheN&cpsidt=8178026.

S. K. Firth, K. J. Lomas, and A. J. Wright. Targeting household energy-efficiency measures using sensitivity analysis. *Building Research & Information*, 38(1):25–41, 2010. doi: 10.1080/09613210903236706. URL http://www.tandfonline.com/doi/abs/10.1080/09613210903236706.

FOEN. Quelle est la quantité de co2 émise par la consommation d'un kilowattheure d'électricité en suisse ? (reference number H367-0066). URL http://www.bafu.admin.ch/klima/09608/index.html.

FSO. STAT-TAB 08.3, Cubes de données pour le thème 08.3 - Consommation d'énergie, Consommation finale d'énergie, par agent énergétique 1910-2009. online database, 2010a. URL http://www.pxweb.bfs.admin.ch. Version: 19.11.2010.

FSO. STAT-TAB, Canton, composante démographique, nationalité, sexe; Enquête ESPOP 1971-2009. online database, 2010b. URL http://www.pxweb.bfs.admin.ch. Version: 19.11.2010 09:07:02.

FSO. STAT-TAB 09.2, Cubes de données pour le thème 09.2 - Bâtiments et logements, Logements selon les cantons, le nombre de pièces, la surface du logement (classes), l'époque de construction, 2009. online database, 2011a. URL http://www.pxweb.bfs.admin.ch. Version: 10.02.2011.

FSO. STAT-TAB 09.2, Cubes de données pour le thème 09.2 - Bâtiments et logements, Domaine de l'énergie: Bâtiments selon les cantons, la catégorie de bâtiment, l'époque de construction, le système de chauffage, la production d'eau chaude, les agents énergétiques utilisés pour le chauffage et l'eau chaude, 2009. online database, 2011b. URL http://www.pxweb.bfs.admin.ch. Version: 10.02.2011.

L. Fu, Zhonghai Zheng. Z., H. Di, and Y. Jiang. Urban building energy planning with space distribution and time dynamic simulation. *Journal of Solar Energy Engineering*, 131(3): 031014, 2009. doi: 10.1115/1.3142725. URL http://link.aip.org/link/?SLE/131/031014/1.

M. Gassner. *Process Design Methodology for Thermochemical Production of Fuels from Biomass.* PhD thesis, Lausanne, 2010. URL http://library.epfl.ch/theses/?nr=4693,http://library.epfl.ch/theses/?nr=4693.

M. Gassner and F. Maréchal. Thermo-economic process model for thermochemical production of synthetic natural gas (sng) from lignocellulosic biomass. *Biomass and Bioenergy*, 33(11):1587 – 1604, 2009. ISSN 0961-9534. doi: DOI:10.1016/j.biombioe.2009.08.004. URL http://www.sciencedirect.com/science/article/B6V22-4X541J4-1/2/3e1d588ef5ce2fd244a9b1f204d5aa92.

C. Ghiaus. Experimental estimation of building energy performance by robust regression. *Energy and Buildings*, 38(6):582 – 587, 2006. ISSN 0378-7788. doi: DOI:10.1016/j.enbuild.2005.08.014. URL http://www.sciencedirect.com/science/article/B6V2V-4HKCYWW-1/2/b913be760243bd747e0a90789ade1e9a.

L. Girardin and F. Maréchal. Études d'options énergétiques pour le quartier "Etraz-Sud". Technical report, 2010. Rapport technique, Décembre 2010, LENI-EPFL.

L. Girardin, M. Dubuis, N. Darbellay, F. Maréchal, and D. Favrat. ENERGIS : A Geographical information based system for the evaluation of integrated energy conversion systems in urban areas. In *ECOS 2008*, 2008. URL http://www.ecos2008.polsl.pl/.

L. Girardin, M. Kallhovd, and F. Maréchal. Application of the district cooling/heating network design models in the GLN area. Technical report, 2010a. URL http://www.tetraener.com/. TetraEner : Optimal balancing of demand and supply through RES in urban areas, Deliverable GE WP 1.1 Del 5.

L. Girardin, F. Maréchal, Dubuis. M., N. Calame-Darbellay, and D. Favrat. Energis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas. *Energy*, 35(2):830 – 840, 2010b. ISSN 0360-5442. doi: DOI:10.1016/j.energy.2009.08.018. URL http://www.sciencedirect.com/science/article/B6V2S-4XF8MHK-1/2/6d27dd362d415304638754961585f7ca. ECOS 2008, 21st International Conference, on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

L. Girardin, J. Rager, M. Cudilleiro, and F. Maréchal. Concept énergétique du développement urbain de la Commune de Nyon. Technical report, 2010c. Rapport technique final, version Décembre 2010 LENI-EPFL.

L. Girardin, G. Ridoux, and F. Maréchal. Management Energétique Urbain - Neuchâtel . Technical report, 2010d. Rapport technique version juin 2010, LENI-EPFL.

I. G. Hamilton, A. J. Summerfield, J. P. Steadman, A. Stone, and M. Davies. Exploring energy integration between new and existing developments. *Building Research and Information*, 38(6):593–609, 2010. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-77957905886&partnerID=40&md5=669e4b9d2e7711a10dcab2a8d218860c.

S. Hammarsten. A critical appraisal of energy-signature models. *Applied Energy*, 26(2):97 – 110, 1987. ISSN 0306-2619. doi: DOI:10.1016/0306-2619(87)90012-2. URL http://www.sciencedirect.com/science/article/B6V1T-497YSJY-47/2/6dadc3e8849090fb0244faef35b81d19.

J. W. Hand, D. B Crawley, M. Donn, and L. K. Lawrie. Improving non-geometric data available to simulation programs. *Building and Environment*, 43(4):674–685, 2008. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-36549070600&partnerID=40&md5=7d2c6138ae682847ce75932c8b8053f9.

Sailor D.J. Heiple, S. Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles. *Energy and Buildings*, 40(8):1426–1436, 2008. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-43049138386&partnerID=40&md5=75772990b7c1a348123b1f8b7a5d8031.

J. R. Herring. OpenGIS®Implementation Standard for Geographic information - Simple feature access - Part 2: SQL option. *English*, 2010.

F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine. *Fundamentals of Heat and Mass Transfer*. Wiley, 6 edition, March 2006. ISBN 0471457280. URL http://www.worldcat.org/isbn/0471457280.

N. Isaacs, M. Camilleri, and L. French. Why bother collecting data? experiences of the household energy end-use project. In *Presented at the American Council for Energy Efficient Economy (ACEEE)*. BRANZ Ltd., 13-18 August 2006.

ISO. *GUM, Guide to the expression of uncertainty in measurement (GUM)-Supplement 1: Numerical methods for the propagation of distributions*, volume ISO draft guide DGUIDE99998. International Organization for Standardization, Geneva, 2004.

M. J. Jiménez and M. R. Heras. Application of multi-output arx models for estimation of the u and g values of building components in outdoor testing. *Solar Energy*, 79(3):302–310, 2005. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-23844505698&partnerID=40&md5=637649a6b265c81e054c9835555ee859.

E. Jochem, G. Andersson, D. Favrat, H. Gutscher, K. Hungerbühler, P. R. von Rohr, D. Spreng, A. Wokaun, M. Zimmermann, F. Gassmann, S. Lienin, and F. Maréchal. *Steps towards a sustainable development: a white book for R & D of energy efficient technologies*. Novatlantis, 2004. ISBN 9783952270509. URL http://books.google.com/books?id=iZ-wPgAACAAJ.

D. Johnston, R. Lowe, and M. Bell. An exploration of the technical feasibility of achieving co2 emission reductions in excess of 60 *Energy Policy*, 33(13):1643 – 1659, 2005. ISSN 0301-4215. doi: 10.1016/j.enpol.2004.02.003. URL http://www.sciencedirect.com/science/article/pii/S0301421504000370.

P. J. Jones, S. Lannon, and J. Williams. *Modelling building energy use at urban scale*. 2001. URL http://www.inive.org/members_area/medias/pdf/Inive%5CIBPSA%5CUFSC421.pdf.

D. E. Kalz, J. Pfafferott, S. Herkel, and A. Wagner. Energy and efficiency analysis of environmental heat sources and sinks: In-use performance. *Renewable Energy*, 36(3):916 – 929, 2011. ISSN 0960-1481. doi: DOI:10.1016/j.renene.2010.09.003. URL http://www.sciencedirect.com/science/article/B6V4S-516CH8R-1/2/5ba52c50cc3b6203a2b6ceac1517c0dd.

M Kavgic, A Mavrogianni, D Mumovic, A Summerfield, Z Stevanovic, and M Djurovic-Petrovic. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7):1683–1697, 2010. URL http://discovery.ucl.ac.uk/149996/.

James Keirstead, Nouri Samsatli, and Nilay Shah. SynCity: an integrated tool kit for urban energy systems modelling. In Ranjan K Bose, editor, *Proceedings of the 5th Urban Research Symposium*, pages 21–42. World Bank, 2009. URL www.urs2009.net.

A. Kirchner, A. Kemmler, W. Baumgartner, M. Keller, M. Jakob, and G. Catenazzi. Analyse des schweizerischen Energieverbrauchs 2000 - 2009 nach Verwendungszwecken. Technical report, Bundesamt für Energie BFE, Mühlestrasse 4, 3063 Ittigen, December 2010.

Hassler U. Kohler, N. The building stock as a research object. *Building Research and Information*, 30(4):226–236, 2002. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0036639678&partnerID=40&md5=ad7bfccde6d000f4697ef0beaa13fb8c.

N. Kohler and W. Yang. Long-term management of building stocks. *Building Research and Information*, 35:351–362(12), July 2007. doi: doi:10.1080/09613210701308962. URL http://www.ingentaconnect.com/content/routledg/rbri/2007/00000035/00000004/art00002.

S. Kraines, C. Weber, H. Komiyama, M. Koyama, D. Wallace, C. Tomoyuki, and I. Toshiharu. A collaborative platform for sustainable building design based on model integration over the internet. *journal of engineering and technology management*, 5(2-3):135–161, 2005. doi: 10.1504/IJETM.2005.006847. URL ,.

S. B. Kraines and D. R. Wallace. Urban sustainability technology evaluation in a distributed object-based modeling environment. *Computers, Environment and Urban Systems*, 27(2):143–161, 2003. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0037310368&partnerID=40&md5=12de596492f3f053dfb7c6a075ad4b9f.

F. Leite, A. Akcamete, B. Akinci, G. Atasoy, and S. Kiziltas. Analysis of modeling effort and impact of different levels of detail in building information models. *Automation in Construction*, 20(5):601–609, 2011. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-79957567251&partnerID=40&md5=e38a4eb883fdfeffe5e57d33b6e457b0.

LEN. Loi sur l'énergie (LEn, L 2 30). Site officiel de l'Etat de Genève, 2010. URL http://www.geneve.ch/legislation/rsg/f/s/rsg_L2_30.html.

LEne. Loi du 26 juin 1998 sur l'énergie (LEne), 1 janvier 2011. URL http://www.admin.ch/ch/f/rs/730_0/index.html.

G. B. Leyland. *Multi-objective optimisation applied to industrial energy problems*. PhD thesis, Lausanne, 2002. URL http://library.epfl.ch/theses/?nr=2572,http://library.epfl.ch/theses/?nr=2572.

LHR. Loi fédérale du 23 juin 2006 sur l'harmonisation des registres des habitants et d'autres registres officiels de personnes (loi sur l'harmonisation de registres, lhr), 23 juin 2006. URL http://www.admin.ch/ch/f/rs/c431_02.html.

K. J. Lomas. Decarbonizing national housing stocks: strategies, barriers and measurement. *Building Research and Information*, 37:187–191(5), March 2009. doi: doi:10.1080/09613210802645874. URL http://www.ingentaconnect.com/content/routledg/rbri/2009/00000037/00000002/art00006.

R. Lowe. Addressing the challenges of climate change for the built environment. *Building Research & Information*, 35(4):343–350, 2007. doi: 10.1080/09613210701345873. URL http://www.tandfonline.com/doi/abs/10.1080/09613210701345873.

A. Makhorin. *GNU Linear Programming Kit, Version 4.47*. GNU Software Foundation, 2011. URL http://www.gnu.org/software/glpk/glpk.html.

M. Manfren, P. Caputo, and G. Costa. Paradigm shift in urban energy systems through distributed generation: Methods and models. *Applied Energy*, 88(4):1032–1048, 2011. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-78650574864&partnerID=40&md5=2f1b2cf8380a077949c09ee89ccfe54f.

F. Maréchal. *Energy analysis and synthesis of industrial sites*. PhD thesis, Laboratoire d'analyse et de synthèse des systèmes chimiques, University of Liège (Belgium), 1995.

F. Maréchal and D. Favrat. Combined exergy and pinch analysis for optimal energy conversion technologies integration. In *ECOS 2005, 18th International Conference on Efficiency, Cost,Optimization, Simulation and Environmental Impact of Energy Systems, Trondheim, Norway*, volume 1 of *ECOS 2005*, pages 177–184, 2005.

F. Maréchal and B. Kalitventzeff. Energy integration of industrial sites: tools, methodology and application. *Applied Thermal Engineering*, 18(11):921–933, November 1998. URL http://www.sciencedirect.com/science/article/B6V1Y-3TP6DM7-2/2/75f7f9cd7168eac36eae47344cac1269.

F. Maréchal, H. Closon, B. Kalitventzeff, and S. Pierucci. A Tool for Optimal Synthesis of Industrial Refrigeration Systems : Application to an Olefins Plant. New Orleans, USA, 2002.

F. Maréchal, D. Favrat, and E. Jochem. Energy in the perspective of the sustainable development : the 2000 W society challenge. *Conservation & Recycling*, 44(3 spec. iss.):245–262, 2005. doi: 10.1016/j.resconrec.2005.01.008. available online via Science Direct.

R. Masciarelli, L. Girardin, and F. Maréchal. Integration of polygeneration in urban systems. Master's thesis, École Polytechnique Fédérale de Lausanne, Industrial Energy Systems Laboratory (LENI), 2009.

MathWorks, Inc. *Version 7.9.0.529 (R2009b)*. The MathWorks Inc., Natick, Massachusetts, 2010.

MathWorks, Inc. *Database Toolbox™User's Guide*. The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, 2011a. URL www.mathworks.com/help/pdf_doc/database/database_ug.pdf.

MathWorks, Inc. *Mapping Toolbox™User's Guide*. The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, 2011b. URL www.mathworks.com/help/pdf_doc/map/map_ug.pdf.

A. Mayer and R. Beck. Success conditions of sustainable energy projects in urban areas key-elements and feed-back from projects belonging to the concerto european programme. In *TetraEner international Seminar*. Service cantonal de l'énergie, Geneva (ScanE), Feb. 3rd 2009, Geneva.

R. McGill, J. W. Tukey, and W. A. Larsen. Variations of box plots. *American Statistician*, 32: 12–16, 1978. URL http://www.jstor.org/stable/2683468?origin=crossref.

M. Medrano, J. Brouwer, M. Carreras-Sospedra, M. Rodriguez, D. Dabdub, and G. S. Samuelsen. A methodology for developing distributed generation scenarios in urban areas using geographical information systems. *International Journal of Energy Technology and Policy*, 6(4):413–434, 2008. ISSN 14728923. doi: 10.1504/IJETP.2008.019958. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-50449089516&partnerID=40&md5=e985a15b5709fc0315668d4530889520.

A. Mermoud, B. Lachal, W. Weber, and P.-A. Viquerat. Tetraener : Optimal balancing of demand and supply through res in urban areas, ge wp 1.3 del 2, "hcr building: Measuring cooling installations and auditing for deep lake direct cooling network connectivity". Technical report, University Center for the Study of Energy Problems, University of Geneva, Switzerland, January 14 2008a.

A. Mermoud, B. Lachal, W. Weber, and P.-A. Viquerat. Tetraener : Optimal balancing of demand and supply through res in urban areas, ge wp 1.3 del 2, "un building: Measuring cooling installations and auditing for deep lake direct cooling network connectivity". Technical report, University Center for the Study of Energy Problems, University of Geneva, Switzerland, January 14 2008b.

Meteonorm. The global meteorological database for engineers, planners and education, available from: http://www.meteonorm.com/.

MeteoSwiss. *IDAweb, The data portal of MeteoSwiss for research and teaching*. Swiss Federal Office of Meteorology and Climatology, 2010. URL http://www.meteosuisse.admin.ch.

N. Metropolis. The beginning of the monte carlo method. *Los Alamos Science*, 15(1945): 125–130, 1987. URL http://jackman.stanford.edu/mcmc/metropolis1.pdf.

A. Molyneaux. *A practical evolutionary method for the multi-objective optimisation of complex integrated energy systems including vehicle drivetrains*. PhD thesis, Lausanne, 2002. URL http://library.epfl.ch/theses/?nr=2636,http://library.epfl.ch/theses/?nr=2636.

S. Morehouse. Arc/info: a geo-relational model for spatial information. pages 388–397, 1985. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0022251309&partnerID=40&md5=e8532adf2a743d1898e75b22f24996b0.

Nyon-Energie. Municipalité de nyon, programme nyon-energie : Politique en faveur de l'énergie et du climat pour la période 2009-2013, rapport n°133 au conseil communal. Technical report.

OGC. Geospatial and location standards. Website, 2011. URL http://www.opengeospatial.org.

T. Oreszczyn and R. Lowe. Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*, 38(1):107–122, 2010. doi: 10.1080/09613210903265432. URL http://www.tandfonline.com/doi/abs/10.1080/09613210903265432.

L. O'Sullivana, L. Boveta, and A. Streileina. Tlm - the swiss 3d topographic landscape model. In *The International archives of the photogrammetry, remote sensing and spatial information sciences*, volume XXXVII of *A*, pages 1715–1720. International Society for Photogrammetry and Remote Sensin, Organising Committee of the XXIst International Congress for Photogrammetry and Remote Sensing, 2008.

T. Ottin. *Etude et simulation du comportement dynamique de chaufferies*. PhD thesis, Zurich, 1986. URL http://library.epfl.ch/theses/?nr=614,http://library.epfl.ch/theses/?nr=614.

F. Palazzi, Z. Périn-Levasseur, R. Bolliger, and M. Gassner. *Osmose, user manual Version 2.0*. October 20 2010.

L. Pérez-Lombard, J. Ortiz, and C. Pout. A review on buildings energy consumption information. *Energy and Buildings*, 40(3):394 – 398, 2008. ISSN 0378-7788. doi: 10.1016/j.enbuild.2007.03.007. URL http://www.sciencedirect.com/science/article/pii/S0378778807001016.

Z. Périn-Levasseur. *Energy efficiency and conversion in complex integrated industrial sites*. PhD thesis, Lausanne, 2009. URL http://library.epfl.ch/theses/?nr=4433,http://library.epfl.ch/theses/?nr=4433.

A. Pfeiffer, M. Koschenz, and A. Wokaun. Energy and building technology for the 2000 w society - potential of residential buildings in switzerland. *Energy and Buildings*, 37(11 SPEC. ISS.):1158–1174, 2005. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-24944445499&partnerID=40&md5=432dfd8e96e1945afa5179082a730454.

PostGIS. PostGIS 1.5.2 Manual, Refractions Research Inc., 2011.

The PostgreSQL Global Development Group PostgreSQL. *PostgreSQL 9.0 Reference Manual - Volume 2 Programming Guide*, volume 2. Network Theory Ltd, 2010. URL http://www.network-theory.co.uk/postgresql9/vol2/.

S. Pullen. Towards a more holistic and complementary approach to modelling energy consumption in buildings. pages 325–337, 2009. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-80052146113&partnerID=40&md5=051a78f7bec879d94a22d36474a1e795.

Quantum GIS Development Team. QGIS. *Quantum GIS Geographic Information System*. Open Source Geospatial Foundation, 2009. URL http://qgis.osgeo.org.

R Development Core Team. R. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2011. URL http://www.R-project.org/. ISBN 3-900051-07-0.

A. Rabl and A. Rialhe. Energy signature models for commercial buildings: test with measured data and interpretation. *Energy and Buildings*, 19(2):143 – 154, 1992. ISSN 0378-7788. doi: DOI:10.1016/0378-7788(92)90008-5. URL http://www.sciencedirect.com/science/article/B6V2V-47X8135-9R/2/b782f6cd2df9f4882f97bd0e9b612dfa.

J. Rager, L. Girardin, and F. Maréchal. Solar Potential Assessment on Roofs of Urban Areas and its Integration. In *EPFL / UNESCO Chair International Scientific Conference on Technologies for Development*, 2010. URL http://cooperation.epfl.ch/page70491.html.

F. Ramm and J. Topf. *OpenStreetMap: Using and Enhancing the Free Map of the World*. UIT Cambridge Ltd., 2010. ISBN 9781906860110. URL http://books.google.fr/books?id=AnCNQQAACAAJ.

RCB. *Registre Cantonal Vaudois des Bâtiments*. Office de l'information sur le territoire,Canton de Vaud, 2010. URL http://www.vd.ch/fr/autorites/departements/dinf/secretariat-general/office-de-linformation-sur-le-territoire/registre-des-batiments/.

RegBL. *Registre fédéral des bâtiments et des logements (RegBL)*. Office fédéral de la statistique, Confédération Suisse, 2010. URL http://www.bfs.admin.ch/bfs/portal/fr/index/themen/00/05/blank/01.html.

REN. Recueil officiel systématique de la législation genevoise, Règlement d'application de la loi sur l'énergie (L 2 30.01). Site officiel de l'Etat de Genève, 2010. URL http://www.ge.ch/legislation/rsg/f/s/rsg_L2_30P01.html.

D. Robinson, N. Campbell, W. Gaiser, K. Kabel, A. Le-Mouel, N. Morel, J. Page, S. Stankovic, and A. Stone. Suntool - a new modelling paradigm for simulating and optimising urban sustainability. *Solar Energy*, 81(9):1196–1211, 2007. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-34548354873&partnerID=40&md5=7c8fef53dda011eaf3cdf52b3c7db10b.

D. Robinson, F. Haldi, P. Leroux, D. Perez, A. Rasheed, and U. Wilke. CITYSIM: COMPREHENSIVE MICRO-SIMULATION OF RESOURCE FLOWS FOR SUSTAINABLE URBAN PLANNING. pages 1083–1090, 2009.

SEAP. *Covenant of Mayors: How to develop a sustainable energy action plan (SEAP) - Guidebook*. European Commission, luxembourg: publications office of the european union, 2010 edition, 2010. URL www.eumayors.eu.

SFOE. Statistique suisse de l'électricité. Technical report, Swiss Federal Office of Energy, 2009a. URL http://www.bfe.admin.ch.

SFOE. Statistique globale suisse de l'énergie 2009. Technical report, Mühlestrasse 4, CH-3063 Ittigen, Postadresse: CH-3003 Bern, August 2009b.

SIA 2032. *Norme SIA 2032, L'énergie grise dans les bâtiments, Cahier thecnique 2032*. SIA, Zurich, 2010.

SIA 380/1. *Norme SIA 380/1, L'énergie thermique dans le bâtiments.* SIA, Zurich, 2009.

SIA 384/2. *Norme SIA 384/2, Puissance thermique à installer dans les bâtiments.* SIA, Zurich, 1984.

(Services Industriels de Genève) SIG. Projet genève lac nations. published online, 2010. http://www.sig-ge.ch/gln/.

J.-U. Sjögren, S. Andersson, and T. Olofsson. Sensitivity of the total heat loss coefficient determined by the energy signature approach to different time periods and gained energy. *Energy and Buildings*, 41(7):801 – 808, 2009. ISSN 0378-7788. doi: DOI:10.1016/j.enbuild.2009.03.001. URL http://www.sciencedirect.com/science/article/B6V2V-4VTVPYP-1/2/ccbbf60e7b1a8db51bf83520ba485f77.

J.-U. Sjögren, S. Andersson, and T. Olofsson. An approach to evaluate the energy performance of buildings based on incomplete monthly data. *Energy and Buildings*, 39(8):945 – 953, 2007. ISSN 0378-7788. doi: DOI:10.1016/j.enbuild.2006.10.010. URL http://www.sciencedirect.com/science/article/B6V2V-4NC5T0N-1/2/befaca146a771981a4c663ef1f25a4e6.

SSIGE. Propriétés du gaz naturel distribué en suisse. Fiche technique G 2007 / 1, septembre 2007. URL www.svgw.ch.

A. J. Summerfield, R. J. Lowe, and T. Oreszczyn. Two models for benchmarking uk domestic delivered energy. *Building Research and Information*, 38(1):12–24, 2010. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-77649235667&partnerID=40&md5=d2a7830cbe394f0e6e426aaca72e3610.

L. G. Swan and V. I. Ugursal. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8):1819 – 1835, 2009. ISSN 1364-0321. doi: 10.1016/j.rser.2008.09.033. URL http://www.sciencedirect.com/science/article/pii/S1364032108001949.

Swisstopo. Swiss Federal Office of Topography, 2009. URL http://www.swisstopo.admin.ch. http://www.swisstopo.admin.ch.

J. E. Taylor and P. G. Bernstein. Paradigm trajectories of building information modeling practice in project networks. 25(2):69–76, 2009. ISSN 0742597X. doi: DOI:10.1061/(ASCE)0742-597X(2009)25:2(69). URL http://dx.doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69).

L. Thuvander. Towards environmental informatics for building stocks. *Doktorsavhandlingar vid Chalmers Tekniska Hogskola*, (1924):1–175, 2002. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0036920964&partnerID=40&md5=04f54a45a5ebf41f8c976b032fdae946.

R. F. Tomlinson and A. R. Boyle. The state of development of systems for handling natural resources inventory data. *Cartographica*, 18(4):65–95, 1981. ISSN 03177173. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0019663184&partnerID=40&md5=6609ad8463273abf012965b6491e3df9.

Thuvander L. Tornberg, J. A gis model for the building stock of goteborg. *Proceedings of the 25th Annual ESRI User Conference*, 2005.

P.–A. Viquerat, B. Lachal, A. Mermoud, W. Weber, and Pampaloni E. Annual report of the energetic balances and environmental state of the project: report on the monitoring installations. Technical report, CUEPE – Université de Genève, Genève, 2008. European Integrated Projects FP6 Priority 6.1 "Sustainable energy systems", TetraEner Project,.

C. Weber. *Multi-objective design and optimization of district energy systems including polygeneration energy conversion technologies*. PhD thesis, Lausanne, 2008. URL http://library.epfl.ch/theses/?nr=4018,http://library.epfl.ch/theses/?nr=4018.

C. Weber and N. Shah. Optimisation based design of a district energy system for an eco-town in the united kingdom. *Energy*, 36(2):1292 – 1308, 2011. ISSN 0360-5442. doi: 10.1016/j.energy.2010.11.014. URL http://www.sciencedirect.com/science/article/pii/S0360544210006407.

C. Weber, I. Heckl, F. Friedler, F. Maréchal, and D. Favrat. Network synthesis for a district energy system: a step towards sustainability. In C. Pantelides W. Marquardt, editor, *Escape 16 : 16th European Symposium on Computer Aided Process Engineering and 9th International Symposium on Process Systems Engineering*, pages 1869–1873. Elsevier B.V., 2006a. URL http://events.dechema.de/pseescape06.html.

C. Weber, F. Maréchal, D. Favrat, and S. Kraines. Optimization of an SOFC-based decentralized polygeneration system for providing energy services in an office-building in Tokyo. *Applied Thermal Engineering*, 26(13):1409–1419, 2006b. doi: 10.1016/j.applthermaleng.2005.05.031.

M. Wegener. Operational urban models state of the art. *Journal of the American Planning Association*, 60(1):17–29, 1994. doi: 10.1080/01944369408975547. URL http://www.tandfonline.com/doi/abs/10.1080/01944369408975547.

J. Whyte, N. Bouchlaghem, A. Thorpe, and R. Mccaffer. A survey of cad and virtual reality within the house building industry. *Engineering Construction and Architectural Management*, 6 (4):371–379, 1999. ISSN 1365-232X. doi: 10.1046/j.1365-232x.1999.00123.x. URL http://dx.doi.org/10.1046/j.1365-232x.1999.00123.x.

WPZ. Prüfresultate wärmepumpen basierende auf der en 14511, 2009. URL http://www.ntb.ch/ies/kompetenzbereiche/waermepumpen-testzentrum-wpz.html.

Y. Yamaguchi and Y. Shimoda. District-scale simulation for multi-purpose evaluation of urban energy systems. *Journal of Building Performance Simulation*, 3(4):289–305, 2010. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-78649556120&partnerID=40&md5=95e7e176f4e096b0ad5053d89a27f6ae.

R. Zmeureanu. A new method for evaluating the normalized energy consumption in office buildings. *Energy*, 17(3):235–246, 1992. ISSN 03605442. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0026825882&partnerID=40&md5=96a4972bda389c4949fed42611b361eb.

R. Zmeureanu, P. Fazio, S. DePani, and R. Calla. Development of an energy rating system for existing houses. *Energy and Buildings*, 29(2):107–119, 1999. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-0032758265&partnerID=40&md5=32e730d5fb7d0e10881b8b28caf6cf04.

Appendices

A Chapter 2

Table A.1: Statistical report of housing densities in Switzerland, 2009. Source: FSO [2011a].

Inhabited area [m^2]	Period	Individual homes	Building with several households	Building partially used for habitation	Housing with other end-use
<30	-1919	813	10148	2382	7199
<30	1919-1945	767	4358	714	2263
<30	1946-1960	594	8680	815	4132
<30	1961-1970	479	15072	1794	7439
<30	1971-1980	254	13574	2482	6407
<30	1981-1990	153	4552	1287	1448
<30	1991-2000	86	2578	600	1009
<30	2001-2005	24	730	113	158
<30	2006-2009	23	480	286	72
30-49	-1919	4580	30872	5304	20318
30-49	1919-1945	3851	18963	1737	7495
30-49	1946-1960	3087	33902	1753	11823
30-49	1961-1970	2852	47221	2490	16522
30-49	1971-1980	1629	39947	3293	12751
30-49	1981-1990	1007	19431	2223	6193
30-49	1991-2000	777	13055	1138	4052
30-49	2001-2005	184	2549	250	319
30-49	2006-2009	164	2608	221	401
50-69	-1919	11217	63797	8085	38157
50-69	1919-1945	8532	56654	2737	16756
50-69	1946-1960	7731	104229	2887	21957
50-69	1961-1970	6014	103747	3182	24132
50-69	1971-1980	4228	68295	2909	15996
50-69	1981-1990	3135	40523	2460	10982
50-69	1991-2000	2090	34406	1929	8951
50-69	2001-2005	667	7144	437	1291
50-69	2006-2009	439	9026	592	1549
70-99	-1919	29791	105824	14511	67462
70-99	1919-1945	23344	73662	5347	25056
70-99	1946-1960	28246	116398	4721	26729
70-99	1961-1970	19312	168757	5522	33298
70-99	1971-1980	16426	140850	4457	26837
70-99	1981-1990	13608	94515	3918	21293
70-99	1991-2000	8676	80559	3067	18231
70-99	2001-2005	2887	21936	412	2445
70-99	2006-2009	2235	29530	591	3264
100-149	-1919	45403	66688	13290	57253
100-149	1919-1945	39343	30841	4355	14957
100-149	1946-1960	43898	32806	3657	11964
100-149	1961-1970	38257	50216	4274	14474
100-149	1971-1980	52993	72430	4468	15008
100-149	1981-1990	53499	76000	4836	18087
100-149	1991-2000	41666	84270	3570	16173
100-149	2001-2005	18051	47702	713	4371
100-149	2006-2009	13569	60221	686	5007
150+	-1919	41010	22268	5945	29186
150+	1919-1945	27280	7969	1746	5856
150+	1946-1960	27193	7076	1387	3928
150+	1961-1970	28645	8892	1566	4417
150+	1971-1980	49452	12295	1689	4787
150+	1981-1990	65272	13679	2115	5671
150+	1991-2000	67527	16376	1593	5122
150+	2001-2005	39262	13544	472	1572
150+	2006-2009	32038	15265	444	1309

Table A.2: Past and predicted mean floor area[ha] by period and type of household in Switzerland.

Categories	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes	Total
- 1919	497	2269	2757	1830	7353
1919-1945	660	2935	4371	3199	11166
1946-1960	803	3588	6707	4655	15753
1961-1970	971	4378	9811	5988	21148
1971-1980	1138	5061	12783	7939	26921
1981-1990	1306	5688	15169	10210	32373
1991-2000	1430	6232	17535	12343	37540
2001-2005	1456	6352	18672	13481	39961
2006-2009	1485	6482	20079	14393	42439
2010-2020	1563	6841	23948	16901	49254
2020-2030	1634	7167	27466	19182	55449

Table A.3: Number of measurements by period of construction/renovation and type of building in Canton Geneva, 1990-2006.

Categories	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes	Total
-1919	2697	12	957	21	3687
1919-1945	4070	6	2740	16	6832
1946-1960	6143	0	10398	76	16617
1961-1970	4099	11	7389	26	11525
1971-1980	3425	32	6007	47	9511
1981-1990	2506	11	2665	29	5211
1991-2000	667	36	1160	11	1874
2001-2005	0	0	5	0	5
Total	23607	108	31321	226	55262

Table A.4: Individual homes: Energy sources and system used in Switzerland for heating and hot water production, 2009 FSO [2011b].

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
-1919	Solar collector	326	81	2	0	26	117	177	102	4	0
-1919	Electricity ohmic	29722	39	325	178	15311	4233	19925	2037	68	91
-1919	Wood	10522	13	17	8	276	99	751	61	4	23
-1919	District heating	36	0	543	1	5	11	47	5	0	0
-1919	Heat pump	173	5	5	0	45	42	235	1260	2	1
-1919	Gas	1061	3	44	16	122	10387	448	10	5	8
-1919	Oil	679	6	25	2	189	255	31081	38	9	11
-1919	Coal	11	0	1	59	1	0	9	4	0	0
-1919	Other	145	0	0	2	11	8	23	2	211	3
-1919	None	0	0	0	0	0	0	0	0	0	0
1919-1945	Solar collector	201	52	2	0	22	113	177	65	1	12
1919-1945	Electricity ohmic	7656	20	158	116	12584	5617	19043	963	41	193
1919-1945	Wood	3016	8	4	2	98	65	259	11	1	9
1919-1945	District heating	15	0	627	0	5	16	28	3	0	0

Continued on next page

Table A.4 – continued from previous page

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
1919-1945	Heat pump	43	2	6	0	24	39	228	730	1	0
1919-1945	Gas	1645	5	13	11	88	13576	510	8	5	65
1919-1945	Oil	242	3	29	3	94	449	30965	58	6	10
1919-1945	Coal	7	0	0	475	2	1	9	0	0	0
1919-1945	Other	47	0	0	0	11	8	11	6	451	2
1919-1945	None	0	0	0	0	0	0	0	0	0	0
1946-1960	Solar collector	134	50	5	0	24	85	246	79	1	0
1946-1960	Electricity ohmic	6104	10	186	181	12813	3469	28400	1125	41	160
1946-1960	Wood	2199	8	3	3	73	39	323	11	4	3
1946-1960	District heating	11	0	419	0	4	14	82	3	3	0
1946-1960	Heat pump	35	1	3	0	35	30	388	912	0	0
1946-1960	Gas	406	2	22	2	50	7549	256	4	3	3
1946-1960	Oil	237	9	40	5	154	327	42703	62	18	13
1946-1960	Coal	5	0	0	140	0	2	5	0	0	0
1946-1960	Other	55	0	1	0	9	3	33	1	420	0
1946-1960	None	0	0	0	0	0	0	0	0	0	0
1961-1970	Solar collector	79	43	1	0	14	46	282	67	0	0
1961-1970	Electricity ohmic	4092	24	174	72	8032	925	17928	808	31	138
1961-1970	Wood	2089	4	6	2	52	20	354	14	1	2
1961-1970	District heating	6	0	451	0	0	8	53	3	0	0
1961-1970	Heat pump	24	2	2	0	23	12	403	758	2	1
1961-1970	Gas	379	4	5	3	38	3643	205	1	2	9
1961-1970	Oil	270	12	35	3	151	230	52942	66	7	7
1961-1970	Coal	5	0	0	2	1	0	6	1	0	0
1961-1970	Other	33	1	0	0	8	1	20	4	57	2
1961-1970	None	0	0	0	0	0	0	0	0	0	0
1971-1980	Solar collector	89	75	2	1	77	67	423	109	4	1
1971-1980	Electricity ohmic	3128	50	135	14	24766	874	13001	2427	25	44
1971-1980	Wood	1906	9	4	1	87	15	374	16	1	1
1971-1980	District heating	11	0	694	0	8	48	258	11	1	0
1971-1980	Heat pump	42	8	6	1	75	27	547	1725	10	1
1971-1980	Gas	233	3	9	1	37	6382	132	6	2	5
1971-1980	Oil	293	14	51	2	170	130	65761	105	5	5
1971-1980	Coal	1	0	0	3	1	0	3	0	0	0
1971-1980	Other	18	0	0	0	13	3	22	5	168	0
1971-1980	None	0	0	0	0	0	0	0	0	0	0
1981-1990	Solar collector	118	82	3	1	79	117	273	204	2	0
1981-1990	Electricity ohmic	4965	61	438	11	34168	2616	27193	10506	40	12
1981-1990	Wood	2708	16	2	2	133	25	253	39	5	1
1981-1990	District heating	9	0	566	0	7	23	89	37	1	0
1981-1990	Heat pump	87	12	17	0	218	84	651	4542	7	0
1981-1990	Gas	170	8	16	2	46	14791	109	36	7	1
1981-1990	Oil	203	8	31	0	183	107	30088	111	2	1
1981-1990	Coal	2	0	1	4	1	0	4	2	0	0
1981-1990	Other	10	0	3	0	11	4	14	21	122	1
1981-1990	None	0	0	0	0	0	0	0	0	0	0
1991-2000	Solar collector	164	142	4	1	20	214	335	369	0	1
1991-2000	Electricity ohmic	2943	54	805	5	5994	4621	20367	16494	60	5
1991-2000	Wood	2642	43	62	0	28	84	106	53	2	2
1991-2000	District heating	28	2	1456	0	5	63	89	54	2	1
1991-2000	Heat pump	78	18	57	0	76	92	331	7406	14	2
1991-2000	Gas	148	9	29	4	41	24145	77	36	6	2
1991-2000	Oil	182	16	19	3	75	111	29811	113	3	2
1991-2000	Coal	3	1	0	2	2	0	7	1	0	0
1991-2000	Other	11	2	3	1	0	9	33	50	228	0
1991-2000	None	0	0	0	0	0	0	0	0	0	0
2001-2005	Solar collector	178	89	12	1	16	210	187	327	25	1
2001-2005	Electricity ohmic	1112	51	578	14	1963	2347	4793	10028	180	1
2001-2005	Wood	957	1	21	0	14	6	16	15	3	1
2001-2005	District heating	29	3	1533	0	1	12	22	35	3	0
2001-2005	Heat pump	55	9	24	0	37	33	80	9192	21	1
2001-2005	Gas	22	1	11	15	19	14376	50	39	8	0
2001-2005	Oil	25	0	0	4	9	22	11600	53	3	0
2001-2005	Coal	0	0	0	11	0	12	8	2	0	0
2001-2005	Other	4	0	1	0	3	12	13	41	439	0
2001-2005	None	0	0	0	0	0	0	0	0	0	0
2006-2009	Solar collector	336	130	12	0	33	438	107	1195	29	0
2006-2009	Electricity ohmic	1028	53	382	5	1488	1113	1033	12033	135	2
2006-2009	Wood	1157	4	18	0	19	5	4	49	2	0
2006-2009	District heating	11	1	1335	0	0	16	6	117	2	0
2006-2009	Heat pump	67	13	11	0	66	60	40	14670	15	0
2006-2009	Gas	20	2	4	2	16	7863	15	52	0	0

Continued on next page

Table A.4 – continued from previous page

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
2006-2009	Oil	11	3	4	1	0	4	2791	21	0	0
2006-2009	Coal	1	0	0	0	0	6	3	2	0	0
2006-2009	Other	13	2	1	0	3	4	9	83	276	0
2006-2009	None	0	0	0	0	0	0	0	0	0	0

Table A.5: Building with several households: Energy sources and system used in Switzerland for heating and hot water production, 2009 FSO [2011b].

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
			collector	heating		ohmic			pump		
-1919	Solar collector	118	26	7	0	10	81	200	53	3	0
-1919	Electricity ohmic	8961	19	310	69	8167	3980	15296	1102	79	12
-1919	Wood	3690	4	11	2	101	54	405	27	4	1
-1919	District heating	14	0	1154	0	8	31	55	5	1	0
-1919	Heat pump	59	1	11	0	16	30	175	733	0	0
-1919	Gas	186	1	72	12	96	11900	652	13	6	3
-1919	Oil	310	11	38	3	118	317	29323	47	13	4
-1919	Coal	4	0	0	53	0	3	3	0	0	0
-1919	Other	13	0	4	0	3	19	43	7	296	2
-1919	None	0	0	0	0	0	0	0	0	0	0
1919-1945	Solar collector	28	16	1	0	9	58	82	20	1	0
1919-1945	Electricity ohmic	1994	8	123	25	4099	2304	8494	336	22	12
1919-1945	Wood	777	3	5	1	26	20	97	7	0	1
1919-1945	District heating	5	0	835	0	0	15	31	0	0	0
1919-1945	Heat pump	17	0	3	0	16	21	95	310	2	0
1919-1945	Gas	78	1	44	5	45	7403	463	6	2	1
1919-1945	Oil	74	2	51	0	48	324	20285	27	7	5
1919-1945	Coal	1	0	0	221	1	2	4	0	0	0
1919-1945	Other	2	0	7	1	3	17	12	0	204	0
1919-1945	None	0	0	0	0	0	0	0	0	0	0
1946-1960	Solar collector	19	15	1	0	2	42	115	23	0	0
1946-1960	Electricity ohmic	1300	5	207	20	3723	1324	10947	314	13	34
1946-1960	Wood	577	1	0	0	18	13	98	2	2	2
1946-1960	District heating	2	3	1052	0	3	35	105	1	7	0
1946-1960	Heat pump	8	0	1	0	12	13	142	309	0	0
1946-1960	Gas	30	0	24	4	13	5088	388	3	3	4
1946-1960	Oil	69	5	48	1	56	280	27805	32	0	33
1946-1960	Coal	1	0	0	60	1	0	4	0	0	0
1946-1960	Other	3	0	23	0	1	39	112	1	456	0
1946-1960	None	0	0	0	0	0	0	0	0	0	0
1961-1970	Solar collector	21	9	1	0	5	37	121	24	1	0
1961-1970	Electricity ohmic	707	5	88	8	1932	297	5277	246	4	2
1961-1970	Wood	650	0	4	0	8	8	155	6	0	0
1961-1970	District heating	6	0	1017	0	0	35	169	2	8	0
1961-1970	Heat pump	7	1	4	0	7	11	129	290	0	0
1961-1970	Gas	18	3	16	0	8	3836	132	0	1	0
1961-1970	Oil	64	3	93	0	32	230	38312	50	25	1
1961-1970	Coal	0	0	0	11	0	0	2	0	0	0
1961-1970	Other	3	0	30	0	0	45	169	2	489	0
1961-1970	None	0	0	0	0	0	0	0	0	0	0
1971-1980	Solar collector	21	29	1	0	13	23	146	43	1	0
1971-1980	Electricity ohmic	678	10	61	0	4542	210	2938	409	9	2
1971-1980	Wood	780	3	1	0	20	7	120	7	1	0
1971-1980	District heating	2	0	909	0	0	33	191	2	9	0
1971-1980	Heat pump	10	4	7	0	28	7	127	360	1	0
1971-1980	Gas	12	0	31	0	8	2862	83	3	0	0
1971-1980	Oil	90	5	65	0	58	157	33708	35	25	0
1971-1980	Coal	0	0	0	0	0	0	0	0	0	0
1971-1980	Other	1	0	9	0	2	12	72	0	512	0
1971-1980	None	0	0	0	0	0	0	0	0	0	0
1981-1990	Solar collector	26	11	1	0	15	19	53	28	0	0
1981-1990	Electricity ohmic	1334	9	125	6	5770	873	6279	1560	16	2
1981-1990	Wood	983	1	7	0	33	7	119	18	1	0
1981-1990	District heating	2	0	555	0	2	35	81	5	2	0

Continued on next page

Table A.5 – continued from previous page

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
1981-1990	Heat pump	19	2	9	0	52	13	173	862	8	0
1981-1990	Gas	18	3	23	2	10	6369	144	22	1	0
1981-1990	Oil	61	9	63	0	56	118	16664	45	13	0
1981-1990	Coal	0	0	0	3	0	0	1	0	0	0
1981-1990	Other	3	1	4	0	0	39	50	6	402	0
1981-1990	None	0	0	0	0	0	0	0	0	0	0
1991-2000	Solar collector	38	34	4	0	8	39	99	42	3	0
1991-2000	Electricity ohmic	895	11	192	0	1266	1411	5642	1974	18	0
1991-2000	Wood	1143	10	12	0	7	33	88	13	0	0
1991-2000	District heating	11	2	898	0	1	52	64	9	9	0
1991-2000	Heat pump	19	3	10	0	7	22	96	1289	0	0
1991-2000	Gas	14	0	42	0	14	8414	106	11	1	0
1991-2000	Oil	52	11	41	0	25	206	12788	64	1	0
1991-2000	Coal	0	0	0	0	0	1	2	0	0	0
1991-2000	Other	1	1	4	0	2	73	133	6	1306	0
1991-2000	None	0	0	0	0	0	0	0	0	0	0
2001-2005	Solar collector	20	17	1	0	5	42	45	55	6	0
2001-2005	Electricity ohmic	264	7	85	0	323	679	1207	1047	26	1
2001-2005	Wood	358	1	11	0	7	1	7	3	0	0
2001-2005	District heating	3	0	586	0	0	9	8	9	3	0
2001-2005	Heat pump	11	6	0	0	3	15	31	1340	2	0
2001-2005	Gas	2	0	3	6	7	4873	20	43	1	1
2001-2005	Oil	5	0	7	1	7	10	3882	20	2	0
2001-2005	Coal	0	0	0	3	0	5	1	0	0	0
2001-2005	Other	2	0	3	0	2	12	1	10	169	0
2001-2005	None	0	0	0	0	0	0	0	0	0	0
2006-2009	Solar collector	84	26	14	0	2	175	38	178	5	1
2006-2009	Electricity ohmic	487	6	145	2	309	597	510	1896	52	1
2006-2009	Wood	835	2	13	0	3	7	3	9	0	0
2006-2009	District heating	16	1	913	0	0	20	14	44	2	1
2006-2009	Heat pump	24	4	8	0	8	47	33	4097	4	0
2006-2009	Gas	26	0	5	2	6	5057	10	74	2	1
2006-2009	Oil	4	2	2	1	3	19	1814	16	0	0
2006-2009	Coal	1	0	0	0	0	1	1	0	0	0
2006-2009	Other	4	0	3	0	0	12	4	11	250	0
2006-2009	None	0	0	0	0	0	0	0	0	0	0

Table A.6: Building partially used for habitation: Energy sources and system used in Switzerland for heating and hot water production, 2009 FSO [2011b].

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
-1919	Solar collector	33	7	1	0	1	18	39	4	0	0
-1919	Electricity ohmic	2173	4	220	32	1900	1466	5193	148	17	50
-1919	Wood	1547	1	7	1	18	55	102	1	0	17
-1919	District heating	20	0	552	0	1	19	57	1	0	0
-1919	Heat pump	17	0	2	0	12	29	129	159	0	1
-1919	Gas	196	0	20	2	29	3700	203	3	2	12
-1919	Oil	135	2	36	3	44	187	11436	23	2	18
-1919	Coal	4	0	0	45	0	0	2	1	0	0
-1919	Other	25	0	1	0	4	6	29	1	102	3
-1919	None	0	0	0	0	0	0	0	0	0	0
1919-1945	Solar collector	13	5	1	0	3	4	13	2	1	1
1919-1945	Electricity ohmic	492	1	48	12	585	388	1903	47	8	19
1919-1945	Wood	467	0	3	0	4	9	30	0	0	1
1919-1945	District heating	4	0	174	0	2	3	22	2	0	0
1919-1945	Heat pump	3	0	2	0	3	6	54	52	0	0
1919-1945	Gas	79	0	3	1	12	1087	82	2	0	1
1919-1945	Oil	26	1	14	0	17	60	4000	10	0	4
1919-1945	Coal	0	0	0	13	0	0	1	0	0	0
1919-1945	Other	11	0	0	0	2	0	8	0	13	0
1919-1945	None	0	0	0	0	0	0	0	0	0	0
1946-1960	Solar collector	8	2	0	0	1	5	11	1	0	0
1946-1960	Electricity ohmic	316	1	60	10	458	269	1930	44	5	14

Continued on next page

Table A.6 – continued from previous page

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
1946-1960	Wood	308	1	3	0	8	9	18	0	1	2
1946-1960	District heating	1	0	171	0	1	5	10	0	0	1
1946-1960	Heat pump	3	1	1	0	2	7	34	41	0	0
1946-1960	Gas	36	0	7	0	2	767	63	0	0	2
1946-1960	Oil	19	1	9	0	9	34	3645	4	2	5
1946-1960	Coal	0	0	0	14	0	2	1	0	0	0
1946-1960	Other	4	0	0	0	1	3	8	1	18	0
1946-1960	None	0	0	0	0	0	0	0	0	0	0
1961-1970	Solar collector	4	2	0	0	0	2	21	3	0	0
1961-1970	Electricity ohmic	239	1	45	2	313	114	1154	34	3	7
1961-1970	Wood	278	2	1	0	0	2	24	0	1	0
1961-1970	District heating	0	0	226	0	0	1	23	0	0	1
1961-1970	Heat pump	1	0	0	0	2	4	45	36	0	0
1961-1970	Gas	58	0	9	0	4	670	55	2	1	3
1961-1970	Oil	21	2	19	0	11	55	4795	12	4	5
1961-1970	Coal	0	0	0	2	1	0	0	0	0	0
1961-1970	Other	10	0	1	0	2	0	10	0	16	2
1961-1970	None	0	0	0	0	0	0	0	0	0	0
1971-1980	Solar collector	2	3	6	0	1	7	21	6	0	0
1971-1980	Electricity ohmic	198	0	30	0	590	106	826	55	7	6
1971-1980	Wood	230	0	2	0	2	4	18	3	0	1
1971-1980	District heating	5	0	235	0	0	9	31	2	0	0
1971-1980	Heat pump	0	0	4	0	7	3	40	60	0	0
1971-1980	Gas	52	1	3	1	3	633	36	3	0	0
1971-1980	Oil	23	0	12	0	16	37	4157	11	2	5
1971-1980	Coal	0	0	0	2	0	0	0	0	0	0
1971-1980	Other	3	0	2	0	0	2	5	0	11	0
1971-1980	None	0	0	0	0	0	0	0	0	0	0
1981-1990	Solar collector	6	2	0	0	0	7	12	5	0	0
1981-1990	Electricity ohmic	221	2	59	0	761	267	1288	208	5	3
1981-1990	Wood	271	2	3	0	3	7	20	3	0	0
1981-1990	District heating	4	1	131	0	2	6	12	1	0	0
1981-1990	Heat pump	7	0	4	0	7	12	66	179	0	0
1981-1990	Gas	25	0	9	0	4	1025	39	4	3	1
1981-1990	Oil	16	1	4	0	12	31	2579	15	1	0
1981-1990	Coal	0	0	0	1	0	0	0	0	0	0
1981-1990	Other	5	0	1	0	1	1	5	1	16	0
1981-1990	None	0	0	0	0	0	0	0	0	0	0
1991-2000	Solar collector	9	11	2	0	0	8	16	11	0	0
1991-2000	Electricity ohmic	198	3	42	3	255	205	738	165	1	4
1991-2000	Wood	219	1	2	0	0	4	15	0	0	0
1991-2000	District heating	4	0	164	0	1	8	11	2	0	0
1991-2000	Heat pump	7	2	2	0	1	11	23	164	0	0
1991-2000	Gas	14	0	12	0	3	935	20	3	0	1
1991-2000	Oil	9	1	3	0	7	35	1618	11	2	2
1991-2000	Coal	0	0	0	0	0	0	0	0	0	0
1991-2000	Other	0	0	2	0	0	5	6	3	32	0
1991-2000	None	0	0	0	0	0	0	0	0	0	0
2001-2005	Solar collector	5	1	0	0	0	3	6	5	0	0
2001-2005	Electricity ohmic	39	0	11	0	48	63	119	53	6	4
2001-2005	Wood	59	0	0	0	1	2	0	0	0	0
2001-2005	District heating	0	0	65	0	0	3	1	2	0	0
2001-2005	Heat pump	0	0	0	0	0	1	3	69	0	0
2001-2005	Gas	5	0	1	0	0	232	0	0	0	0
2001-2005	Oil	1	0	0	0	1	0	242	2	1	0
2001-2005	Coal	0	0	0	0	0	0	0	0	0	0
2001-2005	Other	1	0	1	0	1	4	0	0	13	0
2001-2005	None	0	0	0	0	0	0	0	0	0	0
2006-2009	Solar collector	11	3	2	0	0	10	3	7	0	0
2006-2009	Electricity ohmic	38	0	12	0	38	51	47	82	4	1
2006-2009	Wood	69	0	0	0	0	0	0	0	0	0
2006-2009	District heating	0	1	48	0	0	3	1	4	0	0
2006-2009	Heat pump	0	0	0	0	0	2	2	181	0	0
2006-2009	Gas	1	0	1	0	1	338	1	3	0	0
2006-2009	Oil	2	0	0	0	0	3	118	1	0	0
2006-2009	Coal	0	0	0	0	0	0	1	0	0	0
2006-2009	Other	0	0	0	0	0	0	2	0	6	1
2006-2009	None	0	0	0	0	0	0	0	0	0	0

Continued on next page

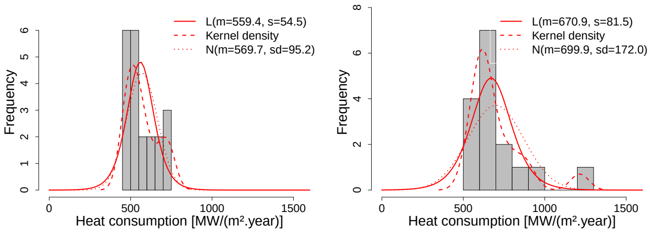
Table A.7: Housing with other end-use: Energy sources and system used in Switzerland for heating and hot water production in 2009 FSO [2011b].

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
-1919	Solar collector	216	28	2	0	6	46	110	41	1	0
-1919	Electricity ohmic	23667	15	359	79	5150	2792	11880	918	47	34
-1919	Wood	17327	11	23	1	177	71	746	46	12	6
-1919	District heating	30	0	976	0	1	24	58	3	0	1
-1919	Heat pump	167	0	6	1	28	33	144	552	2	0
-1919	Gas	247	2	66	3	61	8569	369	13	7	2
-1919	Oil	566	7	49	5	91	278	19710	40	9	5
-1919	Coal	11	0	0	60	0	1	5	0	0	0
-1919	Other	112	1	11	1	4	26	29	6	336	1
-1919	None	0	0	0	0	0	0	0	0	0	0
1919-1945	Solar collector	34	7	1	0	0	7	29	11	0	0
1919-1945	Electricity ohmic	3237	3	64	18	1190	714	3748	210	10	10
1919-1945	Wood	2712	1	2	1	26	12	143	12	0	0
1919-1945	District heating	2	0	346	0	0	4	18	0	0	0
1919-1945	Heat pump	26	0	3	0	1	11	50	120	0	0
1919-1945	Gas	52	1	22	2	19	2521	136	4	3	0
1919-1945	Oil	99	1	9	1	24	122	7607	12	3	2
1919-1945	Coal	3	0	0	29	0	0	2	0	0	0
1919-1945	Other	18	0	3	1	0	13	3	0	76	0
1919-1945	None	0	0	0	0	0	0	0	0	0	0
1946-1960	Solar collector	14	6	2	0	2	5	32	7	0	0
1946-1960	Electricity ohmic	1629	5	80	9	912	439	3208	116	4	4
1946-1960	Wood	1241	2	2	1	9	8	85	4	2	2
1946-1960	District heating	3	0	356	0	2	5	11	0	0	0
1946-1960	Heat pump	19	0	0	0	2	6	59	79	0	0
1946-1960	Gas	14	0	12	0	5	1376	59	1	0	0
1946-1960	Oil	59	2	41	0	18	67	7137	13	6	1
1946-1960	Coal	2	0	0	9	0	0	0	0	0	0
1946-1960	Other	8	0	8	0	1	17	17	0	70	1
1946-1960	None	0	0	0	0	0	0	0	0	0	0
1961-1970	Solar collector	17	8	2	0	0	6	31	9	0	0
1961-1970	Electricity ohmic	833	1	17	3	397	121	1422	75	4	7
1961-1970	Wood	986	2	5	0	7	10	94	1	1	0
1961-1970	District heating	3	0	395	0	0	4	38	1	0	0
1961-1970	Heat pump	12	0	1	0	0	8	81	69	1	0
1961-1970	Gas	22	3	4	0	1	939	45	1	2	0
1961-1970	Oil	47	3	73	0	19	80	8441	13	11	4
1961-1970	Coal	1	0	0	1	0	0	0	0	0	0
1961-1970	Other	3	0	11	0	0	5	23	1	60	1
1961-1970	None	0	0	0	0	0	0	0	0	0	0
1971-1980	Solar collector	18	7	0	0	4	4	47	7	0	0
1971-1980	Electricity ohmic	653	3	22	0	1029	71	908	170	3	1
1971-1980	Wood	1049	1	3	0	8	3	103	4	0	1
1971-1980	District heating	5	0	346	0	1	6	41	3	0	0
1971-1980	Heat pump	7	0	2	0	6	3	65	143	0	0
1971-1980	Gas	10	0	7	0	3	731	32	1	4	0
1971-1980	Oil	68	1	44	0	8	47	7531	15	12	2
1971-1980	Coal	0	0	0	1	0	0	1	0	0	0
1971-1980	Other	4	0	10	0	3	2	19	0	39	0
1971-1980	None	0	0	0	0	0	0	0	0	0	0
1981-1990	Solar collector	19	6	1	0	4	6	23	14	1	0
1981-1990	Electricity ohmic	1045	3	35	1	1474	298	2029	637	13	2
1981-1990	Wood	1272	4	4	0	16	12	65	8	1	0
1981-1990	District heating	2	0	244	0	0	13	15	6	0	0
1981-1990	Heat pump	9	0	4	0	11	6	65	352	4	0
1981-1990	Gas	12	1	7	0	4	2208	47	4	13	0
1981-1990	Oil	25	1	12	0	11	27	4005	15	20	2
1981-1990	Coal	0	0	0	1	0	0	0	0	0	0
1981-1990	Other	2	0	3	0	1	8	8	3	90	0
1981-1990	None	0	0	0	0	0	0	0	0	0	0
1991-2000	Solar collector	26	23	1	0	1	12	30	18	0	0
1991-2000	Electricity ohmic	734	12	74	0	307	356	1498	608	11	2
1991-2000	Wood	1351	4	7	0	8	10	60	6	1	0
1991-2000	District heating	5	0	302	0	0	16	17	5	0	0
1991-2000	Heat pump	18	0	2	0	1	12	36	427	1	0
1991-2000	Gas	16	1	6	1	2	2306	35	1	2	0
1991-2000	Oil	48	1	19	0	8	55	3051	13	0	0
1991-2000	Coal	0	0	0	0	0	0	1	0	0	0
1991-2000	Other	2	0	3	0	1	20	16	6	269	0

Continued on next page

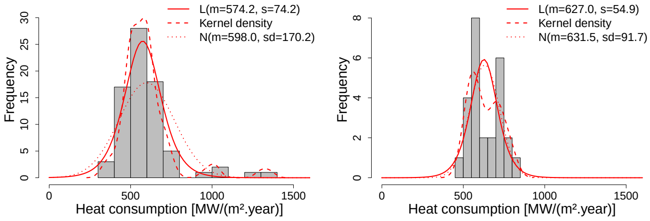
Table A.7 – continued from previous page

Period	Hot water system → Heating system ↓	Wood	Solar collector	District heating	Coal	Electricity ohmic	Gas	Oil	Heat pump	Other	None
1991-2000	None	0	0	0	0	0	0	0	0	0	0
2001-2005	Solar collector	5	3	0	0	1	4	1	8	0	0
2001-2005	Electricity ohmic	95	0	22	0	56	64	153	144	6	0
2001-2005	Wood	145	0	0	0	0	6	3	2	0	0
2001-2005	District heating	2	0	130	0	0	1	2	1	0	0
2001-2005	Heat pump	0	1	0	0	0	1	3	176	0	0
2001-2005	Gas	3	0	1	0	0	535	2	2	0	1
2001-2005	Oil	3	0	1	0	0	3	432	3	0	1
2001-2005	Coal	0	0	0	0	0	0	0	0	0	0
2001-2005	Other	1	0	0	0	1	0	0	2	28	0
2001-2005	None	0	0	0	0	0	0	0	0	0	0
2006-2009	Solar collector	16	3	2	0	1	22	7	34	3	0
2006-2009	Electricity ohmic	60	0	15	0	34	72	49	178	1	0
2006-2009	Wood	138	0	1	0	0	0	1	2	1	0
2006-2009	District heating	0	0	133	0	0	4	3	4	1	0
2006-2009	Heat pump	0	3	5	0	4	8	3	323	0	1
2006-2009	Gas	6	0	1	1	1	471	0	1	6	0
2006-2009	Oil	1	0	0	0	0	0	165	0	0	0
2006-2009	Coal	0	0	0	0	0	0	0	0	0	0
2006-2009	Other	1	0	0	0	0	4	1	1	7	0
2006-2009	None	0	0	0	0	0	0	0	0	0	0



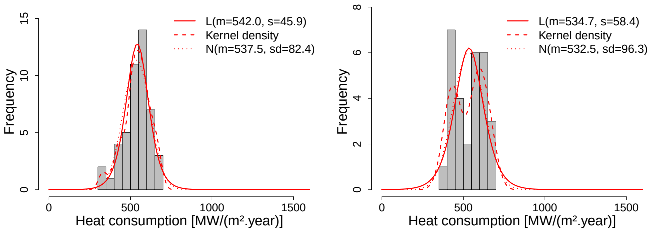
A.1.1: <1919

A.1.2: 1919-1945



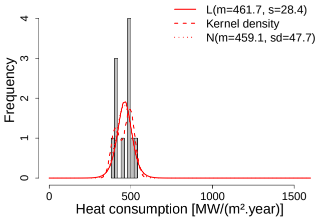
A.1.3: 1961-1970

A.1.4: 1961-1970



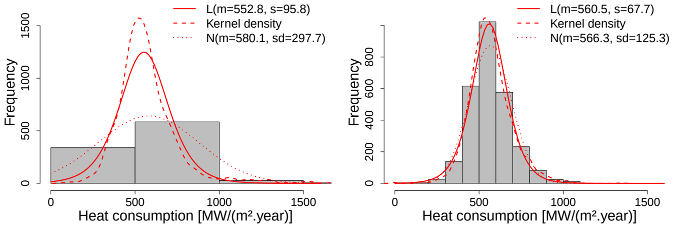
A.1.5: 1971-1980

A.1.6: 1981-1990

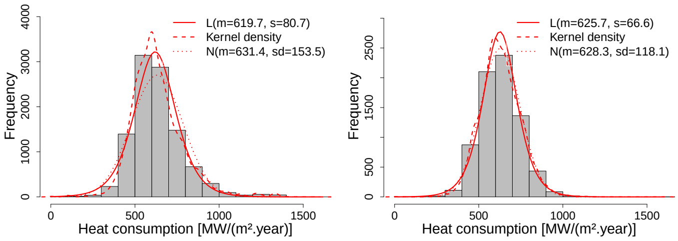


A.1.7: 1991-2000

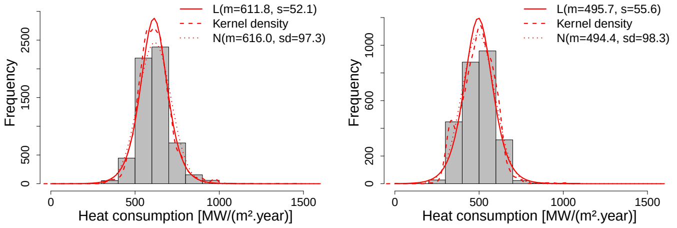
Figure A.1: Individual homes(ResidIndividual): Heat consumption histograms and density function fitting.



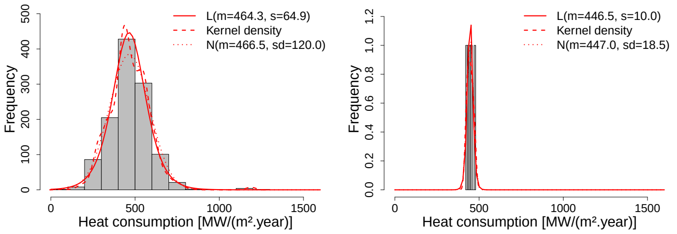
A.2.1: <1919 A.2.2: 1919-1945



A.2.3: 1961-1970 A.2.4: 1961-1970

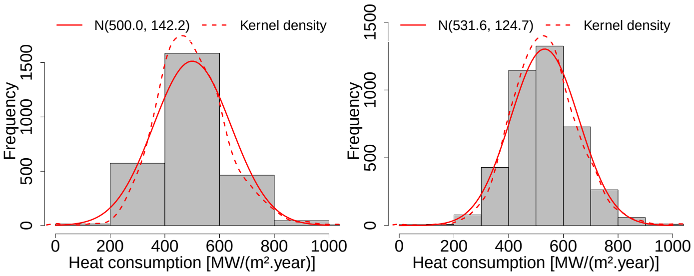


A.2.5: 1971-1980 A.2.6: 1981-1990



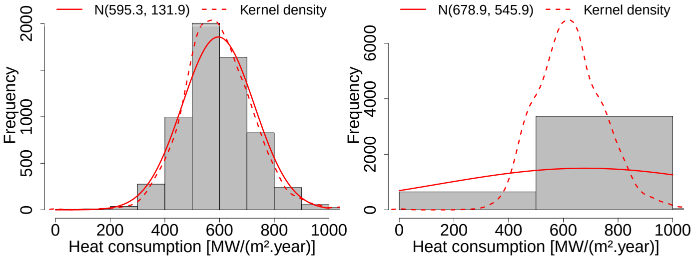
A.2.7: 1991-2000 A.2.8: 2001-2005

Figure A.2: Building with several households(ResidCollective): Heat consumption histograms and density function fitting.



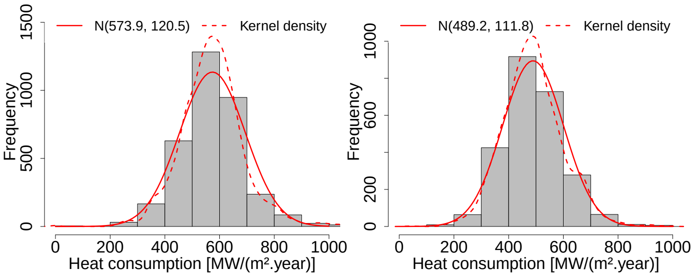
A.3.1: <1919

A.3.2: 1919-1945



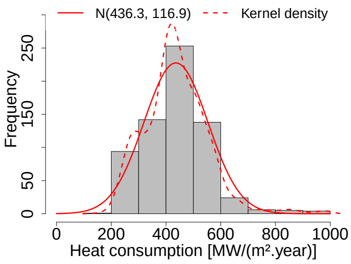
A.3.3: 1961-1970

A.3.4: 1961-1970



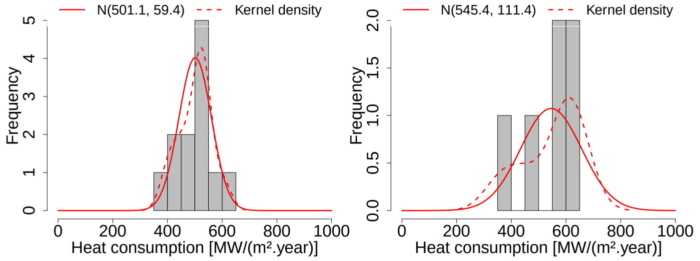
A.3.5: 1981-1990

A.3.6: 1981-1990

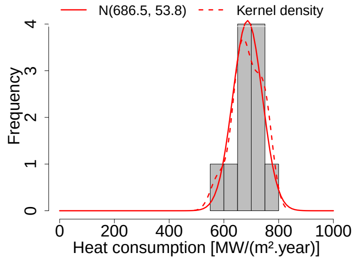


A.3.7: 1991-2000

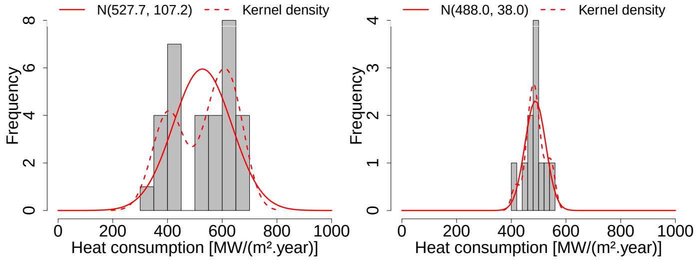
Figure A.3: Building partially used for habitation(Mix) Heat consumption histograms and density function fitting.



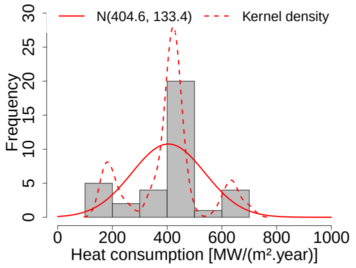
A.4.1: <1919 A.4.2: 1919-1945



A.4.3: 1961-1970 A.4.4: 1961-1970



A.4.5: 1981-1990 A.4.6: 1981-1990



A.4.7: 1991-2000

Figure A.4: Housing with other end-use(MixOther): Heat consumption histograms and density function fitting.

Table A.8: Specific heating and hot water final energy consumption grouped by category for a typical year in Geneva.

A.4.1: Mean values

$\mu(q^{hs+hw}_{f,Y_{ref}})$ $[MJ/(m^2.Y_{ref})]$	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes
<1919	**494**	**501**	**543**	**570**
1919-1945	**529**	**545**	**560**	**666**
1946-1960	**591**	616	**619**	**561**
1961-1970	**623**	**686**	**627**	**631**
1971-1980	**569**	**528**	**610**	**547**
1981-1990	**486**	**488**	**493**	**533**
1991-2000	**427**	**410**	**463**	**459**
2001-2005	392	354	**447**	436
2006-2009	362	340	414	422
2010-2020	294	244	343	350
2010-2030	227	163	305	298

A.4.2: Standard deviation

$\sigma(q^{hs+hw}_{f,Y_{ref}})$ $[MJ/(m^2.Y_{ref})]$	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes
<1919	**118**	**59**	**123**	**95**
1919-1945	**112**	**111**	**107**	**107**
1946-1960	**116**	83	**124**	**88**
1961-1970	**116**	**54**	**111**	**92**
1971-1980	**98**	**107**	**82**	**71**
1981-1990	**101**	**38**	**93**	**96**
1991-2000	**100**	**44**	**106**	**48**
2001-2005	99	41	94	67
2006-2009	97	21	93	60
2010-2020	91	24	86	53
2010-2030	88	9	87	44

Table A.9: Specific heating useful energy requirements.

A.4.1: Mean values

$\bar{q}^{hs}_{u,Y_{ref}}$ $[MJ/(m^2.Y_{ref})]$	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes
<1919	349	239	331	393
1919-1945	378	278	345	471
1946-1960	429	334	394	385
1961-1970	456	391	400	443
1971-1980	411	265	387	373
1981-1990	343	227	290	362
1991-2000	294	169	266	301
2001-2005	265	134	252	282
2006-2009	241	123	227	270
2010-2020	186	82	170	211
2010-2030	136	49	143	168

A.4.2: Standard deviation

$\sigma(q^{hs}_{u,Y_{ref}})$ $[MJ/(m^2.Y_{ref})]$	Building partially used for habitation	Housing with other end-use	Building with several households	Individual homes
<1919	102	96	110	87
1919-1945	97	120	99	98
1946-1960	101	108	113	81
1961-1970	102	97	103	86
1971-1980	87	117	82	69
1981-1990	88	89	88	87
1991-2000	86	85	96	51
2001-2005	85	76	88	64
2006-2009	82	71	85	59
2010-2020	75	50	77	53
2010-2030	68	29	74	46

Table A.10: Estimated share of heating and DHW technologies ([%]) in proportion to the inhabited area in Switzerland, 2009.

A.4.1: Space heating technologies

Technologies	1^{st} Quartile	Median	Mean	3^{rd} Quartile
oil	47.41	54.16	54.10	61.05
gas	10.59	15.53	16.06	20.81
wood	6.28	10.15	10.68	14.59
elec,ohm	4.47	8.06	8.75	12.48
elec,hp	4.31	7.47	7.97	10.96
dhn	0.00	0.46	2.26	3.64
coal	0.00	0.00	0.12	0.00
none	0.00	0.00	0.06	0.00

A.4.2: Domestic hot water technologies

Technologies	1^{st} Quartile	Median	Mean	3^{rd} Quartile
oil	33.03	39.75	39.83	46.60
elec,ohm	28.94	35.70	35.81	42.27
gas	8.48	12.99	13.63	18.13
wood	1.21	3.66	4.52	6.94
elec,hp	1.37	3.36	4.16	6.11
dhn	0.00	0.36	1.97	3.15
coal	0.00	0.00	0.08	0.00

B Chapter 3

Table B.1: Annual final and useful energy requirements of the Geneva case study.

Category	Construction/ Renovation	n_b	Final energy (q^{boil})			Useful energy		
			$\mu \pm \sigma_\mu$	σ	Heating	HW	Cooling	Electricity
		[-]	[$kWh/(m^2 \cdot year)$]			[$kWh/(m^2 \cdot year)$]		
Residential	< 1920	494	166.17±3.11	69.14	115.27	34.28	0.00	27.78
Residential	1920-1970	2533	181.39±0.82	41.51	128.97	34.28	0.00	27.78
Residential	1970-1980	938	174.84±1.20	36.80	123.07	34.28	0.00	27.78
Residential	1980-2005	1582	135.28±1.06	42.24	87.47	34.28	0.00	27.78
Residential	2005-2020	0	-	-	38.77	34.28	0.00	27.78
Residential	2020-2030	0	-	-	26.60	34.28	0.00	27.78
Residential Renovated	< 1920	0	-	-	35.12	34.28	0.00	27.78
Residential Renovated	1920-1970	0	-	-	52.17	34.28	0.00	27.78
Residential Renovated	1970-1980	0	-	-	47.30	34.28	0.00	27.78
Residential Renovated	1980-2005	0	-	-	54.60	34.28	0.00	27.78
Administrative	< 1920	29	137.05±12.04	64.86	111.92	11.43	0.00	22.22
Administrative	1920-1970	32	136.88±6.15	34.80	111.76	11.43	0.00	22.22
Administrative	1970-1980	18	141.64±8.11	34.41	116.05	11.43	13.15	22.22
Administrative	1980-2005	27	124.18±9.59	49.81	100.31	11.43	19.11	22.22
Administrative	2005-2020	0	-	-	55.63	11.43	25.37	22.22
Administrative	2020-2030	0	-	-	44.45	11.43	27.99	22.22
Administrative Renovated	< 1920	0	-	-	52.28	11.43	25.98	22.22
Administrative Renovated	1920-1970	0	-	-	67.92	11.43	26.03	22.22
Administrative Renovated	1970-1980	0	-	-	63.45	11.43	27.55	22.22
Administrative Renovated	1980-2005	0	-	-	70.16	11.43	25.49	22.22
Commercial	< 1920	1	56.11±0.00	0.00	27.65	22.85	0.00	33.33
Commercial	1920-1970	1	111.67±0.00	0.00	77.65	22.85	0.00	33.33
Commercial	1970-1980	1	97.22±0.00	0.00	64.65	22.85	34.33	33.33
Commercial	1980-2005	5	84.67±14.14	31.63	53.35	22.85	44.12	33.33
Commercial	2005-2020	0	-	-	22.87	22.85	52.94	33.33
Commercial	2020-2030	0	-	-	15.25	22.85	56.45	33.33
Commercial Renovated	< 1920	0	-	-	20.58	22.85	53.32	33.33
Commercial Renovated	1920-1970	0	-	-	31.25	22.85	53.39	33.33
Commercial Renovated	1970-1980	0	-	-	28.20	22.85	56.46	33.33
Commercial Renovated	1980-2005	0	-	-	32.77	22.85	53.00	33.33
Industrial	< 1920	4	181.11±18.21	36.43	151.57	11.43	0.00	16.67
Industrial	1920-1970	6	183.75±19.80	48.51	153.95	11.43	0.00	16.67
Industrial	1970-1980	1	146.67±0.00	0.00	120.57	11.43	0.00	16.67
Industrial	1980-2005	5	101.89±16.92	37.84	80.27	11.43	0.00	16.67
Industrial	2005-2020	0	-	-	43.59	11.43	0.00	16.67
Industrial	2020-2030	0	-	-	34.42	11.43	0.00	16.67
Industrial Renovated	< 1920	0	-	-	40.84	11.43	0.00	16.67
Industrial Renovated	1920-1970	0	-	-	53.68	11.43	0.00	16.67
Industrial Renovated	1970-1980	0	-	-	50.01	11.43	0.00	16.67
Industrial Renovated	1980-2005	3	144.26±1.80	3.12	55.51	11.43	0.00	16.67
Education	< 1920	1	100.83±0.00	0.00	67.90	22.85	0.00	11.11
Education	1920-1970	1	192.50±0.00	0.00	150.40	22.85	0.00	11.11
Education	1970-1980	2	196.11±55.00	77.78	153.65	22.85	1.37	11.11
Education	1980-2005	0	-	-	153.65	22.85	3.04	11.11
Education	2005-2020	0	-	-	83.05	22.85	4.83	11.11
Education	2020-2030	0	-	-	65.40	22.85	5.65	11.11
Education Renovated	< 1920	0	-	-	77.75	22.85	5.21	11.11
Education Renovated	1920-1970	0	-	-	102.46	22.85	5.23	11.11
Education Renovated	1970-1980	0	-	-	95.40	22.85	5.52	11.11
Education Renovated	1980-2005	0	-	-	105.99	22.85	4.95	11.11
Hospital	< 1920	0	-	-	96.51	45.71	0.00	27.78
Hospital	1920-1970	0	-	-	86.41	45.71	0.00	27.78
Hospital	1970-1980	5	159.56±13.52	30.24	97.89	45.71	6.14	27.78
Hospital	1980-2005	5	148.22±28.42	63.55	87.69	45.71	8.01	27.78
Hospital	2005-2020	0	-	-	34.33	45.71	9.98	27.78
Hospital	2020-2030	0	-	-	20.99	45.71	10.77	27.78
Hospital Renovated	< 1920	0	-	-	30.31	45.71	10.06	27.78
Hospital Renovated	1920-1970	0	-	-	49.01	45.71	10.07	27.78
Hospital Renovated	1970-1980	0	-	-	43.67	45.71	10.67	27.78
Hospital Renovated	1980-2005	0	-	-	51.67	45.71	10.00	27.78
Hotel	< 1920	5	159.00±10.21	22.82	97.39	45.71	0.00	33.33
Hotel	1920-1970	2	203.33±12.22	17.28	137.29	45.71	0.00	33.33
Hotel	1970-1980	2	223.33±31.11	44.00	155.29	45.71	4.61	33.33
Hotel	1980-2005	2	128.47±2.64	3.73	69.92	45.71	7.56	33.33
Hotel	2005-2020	0	-	-	23.67	45.71	10.83	33.33
Hotel	2020-2030	0	-	-	12.11	45.71	12.49	33.33
Hotel Renovated	< 1920	0	-	-	20.20	45.71	11.11	33.33
Hotel Renovated	1920-1970	0	-	-	36.39	45.71	11.13	33.33
Hotel Renovated	1970-1980	0	-	-	31.76	45.71	11.77	33.33
Hotel Renovated	1980-2005	0	-	-	38.70	45.71	10.78	33.33
Other	< 1920	903	150.49±1.33	39.85	107.69	27.75	0.00	27.78
Other	1920-1970	1421	173.59±1.62	60.90	128.48	27.75	0.00	27.78
Other	1970-1980	473	163.41±1.59	34.67	119.31	27.75	8.51	27.78
Other	1980-2005	715	136.00±1.49	39.95	94.65	27.75	11.69	27.78
Other	2005-2020	0	-	-	45.69	27.75	14.85	27.78
Other	2020-2030	0	-	-	33.45	27.75	16.19	27.78
Other Renovated	< 1920	0	-	-	42.02	27.75	15.10	27.78
Other Renovated	1920-1970	0	-	-	59.15	27.75	15.12	27.78
Other Renovated	1970-1980	0	-	-	54.26	27.75	16.00	27.78
Other Renovated	1980-2005	0	-	-	61.60	27.75	14.89	27.78

Table B.2: Parameters of the energy signature model for typified buildings of the Geneva case study.

Category	Construction/ Renovation	Heating			Cooling	
		k_1^{hs} $W/(C \cdot m^2)$	k_2^{hs} W/m^2	T_{tr}^{hs} C	k_1^{cs} $W/(C \cdot m^2)$	k_2^{cs} W/m^2
Residential	< 1920	-1.81	28.06	15.5	0.00	0.00
Residential	1920-1970	-2.02	31.20	15.5	0.00	0.00
Residential	1970-1980	-2.09	32.32	15.5	0.00	0.00
Residential	1980-2005	-1.52	23.59	15.5	0.00	0.00
Residential	2005-2020	-0.83	12.91	15.5	0.00	0.00
Residential	2020-2030	-0.63	9.77	15.5	0.00	0.00
Residential Renovated	< 1920	-0.99	15.25	15.5	0.00	0.00
Residential Renovated	1920-1970	-0.99	15.28	15.5	0.00	0.00
Residential Renovated	1970-1980	-1.02	15.76	15.5	0.00	0.00
Residential Renovated	1980-2005	-1.06	16.43	15.5	0.00	0.00
Administrative	< 1920	-1.93	27.49	14.2	0.00	0.00
Administrative	1920-1970	-1.93	27.45	14.2	0.00	0.00
Administrative	1970-1980	-2.15	30.56	14.2	1.59	22.65
Administrative	1980-2005	-1.87	26.51	14.2	2.32	32.93
Administrative	2005-2020	-0.80	11.41	14.2	3.08	43.71
Administrative	2020-2030	-0.60	8.52	14.2	3.39	48.22
Administrative Renovated	< 1920	-1.00	14.21	14.2	3.15	44.77
Administrative Renovated	1920-1970	-1.00	14.18	14.2	3.16	44.84
Administrative Renovated	1970-1980	-0.97	13.72	14.2	3.34	47.47
Administrative Renovated	1980-2005	-1.15	16.29	14.2	3.09	43.93
Commercial	< 1920	-0.42	6.94	16.4	0.00	0.00
Commercial	1920-1970	-1.10	18.03	16.4	0.00	0.00
Commercial	1970-1980	-1.01	16.48	16.4	4.16	68.12
Commercial	1980-2005	-0.84	13.81	16.4	5.35	87.54
Commercial	2005-2020	-0.58	9.47	16.4	6.42	105.03
Commercial	2020-2030	-0.45	7.32	16.4	6.85	112.00
Commercial Renovated	< 1920	-0.38	6.15	16.4	6.47	105.78
Commercial Renovated	1920-1970	-0.75	12.19	16.4	6.47	105.92
Commercial Renovated	1970-1980	-0.64	10.39	16.4	6.85	112.03
Commercial Renovated	1980-2005	-0.67	10.89	16.4	6.43	105.16
Industrial	< 1920	-2.08	34.03	16.4	0.00	0.00
Industrial	1920-1970	-2.11	34.56	16.4	0.00	0.00
Industrial	1970-1980	-1.78	29.13	16.4	0.00	0.00
Industrial	1980-2005	-1.20	19.59	16.4	0.00	0.00
Industrial	2005-2020	-0.59	9.70	16.4	0.00	0.00
Industrial	2020-2030	-0.46	7.45	16.4	0.00	0.00
Industrial Renovated	< 1920	-0.74	12.12	16.4	0.00	0.00
Industrial Renovated	1920-1970	-0.74	12.12	16.4	0.00	0.00
Industrial Renovated	1970-1980	-0.68	11.14	16.4	0.00	0.00
Industrial Renovated	1980-2005	-0.78	12.70	16.4	0.00	0.00
Education	< 1920	-1.21	17.27	14.2	0.00	0.00
Education	1920-1970	-2.61	37.20	14.2	0.00	0.00
Education	1970-1980	-2.87	40.87	14.2	0.17	2.37
Education	1980-2005	-2.03	28.84	14.2	0.37	5.24
Education	2005-2020	-0.93	13.19	14.2	0.59	8.34
Education	2020-2030	-0.70	10.02	14.2	0.69	9.75
Education Renovated	< 1920	-0.98	13.88	14.2	0.63	9.00
Education Renovated	1920-1970	-1.10	15.58	14.2	0.63	9.02
Education Renovated	1970-1980	-1.03	14.72	14.2	0.67	9.52
Education Renovated	1980-2005	-1.22	17.32	14.2	0.60	8.54
Hospital	< 1920	-1.45	23.76	16.4	0.00	0.00
Hospital	1920-1970	-1.45	23.76	16.4	0.00	0.00
Hospital	1970-1980	-1.59	25.96	16.4	0.74	12.18
Hospital	1980-2005	-1.44	23.54	16.4	0.97	15.90
Hospital	2005-2020	-0.71	11.62	16.4	1.21	19.80
Hospital	2020-2030	-0.55	9.02	16.4	1.31	21.38
Hospital Renovated	< 1920	-0.81	13.29	16.4	1.22	19.96
Hospital Renovated	1920-1970	-0.81	13.26	16.4	1.22	19.99
Hospital Renovated	1970-1980	-0.79	12.87	16.4	1.29	21.18
Hospital Renovated	1980-2005	-0.91	14.96	16.4	1.21	19.83
Hotel	< 1920	-1.16	19.06	16.4	0.00	0.00
Hotel	1920-1970	-1.71	27.91	16.4	0.00	0.00
Hotel	1970-1980	-2.14	35.00	16.4	0.56	9.14
Hotel	1980-2005	-0.90	14.79	16.4	0.92	15.00
Hotel	2005-2020	-0.81	13.23	16.4	1.31	21.48
Hotel	2020-2030	-0.61	10.00	16.4	1.51	24.78
Hotel Renovated	< 1920	-0.93	15.18	16.4	1.35	22.04
Hotel Renovated	1920-1970	-0.96	15.63	16.4	1.35	22.08
Hotel Renovated	1970-1980	-0.93	15.26	16.4	1.43	23.35
Hotel Renovated	1980-2005	-0.83	13.61	16.4	1.31	21.38
Other	< 1920	-1.33	21.71	16.4	0.00	0.00
Other	1920-1970	-1.69	27.68	16.4	0.00	0.00
Other	1970-1980	-1.78	29.05	16.4	0.00	0.00
Other	1980-2005	-1.27	20.77	16.4	0.00	0.00
Other	2005-2020	-0.69	11.30	16.4	0.00	0.00
Other	2020-2030	-0.53	8.61	16.4	0.00	0.00
Other Renovated	< 1920	-0.76	12.47	16.4	0.00	0.00
Other Renovated	1920-1970	-0.83	13.61	16.4	0.00	0.00
Other Renovated	1970-1980	-0.79	13.00	16.4	0.00	0.00
Other Renovated	1980-2005	-0.86	14.13	16.4	0.00	0.00

Table B.3: Seasonal mean power requirements computed with the energy signature model for the Geneva case study.

Category	Chauffage $[W/m^2]$				Cooling $[W/m^2]$				Hot Water $[W/m^2]$
	Summer	Mid-Season	Winter	Annual	Summer	Mid-Season	Winter	Annuel	Annuel
Residential < 1920	3.44	9.99	24.60	16.19	0.00	0.00	0.00	0.00	3.61
Residential 1920-1970	3.81	11.15	27.25	17.89	0.00	0.00	0.00	0.00	3.61
Residential 1970-1980	3.80	11.50	28.18	18.38	0.00	0.00	0.00	0.00	3.61
Residential 1980-2005	2.81	8.36	20.81	13.69	0.00	0.00	0.00	0.00	3.61
Residential 2005-2020	1.60	4.62	11.54	7.73	0.00	0.00	0.00	0.00	3.61
Residential 2020-2030	1.20	3.50	8.78	5.89	0.00	0.00	0.00	0.00	3.61
Residential Renovated < 1920	1.88	5.45	13.59	9.07	0.00	0.00	0.00	0.00	3.61
Residential Renovated 1920-1970	1.89	5.46	13.62	9.09	0.00	0.00	0.00	0.00	3.61
Residential Renovated 1970-1980	1.96	5.64	14.04	9.38	0.00	0.00	0.00	0.00	3.61
Residential Renovated 1980-2005	1.97	5.85	14.63	9.72	0.00	0.00	0.00	0.00	3.61
Administrative < 1920	3.27	9.39	23.61	15.97	0.00	0.00	0.00	0.00	1.27
Administrative 1920-1970	3.26	9.37	23.58	15.95	0.00	0.00	0.00	0.00	1.27
Administrative 1970-1980	3.50	10.36	26.11	17.49	7.77	4.95	0.00	6.95	1.27
Administrative 1980-2005	3.09	9.02	22.81	15.40	11.30	7.19	0.00	10.10	1.27
Administrative 2005-2020	1.33	3.86	10.08	6.92	15.00	9.55	0.00	13.41	1.27
Administrative 2020-2030	1.04	2.89	7.56	5.23	16.55	10.53	0.00	14.79	1.27
Administrative Renovated < 1920	1.70	4.83	12.49	8.57	15.36	9.78	0.00	13.73	1.27
Administrative Renovated 1920-1970	1.70	4.82	12.46	8.55	15.39	9.79	0.00	13.76	1.27
Administrative Renovated 1970-1980	1.63	4.66	12.06	8.28	16.29	10.37	0.00	14.56	1.27
Administrative Renovated 1980-2005	1.94	5.56	14.26	9.78	15.07	9.59	0.00	13.47	1.27
Commercial < 1920	0.88	2.56	6.34	4.19	0.00	0.00	0.00	0.00	2.54
Commercial 1920-1970	2.28	6.65	16.48	10.90	0.00	0.00	0.00	0.00	2.54
Commercial 1970-1980	2.08	6.07	15.07	9.96	20.30	12.92	0.00	18.15	2.54
Commercial 1980-2005	1.74	5.09	12.62	8.34	26.09	16.60	0.00	23.32	2.54
Commercial 2005-2020	1.19	3.49	8.65	5.72	31.30	19.92	0.00	27.98	2.54
Commercial 2020-2030	0.92	2.70	6.69	4.42	33.38	21.24	0.00	29.84	2.54
Commercial Renovated < 1920	0.78	2.27	5.62	3.72	31.52	20.06	0.00	28.18	2.54
Commercial Renovated 1920-1970	1.54	4.49	11.14	7.37	31.56	20.09	0.00	28.22	2.54
Commercial Renovated 1970-1980	1.31	3.83	9.50	6.28	33.39	21.25	0.00	29.84	2.54
Commercial Renovated 1980-2005	1.37	4.01	9.95	6.58	31.34	19.94	0.00	28.01	2.54
Industrial < 1920	4.29	12.54	31.11	20.57	0.00	0.00	0.00	0.00	1.27
Industrial 1920-1970	4.36	12.74	31.59	20.88	0.00	0.00	0.00	0.00	1.27
Industrial 1970-1980	3.68	10.73	26.63	17.60	0.00	0.00	0.00	0.00	1.27
Industrial 1980-2005	2.47	7.22	17.91	11.84	0.00	0.00	0.00	0.00	1.27
Industrial 2005-2020	1.22	3.57	8.87	5.86	0.00	0.00	0.00	0.00	1.27
Industrial 2020-2030	0.94	2.75	6.81	4.50	0.00	0.00	0.00	0.00	1.27
Industrial Renovated < 1920	1.53	4.47	11.08	7.32	0.00	0.00	0.00	0.00	1.27
Industrial Renovated 1920-1970	1.53	4.47	11.08	7.33	0.00	0.00	0.00	0.00	1.27
Industrial Renovated 1970-1980	1.41	4.11	10.19	6.73	0.00	0.00	0.00	0.00	1.27
Industrial Renovated 1980-2005	1.60	4.68	11.61	7.67	0.00	0.00	0.00	0.00	1.27
Education < 1920	2.09	5.86	15.35	10.61	0.00	0.00	0.00	0.00	2.54
Education 1920-1970	4.32	12.65	32.54	22.22	0.00	0.00	0.00	0.00	2.54
Education 1970-1980	4.69	13.90	35.65	24.27	0.81	0.52	0.00	0.73	2.54
Education 1980-2005	3.40	9.78	25.40	17.42	1.80	1.14	0.00	1.60	2.54
Education 2005-2020	1.65	4.46	11.75	8.14	2.86	1.82	0.00	2.55	2.54
Education 2020-2030	1.25	3.40	8.95	6.22	3.34	2.13	0.00	2.99	2.54
Education Renovated < 1920	1.75	4.71	12.37	8.57	3.08	1.96	0.00	2.76	2.54
Education Renovated 1920-1970	1.86	5.27	13.86	9.57	3.09	1.97	0.00	2.76	2.54
Education Renovated 1970-1980	1.87	5.00	13.10	9.09	3.26	2.08	0.00	2.92	2.54
Education Renovated 1980-2005	2.10	5.88	15.39	10.64	2.93	1.86	0.00	2.62	2.54
Hospital < 1920	3.00	8.75	21.72	14.36	0.00	0.00	0.00	0.00	4.82
Hospital 1920-1970	3.00	8.75	21.72	14.36	0.00	0.00	0.00	0.00	4.82
Hospital 1970-1980	3.27	9.57	23.73	15.69	3.63	2.31	0.00	3.24	4.82
Hospital 1980-2005	2.97	8.68	21.52	14.23	4.74	3.02	0.00	4.24	4.82
Hospital 2005-2020	1.47	4.28	10.62	7.02	5.90	3.76	0.00	5.28	4.82
Hospital 2020-2030	1.14	3.32	8.25	5.45	6.37	4.05	0.00	5.69	4.82
Hospital Renovated < 1920	1.68	4.90	12.15	8.03	5.95	3.79	0.00	5.32	4.82
Hospital Renovated 1920-1970	1.67	4.89	12.12	8.01	5.96	3.79	0.00	5.32	4.82
Hospital Renovated 1970-1980	1.62	4.74	11.76	7.78	6.31	4.02	0.00	5.64	4.82
Hospital Renovated 1980-2005	1.89	5.51	13.67	9.04	5.91	3.76	0.00	5.28	4.82
Hotel < 1920	2.40	7.02	17.42	11.52	0.00	0.00	0.00	0.00	7.55
Hotel 1920-1970	3.52	10.29	25.51	16.87	0.00	0.00	0.00	0.00	7.55
Hotel 1970-1980	4.42	12.90	31.99	21.15	2.72	1.73	0.00	2.43	7.55
Hotel 1980-2005	1.87	5.45	13.52	8.94	4.47	2.84	0.00	4.00	7.55
Hotel 2005-2020	1.67	4.88	12.09	8.00	6.40	4.07	0.00	5.72	7.55
Hotel 2020-2030	1.26	3.68	9.14	6.04	7.38	4.70	0.00	6.60	7.55
Hotel Renovated < 1920	1.91	5.59	13.87	9.17	6.57	4.18	0.00	5.87	7.55
Hotel Renovated 1920-1970	1.97	5.76	14.28	9.44	6.58	4.19	0.00	5.88	7.55
Hotel Renovated 1970-1980	1.93	5.62	13.95	9.22	6.96	4.43	0.00	6.22	7.55
Hotel Renovated 1980-2005	1.72	5.02	12.44	8.22	6.37	4.05	0.00	5.70	7.55
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B.4: Design temperature of the domestic hydronic system of the Geneva case study.

Category	heating				Cooling		
	T.sizing [$^\circ C$]	T.supply [$^\circ C$]	T.return [$^\circ C$]	T.treshold [$^\circ C$]	T.supply [$^\circ C$]	T.return [$^\circ C$]	T.treshold [$^\circ C$]
Residential < 1920	-6/35	65.0	50.0	16.6	12.0	17.0	18.0
Residential 1920-1970	-6/35	65.0	50.0	16.7	12.0	17.0	18.0
Residential 1970-1980	-6/35	65.0	50.0	16.7	12.0	17.0	18.0
Residential 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Residential 2005-2020	-6/35	41.5	33.9	16.0	12.0	17.0	18.0
Residential 2020-2030	-6/35	39.6	32.3	15.9	12.0	17.0	18.0
Residential Renovated < 1920	-6/35	54.4	44.1	16.1	12.0	17.0	18.0
Residential Renovated 1920-1970	-6/35	54.4	44.1	16.1	12.0	17.0	18.0
Residential Renovated 1970-1980	-6/35	53.8	43.8	16.1	12.0	17.0	18.0
Residential Renovated 1980-2005	-6/35	56.3	45.3	16.1	12.0	17.0	18.0
Administrative < 1920	-6/35	65.0	50.0	15.7	12.0	17.0	18.0
Administrative 1920-1970	-6/35	65.0	50.0	15.7	12.0	17.0	18.0
Administrative 1970-1980	-6/35	65.0	50.0	15.8	12.0	17.0	18.0
Administrative 1980-2005	-6/35	65.0	50.0	15.6	12.0	17.0	18.0
Administrative 2005-2020	-6/35	41.5	33.9	14.8	12.0	17.0	18.0
Administrative 2020-2030	-6/35	39.6	32.3	14.7	12.0	17.0	18.0
Administrative Renovated < 1920	-6/35	54.4	44.1	15.0	12.0	17.0	18.0
Administrative Renovated 1920-1970	-6/35	54.4	44.1	15.0	12.0	17.0	18.0
Administrative Renovated 1970-1980	-6/35	53.8	43.8	14.9	12.0	17.0	18.0
Administrative Renovated 1980-2005	-6/35	56.3	45.3	15.1	12.0	17.0	18.0
Commercial < 1920	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Commercial 1920-1970	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Commercial 1970-1980	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Commercial 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Commercial 2005-2020	-6/35	41.5	33.9	16.4	12.0	17.0	18.0
Commercial 2020-2030	-6/35	39.6	32.3	16.4	12.0	17.0	18.0
Commercial Renovated < 1920	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Commercial Renovated 1920-1970	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Commercial Renovated 1970-1980	-6/35	53.8	43.8	16.4	12.0	17.0	18.0
Commercial Renovated 1980-2005	-6/35	56.3	45.3	16.4	12.0	17.0	18.0
Industrial < 1920	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Industrial 1920-1970	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Industrial 1970-1980	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Industrial 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Industrial 2005-2020	-6/35	41.5	33.9	16.4	12.0	17.0	18.0
Industrial 2020-2030	-6/35	39.6	32.3	16.4	12.0	17.0	18.0
Industrial Renovated < 1920	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Industrial Renovated 1920-1970	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Industrial Renovated 1970-1980	-6/35	53.8	43.8	16.4	12.0	17.0	18.0
Industrial Renovated 1980-2005	-6/35	56.3	45.3	16.4	12.0	17.0	18.0
Education < 1920	-6/35	65.0	50.0	14.6	12.0	17.0	18.0
Education 1920-1970	-6/35	65.0	50.0	15.1	12.0	17.0	18.0
Education 1970-1980	-6/35	65.0	50.0	15.2	12.0	17.0	18.0
Education 1980-2005	-6/35	65.0	50.0	14.9	12.0	17.0	18.0
Education 2005-2020	-6/35	41.5	33.9	14.5	12.0	17.0	18.0
Education 2020-2030	-6/35	39.6	32.3	14.5	12.0	17.0	18.0
Education Renovated < 1920	-6/35	54.4	44.1	14.6	12.0	17.0	18.0
Education Renovated 1920-1970	-6/35	54.4	44.1	14.6	12.0	17.0	18.0
Education Renovated 1970-1980	-6/35	53.8	43.8	14.6	12.0	17.0	18.0
Education Renovated 1980-2005	-6/35	56.3	45.3	14.6	12.0	17.0	18.0
Hospital < 1920	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hospital 1920-1970	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hospital 1970-1980	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hospital 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hospital 2005-2020	-6/35	41.5	33.9	16.4	12.0	17.0	18.0
Hospital 2020-2030	-6/35	39.6	32.3	16.4	12.0	17.0	18.0
Hospital Renovated < 1920	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Hospital Renovated 1920-1970	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Hospital Renovated 1970-1980	-6/35	53.8	43.8	16.4	12.0	17.0	18.0
Hospital Renovated 1980-2005	-6/35	56.3	45.3	16.4	12.0	17.0	18.0
Hotel < 1920	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hotel 1920-1970	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hotel 1970-1980	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hotel 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Hotel 2005-2020	-6/35	41.5	33.9	16.4	12.0	17.0	18.0
Hotel 2020-2030	-6/35	39.6	32.3	16.4	12.0	17.0	18.0
Hotel Renovated < 1920	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Hotel Renovated 1920-1970	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Hotel Renovated 1970-1980	-6/35	53.8	43.8	16.4	12.0	17.0	18.0
Hotel Renovated 1980-2005	-6/35	56.3	45.3	16.4	12.0	17.0	18.0
Other < 1920	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Other 1920-1970	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Other 1970-1980	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Other 1980-2005	-6/35	65.0	50.0	16.4	12.0	17.0	18.0
Other 2005-2020	-6/35	41.5	33.9	16.4	12.0	17.0	18.0
Other 2020-2030	-6/35	39.6	32.3	16.4	12.0	17.0	18.0
Other Renovated < 1920	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Other Renovated 1920-1970	-6/35	54.4	44.1	16.4	12.0	17.0	18.0
Other Renovated 1970-1980	-6/35	53.8	43.8	16.4	12.0	17.0	18.0
Other Renovated 1980-2005	-6/35	56.3	45.3	16.4	12.0	17.0	18.0

C Chapter 4

Table C.1: Topological constraint.

Unique root node among starting nodes	$\sum_{s\in N_s} X_s = 1$	(C.1a)
At least one root node having a child	$\sum_{\substack{(s,i)\in P\\ s\in N_s}} Y_{s,i} \geq 1$	(C.1b)
Root node have no parent	$\sum_{\substack{(i,s)\in P\\ s\in N_s}} Y_{i,s} = 0$	(C.1c)
No connection between root nodes	$\sum_{\substack{(s_1,s_2)\in P\\ s_1,s_2\in N_s}} Y_{s_1,s_2} = 0$	(C.1d)
Parent nodes are connected	$Y_{j,n} <= X_j,\ \forall (j,n) \in P$	(C.1e)
Each node has only one parent	$\sum_{(j,n)\in P} Y_{j,n} = X_n,\ \forall n \in N - N_s$	(C.1f)
Unique connection from parent to child node	$Y_{j,n} + Y_{n,j} <= 1,\ \forall (j,n) \in P$	(C.1g)
Minimal delivered power	$\sum_{n\in N} X_n \cdot (\dot{Q}_0)_n \geq \dot{Q}_{target}$	(C.1h)

Table C.2: Flow balances.

Energy balance 1	$\sum_{(j,n)\in P} \left(\dot{Q}_{j,n} - (\dot{Q}_{loss})_{j,n}\right) - \sum_{(n,i)\in P} \dot{Q}_{n,i} = (\dot{Q}_0)_n \cdot X_n,\ \forall n \in N - N_s$	(C.2a)
Energy balance 2	$\sum_{\substack{(s,n)\in P\\ s\in N_s}} \dot{Q}_{s,n} = \sum_{n\in N-N_s} (\dot{Q}_0)_n \cdot X_n + \sum_{(j,n)\in P} (\dot{Q}_{loss})_{j,n}$	(C.2b)
flow constraint 1	$\dot{Q}_{j,n} \leq \dot{Q}_{max} \cdot Y_{j,n},\ \forall (j,n) \in P$	(C.2c)
flow constraint 2	$\dot{Q}_{j,n} \geq \dot{Q}_{min} \cdot Y_{j,n},\ \forall (j,n) \in P$	(C.2d)

$$\Delta P_{loss}^{pipe} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot \left(\frac{\gamma \cdot L}{d}\right) \tag{C.3}$$

$$\dot{Q}_{loss}^{pipe} = \dot{m} \cdot c_{p_w} \cdot \left(T_{in}^{pipe} - T_{out}^{pipe}\right) \tag{C.4}$$

D Chapter 5

Table D.1: Temperatures as a function of the Heat Load.

D.0.1: Scenario as Usual

T_x $[C]$	Duration $[hour]$	Load $[kW]$	Water Flow $[m^3/h]$	Supply T $[C]$	Return T $[C]$	Target T $[C]$
19	163	80.0	20.7	22.2	24.5	25.5
20	173	120.0	20.7	20.5	23.7	25.5
21	153	160.0	20.7	18.7	22.9	25.3
22	167	200.0	20.7	16.9	22.2	25.2
23	137	240.0	20.7	15.0	21.4	25.0
24	122	280.0	20.7	13.2	20.6	24.8
25	99	320.0	24.8	13.0	19.8	24.1
26	86	360.0	30.9	13.0	19.1	23.0
27	88	400.0	39.9	13.0	18.3	21.6
28	79	440.0	55.5	13.0	17.5	19.8
29	60	480.0	84.9	12.9	16.8	17.7
30	52	520.0	85.7	11.8	16.0	17.0
31	45	560.0	80.8	10.6	15.2	16.5
32	26	600.0	73.7	9.2	14.5	16.2
33	16	640.0	67.1	7.8	13.7	16.0
34	9	680.0	61.7	6.4	12.9	15.9
35	2	720.0	57.6	4.9	12.2	15.7
Total	1477					

D.0.2: Refurbishment scenario

T_x $[C]$	Duration $[hour]$	Load $[kW]$	Water Flow $[m^3/h]$	Supply T $[C]$	Return T $[C]$	Target T $[C]$
21	153	72.0	20.7	24.5	24.4	27.5
22	167	108.0	20.7	23.0	23.5	27.5
23	137	144.0	20.7	21.5	22.7	27.4
24	122	180.0	20.7	19.8	21.9	27.3
25	99	216.0	20.7	18.2	21.1	27.2
26	86	252.0	20.7	16.6	20.3	27.0
27	88	288.0	20.7	14.9	19.5	26.9
28	79	324.0	20.7	13.3	18.6	26.7
29	60	360.0	23.6	13.0	17.8	26.1
30	52	396.0	28.0	13.0	17.0	25.2
31	45	432.0	34.0	13.0	16.2	23.9
32	26	468.0	43.1	13.0	15.4	22.3
33	16	504.0	59.5	13.0	14.5	20.3
34	9	540.0	83.2	12.7	13.7	18.3
35	2	576.0	81.7	11.6	12.9	17.7
Total	1141					

Table D.2: Power Requirement of the system as a function of the Outlet Temperature and the Cooling Load.

D.0.1: Scenario as Usual

T_x $[C]$	Load $[kW]$	Estim. $[kWe]$	Electricity $[kWe]$	Flow $[m^3/h]$	Temp $[C]$	Direct Cooling $[kW]$	COP
19	80.0	0.0	3.8	6.5	20.0	83.5	21.2
20	120.0	0.0	3.8	9.7	20.0	123.4	31.6
21	160.0	0.0	3.8	12.8	20.0	163.3	41.9
22	200.0	0.0	3.8	15.9	20.0	203.2	52.1
23	240.0	0.0	3.9	19.0	20.0	243.1	62.3
24	280.0	0.0	3.9	22.2	20.0	283.1	72.3
25	320.0	0.0	3.9	25.3	20.0	323.0	82.1
26	360.0	0.0	3.9	28.4	20.0	362.9	91.5
27	400.0	0.1	4.0	38.2	18.1	402.7	99.1
28	440.0	0.2	4.2	45.8	17.3	442.5	104.3
29	480.0	0.9	4.9	70.2	14.9	482.1	97.4
30	520.0	3.0	7.9	79.8	14.7	524.7	66.1
31	560.0	6.0	17.1	76.5	15.4	574.0	32.8
32	600.0	10.0	25.4	71.1	16.5	622.5	23.6
33	640.0	14.8	32.8	65.9	17.8	669.9	19.5
34	680.0	20.4	40.5	63.6	18.7	717.7	16.8
35	720.0	26.8	53.9	66.8	18.9	770.9	13.4

D.0.2: Refurbishment scenario

T_x $[C]$	Load $[kW]$	Estim. $[kWe]$	Electricity $[kWe]$	Flow $[m^3/h]$	Temp $[C]$	Direct Cooling $[kW]$	COP
21	72.0	0.0	3.5	5.9	20.0	75.3	20.8
22	108.0	0.0	3.5	8.7	20.0	111.3	30.6
23	144.0	0.0	3.6	11.5	20.0	147.3	40.1
24	180.0	0.0	3.7	14.3	20.0	183.3	49.3
25	216.0	0.0	3.7	17.2	20.0	219.3	58.2
26	252.0	0.0	3.8	20.0	20.0	255.3	66.7
27	288.0	0.0	3.8	22.8	20.0	291.3	75.0
28	324.0	0.0	3.9	25.6	20.0	327.3	83.0
29	360.0	0.0	4.0	28.4	20.0	363.3	90.6
30	396.0	0.0	4.0	31.2	20.0	399.3	97.9
31	432.0	0.1	4.1	34.1	20.0	435.3	104.6
32	468.0	0.1	4.3	40.4	19.0	471.3	108.2
33	504.0	0.3	4.7	49.3	17.9	507.3	107.4
34	540.0	1.2	5.6	70.7	15.6	543.3	95.7
35	576.0	3.1	8.6	77.4	15.5	582.1	67.1

吾唯

足知

“Ware Tada Taru (wo) Shiru”
“Connaissons nos besoins”

Calligraphie de Pascal Krieger,
Octobre 2011

Luc Girardin Swiss
Chemin du Bois-de-By, 36 Single
1286 Soral 02.12.1975

tél : +41 21 693 38 29
e-mail : luc.girardin@epfl.ch

Studies

Mechanical Engineer, Master of the Swiss Institute of Technology (EPFL)	2000-2005
University of Geneva, Section of Mathematics	1997-1999

Main skills: Numerical simulation, Energy Conversion systems and Control.

Projects at the EPFL

EnerGIS: evaluation of Integrated Energy conversion Systems in urban areas.	2007-2011
Methodology for the Integration of Low Temperature District Network **(Tetraener, GLN)**	2009
Process Integration techniques for Optimal Steam Cycle Configurations **(Swisselectric,ALSTOM)**	2008
Strategic Thermal Energy planning of the Canton of Geneva **(SIG-SCANE-BG)**	2007
Thermo-economic Optimization of Power plants with C02 Mitigation **(CCEM-CH)**	2007
Swiss Deep Heat Mining Geocon Project, **(Swiss Federal Office of Energy, LENI, Gruneko)**	2006
Geothermal Heat Integration for the central DHN system of Martigny **(CREM)**	2006
Methodology for optimal Design of Industrial Hydrogen Network **(LENI-EPFL & Air Liquide)**	2005
Distant Heating in Switzerland: Application to the Thermoréseau of Porrentruy **(LENI)**	2004
Mechanical processing, Practical internship **(Mikron SA Boudry)**	2001

Computer knowledge

Programming Languages: Matlab, AMPL, Fortran, C++, Qt, Python, SQL
Conception & Simulation : Catia, Tecplot, Belsim-Vali

Professionals Experiences

Research Assistant - Phd Student EPFL	2006-2011
Student Assistant EPFL	2003-2004
Swiss snowsports ski instructor and trainer.	2002-2011
Swiss army infantry	1998-2009

Languages

French : mother tong

English & German : written, spoken

Training courses attended

Advanced Qt Programming for Maemo platforms	2010