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Nantes' and Oslo's urban water systems: Assessing benefits from water-energy nexus interventions.

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Summary

In this thesis is investigated the *water-energy nexus*, the intricate relation that exists between water use in energy, and energy use in water. Indeed, literature review shows the importance of this relation and the necessity to reduce the impact from the water utility's side, the influence at the heart of this work.

To lead such a study, the cases of two cities, Nantes and Oslo have been explored. Oslo is the capital of Norway, inhabited by 560,000 people in 2007, the baseline year for the study. This city benefits from an important economic and demographics dynamics, as it is attractive to both Norwegians from outside Oslo and foreigners. Nantes Métropole is a conurbation of 24 towns around Nantes, the administrative capital of the Region Pays de la Loire in France. Its population of 590,000 in 2010 (baseline year for Nantes) and its position make it an economic and demographic centre.

In these two cities, it was possible to develop a model of the urban water cycles systems, associating the identified material, water and energy flows to their energy contents and carbon emissions. Then was investigated the possibility to reduce the footprints of water consumption, a question that was answered by the forecast of future drivers, technologies, and trends.

Energy consumption throughout the urban water system is respectively of 116 and 311 kWh/cap.year in Nantes and Oslo. This is far from the total energy used directly and indirectly by individuals in France or Norway. However, such values are by no means unimportant, with 2.19 kWh/m^3 final consumption in Nantes versus 1.83 in Oslo. A direct consequence to this opposition is thus that it becomes possible not stop at the total figures per capita and rather split it up, in order to aim for improvement, either on the requirement per unit volume, or on consumption trends. The carbon footprints associated to the consumption of water in Nantes and Oslo can also be viewed as not extremely high with regards to other services, with 25 kg CO_2e/cap.year in Nantes and 45.5 kg CO_2e/cap.year in Oslo. However, carbon impacts related to the amount of energy used are quite high: 215 g CO_2e/kWh for the French utility and 145 g CO_2e/kWh for the Norwegian one, equivalent to fossil fuel electricity mixes. Indeed, water cycles depend on indirect energy flows such as chemicals, which rely on fossil resources.

The other outcome of this work is based on the water utilities' role: not only to produce water but also to clean wastewater. Thanks to policies and technologies, they are able to recover the useful resources: carbon, nitrogen and phosphorus, and the choice of use of these elements can offset a part of the energy used and carbon emitted.

Such an element has great importance. Scenarios show that in a few years, up to two thirds of the energy used by the utilities could be offset, and several times their emissions in carbon as well, if the by-products (biogas and sludge) are used properly. In order to make the change effective, the utilities have access to a span of different measures to create impacts. Anaerobic wastewater treatment associated to biogas use as bus fuel, sludge use as fertiliser, are direct ways to offset emissions. Decentralisation of the water supply and rainwater harvesting are also major policy measures that can be implemented to decrease the reliance of UWCS on external resource.

Acknowledgement

Six years have now past since I have begun my studies, and I feel that I have reached their other extremity. This is both an opportunity to look back to what has been accomplished and look forward to what more can be accomplished. To that extent, writing my Master Thesis was an excellent opportunity to take the time for such reflexion, as it nurtures thoughts, and teaches responsibility and self-reliability.

Thus, I believe that coming to and overcoming such a milestone cannot be done without help. Throughout the last two years in Industrial Ecology, and during this last year as a student, I could experience this very point and acknowledge how important it is, to be able to rely not only on myself but others as well.

For that reason, I would like to deeply thank **Prof. Dr. Helge Brattebø**. Not only has he proposed me to work on this exciting because essential topic of *water-energy nexus*, but he has also a great role in the development and successes of Industrial Ecology in NTNU. I am therefore extremely grateful to him both for his helpful support during this year, and for his implication in such great projects. I also want to thank **Dr. Venkatesh Govindarajan**, who has probably been the most trustworthy and kindest co-supervisor one could have. I have been amazed numerous times by his rapidity to answer any question and by the quality and comprehensiveness of his answers; I cannot thank him enough for that.
The choice of working in cooperation with Nantes Métropole has been an excellent opportunity, by the quality of the data and the friendliness of the people I met there. I want therefore to thank **Yves Gouriten**, **Michel Blanche**, **Tatiana Lécossais**, for having received me several times, and provided me with valuable help in the course of completing my project and thesis. I am extremely thankful to all the **personnel of the water utility of Nantes Métropole**, without which I would not have collected and understood the data necessary to my work.
I also want to thank **Xyntéo AS**, which gave me financial support to travel to Nantes; the interesting exchanges and the collaboration I have had with their analysts have not only helped me in my academic work but also given me experience for my future as an engineer.

Finally, I want to thank all my friends, all the professors and people somehow related to **Industrial Ecology in NTNU**, everyone I have met in Trondheim during these two years. I do not think this experience would have been the same without my daily relation to them, in which I learnt much more than in courses only. This experience would also not have been the same elsewhere than in Norway, a country that I will keep in mind as a model in many ways, and which I hope shall remain as pure and kind-hearted as it is now.

This work is dedicated to the memory of Marilou, who teaches me everyday to give the best of myself in everything.

Trondheim, June 2012
Matthieu Vachon

Acronyms and language elements

Before starting this thesis, it seems important to refer properly to a number of elements and terms that the reader will encounter often, and define them. As far as spellings are concerned, British English has been used in this thesis.

- WTP: Water Treatment Plant
- WWTP: Wastewater Treatment Plant
- WT: Water Treatment
- WWT: Wastewater treatment
- WW: Wastewater
- GHG: Greenhouse Gases
- IPCC: Intergovernmental Panel on Climate Change
- MDG: Millennium Development Goals
- UWCS: Urban Water Cycle System
- O&M: Operation & Maintenance
- COD: Chemical Oxygen Demand
- BOD: Biological Oxygen Demand
- GWP: Global Warming Potential
- CHP: Combined Heat and Power *or* Cogeneration
- LCA: Life Cycle Assessment
- MFA / SFA: Material Flow Analysis / Substance Flow Analysis

The reader should in addition be warned about an intentional element of vocabulary:

In this document, the terms **GHG, GWP, carbon emissions will be used interchangeably** to a certain extent, despite the fact that they do not represent the exact same entity. Indeed,

- GHG represents a family of gases that have proven effects on the climate
- GWP is their quantitative effect, often calculated in kg CO_2 equivalent
- Carbon emissions are related to gases that have carbon atoms in their molecules.

However, as one of the outcomes of this thesis will be to calculate the Global Warming Potential pertaining to water services in two case cities, all terms will be used as substitutes. GHG emissions will hence depict both the inventory and the effect; and carbon will not only mean C, but all gases that have a global warming potential and that will be taken into account.

Moreover, the terms of Nantes and Nantes Métropole will also be used interchangeably, depicting the whole Nantes Métropole conurbation, unless stated otherwise. It shall be referred to as “NM” in certain cases in the appendices.

Table of contents

List of figures

List of tables

1. Introduction

This chapter briefly describes the context of the analysis presented in this thesis. The role of water in human activities, its current status in terms of availability (in sufficient quantities and required quality), and its indispensability for sustainable development are discussed. Thereafter, energy consumption for economic growth and social welfare; and the associated environmental impacts – global warming being the chief among them – are dwelt upon. Water, energy and emissions are then considered as essential aspects to be addressed when one embarks on the path of sustainable development. Towards the end, the research questions which this thesis intends to address and answer in the pages that follow are listed, and the case studies carried out are introduced.

1.1. The status of water

Water is indispensable to the sustenance of any human settlement. According to historical and archaeological research, the oldest proofs of human management of water through irrigation for agriculture date from 5000 B.C., concomitant to the start of agriculture itself (FAO, 2006). This happened particularly in Mesopotamia, a part of the world known for having developed the earliest writing forms. Although coincidence should not be mistaken for causality, one should not overlook the role of agriculture and thereby water used for irrigation, in catalysing the civilisation's breakthroughs and progress.
Water is needed for almost every single process one can think of, from the survival of a living body (1.5 to 2L of water are required each day for an adult (Wikipedia, 2012a)), to the production of energy, the growth of cotton for textiles, and it represents 71% of the Earth's surface, hosting about 230,000 known living species (Wikipedia, 2012b). In a nutshell, water is a *sine qua non* for human life and anthropogenic activities, directly and indirectly.

However, according to the UN (United Nations General Assembly, 2000), a large share of humanity does not have access to the desired water services required to ensure fulfilment of the basic needs of individuals, and thereby of the economic activity of settlements and societies. This gleaning led to the inclusion of access to drinking water and sanitation in the Millennium Development Goals (MDG) of the United Nations. This MDG targets a halving of the number of people without access to improved drinking water sources and good sanitation by end of year-2015, *vis-à-vis* year-2000. This situation has been confirmed in the ten-years' update on sanitation and drinking water (WHO and UNICEF, 2010), which states that 2.6 billion people still do not enjoy access to improved sanitation facilities; 884 million are not supplied with good-quality potable water. The sanitation goal of the UN is "off-track" according to the report. In addition, although the drinking water goal will be reached, 672 million people will still lack potable drinking water by 2015. It is hence mandatory to focus on increasing the coverage of water supply services. Either the basic water supply infrastructure does not exist in many countries in the developing world (from where the said 672 million people hail), or there is a paucity of raw water sources, or both. Sustainable development of water supply (and sanitation services) would thus perforce entail the addressing of concerns in totality.

1.2. The status of energy

As we shall observe in this thesis, water use is closely linked to energy consumption, and a few words should be here written about the status of energy. Humanity consumes energy at a level that has never been reached in historical ages, attaining a total of 12267 Mtoe (Mega Tons Oil Equivalent) in 2008 (International Energy Agency, 2010). With a population of 6.7 billion humans on earth on 2008, this represents a daily use of 5kg oil equivalent per day and human being and 210MJ/cap.day in average. This can be compared to the useful mechanical work given by a professional cyclist on a mountain stage of the Tour de France (4000m positive vertical drop (Letour.fr, 2011), with 10% mechanical inefficiency from friction (Piednoir, 2008)). Under these conditions, about 3.4MJ of useful work are given by the athlete. This means that the average human being consumes everyday the useful work produced by at least 60 "professional athletes equivalents". Furthermore, statistics indicate a high variability of the electricity use by country (International Energy Agency, 2010). Whereas the average use stands by 2'782kWh/cap.year in 2008, it is 49'818kWh/cap.year in Iceland and 23kWh/cap.year in Haiti. Thus, energy inequality exists and is high, as it is for water.

In addition to a difficult access to energy for the poorest populations, humanity is also facing a depletion of its energetic resources. Indeed, 87.1% of the energy consumption in 2008 was based on non-renewable resources such as Coal, Oil, Gas, Nuclear resources (International Energy Agency, 2010). All of those resources are characterised by a certain amount of reserves that do not increase significantly within shorter periods than millions of years. As a direct consequence, their exploitation cannot be led infinitely and the fossil fuel production has to peak before declining (Höök, Sivertsson, & Aleklett, 2010). In its latest update, the International Energy Agency expresses that the Peak Oil has been reached: "Production of conventional crude oil – the largest single component of oil supply – remains at current levels before declining slightly to around 68 Mb/d by 2035. To compensate for declining crude oil production at existing fields, 47 Mb/d of gross capacity additions are required, twice the current total oil production of all OPEC countries in the Middle East" (International Energy Agency, 2011).

Thus, even if global energy consumption is not the main subject studied in this thesis, one shall acknowledge its primary importance, as it is notably inter-connected to water use: large quantities of energy are necessary to treat and transport water, as large quantities of water are entailed to produce energy. This relation is called the water-energy nexus, and will be investigated in this work, particularly under the "energy for water" aspect.

1.3. Global warming as a concern

A last element should not be overlooked here, in order to provide the reader with the general context in which this work is being led. The world scientific community has acknowledged global warming: in the Fourth Assessment Report, the IPCC (2007) states:

> *Eleven of the last twelve years (1995-2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906-2005) of 0.74 [0.56 to 0.92]°C is larger than the corresponding trend of 0.6 [0.4 to 0.8]°C (1901-2000) given in the TAR). The linear warming trend over the 50 years from 1956 to 2005 (0.13 [0.10 to 0.16]°C per decade) is nearly twice that for the 100 years from 1906 to 2005.*

The straightforward conclusion is thereby that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (*ibid.*). The main reason to this global warming is the anthropogenic greenhouse gases emissions (GHG), which induce a radiative forcing of the climate system; Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 (IPCC, 2007). Global warming can been seen more generally as a climate change, because of the extremely high complexity of the climate mechanisms, which lead to many different consequences to a same global cause. Hence, when it comes to water in particular, some regions are very likely to be subjects to droughts, others to high precipitation. It is in addition very likely that ground and surface water suffer from loss of quality (IPCC, 2007). But another element, particular to water systems, is that water utilities, by improving their efficiency and also generating renewable energy such as biogas can contribute to reduction of global warming (IPCC, 2007).

1.4. Water, energy, environment and sustainable development

We are at a point in history where some of the most far-reaching and all-encompassing consensuses have been reached. The 1992 United Nations Framework Convention on Climate Change (United Nations, 1992) stated in its introduction that the parties were

> *Concerned that human activities have been substantially increasing the atmospheric concentrations of greenhouse gases, that these increases enhance the natural greenhouse effect, and that this will result on average in an additional warming of the Earth's surface and atmosphere and may adversely affect natural ecosystems and humankind.*

By the end of 2011, this text has been signed and hence acknowledged by more than 190 parties: most of the UN member states, including the major polluters. It is hence an indisputable fact that by and large, the international community admits and acknowledges the reality of the concerns and challenges faced by humanity as a whole. One may say that the hard work on sustainable development carried out during the second half of the 20th century is now bearing fruit. Indeed, the Brundtland Commission gave the first definition of sustainable development in *Our Common Future* (World Council for Environment and Development, 1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Later, this was rechristened to suit business interests as the triple bottom line approach to development (Elkington, 1997). This approach highlights three criteria or 'bottom lines' to look at in order to live, act and develop sustainably: "people, profit, planet". Thus, by classifying their major goals under financial, social and environmental issues, the UN member states seem to have gone a longer way in the acknowledgement of sustainable development needs than what could have been expected earlier in the century.

This definition of sustainable development and the acknowledgment of climate change are very broad-based and overarching. More specific questions can be asked. One can narrow down the scope of analysis to more specific domains of human activity. Water services form one such domain. When it comes to water services, it is indeed important to embrace the major processes in which water takes part as well as their requirements and outcomes. Here, the two major activities that have to be considered in terms of environmental adversity might be the energy generation (to fulfil the energy demands of the processes in the water-wastewater cycle; refer sections 1.2 and 1.3) and wastewater treatment. In the course of electrical power production, large quantities of fresh water are pumped in rivers to cool the plant. The remaining part is then disposed of in the same river. This can lead to water scarcity due to evaporation, but also to adverse effects for the local water life that could be unable to sustain itself in warmer water. Wastewater treatment will not only change the physical properties of water but also its chemical properties: at the end of the consumption cycle for human activities (both from human consumption and economic activities), water has been deeply affected by chemicals from drinkability treatment, industrial processes or substances from human consumption. Wastewater treatment is hence vital in order to give back to water a chemical composition that makes it suitable for a release in the environment. Insufficient treatment is a major source of pollution in developing countries, where people are deeply suffering from water-borne diseases and where the environment is affected by heavily loaded waters. These two elements give a first insight on water-energy nexus, as evocated above.

Trying to assess the quality of anthropogenic infrastructures is hence one of the challenges to tackle (Sahely, Kennedy, & Adams, Developing sustainability criteria for urban infrastructure systems, (2005) and Lundin & Morrison, (2002)). In these two papers, criteria and indicators are developed and applied to different cases, the major points of both being the systematic aspect of the assessment. This is operated through general approaches that could be compared to the triple bottom-line, but also water infrastructure related indicators that allow an investigation of the important aspects and elements of performance. The methodologies adopted to study sustainability of water systems may be different from each other, but they all are based on the understanding and the belief that water can no longer be demoted down on the priority list, as far as sustainable development programmes are concerned. And, when one considers water services, energy, greenhouse gas emissions and money figure prominently as factors / consequences of service provision, As we will see in this work, it becomes more and more possible to study and determine with an appreciable extent of certainty, the energy and carbon costs of a given service level.

1.5. Towards integrated models

As a direct corollary to the approach developed in the papers cited in the earlier sections, water systems and methodologies adopted to analyse them, have been evolving and adapting over the years. Indeed, most of the Urban Water Cycle Systems (on which this work will mainly focus; referred to hereafter as UWCS) have long been seen as open systems. A source was an infinite water provider and the environment was an infinite sink, thus making a simple end-of-pipe approach relevant and acceptable. But today, the way of thinking has changed. Elements such as the energy cost of water and/or wastewater treatment, and the scarcity of water resources make treated water a valuable (value-added in other words) asset. We can refer here to the case of the Colorado River, which runs dry for most of the year before reaching the sea (Cohen, Henges-Jeck, & Castillo-Moreno, 2001). In other countries such as Israel (Israel Ministry of Environment, 2010), treated wastewater is used to resupply aquifers that could not sustain themselves because of the environmental pressure. Those examples describe a challenge and also enlighten readers about the strategies chosen to adapt to these inevitable realities. Adversities, as they say, are opportunities in disguise – in these instances, opportunities to start thinking anew, about water systems as ‘closable’ and not open cycles.

In one of the succeeding chapters, a framework (or basis) of integrated models is proposed. As an introduction leading in to this, the typologies of such frameworks can be reflected upon at this juncture. The first point evocated above goes along the path followed by other sectors, encompassing a new understanding of material flows, which could be formulated, as “there is no such thing as waste”. This has been theorised notably in *Biomimicry: Innovation Inspired by Nature* (Benyus, 1997) and in *Natural Capitalism* (Hawken, Lovins, & Lovins, 1999) and is inspired by the fact that all natural flows are useful to a certain extent, and to certain life forms. Water in water systems can hence be seen the same way, and new uses of water through water reuse, water reclamation, energy recovery from wastewater, rainwater harvesting… participate from that perspective.

The second point is perhaps more theoretical but as important for the global understanding: system analysis is more and more widely used, and leads to more aggregated indicators. Indeed, a UWCS being less seen as a succession of steps from source to sink, the interconnection of flows and stocks is hence more easily acknowledge. This means *inter alia* that is it in fact possible to assess such systems globally by mathematical models. This has been done for example in Venkatesh (2011), using the city of Oslo as a case study. This reference source has applied Life Cycle Assessment, Cost Benefit Analysis and Material Flow Analysis (resp. LCA, CBA, MFA), among other tools, in the sustainability assessment of the water and wastewater utility in Oslo. The main outcome of the application of such methods is the identification and understanding of impacts all across the life cycle. It allows finding out hotspots where interventions and changes would yield the best results, thus avoiding problem shifting. These calculations, interpretations, reflections and pathway-exploration will be the milestone, in that order, in this thesis.

1.6. Motivation and research questions

The chief motivation of this thesis is two-pronged. First, it shall aim to provide the reader with a theoretical framework of assessment, in the fields of energy and carbon within UWCS. Undeniably, in today’s context of sustainability, they are necessary indicators of performance for all public utilities, industrial outfits and households. We acknowledge the fact that no specific attention will be given here to ecotoxicology indicators such as eutrophication. Indeed, not every aspect of water utilities’ impact could be examined in this work. This can also be justified by the fact that regulation is probably the main driver regarding ecotoxicology, as it addresses the limit concentrations of chemicals in released water. Secondly, the analysis will yield graphical representations of water and energy consumption, greenhouse gas emissions, etc., and uncover differences between the two cities, which are being studied and compared in the thesis.

If we want to develop further this motivation into specific questions, it seems that it is possible to assess with a correct precision the specific requirements of, and impacts from urban water systems. Furthermore, the methodology described and applied in this thesis to two cities, can also be modified and tailor-made for application to other cities, states and regions of the world. . The thesis desists from being purely theoretical; in fact, it uses theory to investigate and explore possible practicable options for the future. Having said that, the complexity of sustainable development, and the fact that it is at best a ‘moving target’, should not be overlooked. . The choice of system boundaries is likely to have an impact on the final results and interpretations. . A second remark is that our results will provide a snapshot of both case study cities in a given year, not taking into account prospective evolutions of the context (environmental, economic…). It seems thus a good idea to provide a dynamic perspective to such a study, by incorporating both probable changes (which are known and confirmed from reliable sources) and best practices which could probably be enforced in the future, giving thereby a reference scenario to each of the cities.

Hence, our research questions for this study will be the following ones:

1. At what energetic cost are urban water services delivered in Nantes and Oslo?
2. What is the carbon footprint of the utilities in Nantes and Oslo, as far as energy consumption (and generation) is concerned?
3. Can the energetic and carbon footprints be decreased in the future, and through which measures from the water utilities?

The first question will emphasise on the status quo, and baseline scenario for both cities. The second question concerns the carbon emissions related to the energy consumption considered in the first question. The third question will address the development of scenarios, based on the elements highlighted above on theoretical framework and practical data. These elements will be developed in the literature review, as well as in the methodology chapter.

1.7. Nantes and Oslo

Nantes is the administrative capital of the Pays de la Loire region in France. This study will focus not just on the city of Nantes *per se*, but the whole of the Nantes Métropole, a 'conurbation' of 24 towns around Nantes, sharing certain common policies and service utilities, such as the water utility. The population of the Nantes Métropole was 590,000 in 2010, the baseline year for this work. The urban community is situated on the Loire River, which supplies over 90% of the water, and 45 km away from the Atlantic Ocean into which the river drains. The climate is oceanic and temperate, with precipitation in the range of 750 mm and 900 mm per year – the average value for France. Water scarcity is thus not a concern both at the time of this study and in the medium-term future.

Oslo is Norway's capital city, situated on the *Oslofjorden* contiguous to the Atlantic Ocean. Oslo was inhabited by 560,000 inhabitants in year-2007 (baseline year), but the population is rapidly increasing due to the attraction of Oslo to Norwegians from other parts of the country, and immigrants alike. The water supply comes mostly from the Maridalsvannet lake (90%); with two other lakes making up for the remaining 10%. The climate is colder than in Nantes and the temperature is below 0°C during the winter months. However, as Norway benefits from the effect of the Gulf Stream, the climate is milder and wetter than in other sub-polar regions (750 mm of average rainfall annually).

Figure 1-1: Oslo and Nantes in Europe

2. Literature review

In this chapter, some of the case studies, which have been carried out in the past, for UWCS have been reviewed. Some of them have focus on the water-energy-carbon nexus. Some others concern more generally the nexus between water supply and wastewater treatment on the one hand, and the energy consumption/generation in the utility and the associated environmental impacts on the other. There is a host of methodologies, which can be adopted to perform environmental assessment of UWCS; and literature survey uncovers published references and descriptions of some such. Previous research has also segmented the water cycle into its component sub-systems and analysed the performance of each of these, as well as interventions, which water utilities can think of, to improve their performance. Here, a preliminary remark must be made, concerning the scope of this work and hence the information gathered in this literature review. The main interest will be to detail the consumptions and impacts of the utility as such, without accounting for the user consumption stage. It is actually physically and administratively separated from the utility. Tackling this aspect of the urban water systems could not be undertaken here, although one must acknowledge its importance, and the possibility to find synergies between the consumption stage and the rest of the UWCS.

2.1. Systematic environmental performance analysis of UWCS

In Lundin & Morrison (2002), the authors had stressed on the fact that despite a growing interest in attaining environmental efficiency and the awareness of the need to perform environmental assessments, no systematic framework that can be made applicable to any urban water utility, existed. They had thereby embarked on the proposition of a simplified life-cycle analysis method, analysing the urban water cycle, in terms of its individual stages.

The said paper showed that by defining the purpose and motivation behind such a study, defining system boundaries (Figure 2.1) and developing a framework to guide the choice of environmental indicators, it is possible to determine the most important vectors of sustainability and environmental damage. The paper studies two cases – Swedish and South African - the first one faced with issues related to heavy metal content in sludge and water, and the latter combating concerns of water scarcity.

The final point of their reflexion concerns the system boundaries. They call attention to the multiplicity of points of views that can be adopted, depending on the choice of the system boundaries. The smallest system (1a and 1b on the figure) stays very close to the processes themselves and allows a sharp analysis by engineers, whereas the intermediary (2 on the figure) system boundaries are more appropriate from an organisational perspective, encompassing the utility's domain. The broadest scope takes into account the interactions of the urban water system with its surroundings, through the exchange of by-products like sludge and biogas. This extension can be adopted in a multidisciplinary study. This remark is of primary importance for this thesis and we shall come back to it when we reflect upon the boundaries for Nantes and Oslo, and try to embed several levels of visions in our work.

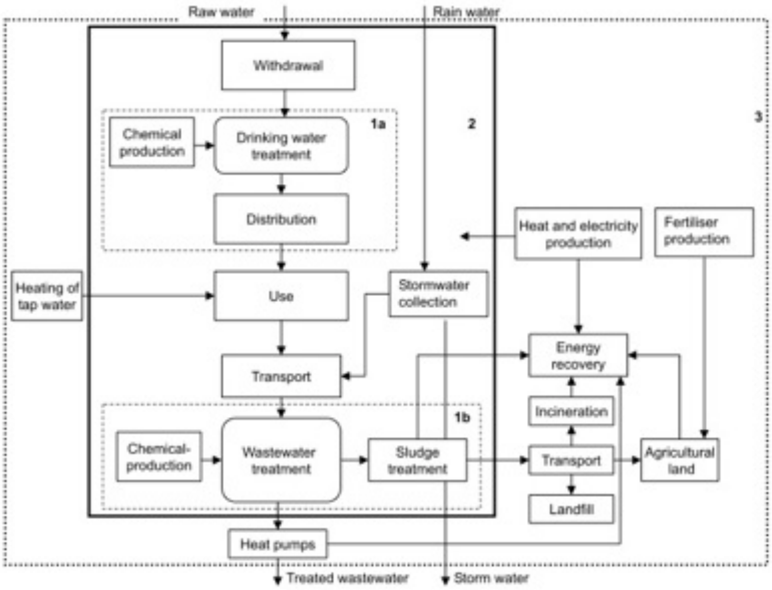


Figure 2-1: System boundaries option (Lundin & Morrison, 2002)

The importance of choosing the correct indicators has not only been raised in theoretical works, but some case studies also try to embed such aspects. In a study of the water and wastewater system in the Norwegian capital city of Oslo (Venkatesh, 2011), it is shown that one type of system boundaries can encompass all the required, key sustainability indicators (Figure 2.2)

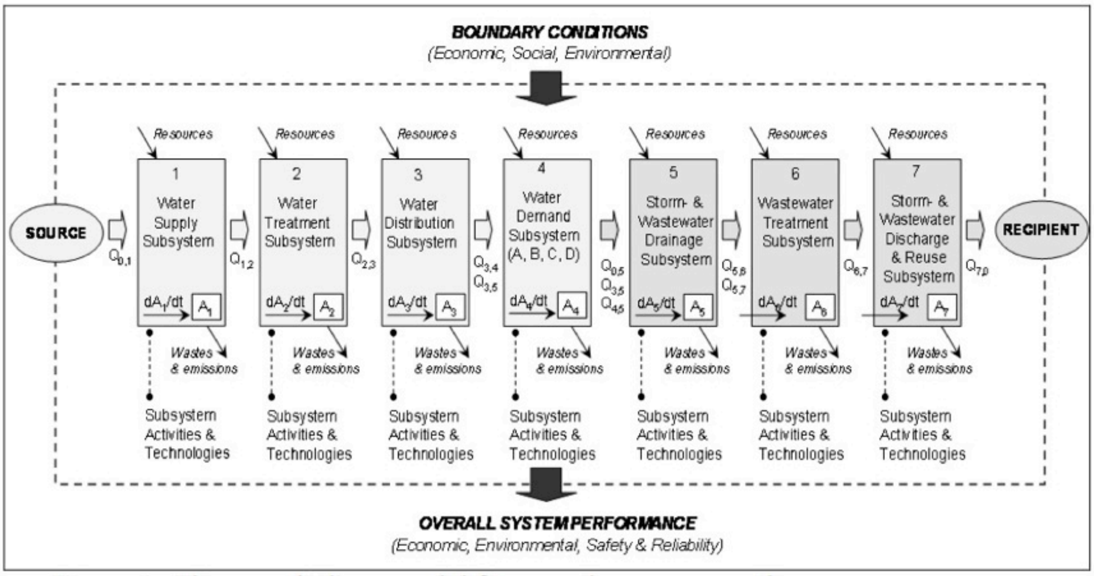
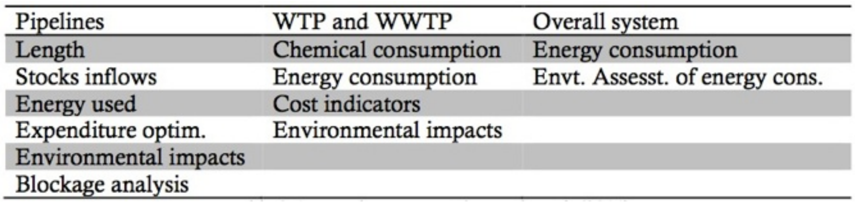


Figure 2-2: Model of a UWCS (Venkatesh, 2011)

While acknowledging the fact that the data-gathering process can often be time-consuming, the work carried out in Venkatesh (2011) points towards a possibility of a theoretical, exhaustive systems analysis. The backbone of the analysis is similar to one adopted by Lundin & Morrison (2002). It proceeds from upstream source of raw water to the downstream, sink or recipient of treated/untreated wastewater. It encompasses all the intermediate stages of the UWCS, which are within the domain of the water utility. This permits a good understanding of the urban water system, without congesting it with a lot of data *a priori*. The second major feature of the model outlined in Figure 2.2 and used in Venkatesh (2011) – which after subsequent enhancement, has been labelled as the

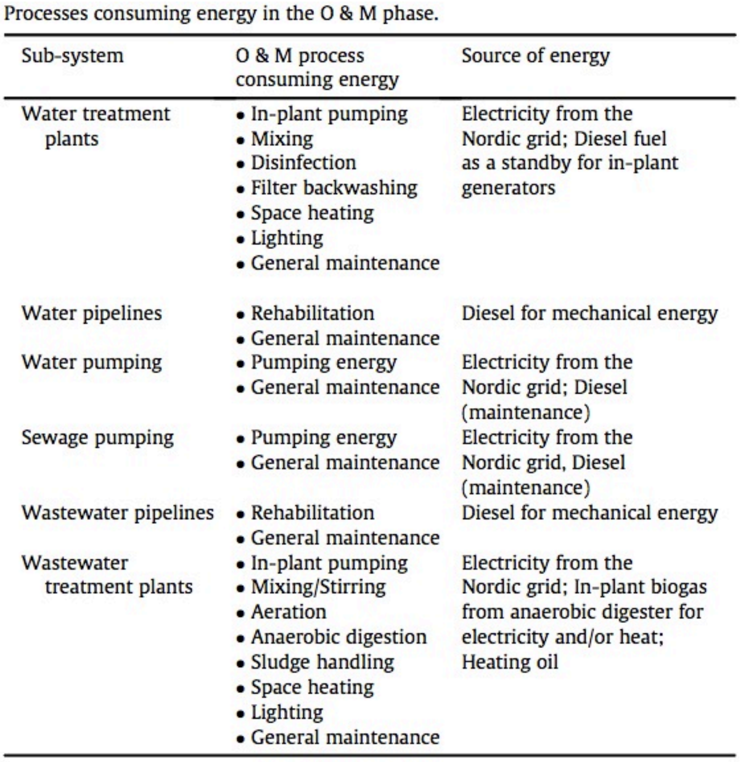
Metabolism Model – is a systematic accounting of all the characteristics at each stage of the cycle, referred to in the Figure as resources inputs, activities and technologies, wastes and emissions. This accounting and assessment carried out on Oslo's water and wastewater system, and the subsequent discussion and interpretation, brings out the possibility of applying the theoretical results to practical decision-making. The model – the Metabolism Model – is amenable to the use of Industrial Ecology tools, written about later in this chapter. The scope of the work carried out in Venkatesh (2011) can be summarised as under.



Pipelines	WTP and WWTP	Overall system
Length	Chemical consumption	Energy consumption
Stocks inflows	Energy consumption	Envt. Assesst. of energy cons.
Energy used	Cost indicators	
Expenditure optim.	Environmental impacts	
Environmental impacts		
Blockage analysis		

Table 2-1: Scope of work in Venkatesh (2011)

This table means essentially that through a correct choice of complementary system definition and work schemes, several levels of indicators can be taken into account. One can refine the scope of work. Comprehensiveness and accuracy, width and scope and depth of detail, can thereby be balanced. This adds to a choice between focus on individual sub-systems, the utility as a whole, or system-surroundings interactions, by regarding the utility as the system and the atmosphere, lithosphere, hydrosphere, and anthroposphere around it. Such studies permit a better understanding of the implications of energy consumption by the utility and the environmental impacts associated with its functioning. Refer Table 2.2 and Figure 2.3 (Venkatesh & Brattebø, 2011).



Processes consuming energy in the O & M phase.

Sub-system	O & M process consuming energy	Source of energy
Water treatment plants	• In-plant pumping • Mixing • Disinfection • Filter backwashing • Space heating • Lighting • General maintenance	Electricity from the Nordic grid; Diesel fuel as a standby for in-plant generators
Water pipelines	• Rehabilitation • General maintenance	Diesel for mechanical energy
Water pumping	• Pumping energy • General maintenance	Electricity from the Nordic grid; Diesel (maintenance)
Sewage pumping	• Pumping energy • General maintenance	Electricity from the Nordic grid, Diesel (maintenance)
Wastewater pipelines	• Rehabilitation • General maintenance	Diesel for mechanical energy
Wastewater treatment plants	• In-plant pumping • Mixing/Stirring • Aeration • Anaerobic digestion • Sludge handling • Space heating • Lighting • General maintenance	Electricity from the Nordic grid; In-plant biogas from anaerobic digester for electricity and/or heat; Heating oil

Table 2-2: Processes consuming energy in O&M (Venkatesh & Brattebø, 2011)

As a conclusion to this methodology review, and in order to introduce the case approaches, we can reflect briefly on the outcomes of the energy accounting and analysis carried out in Venkatesh (2011), as seen on Figure 2.3.

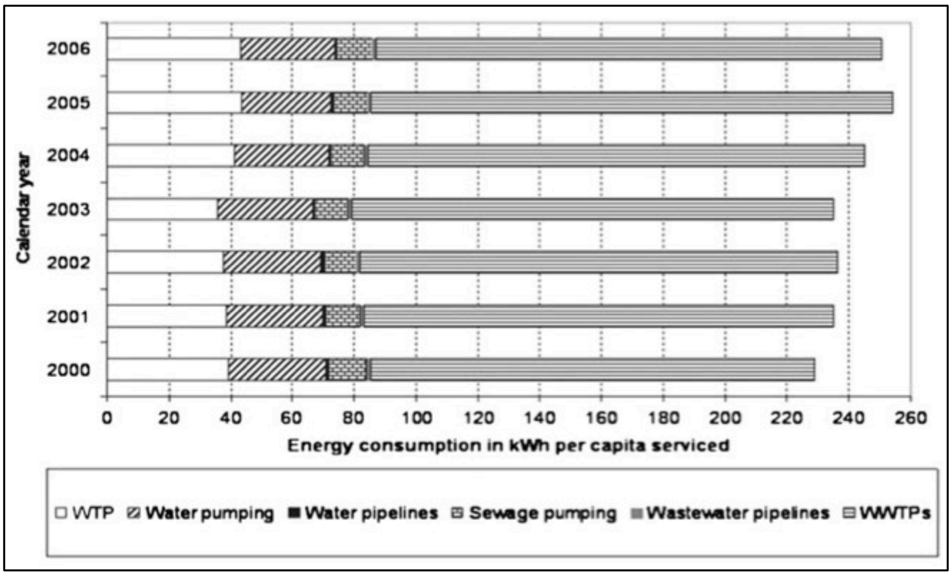


Figure 2-3: Per capita energy consumption in Oslo (Venkatesh & Brattebø, 2011)

The aggregated results presented show the per-capita energy consumption in the Operation and Maintenance phases (O&M) in Oslo, between 2000 and 2006. They give several indications such as the total score of 230 to 255 kWh/cap.year, which gives approximately 10% variability over 7 years. We can note that the wastewater treatment plant (WWTP) contributes the most. It reaches a maximum of 170 kWh/cap.year in 2005. It is certainly quite intuitive that there are no conspicuous changes among the respective weights of each stage. These are important indications in general for the weighting of the different life-cycle stages in UWCS, but also for the particular case of Oslo, which we shall work upon in this thesis. We will now work on common reflections and values that can be found in literature pertaining to UWCS performance assessments.

2.2. Case studies of water-energy nexus in UWC: approaches and figures

Mention has already been made of the growing interest of water utilities and researchers in the water-energy nexus (in this thesis, the energy consumption and generation in the water and wastewater sector will be dwelt upon, and not the requirement of water in the energy sector) and the evaluation of the consumptions and impacts of UWCS. In this section, we will try to review global assessments that have been made in different countries and cities, in order to get a glimpse of the current situations and of prospective evolutions. These shall come in handy when the work outline for the two case studies conducted in this thesis, will be subsequently drawn.

2.2.1. Benchmark on energy consumption throughout UWCS

Recent studies acknowledge the important role played by energy in the water supply and wastewater treatment systems, and emphasise the imperativeness of developing alternate technologies and diversify water resources. As mentioned in a recent article by Lazarova, Choo, & Cornell, (2012), “solving the water-energy nexus to preserve our environment is undoubtedly the challenge of this century. Population growth and increasing living standards have depleted resources and caused biodiversity losses, and even climate change. It is therefore vital to revise our models of development, especially in terms of holistic management of water and energy". Therefore, several types of approaches aiming to understand this (part of the) nexus can be found. Indeed, both institutional reports and research studies examine the current situation and try to assess the situation in several UWCS. However, the analyses do not terminate at this juncture. Many studies are also prescriptive in nature, providing suggestions and investigating pathways, which utilities could adopt to move further on the path of sustainable development.

Thus, we can synthetize partly the information found in those two types of studies. To be pointed out at this juncture, is the fact that the ranges of values for different aspects of the UWCS found in literature are wide. Types of water sources (freshwater, seawater or wastewater), climatic conditions, water availability or scarcity, patterns of water use and population density are important drivers to the system's efficiency (Lazarova, Choo, & Cornell, 2012), and these undeniably vary widely from one region to region This fact is confirmed in a study about energy use in the provision and consumption of urban water in Australia and New-Zealand by Kenway, Priestlay, Cook, Seo, & Inman (2008), where the authors note in addition that topography has an important influence, as well as the pumping distances from the source to the city, susceptible to increase considerably the energy use. Venkatesh & Brattebø (2011) also hint at the need of improving (or maintaining) the quality of the level of service provided to the consumer.

Talking of quality of level of service, Kenway et al. (2008) has found out that tertiary treatment in wastewater treatment plants entails doubling the energy consumption from primary and secondary treatment methods, and quadrupling it from primary treatment.. Future regulations, imposing more stringent requirements on water utilities may put utilities in a challenging situation. As mentioned in Høibe, Clauson-Kaas, Wenzel, Larsen, Jacobsen, & Dalgaard (2008), the EU countries will have to use more advanced technologies in order to decrease the release of hazardous substances, as a consequence from the EU Water Framework Directive. According to these authors, the additional treatment could lead to an increase of the global warming potential by 0.12 kgCO$_2$-eq/m^3 of wastewater treated.

When it comes to a closer analysis of precise figures to weigh the system stages or the processes comparatively, other elements can be found in the literature. As seen in the previous paragraph on Figure 2.3, wastewater treatment outweighs all other precedent stages of Oslo's urban water cycle, if the O&M consumptions are considered. But as a direct consequence of the previous remarks, a comparison of several cities from Oceania shows a large diversity in the direct energy consumptions (Kenway et al., 2008), displayed on Figure 2.4 showing the 2006/2007 year:

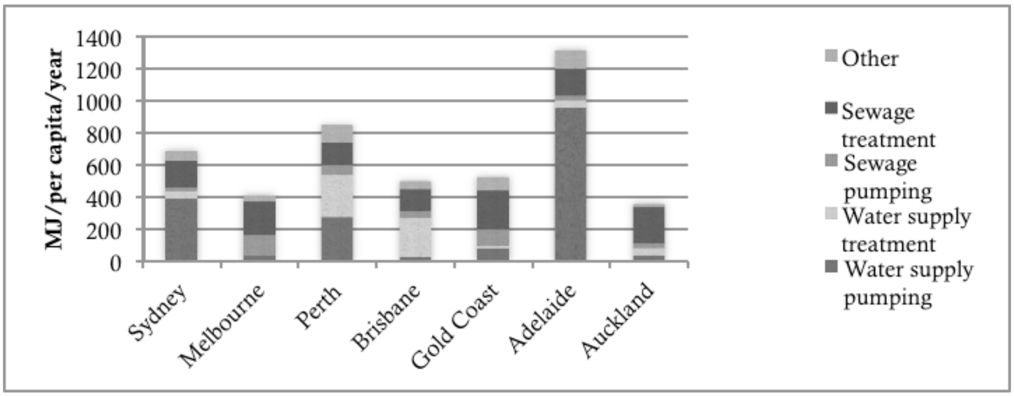


Figure 2-4: Per capita energy use in UWCS in Oceania (adapted from Kenway et al., 2008)

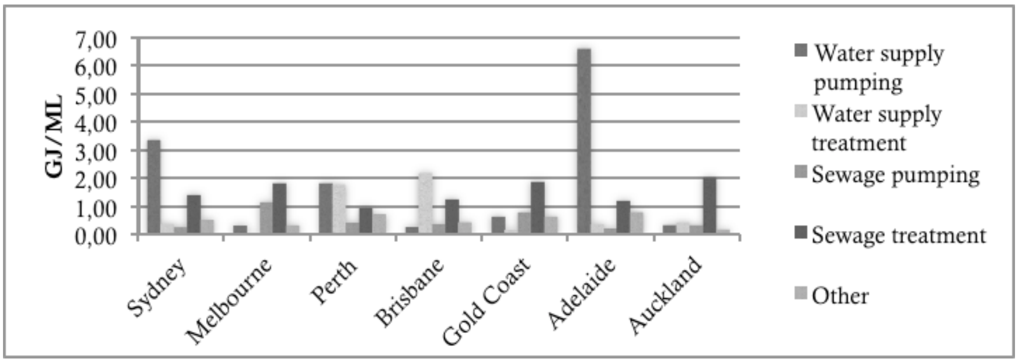


Figure 2-5: Per cubic metre energy use in UWCS in Oceania (adapted from Kenway et al., 2008)

Before coming to the specific comparison of the weights of each stage of the urban water cycles, we can assess the total consumption, ranging from 350 to 1300 MJ/cap.year (97 to 360 kWh/cap.year). One thus sees a wide range of values for this specific consumption indicator. The average value of 240 kWh/cap.year in Oslo (Venkatesh, 2011) is thus above the mean value of this range. Although the system boundaries of the Australian review in terms of energy consumption is not explicitly stated, they concern mainly the direct energy consumption within the plant – a good proxy to the O&M phase energy consumption in the case of the Oslo study. If we give closer attention the breakdown of the energy consumption, we can again see a large variability among the different stages. Instead of the large preponderance of wastewater treatment as in Oslo, we observe in some cases up to 75% of energy consumed in water distribution. This is the case because of droughts that led the cities of Sydney and Adelaide to import water over longer distances. In addition, the other large variability concerns water treatment, ranging from "simple treatment" (water supplied from a tank) in Gold Coast to desalination plants in Perth.

Looking at those figures, we can hence acknowledge that, in a water-scarce country as Australia, the importance of the water supply side of the UWCS is subject to dramatic variability and increase of energy requirements compared to water-rich countries as Norway or New-Zealand. This is contrary to the relatively more stable energy need for sewage pumping and wastewater treatment, more standardised and less subject to the direct environment, except stormwater infiltration. One can however note that, although less subject to variability, wastewater treatment still proposes a large range of values that directly depend on the level of treatment (as stated above), from 1.5GJ/m^3 (0.42kWh/m^3) in Sydney (primary treatment and deep sea release) to 2.7GJ/m^3 (0.75kWh/m^3) in Auckland (tertiary treatment). Those values are thus a little below an average of 0.8kWh/m^3 in Oslo in 2006.

Before moving over to impact-assessment-related studies, other works related to energy consumption warrant mention. Lazarova et al. (2012), has compared the energy requirements for various water projects in USA, Europe, Africa and Asia (refer Figure 2.5) :

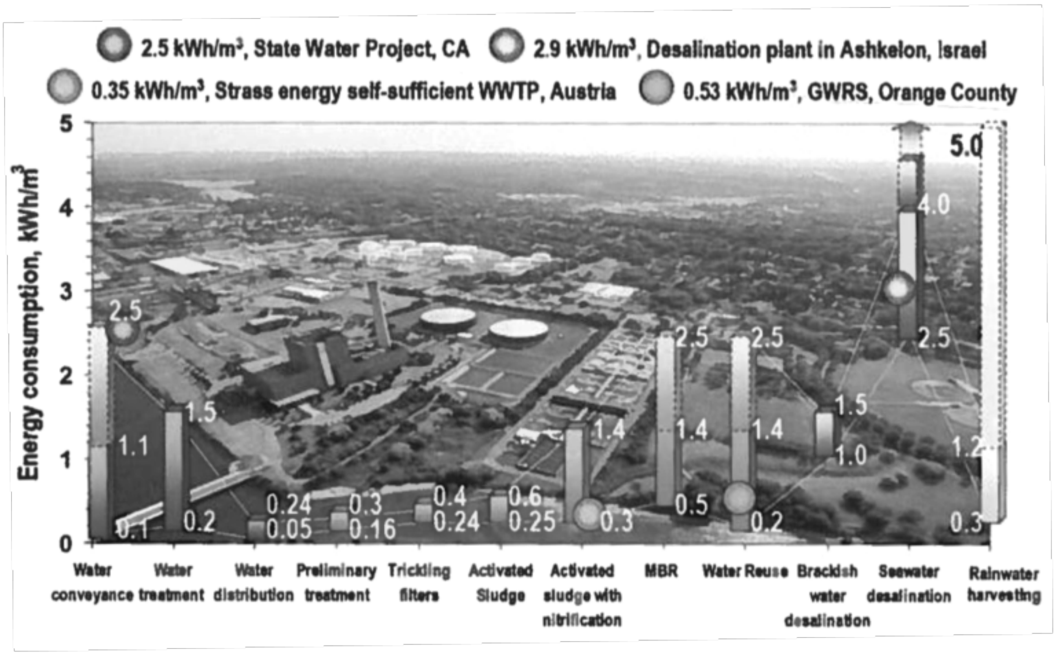


Figure 2-6: Typical energy figures (Lazarova et al. 2012)

The first three bars depict energy requirement for water treatment; the next four pertain to wastewater treatment, and the others are related to water reuse, desalination and rainwater harvesting. Interestingly, this paper gives the same ranges of energy requirement for water and wastewater treatment (0.2/0.3 to 1.4/1.5 kWh/m^3 treated). The difference in the ranges is a consequence of the differences in technologies adopted (efficiencies etc.), pumping heads and plant capacities. The authors also note the extremely high requirement for desalination, a method mostly used in water-scarce countries, where seawater is the only possibility to meet the population's water needs. When it comes to "transversal" water treatment, such as water reuse or rainwater harvesting (which will be more thoroughly reviewed in the next paragraph), we can see a very large range of values, in extreme cases as high as 2.5kWh/m^3 or 5kWh/m^3. A possible reason for such an inconsistency could be the novelty of such techniques, which are not optimised everywhere. Besides, the need to supply water is uppermost; optimisation of energy consumption is rightfully accorded a lower priority. However, the authors note that water reuse "is one of the most cost-, and energy-efficient alternative water resources compared to desalination and long-distance water transportation". This can easily be verified from Figure 2.5. The authors have also mentioned that rainwater harvesting is becoming increasingly popular as the desire for buildings to become more adaptable and resilient to climate change and population growth increases". They however issue caveat here – the major drawback behind popularising rainwater harvesting could be the inefficiency of the small-scale pumps utilised in such cases.

Finally, it is interesting to point out a more precise analysis of the energy usage in the two complex parts of UWCS - water and wastewater treatment. This has been done, *inter alia,* in two articles – by Menendez & Veatch (2010) and Racoviceanu, Karney, Kennedy, & Colombo (2007). In these two articles, the scope of the analysis is a little different from the works cited earlier. Racoviceanu et al (2007), by adopting a life-cycle assessment approach to water treatment has analysed not only the direct energy consumption but also the energy consumed upstream to produce and transport chemicals. The primary energy requirements have also been factored in. This paper has broken up the energy consumption of Toronto's water treatment plant, process-wise. Menendez et al (2010) have adopted a more straightforward method to analyse the direct energy consumption, but with comparable results for the average of U.S. wastewater treatment plants. The results of both studies can be found in Figures 2.6 and 2.7 below:

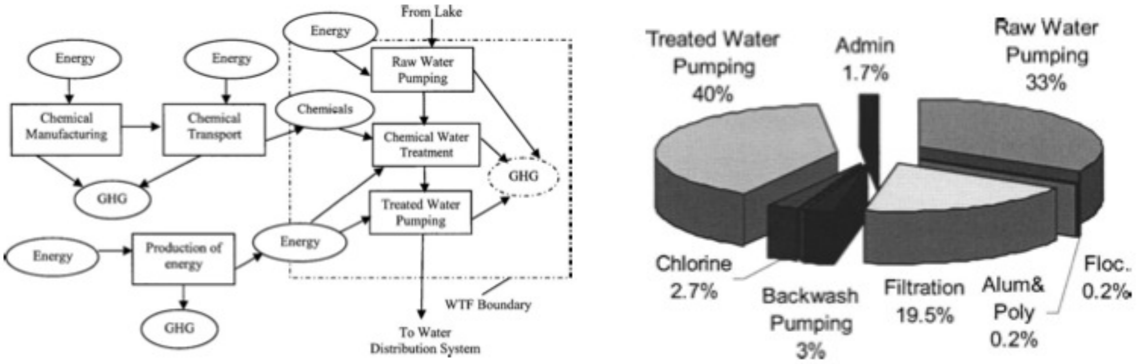


Figure 2-7: System boundaries and energy use at a WTP (Racoviceanu, 2007)

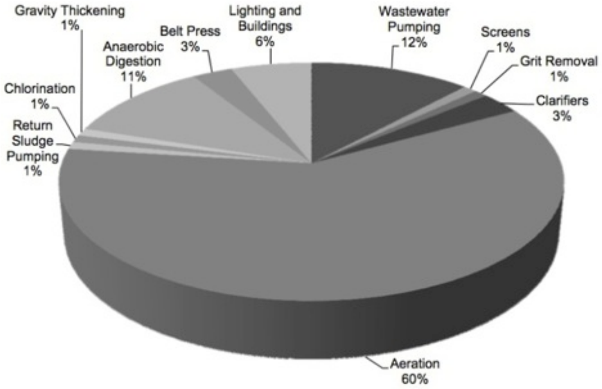


Figure 2-8: Process-wise split of energy consumption in a WWTP (Menendez et al., 2010)

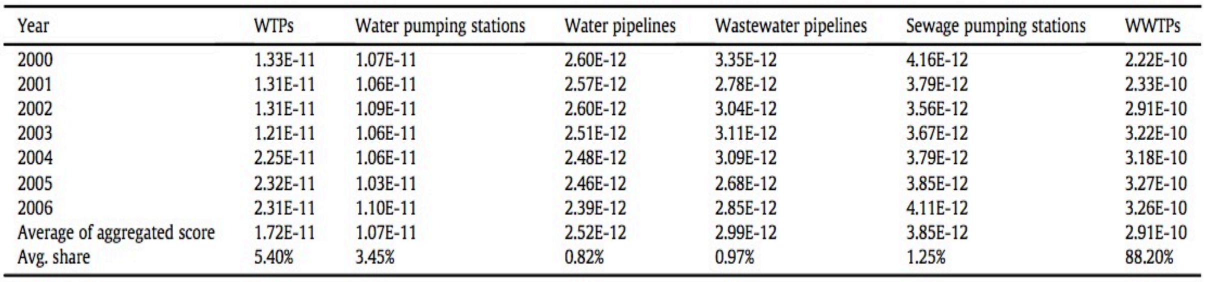
A short analysis allows pointing out two major elements. In water treatment, pumping consumes the most energy by far. Both raw water and treated water pumping sum up to almost 75% of the total energy. In addition, we should note that the considered water treatment plant is situated on the shore of Lake Ontario and serves a particularly flat area, hence diminishing the necessary water heads (pressures) to reach the user, compared to an average plant.

For wastewater treatment, the lion's share of the energy consumption is in aeration, which occurs during the COD and BOD removal in activated sludge plants. Hence, the choice of a particular treatment process would probably not impact the water supply side. On the contrary, the choice of anaerobic sewage treatment over activated sludge treatment could have consequences for the energy balance of wastewater treatment (as energy generation in-plant reduces the need for external energy supply).

2.2.2. Benchmark on carbon emissions throughout UWCS

In this paragraph, we will reflect upon the carbon emissions linked to the activities outlined and examined in the previous paragraph. It is possible to first go through complementary carbon analysis on the works that were already mentioned. Then we shall investigate on other estimations given by other studies.

The case of Oslo gives information about the environmental impacts. Venkatesh & Brattebø (2011), detail the aggregated environmental impact scores per capita in the city's utility, along the different water cycle stages, in the O&M phases. They consider direct energy consumption and use the Nordic electricity mix. We have to note here that not only the global warming potential is depicted but also other impact categories, corresponding to the LCA method CML 2001. However, as depicted on Table 2.3 and Figure 2.8, the specific weight of global warming potential can be deduced, as well as the shares of each stage:



Year	WTPs	Water pumping stations	Water pipelines	Wastewater pipelines	Sewage pumping stations	WWTPs
2000	1.33E-11	1.07E-11	2.60E-12	3.35E-12	4.16E-12	2.22E-10
2001	1.31E-11	1.06E-11	2.57E-12	2.78E-12	3.79E-12	2.33E-10
2002	1.31E-11	1.09E-11	2.60E-12	3.04E-12	3.56E-12	2.91E-10
2003	1.21E-11	1.06E-11	2.51E-12	3.11E-12	3.67E-12	3.22E-10
2004	2.25E-11	1.06E-11	2.48E-12	3.09E-12	3.79E-12	3.18E-10
2005	2.32E-11	1.03E-11	2.46E-12	2.68E-12	3.85E-12	3.27E-10
2006	2.31E-11	1.10E-11	2.39E-12	2.85E-12	4.11E-12	3.26E-10
Average of aggregated score	1.72E-11	1.07E-11	2.52E-12	2.99E-12	3.85E-12	2.91E-10
Avg. share	5.40%	3.45%	0.82%	0.97%	1.25%	88.20%

Table 2-3: Aggregated environmental. Impacts in Oslo per capita. in O&M, from direct consumption and Nordic electricity mix (Venkatesh et al., 2011)

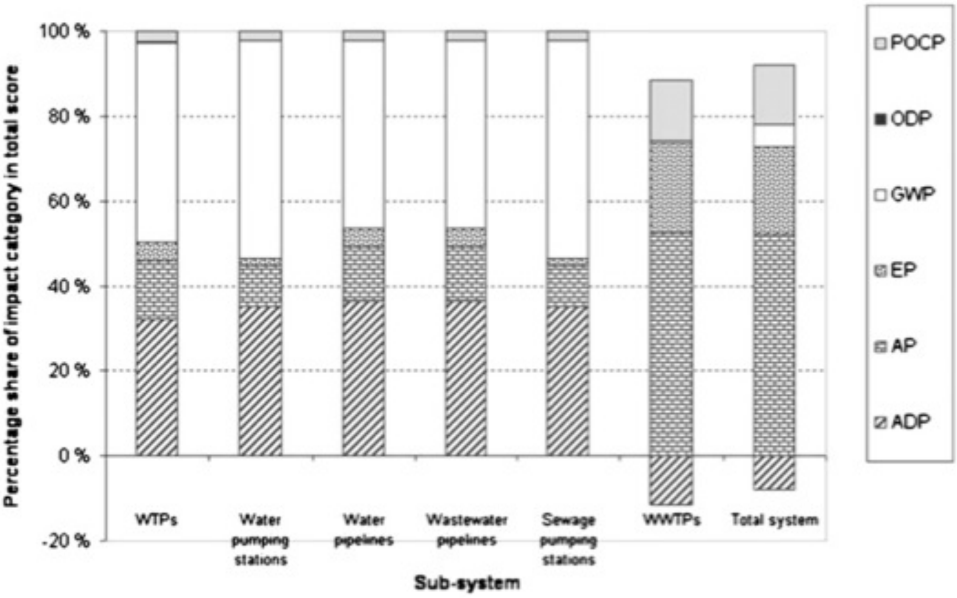


Figure 2-9: Shares of impact categories in the UWCS in Oslo (Venkatesh et al., 2011)

Some key conclusions can be drawn from those figures. Firstly, it can be seen on Figure 2.8 that Global Warming Potential (GWP) accounts for over half of the impacts from the WTP to the sewage collection. However, in wastewater treatment, it is acidification that accounts for most of the impact score - largely due to the generation of sulphur dioxide and nitrogen oxides during biogas combustion. In addition, wastewater treatment has relatively small net impact as far as greenhouse gases and global warming are concerned, owing to the fact that it generates renewable energy from biogas (electricity and heat), which avoids production/generation elsewhere. However, it should be noted that GWP in wastewater treatment still represents an important part of the total GWP, since the total impact (the aggregated score) of WWTP is much higher than the other ones. Moreover, one can also integrate here the further analysis made by Venkatesh (2011) concerning not the direct energy in the Operation and Maintenance phases, but the impacts of both direct and indirect energy consumption due to chemical consumption in the WTPs (left) and WWTPs (right) (Norwegian electricity mix used), as seen on Figure 2.9.

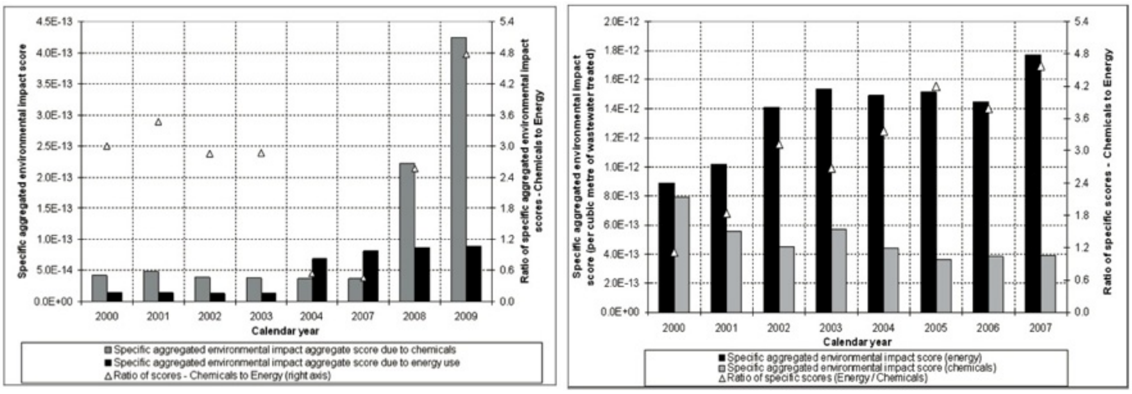


Figure 2-10: Environmental impacts in WTPs and WWTPs in Oslo – Energy versus chemicals, Norwegian electricity mix (Venkatesh, 2011)

It is seen that wastewater treatment Concerning the weight of each, one can note that water treatment is responsible of less impact than wastewater treatment, as seen on Table 2.3. Furthermore, both impacts are by 2006 below the impacts of Table 2.3, because of the use of the Norwegian v. Nordic electricity mixes. When it comes to single assessment of WTP, one can acknowledge that chemicals impact much more than energy, because of the quantities used. On the contrary, it can be seen for WWTP that even though the Norwegian electricity mix is particularly clean (99% hydroelectricity), direct energy consumption accounts for much more than the chemical consumption, probably as a consequence of the plant energy production and consumption.

In another study (Lassaux, Renzoni, & Germain, 2007), the authors embed the whole UWCS of the Walloon region in Belgium into a single Life Cycle Assessment. The authors assess several scenarios illustrating the development of the region, vis-à-vis a "no wastewater treatment scenario", with the functional unit of "having one cubic meter of water at the consumer's tap". The results are the following (Figure 2.10, method CML 2001):

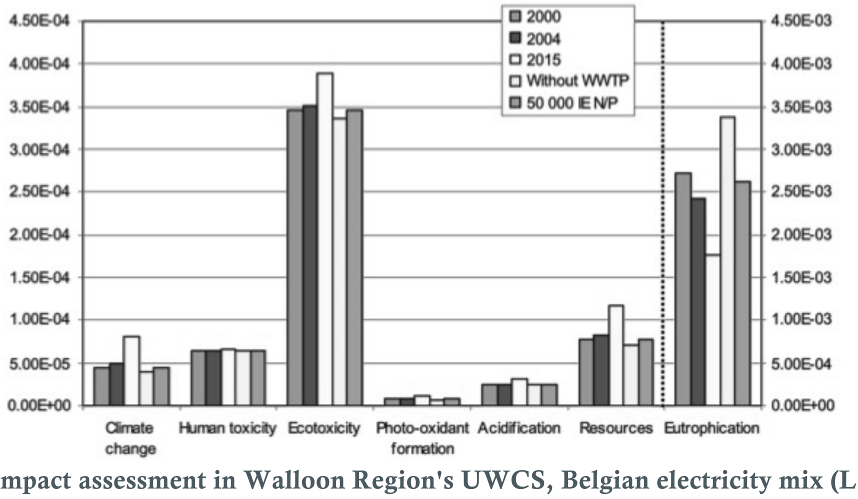


Figure 2-11: Impact assessment in Walloon Region's UWCS, Belgian electricity mix (Lassaux et al., 2007)

Interestingly, the year-2015 scenario, which corresponds to the highest level of wastewater treatment, has the highest score for all impacts considered, except for eutrophication. According to the authors, this is mostly due to the fact that avoiding the discharge of certain chemicals into the environment entails using other chemicals. We have to recognise in addition that the aggregated impact scores are much higher –

numerically - in this study than they are in Venkatesh (2011). This is because the authors consider here eco-toxicity indicators, which have a large impact on the results.

Many other studies focus on a specific stage in the UWCS and carry out life-cycle assessment and carbon footprint calculation for the stage chosen. Thus, we can still try to analyse the outcomes independently, without benefiting from a large overview over the different stages. Another article by Keller & Hartley (2003) about greenhouses gases (GHG) in wastewater treatment evaluates the global warming potentials from several technologies, concluding that "major advantages can be gained by using primarily anaerobic processes", reducing the total GHG production form 2.4kgCO_2e/kg COD removed to 1.0kgCO_2e/kg COD removed assuming a coal-based electricity production. Houillon & Jolliet (2005) have investigated more specifically different ways of treating and disposing of wastewater sludge. By defining the chains of the required upstream treatment processes for different types of disposal, the authors have notably managed to rank ranking the emissions for 6 possible scenarios (using the average European electricity mix, UCTE), as depicted on Figure 2.11:

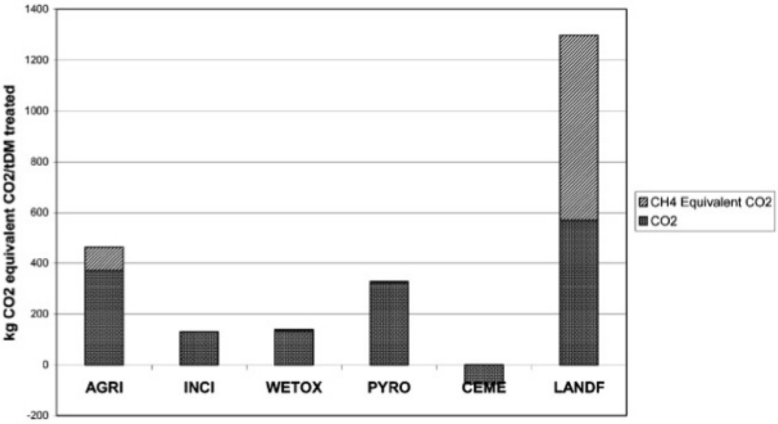
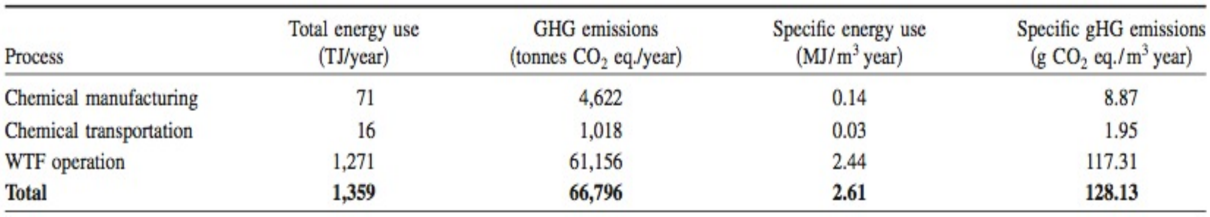


Figure 2-12: Sludge Treatment Scenarios (Houillon et al., 2005)

In Figure 2.11, AGRI represents agricultural land-spreading, INCI specific incineration in fluidised bed, WETOX wet oxidation of liquid sludge, PYRO pyrolysis of dried sludge, CEME incineration in cement kilns of dried sludge, and LANDF stands for landfilling. Thus, according to Houillon & Jolliet (2005), sludge burning in cement kilns is the soundest option environmentally speaking, because dried sludge permits the avoidance of the usage of fossil-based fuel material in the kiln. On the contrary, landfilling is the worst option because of the imbalance in costs (energy to produce the sludge and the use of lime) and benefits. In this case, methane leakage happens at the landfills, contributing to global warming.

Referring back to Table 2.3, the second-most impacting stage in the UWCS is the water treatment. In Racoviceanu et al. (2007), the authors differentiate among the plant operation, chemicals production and chemicals transportation; and arrive at the results tabulated in Table 2.4



Process	Total energy use (TJ/year)	GHG emissions (tonnes CO_2 eq./year)	Specific energy use (MJ/m^3 year)	Specific gHG emissions (g CO_2 eq./m^3 year)
Chemical manufacturing	71	4,622	0.14	8.87
Chemical transportation	16	1,018	0.03	1.95
WTF operation	1,271	61,156	2.44	117.31
Total	**1,359**	**66,796**	**2.61**	**128.13**

Table 2-4: GHG emissions in water treatment (Racoviceanu et al., 2007)

According to this table, GHG emissions are predominant in the operation phase of the plant. Indeed, the plant operation represents 90% of the 128g CO_2e/m^3 treated. However, the chemical manufacturing and transportation represent respectively 5% and 1% of energy consumption, compared to 7% and 3% of GHG emissions. This permits acknowledging that the energy used for those processes are more carbonated than the energy used at plant: the quotient GHG/Energy is higher for chemical manufacturing and transportation than plant operation.

2.3. System approaches to the water-energy nexus management

The IPCC estimates that waste management and water supply- wastewater treatment sectors contribute less than 5% of the total GHG emissions (Bogner, et al., 2007). This is lower than other sectors, but by no means unimportant. We could here only mention the fact that wastewater treatment can actually become a net carbon sequestration sink: one finds mention for example that "the potential GHG emissions which can be converted to a net equivalent CO_2 credit can be as large as $1.21*10^4 tCO_2e/day$ by 2025" (Rosso & Stenstrom, 2008). Thus, whereas no specific targets have been set for the water and wastewater sector in terms of CO_2 emissions (Prof Arun Kansal & Prof Shobhakar Dhakal, 2012), it remains important to assess the seemingly large and untapped potential of improvement within this sector. As far as recent literature is concerned, researchers promote two main elements as leverage points – Energy independence and sustainability. Firstly, they support the decentralisation and integration of water and wastewater systems; secondly, they canvass for efforts towards energy-positive wastewater treatment.

Thus, several authors point out the necessity to close the urban water-energy cycle and more generally, the urban metabolic cycle (Novotny, Ahern, & Brown, 2010). This can occur thanks to more conservative options such as water conservation and reuse, stormwater and grey water management, energy extraction from wastewater, nutrient recovery from wastewater sludge etc. Furthermore, it can be added that all those elements are characterised by a varying level of decentralisation (Biekel, Cornell, & Wagner, 2010). It goes without saying that future cities will necessarily have to integrate water reuse and reclamation in the water cycle planning, thus giving to the UWCS a more precise and adaptable supply infrastructure. According to the authors, semi-centralisation taken along with integration measures can have several advantages, such as water savings, higher flexibility, higher potential for heat recovery and decreased capital commitment within the grid system. As a final comment concerning alternative sources, one should consider as noted in Lazarova et al. (2012) that resources need not necessarily compete within an UWCS, but may often provide synergistic opportunities for efficiency improvements.

Regarding energy efficiency in wastewater treatment, it is firstly stressed in Lazarova et al. (2012) that self-sufficiency should not be viewed as a goal *per se*. It is, of course, a component of the global water cycle, and the performance of the wastewater treatment plants should be given due importance in the planning process. It should thus precede the energetic choices, made in accordance to the larger context. However, this does not prevent the utilities from having an overarching framework of measures within which they can decide on their energy policy in wastewater treatment. Thus, two Austrian wastewater treatment plants have achieved energy self-sufficiency notably thanks to an optimisation of processes (Nowak, Keil, & Fimml, 2011). They consist *inter alia* of optimal aeration control, particulate carbon recovery, optimised anaerobic sludge digesters, and combined heat and power (CHP) units. The authors note in addition that the high level of results have been achieved in particular through "a long-standing and on-going optimisation process", hence justifying the role of the plant performance over the energetic performance.

2.4. Benchmarks for improvement

In the previous section, different points of view regarding UWCS management were discussed. In this section, the focus will be on possible improvements and best practices, which UWCSs around the world could implement / adopt in the years to come, in the different stages of the urban water cycle.

- The first stage is the supply of raw water. As seen in the previous paragraph, prospective evolutions of raw water supply are closely related to the decentralisation of water systems, allowing the multiplication of water sources (Biekel, Cornell, & Wagner, 2010). In a study of the Institute for Sustainable Future by Retamal, Glassmire, Abeysuriya, Turner, & White (2009), current rainwater tank systems would entail energy consumptions of approximately 1.5kWh/m^3, vis-à-vis 1kWh/m^3 in centralised systems. However, the authors note that such values are context-specific, and envision the development of smaller-scale pumping systems that would reach much higher yields. Thus, by combining neighbourhood-scale systems and higher-efficiency pumps, it is possible to reduce the total energy consumption in urban water systems.

- The second stage of the urban water cycle is water treatment. In an American study of SBW Consulting, Inc. (2006), it has been agreed that "for many treatment facilities, the regulations are likely to require the use of relatively new treatment techniques […] requiring a significantly greater use of electricity". As a consequence, energy efficiency programmes to assess both pumping water and treatment techniques have been administered. This study, going through the different technologies of treatment, provides some suggestions for the attainment of higher energy efficiency. These are oriented more towards individual process efficiencies rather than towards the integration of processes in general. The study focuses particularly on certain characteristics of the UV/Ozone disinfection (low instead of medium pressure) or particular aspects for the pumps, as reduced head loss, and use of buster pumps.

- The third stage of the cycle is water distribution. As we have seen earlier, the energy consumption at this stage can vary widely (Kenway, Priestlay, Cook, Seo, & Inman, 2008), depending not only on the distance over which the water is to be transported, but also the topology of the serviced areas. Thus it often occurs that a certain head is given to the treatment water out of the plant, but this head is too high for certain parts of the cities, where the pressure needs to be broken. An innovative solution can consequently be the use of micro-turbines (McNabola, Coughlan, & Wiliams, 2011). Indeed, the use of break pressure tanks usually only dissipates the energy given to water through pump-pressure. However, forcing the water through micro-turbines when it leaves the pipeline to the tank allows the recovery of part of the energy. In an Irish case study, the potential of micro-turbines for a locality has been identified as between 2kW to 27kW. This corresponds to the energy needs of 5 to 48 average homes. A pilot project has furthermore been installed in South Africa (McCann, 2012). According to the article, the current installations can generate up to 15kW, and if this is projected onto the entire country, a possible 26GWh/year can be generated.

- The fourth stage of the water cycle, post-consumption, is sewage collection. This stage is in fact closely related to the consumption itself, because using the wastewater heat is a way of recovering waste heat from consumption. Thus, projects have been led, for example in Japan, in order to recover wastewater heat (Funamizu, Iida, Sakakura, & Takakuwa, 2001). According to the authors, such projects are desirable, under the consideration of key factors such as "setting the pumps near the demand points", "technical development of equipment to prevent system from clogging corrosion and decrease in the heat transfer efficiency".

- Finally, as mentioned previously, most of the environmental impacts occur in the wastewater treatment stage. But at the same time, this stage also presents wonderful opportunities for energy recovery (Nowak, Keil, & Fimml, 2011).

2.5. Using the Industrial Ecology toolbox

Industrial ecology tools will be availed of, in this thesis. Hence, it is opportune to define Industrial Ecology at the outset.

Robert White has defined industrial ecology as:

> *The study of flows of materials and energy in industrial and consumer activities, of the effect of these flows on the environment, and of the influence of the economic, political, regulatory and social factors on the flow, use and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities. This integration an on-going process, is necessary if we are to address current and future environmental concerns.* (Ehrenfled, 2002)

This definition, it can be said, guides the work of every industrial ecologist. It is in essence the *summum bonum* of industrial ecology research, and can be said to apply to any production-consumption-disposal system.

Industrial ecology, a relatively new discipline, supports holistic, systems-oriented thinking in research and planning. By this it is not only implied that systems must be seen as aggregates of several sub-systems, but also as interdependent sub-systems (with different extents of interdependence) Thus, industrial ecology advocates for the complexity of systems and the understanding that a mere separation of topics (or indicators, or criteria) is often not enough to understand the global dynamics when several issues are being investigated. It however, is not merely about the flows of materials and energy. As White says, when the scale of the analyses is expanded to include larger regions, cities and countries, politics, economics, legislation and even human behaviour become essential aspects of industrial ecology research. Systems analysis (a non-parochial approach in other words), enables the researchers to factor in possible rebound effects (Hertwitch, 2005), which come about when the benefits associated with a change in technology to a more environment-friendly one, is often offset by a subsequent rise in consumption (the use of that technology in other words); when it comes to absolute environmental impacts.

Industrial ecology bases its understanding on a handful of tools that allow the analyst to cope with the scale and boundary concerns mentioned earlier. The most-commonly-used ones are Life Cycle Assessment (LCA) and Material (or Substance) Stock and Flow Analysis (MFA or SFA). More details about these tools will be provided in the next chapter. LCA can be either product-focused or service-focused; it is generally performed in order to assess the impacts of a product or service (a car, an aluminium can, a phone call, etc.) on the environment throughout the life cycle. In other words, in addition to the use-phase, the production and end-of-life phases are also factored in. LCA studies abound in literature. For example, comparisons have been made (Majeau-Bettez, 2011) to assess which kind of electric car battery would be the most suitable one, from an environmental point of view. Hertwitch, (2005) has pointed out that lack of data is always a challenge faced by LCA analysts. The databases available to the researchers do not always have the required definition level; this is true especially in developing countries or for specific sectors of the economy like agriculture.

Another widely used methodology is MFA, which focuses on the flows and stocks of materials (or substances). The life-cycle approach (same as the one adopted for an LCA) applies to MFA as well. Substances or materials or products are tracked from cradle to grave or cradle to cradle (when recycling is well-entrenched into the system)., with the chain of processes in the life-cycle clearly identified and described. Among its applications are the tracking the flows of toxic or hazardous substances or identifying the distribution of stocks of specific materials in a society/city/country. For example, by describing the US anthropogenic iron cycle and its dynamics since the 1800s (Müller, Wang, Duval, & Graedel, 2006), it has been possible to calculate the global mass of iron throughout the USA and both its current state of use (lithosphere, use, slag etc.) and the sector using it (transportation, construction…). Such an approach presents an opportunity for urban mining, as it uncovers the option of recovering metal at lower costs from the stocks in the anthroposphere (as and when these would reach the end-of-life). Additionally, one may also use MFA to forecast the flows and stock-changes for the future; as Brattebø (2009) has done for the urban built environment. Finally, a combination of current stocks and flows combined with forecasts can be used to estimate the potential reduction in greenhouse gas emissions, as done by Liu et al. (2011) for the US aluminium sector. MFA, it must be said at this juncture, relies to a less extent vis-à-vis LCA, on emissions databases. Nevertheless, quite like LCA, it is data-intensive and necessitates spending a lot of time on data gathering prior to the analysis.

Databases are being constructed with a stress on higher accuracy of the data they contain; and more complex systems are being analysed using sophisticated hybrid models, which are evolving from the static to the dynamic. Here, the Multi Unit Input Output (Hawkins, 2007), which enables one to track material flows in an economy instead of money flows (as is common in the conventional Input Output Analysis) deserves mention. Using highly integrated models, it would be possible to analyse systems by widening the scope and also delving down to greater levels of detail.

3. Presentation of the case studies

In this chapter, the background of both cities shall be developed, in order to provide the reader with a clear overview of the cities' dynamics and of their specific water utilities. Points of comparison will be developed for a better readability.

3.1. Cities presentation

Nantes Métropole is a community of towns around Nantes, the administrative capital of the region of Pays de la Loire. On date, 24 towns (including Nantes) are part of this community, which covers an area of 523 km^2 and has a global population of almost 590,000 inhabitants (in 2009/2010), which gives a population density of around 1130 capita/km^2, 10 times the national average. The city of Nantes has 283,000 inhabitants (2008 figures) and an area of 65 km^2, which represents 4340 capita/km^2. Both figures lead in consequence to an average density outside of Nantes of 670 capita/km^2. The community was created on the 1st of January 2001. It is therefore only a decade old and its existence came as a sequel of a will of political and social union, but later than the establishment of number of different services to the users and inhabitants for the different towns.

Oslo is Norway's capital. Its population for the baseline year of 2007 was 560,000 inhabitants, increasing rapidly because of its attraction to Norwegians from other parts of the country, and immigrants alike. Its density is 1230 inhabitants per square km, which is about one hundred times the national average. The city constitutes one communal district *fylkeskommune*, administrated by the city council.

City	Nantes M. (2010)	Oslo (2007)
Population	590,000	560,000
Density	1140 capita/km^2	1230 capita/km^2
Water demand	30.4 Mm^3/year (million m^3)	95.2 Mm^3/year

Table 3-1: Background information in Nantes and Oslo

3.2. Water utilities

As a multi-cities community, Nantes Métropole chose to orient its services model towards a mixed exploitation mode based on different concerns, water & wastewater being one of these. The urban water (water treatment and distribution) system has therefore been differentiated (Nantes Métropole, 2010). A municipal utility is operating in Nantes and its adjacent towns. This public operator also owns and runs the major water treatment plant, which supplies around 90% of the water consumed in the community. Private companies have been delegated in the rest of the agglomeration. To date, the companies managing the rest of the system are Veolia and Saur.

Concerning wastewater collection and treatment, an equivalent mixed mode of exploitation exists, with other operators (Nantes Métropole, 2010). Indeed, public operators mostly run the service to the consumer but not all stages in the wastewater treatment process. The sewage network operation is split up and organised similar to the water treatment and supply operations. Nantes and bordering towns are run by public concerns, whereas other parts are being delegated to private companies (CEO, SAUR, Suez). The company Epuria (owned by Suez) operates the two major wastewater treatment plants under the direction of Nantes Métropole. This means that Nantes

Métropole has the financial responsibility of the plants and owns them, but the private company has the technical responsibility of running them. Overall, the public operator is accountable to and responsible for servicing about 62% of the subscribers to the water utility, and for about 68% of the subscribers to the wastewater services.

3.3. Water systems

In this paragraph shall be explained as synthetically as possible the main features of both urban water systems, in each of the subsystems. All elements for both cities come from institutional reports, personal communication with the staff in Nantes and G. Venkatesh (the co-supervisor of this thesis) about Oslo's utility. All sources are cited in the paragraph 4.5 "Data Collection" of the Methodology chapter.

♣ Supply

As explained previously, the main source of water is the river Loire. It carries a flow that is big enough to support the society's needs: averages intakes from the river are around 1.2 m^3/s on a yearly basis, compared to a total river flow between monthly averages of 242 m^3/s in August and 1830 m^3/s in January (Wikipedia, 2011). The supply station is situated in Mauves sur Loire, 15 km upstream of Nantes, in order to avoid the points of higher turbidity. After being screened, water is sent to Nantes Métropole's main WTP, the La Roche treatment plant. Here, it must be mentioned that another WTP exists in Nantes Métropole in Basse Goulaine, which does not primarily supply drinking water to Nantes Métropole. So, this will be kept out of the scope of this study. Some water is imported to Nantes Métropole from this WTP (less than 10% of the total), but since the net import of water in the urban community is negative, all drinking water will be approximated to the water produced in La Roche.

Oslo's water comes mostly from the Maridalsvannet Lake near Oslo (85% of Oslo's population is supplied in this fashion). Of the 184 Mm^3 through-flow of the lake, 95 million cubic metres are directed to the Oset WTP. Water is supplied directly to the plant, which is situated close to the source. Until recently, three other plants were in activity (Langlia, Skullerud and Alunsjøen), but the Alunsjøen WTP was taken out of operation.

Distribution	Nantes M. (2010)	Oslo (2007)
Source	Loire (90%)	Maridalsvannet (90%)
Quantity	±40Mm^3/year	±110Mm^3/year

Table 3-2: Water supply in Nantes and Oslo

♣ Treatment

The main elements of the water treatment plant in **Nantes** are the following. Water is first supplied through an open-air channel, **screened and pumped** to the top of the treatment chain. The first step of the treatment itself is **pre-ozonation** to break down some algae and microorganisms. Ozone being unstable, it is produced on-site by utilising electricity and oxygen. Then occurs **decantation**, to separate all solid particles from the water. Particles fall with gravity, after having been aggregated thanks to a flocculent and a coagulant. After decantation, **activated carbon** is used if necessary to adsorb micro-pollutants. Water is then **filtrated on sand** to capture the last suspended matter. Thereafter occurs **post-ozonation** with a higher content of ozone, to kill all viruses and bacteria. A **second activated carbon use** allows cleaning the last micro-pollutants present in the water. The final stages of water treatment occur with **corrosion regulation** (to avoid aggressing pipelines) and **final disinfection**, through use of chemicals.

Concerning **Oslo**'s WTP, the following treatments occur. According to Venkatesh (2011): "All the three plants do not treat the water in the same manner. While Langlia resorts to **filtration and disinfection** with sodium hypochlorite, Oset and Skullerud adopt **microfiltration**, chemical treatment, and **disinfection** with sodium hypochlorite and ultraviolet radiations (the so-called second line of hygienic barrier). However, **before 2008**, the methods of treatment at Oset and Langlia were nearly the same – except for the fact that **Langlia used chlorine gas** for disinfecting the water. After 2008 the consumption of chemicals has risen owing to the fact that 90% of the supply, which earlier was not subjected to chemical treatment, now consumes polyaluminium chloride, calcined lime, carbon dioxide, microsand and polymer, in addition to sodium hypochlorite". Here again must be noted that the **baseline year is 2007**, and subsequent changes in the treatment methods shall be taken into account for future scenarios.

- **Distribution**

Water produced in the main WTP is stored in the centre of Nantes and then sent to the rest of the conurbation through intermediary pumps and water towers. In Oslo, each WTP serves a part of the city, accordingly to its size, and a certain number of pumps and storage allow the adaptation of the flow to the demand.

Distribution	Nantes M. (2010)	Oslo (2007)
Pipelines	3100 km	1500 km
Pumps	7	28
Losses	20%	20%

Table 3-3: Water distribution in Nantes and Oslo

- **Demand**

Demand is a complex issue and it is not possible to give interesting qualitative statements without going too much into details and suppositions. However, a modelling work for current and future demand in both cities shall be led in this thesis (refer to Appendix 3), based on the utilities' knowledge about consumption. We can notice that the 2009 administrative report for **Nantes** (Nantes Métropole, 2009) on water quality gives a rough estimation of **78% of water consumed by individuals and/or small consumers** (the differentiation is difficult to make). Another research report has been made by Nantes Métropole and CEMAGREF by Montginoul, Even, & Verdon (2010) in order to analyse the dynamics in the consumption.
In **Oslo,** water is estimated to be consumed in the ratio 57-43 between **households and industries/commercial establishments respectively**. Figures for demand are depicted in Table 3.1.

- **Sewage collection**

In the Nantes Métropole, after water has been consumed, most of it is sent to the sewage network, towards the WWTP that clean the water before discharging it to the river. No exchange, import or export of wastewater is made. The most **ancient** part of the network, inside the city of **Nantes**, is a **mixed sanitary sewer**, used for over a century, and

intended to collect both sewage and stormwater. Despite the share of rainwater, this mix is polluted and must be treated, even if overflow can cause a direct release. More r**ecent network separates wastewater from stormwater.** This leads to lesser treatment needs thanks to the smaller flow, and also prevents overflow events and discharges rainwater directly to its natural environment. Costs and infrastructure reasons are the main drawbacks to not installing separate sewage in the city centre.
In **Oslo,** the **three types of wastewater/stormwater pipelines** are also present, which leads thus to a certain number of infrastructures to allow overflowing.

Sewage	Nantes M. (2010)	Oslo (2007)
Pipelines (total)	3530 km	2200 km
Combined flow	359 km	660 km
Sewage pipelines	1652 km	792 km
Stormwater pipelines	1654 km	748 km
Pumps	378	65
Outlets	69	528

Table 3-4: Sewage Collection in Nantes and Oslo

- ♣ **Wastewater treatment**

Nantes Métropole has essentially two WWTPs, Tougas and Petite Californie, treating a large majority of the wastewater (resp. 72% and 21%), along smaller-scale WWTP, which we will not study.
The treatment in the **Tougas** WWTP begins with **screening and pumping** of the incoming wastewater. After pre-treatment, there is **grit removal and oil separation**: grit settles down to the bottom and oil being lighter floats on the water surface, before being removed. In the biological treatment that follows, carbon, nitrogen and phosphorus are removed to an appreciable extent.. In Tougas, activated sludge treatment is employed to remove carbon, nitrogen and phosphorus from the wastewater Activated sludge treatment – aerobic and anaerobic – accomplishes the removal of carbon, nitrogen and phosphorus. The wastewater proceeds thereafter to the **clarification lagoons** where the sludge formed, begins to decant and thicken. Most of it is drained away and proceeds to the sludge treatment; a part is re-circulated to the aerobic and anaerobic lagoons to maintain the bacterial concentration. Water is clear enough and meets the desired standards to be released into the river. Sludge treatment entails **flotation**, **centrifugation** and polymer addition. Finally, lime is added to the sludge (mass equal to 50% of the wet weight of the sludge), to reach 30% dryness, which is considered to be sufficient for agricultural use of sludge, as a fertiliser substitute.
Until 2011, the **Petite Californie** WWTP was **similar** to Tougas. But to increase its capacity, compactness and sustainability, the biological treatment has since been **switched to anaerobic digestion,** in which bacteria decompose organic matter in the sludge without the need for oxygen, generating heat (making the reaction auto-thermic in the process) and biogas. The biogas is combusted in a Combined Heat and Power turbine (CHP) producing heat and electricity. Heat is used in-plant and electricity is sent to the grid. Since the baseline year for this study is 2010, we shall consider the “old” plant for the study, and use the latest developments for scenarios.

Oslo has two major WWTPs, BEVAS and VEAS treating respectively 37% and 63% of the wastewater flows. In these two WWTPs, the biological treatment is different, in that **anaerobic digestion** was chosen. Both plants thus produce biogas and have used it differently: **until recently both of them burnt the biogas to produce heat and electricity**, but BEVAS is **now** (thus later than 2007) **selling biogas as fuel** to Oslo's bus companies. Sludge is used for agricultural purposes.

Wastewater Treatment	Nantes M. (2010)	Oslo (2007)
Major Plants	Tougas (72%), Petite Californie (21%)	VEAS (63%) BEVAS (37%)
Technologies	Activated sludge Agricultural use	Anaerobic digestion Agricultural use
Quantities Treated	42.3Mm^3/year	111.4Mm^3/year

Table 3-5: Wastewater Treatment in Nantes and Oslo

3.4. Challenges and evolutions

Nantes Métropole has experienced, since the 1970s, stagnation in the volume of water treated and supplied, despite a noticeable increase in the population: consequently, many pipelines are now oversized compared to their water through-flow. The urban community is hence working on a smaller and more efficient WTP on the site of La Roche. Nevertheless, the demand decrease might cause issues in the underused network because of water stagnation, a problem Nantes Métropole is aware of. A second challenge is securing the water resource by bringing new sources on-stream. Nantes Métropole is the only supplier able to supply 700,000 persons in the region, and a net exporter of water. If any unforeseen detrimental incident were to occur, water shortages may result.. This possible risk has been countered (pre-empted) by installing another water intake in the Erdre River. A last challenge in Nantes concerns of course the environmental performance of the water utility. Future regulations may necessitate a greater degree of wastewater treatment; as well as an improvement in the quality of supplied potable water. On the other hand, the energy and carbon footprint of the utility and water services is a major concern. The status quo is being studied through the use of the French "Bilan Carbone®" Methodology, and several actions are planned to reduce emissions, energy use, and the related costs. We shall investigate in this work on the possible actions and their environmental outcomes.

In Oslo, as noted by Venkatesh (2011), the level of consumption of water and production of wastewater per capita has decreased over the last decade. However, Oslo may witness a growth in its population in the coming years, leading to a rise in the total demand for water supply and wastewater services. A more important challenge for Oslo's water utility is the need to renovate / rehabilitate the saturated water (and wastewater) pipeline networks, an issue that entails proper management, as described in Ugarelli, Venkatesh, Brattebø, & Sægrov, Asset Management for Urban Wastewater Pipeline Networks (2010). When it comes to water quality and entailed treatment, Oslo's major treatment plant Oset introduced more intense chemical treatments. This resulted in a 10-fold increase in chemicals consumption over the 2000-2009 period, and the question of process optimisation can be asked, without compromising water quality. There are also plans to improve environmental performance, by reducing the percentage of untreated wastewater overflows. Plans of this nature, will be discussed in the chapters to follow.

4. Methodology

This chapter is split up broadly into three sections. The first one re-introduces the research questions and refines them to a more practical level. This is done in order to define clearly the issues to be addressed, and determine the correct system definition associated with these questions. The second part will reflect on the methodologies adopted to calculate energy consumption and carbon emissions – direct and indirect. The third one shall aim at the definition of scenarios.

4.1. Development of the research questions

The research questions introduced first in the Introduction chapter are reiterated hereunder:

1. At what energetic cost are urban water services delivered in Nantes and Oslo?
2. What is the carbon footprint of the utilities in Nantes and Oslo, as far as energy consumption (and generation) is concerned?
3. Can the energetic and carbon footprints be decreased in the future, and through which measures from the water utilities?

These questions have to be refined in order to structure the general analytical framework for this thesis. The first question pertains to the energetic costs – in other words, this will entail the determination of the energy requirements of the water-wastewater utility in the two cities. Indeed, as discussed earlier in the thesis, it is possible to differentiate between direct energy, consumed by the utility, and the indirect energy used in the production of chemicals and fabrication of infrastructure components like pipelines etc. Understanding the energy consumption in terms of the different processes and stages of the water-wastewater system, will feed into a life-cycle analysis. Often, availability of data determines the width and depth of an analysis of this nature.

The first question having been addressed, one moves on seamlessly to the second. To answer the second, it is essential to first answer the first question. The greenhouse gas emissions attributable to the water-wastewater system can further be apportioned (allocated) to the different energy-consuming processes/stages/equipment. However, because of the existence of specific GHG emissions in the treatment processes (such as biogenic or non-biogenic CO_2, N_2O, CH_4), particular attention should be given to identify these emissions from the different processes.

Finally, the third question can be answered by deliberating on future scenarios – possible drivers and responses thereto. Answering this question satisfactorily will entail a choice of realistic drivers (such as population or water demand) for the chosen scenarios. In addition, decisions shall be taken concerning the best choices, either for technologies or overall utility management (e.g. decentralisation and rainwater harvesting, as seen previously). It is in addition possible that such scenarios will call for redefinition of the system boundaries. Indeed, some practices can affect not only the utility, but also other public services or the environment (typically, biogas produced and sold as a substitute to diesel for buses). Consequently, the decrease of energy consumption and/or GHG emissions shall be investigated with respect to the part of the utility/surrounding environment affected in order to be as clear and define as possible.

4.2. Delimitation of the processes investigated

This paragraph provides an exhaustive list of the elements to be accounted for in the energy and global warming calculations. This means essentially choosing the level of detail of the utility description. To that respect, one main hypothesis will lead our reflexion. Indeed, we will consider that operational flows have more impacts than infrastructures, as stated in Sahely & Kennedy, Water use model for quantifying environmental and economic sustainability indicators (2009) and summarized by Venkatesh (2011): “the operational environmental impacts are much more important for the key environmental indicators than capital infrastructure over the life-cycle of urban water systems”. As a consequence, we will not consider the capital infrastructure of the utilities in Nantes and Oslo. This means factually that no energy consumption related to the construction, destruction of the treatment plants or distribution and sewage networks shall be accounted for. However, this does not imply discarding the flows of materials into the utility’s domain to maintain the networks for example: these are operational flows *per se*. Hence, basing our understanding of the UWCS structure on Venkatesh (2011) (refer Figure 2.2), we will here identify the main processes to look at. They are principally the same as depicted in Table 2.2.

♣ **Raw water supply:**

This stage includes the pumping of raw water from the initial source, and the supply to the Water Treatment Plants. No other process (mechanical or chemical) occurs at this phase. Thus, since the infrastructure itself is not considered, the **pumping** will be the only process taken into account here. No maintenance will be added, as one can assume it is negligible compared to the renovation of the water and wastewater networks.

♣ **Water treatment:**

This stage includes all the processes taking place at the WTP in order to impart to the raw water, a potable quality, before sending it for distribution to the pipeline network. It includes **mechanical and chemicals treatment processes**, **intra-plant water pumping,** as well as other routine plant demands like heating and lighting. We shall be clubbing all these different demands together in this analysis. In addition, as mentioned earlier, chemicals account for a significant fraction of the life-cycle energy consumption (and thereby environmental impacts) of the operation-phase of the water treatment plants, Therefore, the **manufacturing and transportation of the water treatment chemicals** will be considered. As mentioned for raw water pumping, no infrastructure or infrastructure maintenance will be included. Furthermore, the pumping of treated water into the water distribution system shall be allocated to the distribution stage.

♣ **Water distribution:**

Water distribution is comparable to raw water supply to the WTPs in that both entail the pumping of water by resorting to electricity-powered mechanical devices like pumps and transportation media like pipelines. The main difference however, is the size of the distribution grid, vis-à-vis the raw water supply infrastructure. In addition to pipelines (which themselves span out to encompass the entire urban area), there is a need for other components like reservoirs, manhole covers, etc. Thus, the processes considered will firstly be the **pumping and storage**, **including the pumping out of the treatment station**, because the given head is highly dependent on the topography of the served area. In addition to them, and as stated above, the water distribution stage shall incorporate the flows related to the renovation and maintenance of the network infrastructure – this includes the **fabrication of the pipelines** which replace the older ones disconnected from the network, **rehabilitation materials**, **transportation and installation-related energy consumption.**

- **Water consumption:**

As stated in introduction to the literature review chapter, the processes specific to water consumption are beyond the scope of this thesis. However, one can note that usage of domestic appliances will result in the release of heat in the wastewater, which can be recovered and reused under certain conditions.

- **Wastewater pipeline network:**

This stage of the UWCS is comparable to the water distribution network, because its main goal is to collect wastewater and route it to the wastewater treatment plant. There are a few marked differences of course. The absence of reservoirs or storages in the wastewater pipeline network, and the fact that this network can be categorised into three classes – sewage carriers, stormwater (rain and snowmelt) pipelines and combined flow pipelines. Thus, the processes embedded for the analysis here are the **functioning of the pumps**, and the **flows related to the infrastructure maintenance**: material manufacturing, transportation and installation.

- **Wastewater treatment:**

This is the last stage of UWCS, involving the mechanical and chemical treatment of wastewater in order to make it suitable for release into the environment, as well as the handling of the various effluents/by-products from the treatment plants (sewage sludge, grease, sand, heat, electricity, biogas, etc.) Thus, this stage will be analogous to the water treatment but not completely symmetrical because of these additional flows. Thereby, the processes for this stage's study are the following. Firstly, the operation of the plants, with the **mechanical and chemical treatment, pumping for the intra-plant water circulation** as well as the lighting and heating demand. Secondly, the material flows entering into the plants: **chemicals with respect to their manufacturing and transportation**. Thirdly, **the material and energy flows concerning the handling of any type of aforementioned by-products/outflows and their end of life treatment**. As noted previously, the specific impacts of the end of life shall be carefully accounted for. They can have large repercussions, if they are substituted to any other flow outside of the water utility's jurisdiction for example.

As a conclusion, the processes under the scope of this study can be summarised on Table 4.1 below:

Stage	Processes
Raw water supply	Pumping
Water treatment	Pumping, mechanical and chemical treatments, heating, lighting
Water distribution	Pumping, storage, network operation and maintenance (O&M)
Consumption	-
Sewage collection	Pumping, storage, network O&M
Sewage treatment	Pumping, mechanical and chemical treatment, heating, lighting, handling of by-products and emissions

Table 4-1: Processes taken into account

4.3. Methodology for energy accounting

It was stressed earlier that the delimitations of the scopes for energy and GHG emissions' analyses would not be the exactly similar, but as close as possible. Indeed, some types of accounting are more easily found and handled when it comes to energy, and some others are more usual for GHG emissions. Thus, the goals of this paragraph and the next one will be to detail the mathematical embedding of energy and GHG respectively, based on the processes described above.

In this work, as we shall investigate on the energy consumed by water utilities, it has seemed more logical to stick to the **final energy consumption**. This means using the figures corresponding to **the quantities of energy the water-wastewater utility pays for**, to the power utility. This also means **not considering the energy generated or the primary energy.** For further distinction between these indicators and in order to avoid any misunderstanding, primary energy is the total potential energy recoverable from an energy source. It is greater than the energy generated, due to the inefficiencies of the thermodynamic conversions. Finally, the energy generated is greater than the final energy consumed (at the consumer's plant, house, office…), the difference being equal to the amount of losses during the energy transmission. Thus, reflecting upon the final energy allows giving a same framework to all numbers indicated and moreover having figures that make more sense in a case-study-oriented work.

To add to this first consideration, it is important to give more readability to the energy taken into account. Electricity from the grid consumed within the treatment plants, and diesel consumption on-site are different. The same goes between on-site electricity for pumping and electricity used to manufacture chemicals. Hence, we shall further divide the sources of energy along two indicators.

Firstly, we shall differentiate on the status of energy, depicting the physical typology of the energy sources used. It is actually an essential point, as the physical form of the energy is closely linked to both the type of use and to the resultant emissions. The most straightforward differentiation is to choose electricity, fossil fuels (for transportation and machinery operation) and heat (from district heating or in-plant heating). Thus, the type and role of each energy source can be appreciated from two different angles. *A priori*, as electricity, fossil fuels and heat have specific roles that cannot always be carried out by alternate sources of energy. *A fortiori*, by weighting the importance of the sources for a single process.

Secondly, the differentiation shall be made upon the incidence of the energy flow in the UWCS. This term actually means stating for each energy flow its place in the UWCS. This implies concretely distinguishing between the energy that is consumed directly by the utility, and any other type of energy indirectly consumed or produced. Thereby, the distinctions to draw within the energy flows are the following.

- ♣ The **direct energy consumption**, including the whole energy consumed inside the water utility's jurisdiction: electricity for processes, heat for the employees or for anaerobic wastewater treatment, fossil fuel for the renovation of the pipelines networks, is included.
- ♣ Then, the **indirect energy consumption** shall be considered. It corresponds to the upstream energy necessary to produce all other flows than energy entering the

utility: for chemical and pipeline manufacturing, and their transportation. Here we have to note that the total final energy shall be accounted for, i.e. the sum of all manufacturing energies for example. Indeed, many chemicals are made through several processes and the most energy is not necessarily required at the last one. It is hence necessary to have in the analysis scope the total final energy and not only the energy consumption at the last stage of manufacturing.

- In addition, we shall account for the **energy generated by the utility**. Several processes allow energy generation, as seen at earlier stages of this work. This energy can take several forms. It can for example be electricity, biogas (used in CHP or resold), or it can be the energy indirectly generated by the sludge (by avoiding the manufacturing of fertilizers). Thus, this shall lead to further separation within the types of energies generated. On the one hand, the **energy generated by the utility and used by the utility**, which stands within the system boundaries for the utility, even if it is sold later. It is important to note that there is no need to mention here any avoided energy. Indeed, the energy used by the plant leads to a direct decrease of its external needs (from the market). Thus, the balance is already made and no specific calculation is needed.
- On the other hand stands the **energy avoided.** This represents all kinds of energy forms, which are avoided by using the services of the water utility. Indeed, electricity from CHP can be substituted to the Nordic/French generation; biogas can substitute to natural gas or other fossil fuels, chemical fertilisers can be substituted by sludge (its nitrogen and phosphorus content, in sooth). The rules of calculations will be the same as for the rest of energy, as the total final energy avoided will be considered. More concretely, when the flow considered is energy (electricity put on the grid, heat), its total value will be affected to the "avoided energy" value, because the necessary flow to replace it would be the same (in terms of final energy). But when it comes to indirect energy flows (e.g. sludge, which is not energy as such), the value given to the "avoided energy" flow will be the one corresponding to final energy content of the flow that would have been needed otherwise. If biogas replaces diesel, the energy content of the diesel is chosen, if sludge replaces fertilizers, the embedded energy of the fertilizers (manufacturing, transport) is taken.

The table below summarises the accounting of energy, and the different flows that shall be included in each category:

Energy (GWh)		I: Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment
A - Direct Requirements	Fossil Fuels Electricity Heat	pumps	heat, processes, comfort, pumps	pipelines installation, pumps	beyond scope	pipelines installation, pumps	heat, processes, comfort, pumps
B - Indirect Requirements	Fossil Fuels Electricity Heat		chemical manufacturing &	pipelines manufacturing & transportation	beyond scope	pipelines manufacturing & transportation	chemical manufacturing & transportation
C - Energy Generation	Electricity Heat	energy generated and used by utility	energy generated and used by utility	energy generated and used by utility	beyond scope	energy generated and used by utility	energy generated and used by utility
D - Avoided Energy	Fossil Fuels Electricity Heat	energy avoided outside utility	energy avoided outside utility	energy avoided outside utility	beyond scope	energy avoided outside utility	energy avoided outside utility

Table 4-2: Accountability of the final energy

4.4. Methodology for greenhouse gases accounting

The major accounting choice for energy was to consider the final ("paid for") energy, as it depicted better the economic reality of the consumption. When it comes to accounting for carbon and greenhouse gases emissions, this reality is different. Indeed, emissions do not necessarily occur on the main production chain of energy. This can be the case for some electricity mixes (e.g. nuclear or hydro, the largest productions shares for France and Norway respectively), where infrastructure can have a large impact, as well as emissions that are not directly related to the fuel conversion to electricity. In addition, **life cycle GHG emissions** are one of the most standardised and best-reported environmental impacts. Thus, the GHG accounting will be led along this indicator, in order **to calculate the Global Warming Potential (GWP) linked to the life cycle GHG emissions due to the energy use reported previously**. Stated in other words, the scope of the work does not change, as the same processes are being considered, but the accountability changes in that not only the final but also all emissions are listed.

Since the focus of this work is to analyse the consequences of energy consumption, it seems relevant to keep the same distinctions as for the energy part, between the three fossil fuels, electricity and heat. Indeed, it shall allow drawing comparisons inside the GWP analysis, as well as with the energy analysis part. In addition, the main element of divergence among those energies, apart from their physical form, is their emission intensity. Fossil fuels are usually much more GHG intensive than electricity, and we will be able to reflect upon this fact in the UWCS context.

Finally, in order to finish the comparison with the energy side of the work, it is necessary to define a framework corresponding to the incidence of the emissions. Indeed, a single energy or material flow will lead to emissions all along its life cycle. For instance, diesel will of course emit much carbon dioxide when it is burnt, but its production will as well. On the contrary, electricity consumption does not lead to emissions at the plant, but only upstream. For these reasons, the following pattern is chosen:

♣ **Direct emissions**:

The direct emissions are the ones occurring directly at the utility's plants or in the network. They can occur as a consequence of combustion of fuels (diesel for transportation, pipelines installations, natural gas for heating…), but also as a consequence of the treatment processes. In that case too types of emissions exist, both biogenic and non-biogenic, depending on the chemical species emitted. Direct emissions hence represent chemical reactions and a part of the direct consumption, but not all of it, as some energy flows do not directly emit GHG.

♣ **Indirect emissions from direct consumption**:

For these flows, the emissions will count as indirect emissions from direct consumption. It will portray the emissions from the generation of all energies directly consumed. Thus, electricity and heat (not from plant biogas burning) related emissions will be depicted, but also the emissions needed to produce the final diesel. By adding the direct and indirect emissions from direct consumption (except the emissions due to the chemical processes), one find the total life-cycle emissions (GWP) from the direct energy consumption. Mention must be made here to the fact that French electricity mix will be allocated to Nantes Métropole, and the Nordic mix will be allocated to Oslo.

♣ **Indirect emissions from indirect consumption**:

The emissions from indirect consumption will represent the life cycle GHG emissions occurring within the processes corresponding to the indirect energy flows (chemicals and pipeline manufacturing and transportation). Thus, the scope will be, as for the primary system, considering both direct and indirect emissions in the chains of productions. This will be allowing us not to overlook any important impact occurring upstream of the final stages.

♣ **Avoided emissions in the utility**:

As for energy generation and energy avoided, we have to distinguish carefully the impacts of the by-products of the water cycle. Indeed, some outflows from the utility are a direct energy source (biogas, or electricity plus heat); some other will replace materials flows, and consequently their embedded energy and emissions (sludge). Thereby, distinction shall be made between the utility's outflows, which are directly reused inside its activities and the ones that are leaving its influence to be used in other services. Henceforth, the avoided emissions in the utility will correspond the energy generated in the utility and used in it. As seen in the previous paragraph, no balance needs to be made, as the production of energy inside the utility decreases directly the needs of purchase from the market: the emissions are decreased as well, directly in the direct or indirect emissions, and no GHG are allocated to the production of energy (which is a by product here).

♣ **Avoided emissions outside the utility:**

The emissions avoided outside utility correspond strictly to the energy paragraph: the emission content of the flows replaced is taken into account as avoided. Emissions from the used utility's by-product are taken into account in case it occurs. This would be the case for example for sludge landfilling: no emission is avoided, and methane is emitted.

The table below summarises the accounting of GHG emissions, and the different flows that shall be included in each category:

GHG (tons CO2e)		I: Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment
A - Direct Emissions	Processes NON-BIO Combustion		processes emissions, at plant heat	pipeline installation	beyond scope	pipelines installation	processes emissions, at plant heat
B - Indirect Emissions from Direct Consumption	Fossil Fuels Electricity Heat	pumps	processes energy, heat	pumps	beyond scope	pumps	processes energy, heat
C - Indirect Emissions from Indirect Consumption	Total GWP		chemicals manufacturing and transport	pipelines manufacturing and transport	beyond scope	pipelines manufacturing and transport	chemicals manufacturing and transport
D - Avoided Emissions outside utility	Total GWP	emissions avoided outside utility	emissions avoided outside utility	emissions avoided outside utility	beyond scope	emissions avoided outside utility	emissions avoided outside utility

Table 4-3: GHG accounting

In addition, the figure below summarises the flows and stages considered in the overall UWCS system for both Nantes and Oslo.

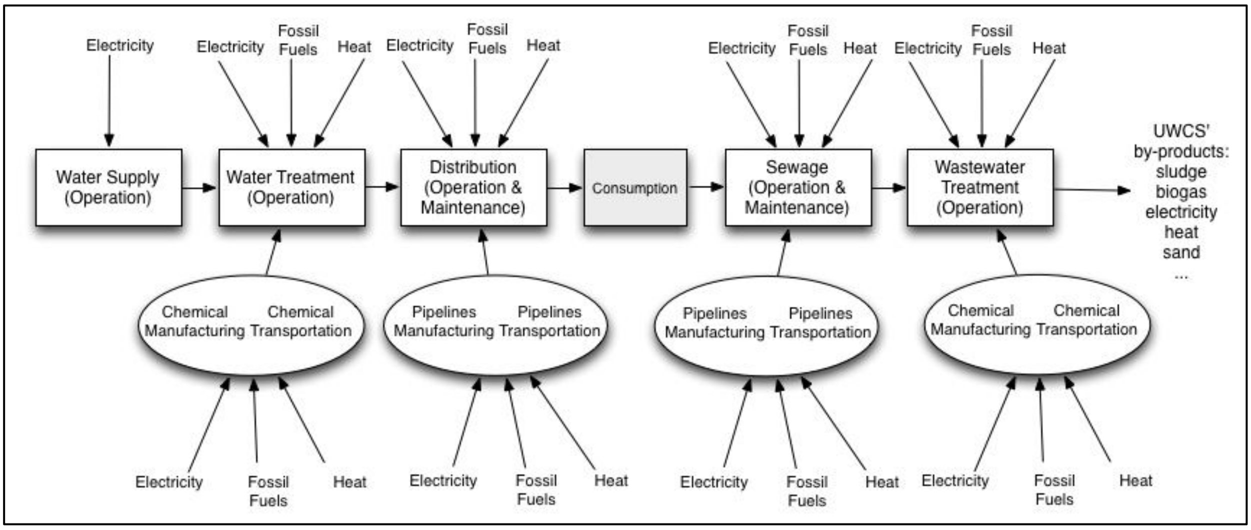


Figure 4-1: Processes for the UWCS system

4.5. Indicator Choice

It is necessary to reflect upon the appropriateness of the indicators to use in order to display the results and communicate with the entities who need to be informed. These indicators are in effect, tools to compare one system with another, or a given system with itself in the past. It is thus of utmost importance to specify and understand the type and nature of background data behind the indicators. When it comes to urban water systems, the indicator-denominators that spring to mind are ‘per capita’ and ‘per cubic metre of water’. The first one focusses on the consumer – sufficiency, consumption patterns, degree of affluence, level of awareness etc. The second one is directed towards the utility per se, and focuses on the efficiency aspect. Thus, these two indicators seem a good choice because they allow dividing the total impact between two important drivers of a water system: the demand from consumers and the technologies adopted by the utility to fulfil this demand. However, we need here to mention the exact definition of both indicators:

- **Energy (resp. GWP) per capita**: This one is the most straightforward, because it only entails dividing the total impacts by the population serviced. Further distinction might be made if necessary to detail the impacts for each category of consumers: households, industries… but the per capita indicator will be a primary assessment of the consumption of the whole city’s economy.

- **Energy (resp. GWP) per cubic metre demand:** Several types of volumes could be regarded in the assessment. One has the possibility of considering the volume of drinking water produced by the utility, the volume consumed, or the volume of wastewater treated. Here, the demand was chosen as indicator because it represents the main driver to the system. Moreover, it embeds the losses from the network, which are far from negligible (about 20% for both cities). Finally, accounting for the wastewater treated is much more complicated because of the importance of stormwater, which cannot be forecasted. Through its central role in the overall system, dividing the impacts by the demand seems hence a good option. For Nantes Métropole, demand shall embed the net export of water.

4.6. Data collection

Due to the large variety of data gathered or modelled, the sources/methods resorted to, in the process of data collection, are diverse.

Firstly, as the work is based on two case cities, as much data as possible has been gathered directly from the utilities. This was done mostly in two ways, by exploiting the existing **institutional reports** on the utilities' activities: Nantes Métropole (2008),Nantes Métropole (2009), Nantes Métropole (2010a), Nantes Métropole (2010b), Montginoul, Even, & Verdon (2010), VEAS (2008), VEAS, (2009), VEAS (2010), BEVAS (2007), BEVAS (2009), BEVAS (2010), VAV (2006), Oslo Kommune (2011), but also through **direct communication with the employees** of the utility in Nantes Nantes Métropole (2012). In the case of Oslo, the sources which were useful, in addition to personal communication with Venkatesh (2012), were as follows: Venkatesh (2011), Venkatesh & Brattebø (2011) Ugarelli, Venkatesh, Brattebø, & Sægrov (2008), Ugarelli, Venkatesh, Brattebø, DiFrederico, & Sægrov (2010), Ugarelli, Venkatesh, Brattebø, & Sægrov (2010). All of these sources represent part of the empirical data, hence based on the experience of both cities, and extremely important for an objective of accuracy and detail.

When some data were either not available or unreliable, they had to be modelled or assumed to a certain extent. In such cases, literature was used as much as possible in order to defend / justify the assumptions. Most of the sources used can be found in the literature review chapter, sorted according to the type of topic being dealt with. In the description of the current situation for both cities, the need to obtain data from another source than the utility was encountered quite seldom. On the contrary, the scenarios (to be detailed in the sections to follow) entailed modelling certain practices that are not yet existent: this means using **literature data** to a higher level, as well as modelling based on the laws of **physics wherever possible**. The application of scenario modelling was grounded to a very large extent on geographic and demographic data (current values and forecasts), which were accessed through the use of statistical bureaux of France and Norway (INSEE, 2011a), (SSB, 2011), and Wikipedia for more detail about each metropolis (Wikipedia, 2012c).

Most of the calculations were carried out by using more theoretical methods. This was the case for example, when it came to the calculations for final energy consumption and Global Warming potentials. Data concerning many elements (and processes) in the production chains were obtained, from the Ecoinvent database and the LCA software SimaPro (PRé Consultants, 2008). The overall flow model was constructed in accordance with Industrial Ecology methods such as MFA and LCA, as described in the Literature Review chapter. Other theoretical assessments and forecasts were calculated thanks to basic thermodynamics or fluid mechanics for example. The frameworks used shall be detailed appropriately for the scenarios when necessary.

4.7. Scenario modelling

The second part of this methodology chapter aims at establishing the choice of the scenarios investigated. In the first paragraph, we shall develop the important choices to make in order to decide on the main features of the scenario models. The subsequent paragraph will then detail more precisely the features of each chosen scenario, and the model chosen for socio-economic factors, which are independent from the choices of the utilities.

4.7.1. Choice of the main scenario features

As mentioned before, several scenarios will be developed in order to answer the third research question, that is to know if and how the energy and carbon footprints in Nantes and Oslo can be decreased between the baseline years and 2030. To that respect, several hypothesis and choices will be made in order to identify and model their main aspects.

Firstly, it is of primary importance to divide elements of influence on the final results. Some of them are independent of the choices of the utility, such as the demand and the population to be serviced, while others can be influenced by them – like the technologies adopted for instance. Indeed, the first ones are rather drivers to the system, as a result of the socio-economic development of the region, or result from external constraints: regulations, climate change, and safety standards… The second ones on the contrary are direct consequences of the choices made by the utility to these external drivers. They can hence put the focus on one of them (e.g. resource safety in water-scarce countries) or try to answer them all through multi-level policies. Nantes and Oslo are today meeting high standards in terms of drinking water quality and wastewater treatment and do not face one particular overarching threat. They are thus more in the second case, more trying to forecast any development and trends than overcome a major difficulty.

In consequence, we will need first to describe the drivers, and decide the one that can and should be modelled.

4.7.2. Modelling of the drivers

As mentioned previously, several drivers must be taken into account for Nantes and Oslo, as the utilities will have to base their activities on several elements. The list below details the important elements and their role in this work.

- Population is a major driver to the total demand. For a given techno-economic *status quo*, the demand in water/energy and the emissions will be directly related to the population served, and it is hence necessary to have a good **estimation of** what **both populations will be by 2030**. To do so, statistical studies have been used. (SSB, 2011), (INSEE, 2011a). **Refer to Appendix 4 for calculations**.
- The second driver of importance is the **demand per capita**. A decrease in water consumption has been seen in both Nantes and Oslo. Whether or not this decrease is sustained over time, will have a significant influence on the total demand for services, and the necessary energy consumption. In that goal, several elements have been used in order to detail economy and households as precisely as possible. Detailed employment statistics in Nantes and Oslo have been used to determine the economic weights of different sectors on the baselines years (SSB, 2012) (INSEE, 2011b). In addition to these figures, statistics about the water intensity in the economy from Denmark (Statistics Denmark, 2012) have been used as a good proxy for Oslo. As far as Nantes is concerned, the corresponding source is (Montginoul, Even, & Verdon, 2010). The use of these statistics and data shall lead towards the evaluation of two different elements. Firstly, to give a detailed snapshot of the consumption categories for the baseline years considered; and thereafter, **envision (forecast) the future consumptions in these categories, based on identified and estimated** trends. **Refer to Appendix 5 for calculations.**

Even if these two drivers are straightforward and can be modelled to some extent, mention must be made of several other elements that will have a large influence in the future on the operations of UWCSs.

- Among these elements/drivers, water quality to the consumer, and treated wastewater quality for the final sink, are uppermost.. Having a higher quality of water (and wastewater prior to disposal to sink) entails a higher degree of treatment. Water treatment level has consequences on the energy consumption for disinfection (UV, ozone), and chemical consumption (activated carbon, chlorine inter alia). Similarly, having a higher degree of wastewater treatment calls for greater energy consumption for aeration and heating onsite and indirectly for the production of the chemicals used. In any case, higher energy requirements and consequently carbon emissions must be expected, to the exception of anaerobic treatments in WWTPs, where biogas recovery can yield interesting results in terms of energy recuperation.

- An additional driver is **water safety**, **the ability for both cities to keep supplying enough water under any conditions**. As mentioned before, Nantes Métropole and Oslo might not be threatened by water scarcity, given their geographic location and climate.. However, the specificity of their sources is that there is one major source for each city. There is thus a probability that a major accidental occurrence could affect the ability of the utilities in the cities to supply clean water to its consumers. Accordingly, Nantes Métropole and Oslo might have to work on two specific issues: bringing more water sources on stream, and concentrating on water hygiene and health issues. This can have multiple consequences depending on the adaptation chosen by each utility. Source-management can, for example, be done through decentralisation and rainwater harvesting, wastewater reuse and reclamation, leakage control, thus limiting the dependence of the consumers on one single source of raw water. It can also be done more conventionally by using other water streams: other lakes surrounding Oslo for example; the situation being a little more complex in Nantes, because no water resource nears the supply capacity of the Loire.

- A final important element to be mentioned is the **integration of climate change, energy and environment into the main concerns of the utilities**. This entails, as mentioned in the previous chapters at several junctures, considering the water-energy nexus as being part of the utility's domain of work. It means decreasing the pressure of the UWCS and its subsystem on non-renewable resources and the related emissions. More concretely, such decisions would lead to considering new ways of integrating the subsystems, and looking towards benefits external to the utility. Examples can be given of rainwater harvesting, pressure and leakage management, biogas production and sale, sludge solar drying, micro-turbines in the network, etc.

Even if the drivers (except population and demand) can or will not all be modelled, the scenario choice shall take into account their concrete consequences as much as possible, to the extent they answer the question of “energy diminution, carbon emissions reduction”, which remains the objective of this thesis. The next paragraphs will hence present several scenarios turned towards such objectives.

4.7.3. Scenario 1: Business As Usual

Having a touchstone for comparison is necessary, as improvements are always defined with respect to the status quo and the yardsticks one desired to attain to. Thus, adopting a business-as-usual case as a baseline for comparison, is a good idea.. Minor adjustments compared to the baseline years are introduced, as the situation (as it stands at the time of writing this thesis) has changed with respect to the baseline years considered. Business as usual is hence modelled as follows:

- The two drivers to the system are **population and demand** for water and sewerage services by all the consumers in the cities. These two elements shall remain a constant for all scenarios. Multiplying one by the other, gives one the total volume of water that needs to treated and supplied to the consumers by the water utilities.

Most of the elements collected and presented for the baseline years shall remain the same (on a per volume produced/treated etc. basis), except the following points.

- Both utilities are currently **suppressing any direct energy generation by combusting fuel oil** (at plant, for electricity or heat). Any such consumption shall thus be replaced by electricity or heat accordingly.
- The **BEVAS** WWTP is now **selling its biogas as a transportation fuel for public transport,** a change that shall be accounted for.
- **Oslo's water treatment** has evolved over the last few years, and **chemical use** has been increased almost 10 times in terms of mass. The latest numbers shall hence be used for the model.
- Nantes' WWTP **Petite Californie has been upgraded** in terms of capacity and now adopts anaerobic treatment. Biogas is burnt on-site, heat is used and electricity sold to the grid. Some more electricity is produced by solar panels.

4.7.4. Scenario 2: Water Quality and Safety

In this second scenario, trends that are more foreseeable for the development of both utilities, are embedded. It shall thus embed firstly the same elements as in the business-as-usual case, but also other ones associated with (intending to achieve) better water quality, and also water safety to some extent. Indeed, it seems logical for the utilities to maintain and increase their levels of service, at the same time as they try to improve the overall efficiency of their network, thereby promoting water efficiency (and safety). No revolutionary innovation shall be integrated here in terms of overall system integration such as decentralisation or major change for sources, but global efficiency measures:

- **Same drivers** as above
- **Same elements** as modelled in Scenario 1
- As mentioned earlier, Nantes Métropole is currently planning to **renew the La Roche WTP to a large extent**. It shall be more efficient and include alternative treatments to today. In addition, it shall be somewhat smaller than the one that currently exists, as the present one is oversized and has surplus unused capacity.
- **Distribution network management** shall be implemented: it comprises micro-turbines to recover energy wherever possible, in addition to leakage reduction, pressure management and pumping efficiency)
- **Solar drying** (in greenhouses) **of sludge** shall be implemented in Nantes and Oslo, replacing partly liming.

- **Total sales of produced biogas in Oslo** (not only in the smallest plant). All of Nantes biogas shall also be sold as fuel for buses.
- **Heat recovery from wastewater** shall be modelled in Oslo were the difference between water temperature and air temperature is high in winter.

4.7.5. Scenario 3: Energy Management and Enhanced Water Safety

The last scenario goes into much less common and more prospective actions in the UWCS. Indeed, it was evocated in the literature review chapter that only more comprehensive understanding of the urban water systems could lead towards sustainability, which is the core of this scenario. Its basis was the acknowledgement that the annual precipitation in both the cities represented much more than the actual total consumption. This is also true when one considers only the concrete-paved parts of the cities, where water is supposedly recovered and sent back to other water streams: In Nantes, 700 mm of rainfall represents 110 Mm^3 of collected stormwater, and the same precipitation leads to the collection of only 90 Mm^3 in Oslo. Consequently, this scenario builds upon decentralisation, and the following elements are modelled.

- **Same drivers** as in both previous scenarios.
- **Complete decentralisation of drinking water production**: neighbourhood scale rainwater collection, storage, treatment and supply. It must be mentioned here that elements regarding quality (notably regarding water quality versus long time storage) of treatment will be overlooked to a certain extent, with the assumption that technical solutions (chemical treatment essentially, but also storage hygiene safety and high level treatment with UV for example) will overcome such obstacles to decentralisation.
- As rainfall is difficult to estimate, and because it might not reach the desired levels at certain time-periods during the year, **the "normal" treatment facilities shall remain operative, albeit being used sub-optimally**. They will be coupled to large storage tanks (as existing already) in order to ensure supply safety. Their level of treatment will also be less as this treatment can be coupled to the smaller-scale treatment. This will facilitate the avoidance of water-stagnation in the network, as water now can be treated (disinfected) after distribution.
- These actions will be **associated to the actions planned in Scenario 2**.

5. Results

This chapter will aim at presenting and analysing the results of the studies undertaken under the scope of the research questions in the introductory chapter of the thesis. Further analysis and reflection shall be done in the next chapter titled "Discussion". The structure of this chapter is as under:

- The physical flows will be presented for each city, in order to depict "visually" the dynamics of the systems for the baseline years.
- Then, the results of the energy calculations will be shown and analyse, along the results of the carbon/global warming potential.
- This will be followed by results from the scenario modelling and associated calculations.

5.1. Flowcharts

This first paragraph provides the reader with the global flowcharts for Nantes Métropole and Oslo, for the respective baseline years of 2010 and 2007. Both figures are displayed on the two next pages, and should be read as follows. Firstly, all thick arrows depict water flows. Their unit is Mm^3/year (million cubic metres per year). All related figures have been calculated/determined through three different means: directly from reports or internal sources, by mass balance (no water accumulation in the system), or by hypothesis. Mass balance data is depicted in bold font, and data from the hypothesis is in italics. The non-thick arrows depict the other direct flows accounted for in this work. These are the direct energy use (aggregated into the final value in GWh), the chemical use (aggregated into the final value in tons), the material use for network O&M (aggregated into the final value in tons), and the by-products out of the WWTP (aggregated into the final value in tons). The specific calculations that led to the estimation of the flows from hypothesis **can be found in the annexes**. When it comes to the specificities of both flowcharts, the following statements should be taken into account.

In Nantes Métropole:

- Water import and export have been depicted. However, for all subsequent calculations, only the net consumption will be used.
- Wastewater flow to non individual sewage (not exploited by the utility) has been estimated in Appendix 2
- All flows concerning rainwater have been estimated in Appendix 3. Energy use, if any, in the stormwater network, has been allocated to sewage collection.
- The sludge flows give the total matter content (not the dry matter content)

In Oslo

- Energy use in the water supply has been allocated to the water treatment, as the utility accounts directly for it in the plants themselves.
- Rainwater flows to sewage collection and to stormwater collection were estimated in Appendix 3.
- Figures to and from both WWTPs where allocated proportionally from the wastewater volume treated by both of them. This is probably not exact, but subsequent calculations will treat the total numbers, thus not making differences between the plants.
- Sand and NH_4NO_3 figures were allocated to the VEAS WWTP for readability reasons.

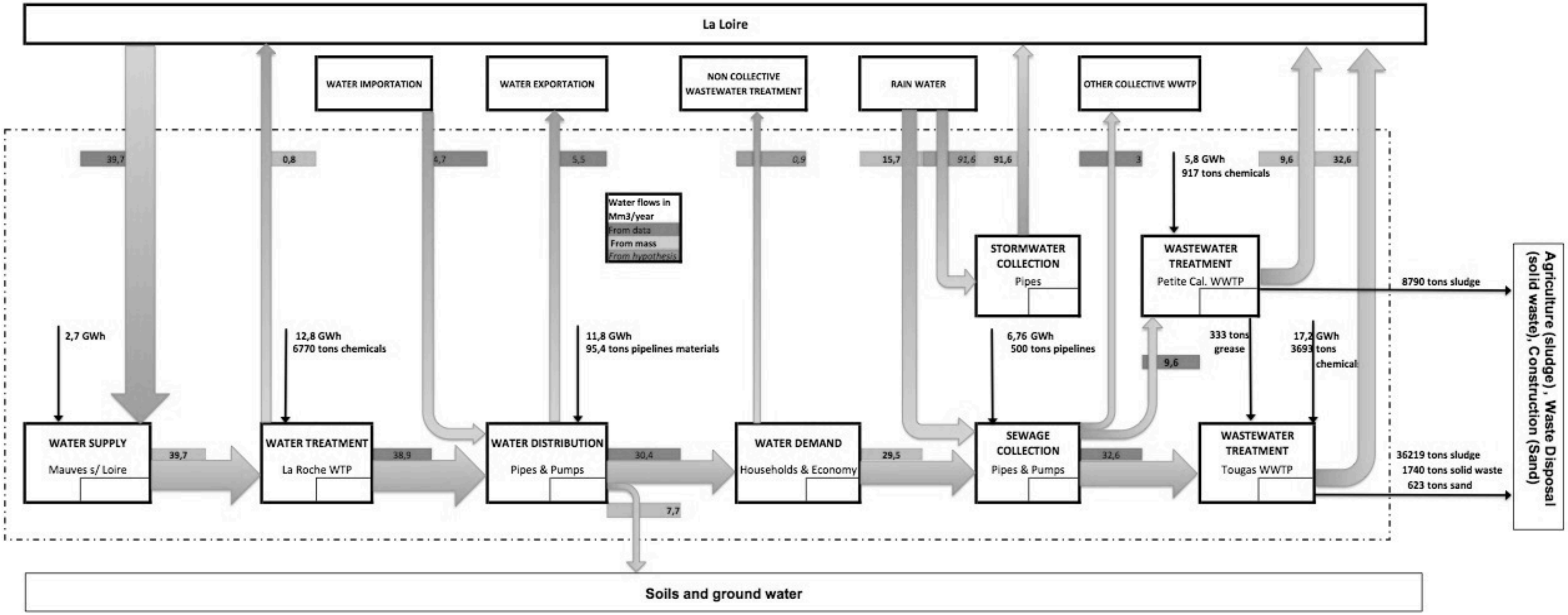


Figure 5-1: Flowchart, Nantes Métropole 2010

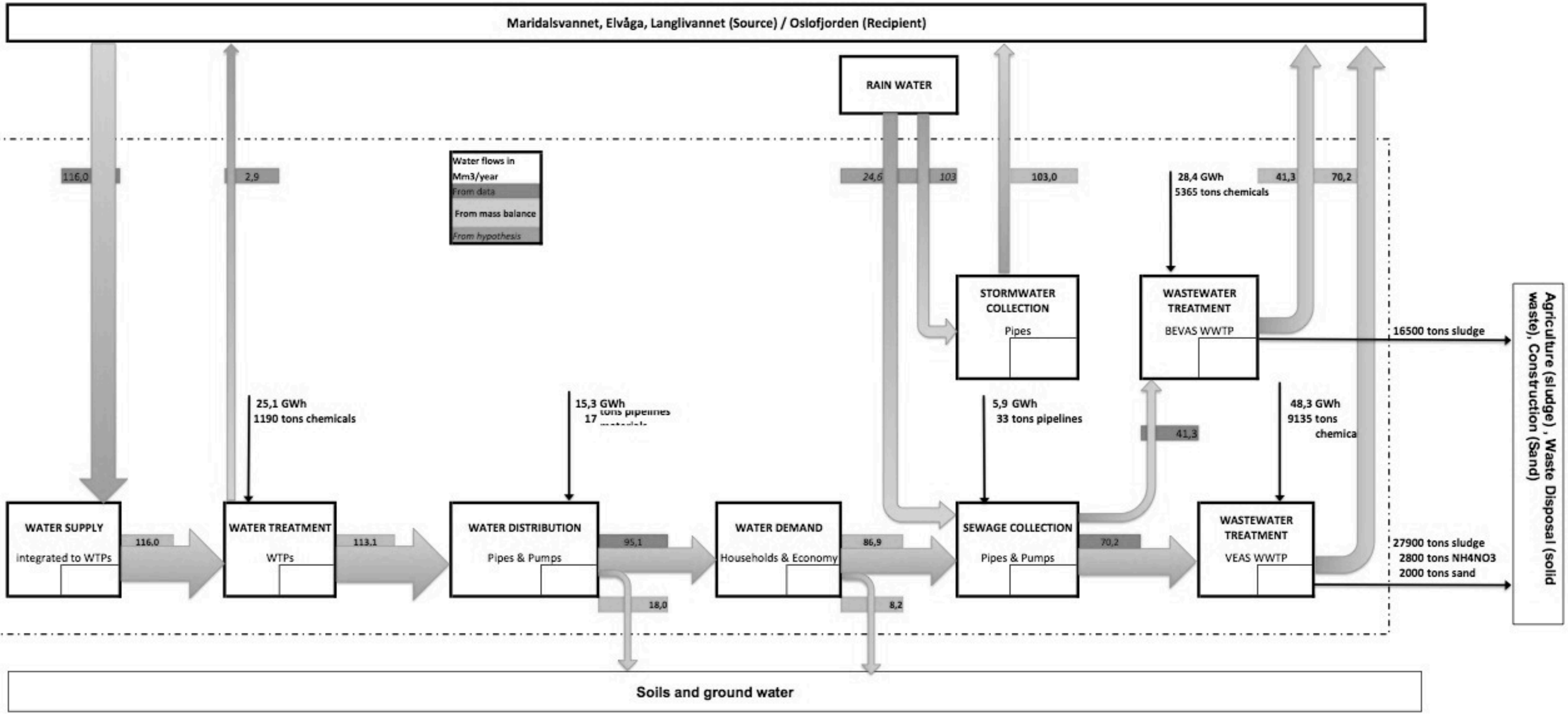


Figure 5-2: Flowchart, Oslo 2007

It is seen from Figures 5.1 and 5.2 - depicting the UWCSs in the two cities - that they are quite similar to each other. In effect, they are systems operating linearly from source of raw water to sink of treated wastewater (and rainwater/snowmelt). The major differences are that Oslo's UWCS has several primary sources (with Maridalsvannet being the predominant one); and the source and sink for Nantes is the same river. Nantes Métropole also has some other WWTPs in more remote parts of its territory, treating smaller quantities of the wastewater. Similarly and as pointed out at earlier stages, both cities work with two major WWTPs treating the flows. Both of them recover part of the rainwater along with the wastewater from consumption: refer to Appendix 3 for the rainwater model.

When it comes to more quantitative statements, several elements come to mind. We shall first reflect upon the water and wastewater flows, before looking at the other flows (energy, materials) entailed in the UWCS operations.
First of all, the quantity of water carried throughout Oslo's UWCS is much larger than in Nantes. Based on the fact that both populations served were quite close at their baseline years (2007 for Oslo and 2010 for Nantes), the drinking water consumption per capita is 3.5 times higher in Oslo than in Nantes Métropole. As seen on the flowchart, this can be explained partly by the use of water for consumptive purposes (which do not return the consumed water to the wastewater transport network). This is depicted in the flow from consumption to the outside of the system. Indeed, Oslo's inhabitants tend to live more in private houses than it is the case in Nantes, a model that promotes other usages of water: gardening and car-washing for instance. However, this specific flow only represents 8.2 Mm^3 in 2007, a little less than 10% of the total consumption (corresponding to 14 cubic metres per capita per year). This means that the daily use of water by Oslo's inhabitants is more intensive than in Nantes Métropole, to all respects, because it is probable that households' appliances are quite similar throughout Europe's. A detailed calculation of water's repartition between economy and households (cf. Annexe 3) show indeed that private persons consume about 3 times more water in Oslo than Nantes (without accounting for flows to economy). In addition, we can note that both distribution networks lose 20% of the water by way of leakage.

A second element to be analysed regarding quantities is the influence of rainwater on the dynamics of the system. Indeed, there is a non-negligible share of the rainfall that enters the combined sewers directly ((usually the oldest sewers, in the city centres) or infiltrate the sewage pipelines. It must be noted here that the model for rain infiltration has been established on Nantes and is probably quite accurate by construction; it has been extended to Oslo and might not be as accurate, although good enough for the estimation made here. Given the urbanisation rates, the respective sizes of the cities and the lengths of the pipelines in the combined-flow and sewage networks, more rainwater comes into the WWTPs in Oslo: 24.6Mm^3 compared to 15.7Mm^3 in Nantes. The ratio between the cities is higher than the ratio between the rainfalls in the baseline years (937mm v. 690mm), which means that more stormwater is proportionally recovered in Oslo. This is actually understandable from the fact that the combined flow pipeline network is twice as long in Oslo as in Nantes (792km v. 359km). On the contrary, the stormwater network proportionally recovers less rainwater in Oslo than Nantes Métropole (103 v. 92Mm^3). However, the influence of rainwater in the treatment plants is much higher in Nantes, because of the relatively smaller amount of wastewater to be treated. In Nantes Métropole, rainwater represents one third of all inflows to the WWTPs, whereas its share is of 22% in Oslo.

5.2. Baseline years energy results

To start with, specific energy consumption values are depicted graphically for the different sub-systems of the systems in Oslo and Nantes, in the Figures below.

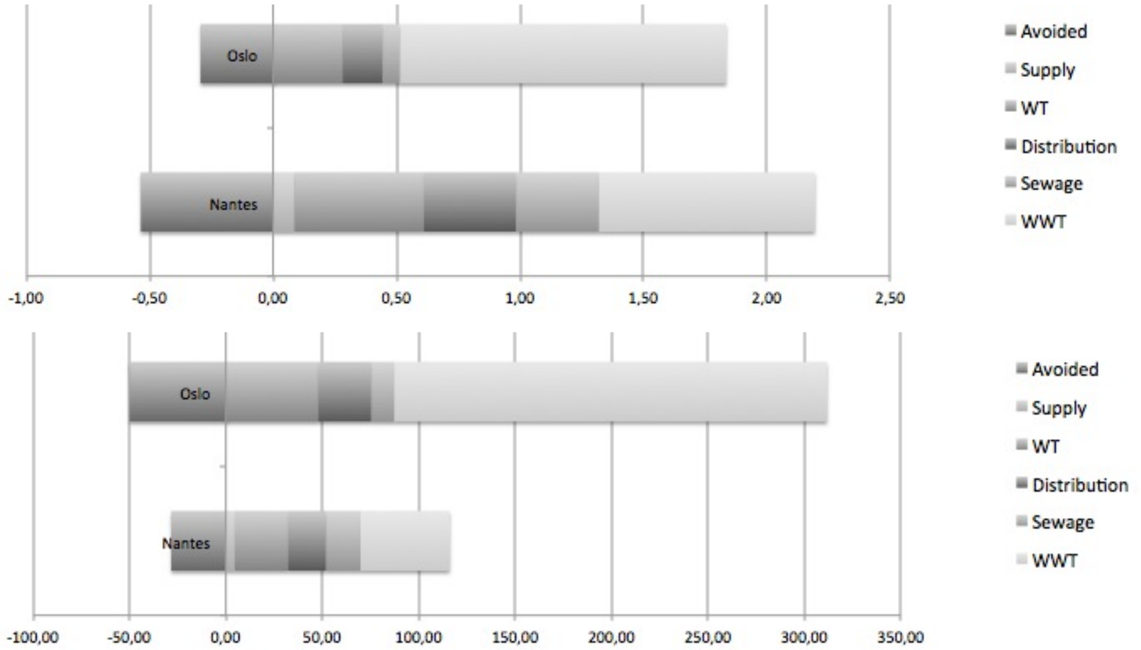


Figure 5-3: Energy per unit demand and per capita in baseline years (kWh/m^3; kWh/cap.year)

In both the Figures above, the importance of total water consumption appears in that Oslo's UWCS, which has to lower consumption per unit demand (1.83 kWh/m^3 v. 2.2 kWh/m^3 in Nantes), but much higher energy requirements per capita (311 kWh/cap.year v. 116 kWh/cap.year in Nantes). Mention must also be relative shares of the different stages, as shall be seen below: Wastewater treatment accounts for almost 75% of the energy consumption in the Oslo UWCS (figures include also energy generation) and a little more than one third in the Nantes UWCS. It is followed by water treatment, and the energy avoided offsets important shares of the total consumption, respectively 16% and 24% in Oslo and Nantes.

In addition to these first statements, the share of each fuel can be accounted.

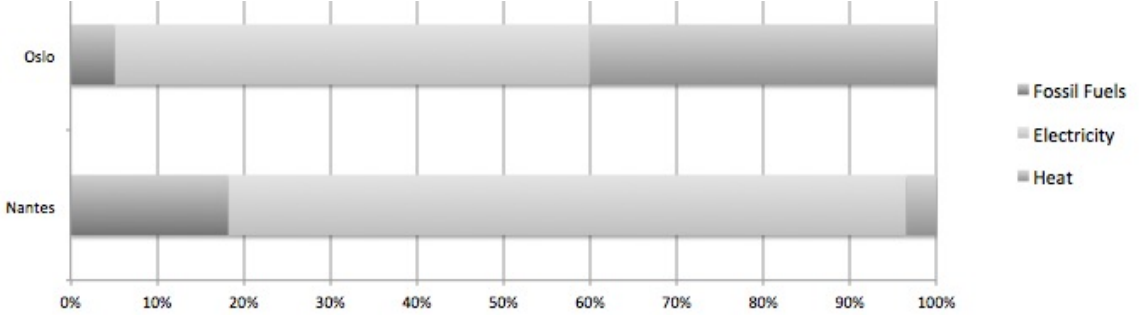
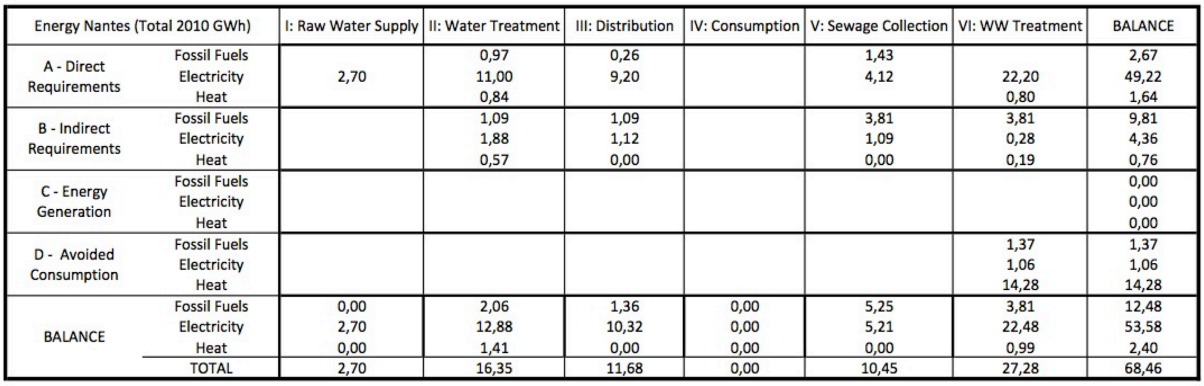


Figure 5-4: Energy Sources in Nantes and Oslo

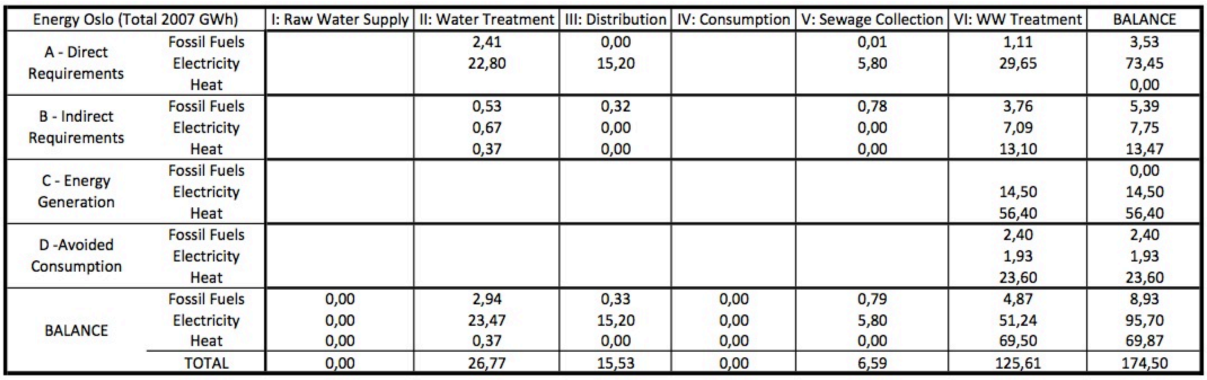
It can be seen that while electricity accounts for a major share of the energy needs in both cities (almost 80% in Nantes, about 55% in Oslo), the Norwegian utility relies more on heat, which is generated within the WWTP. On the contrary, Nantes uses more fossil fuels, especially because network maintenance and renovation is more intensive in the French city (refer to the next paragraph).

The following two tables present the results for Nantes and Oslo, which shall be subsequently analysed. It must be noted for the sake of readability, the 'Avoided Consumption' has not been included as part of the balance towards the bottom of the table.



Energy Nantes (Total 2010 GWh)		I: Raw Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment	BALANCE
A - Direct Requirements	Fossil Fuels		0,97	0,26		1,43		2,67
	Electricity	2,70	11,00	9,20		4,12	22,20	49,22
	Heat		0,84				0,80	1,64
B - Indirect Requirements	Fossil Fuels		1,09	1,09		3,81	3,81	9,81
	Electricity		1,88	1,12		1,09	0,28	4,36
	Heat		0,57	0,00		0,00	0,19	0,76
C - Energy Generation	Fossil Fuels							0,00
	Electricity							0,00
	Heat							0,00
D - Avoided Consumption	Fossil Fuels						1,37	1,37
	Electricity						1,06	1,06
	Heat						14,28	14,28
BALANCE	Fossil Fuels	0,00	2,06	1,36	0,00	5,25	3,81	12,48
	Electricity	2,70	12,88	10,32	0,00	5,21	22,48	53,58
	Heat	0,00	1,41	0,00	0,00	0,00	0,99	2,40
	TOTAL	2,70	16,35	11,68	0,00	10,45	27,28	68,46

Table 5-1: Energy use in Nantes Métropole, 2010



Energy Oslo (Total 2007 GWh)		I: Raw Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment	BALANCE
A - Direct Requirements	Fossil Fuels		2,41	0,00		0,01	1,11	3,53
	Electricity		22,80	15,20		5,80	29,65	73,45
	Heat							0,00
B - Indirect Requirements	Fossil Fuels		0,53	0,32		0,78	3,76	5,39
	Electricity		0,67	0,00		0,00	7,09	7,75
	Heat		0,37	0,00		0,00	13,10	13,47
C - Energy Generation	Fossil Fuels							0,00
	Electricity						14,50	14,50
	Heat						56,40	56,40
D -Avoided Consumption	Fossil Fuels						2,40	2,40
	Electricity						1,93	1,93
	Heat						23,60	23,60
BALANCE	Fossil Fuels	0,00	2,94	0,33	0,00	0,79	4,87	8,93
	Electricity	0,00	23,47	15,20	0,00	5,80	51,24	95,70
	Heat	0,00	0,37	0,00	0,00	0,00	69,50	69,87
	TOTAL	0,00	26,77	15,53	0,00	6,59	125,61	174,50

Table 5-2: Energy use in Oslo, 2007

- The first flows are the ones going into the **raw water supply**. It was not possible to isolate the energy consumed by the raw water pumping stations in Oslo from the total WTP consumption. Contrariwise, in the Nantes Métropole, about 15 km of pipelines have been installed to transport raw water to the WTP. Thus, it can be assumed with a good deal of certainty that a greater amount of energy would be needed to transport raw water to the WTP in Nantes, as compared to Oslo. As noted in the methodology chapter, no indirect energy is required here, as only the pumps usage is accounted for. No energy is recovered.

- In the **water treatment** facilities, other differences can be found. The direct energy supply is lower in Oslo, where 0.22kWh are needed per m^3 produced, contrary to Nantes where 0.33kWh is consumed per cubic metre. The loads on the treatment plants can perhaps explain this difference, as the level of treatment in Oslo, in year-2007, was much lower than it is today. Correlatively comes the fact that an absolute 6-times higher chemicals quantity is needed in Nantes. Comparatively to the drinking water production, this represents quantities of chemicals of 10.5 g/m^3 produced in Oslo and 174 g/m^3 produced in Nantes. This is shown here through the indirect energy requirement (chemical production and transportation to the plant): more than 2 times more energy is necessary in Nantes to that respect. Here again, no energy is recovered or energy use avoided outside the system.

- Concerning **water distribution**, it must be noted that in Oslo, the raw water sources (lakes) are at a higher altitude vis-à-vis the consumption centres. The Maridalsvannet Lake, for instance, is situated at an altitude of approximately 200 metres above sea level. Thus, although energy is necessary to transport water over the whole network, an important share of the energy is provided by gravity, which provides water with a larger pressure. On the other side, Nantes water intake is from the Loire River, approximately 6 metres over sea level. Thus water must be raised towards much higher levels once it leaves the La Roche WTP, which is situated at the same height. Indeed, other parts of Nantes Métropole are as high as 50 or 60 m over sea level. In terms of results, the situation leads to twice higher energy requirements in Nantes Métropole than Oslo per unit demand 0.3kWh/m^3 consumed compared to 0.15kWh/m^3 consumed. Indirect requirements are also much higher in Nantes. Indeed, network renovation is made almost entirely through pipeline replacement, whereas Oslo's utility prefers intern coating of the old pipelines with epoxy resin for example. As a consequence, the direct energy for pipeline installation is higher in Nantes, and the indirect energy for pipeline material production and transportation is also about 10 times higher in the French conurbation. Not any of both cities currently recovers energy from the network.

- The situation is approximately the same for **sewage collection**, with a small difference in absolute figure despite the large difference in flows carried. Sewage network renovation in Nantes benefits from a larger share of pipeline coating instead of replacement (less hygiene issues in sewage) but still smaller than Oslo.

- The following statements can be made about **wastewater treatment**, which is by far the most important subsystem of the UWCS in terms of energy use, but also production. Direct energy use (from the grid) is higher in Nantes on a per cubic metre demand basis (0.73 kWh/m^3 in Nantes compared to 0.31 kWh/m^3 in Oslo). However, this represents only the pressure on the external grid, and much more energy is actually used in Oslo when the plant energy generation is taken into account: 1.05 kWh/m^3 treated is consumed in Oslo in reality. Mention must be made nonetheless that most of it comes from heat generation (0.5 kWh/m^3), which is not used fully efficiently. On the contrary to water treatment, chemical consumption only comes second in the energy use of the subsystem, with 0.14 kWh/m^3 treated in Nantes and 0.25 kWh/m^3 in Oslo. The Norwegian utility thus entails more upstream energy despite a lower chemical amount consumed. This is mostly due to the use of HNO_3 and CH_3OH, whose production require very large amount of heat, and which are not consumed in Nantes. The very interesting fact about wastewater in addition, is that its by-products (namely sludge; Ammonium Nitrate in Oslo) replace fertilisers outside the utility. These fertilisers actually require large amounts of energy for production and using sludge can thus offset part of the energy used by the utility. Ammonium Nitrate (for N) and Di Ammonium Phosphate –DAP- (for P) have been chosen as they are the most used in Norway and France (Ministère de l'Alimentation, de l'Agriculture et de la Pèche, 2010). In terms of results, Nantes Métropole and Oslo's water utilities offset respectively 16.7 and 27.9 GWh of energy. When reported to the total energy use, it represents 24% and 16% in each city, 28% in Oslo when the energy produced by the WWTPs is not considered. Consequently, the "energy investment" at the plant to recover nutrients from wastewater seems very interesting in terms of global energy balance.

5.3. Baseline years emissions

Comparatively to the energy analysis, the emissions analysis begins with an understanding of the specific values of the carbon footprint as shown in the Figures below. The reader is reminded here that electricity mixes are respectively the French and Nordic ones for Nantes Métropole and Oslo.

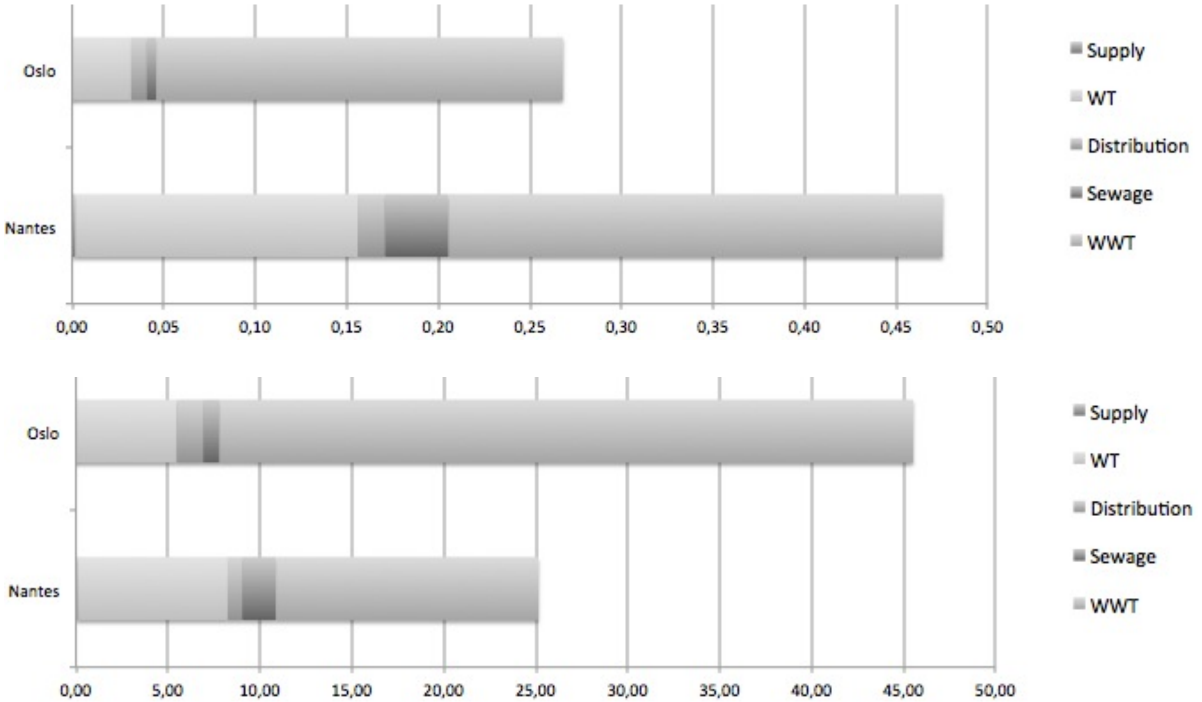


Figure 5-5: Carbon footprint per unit demand; per capita ($kgCO_2e/m^3$; $kgCO_2e/cap$), Nordic and French el. mix

Figure 5.5 brings out the difference between the two cities. While Oslo's utility yields a carbon footprint per capita of $45kgCO_2e/cap.year$, the average Nantes Métropole consumer's footprint is lower, at $25kgCO_2e/cap.year$, almost half of the Norwegian consumer. However, the carbon footprint per cubic metre demand is much higher in the Nantes Métropole: $0.47kgCO_2e$ are emitted during the life-cycle of $1m^3$ of water consumed in the French conurbation, versus 0.27 in Oslo, thus leading to the inverse situation. The most impacting stages of the urban water cycle is the wastewater treatment for both cities, although Nantes water treatment is responsible for greater quantities of GHG compared to Oslo. Raw water supply, water distribution and sewage impact only to a less extent.

The following figure gives more clues for comprehension.

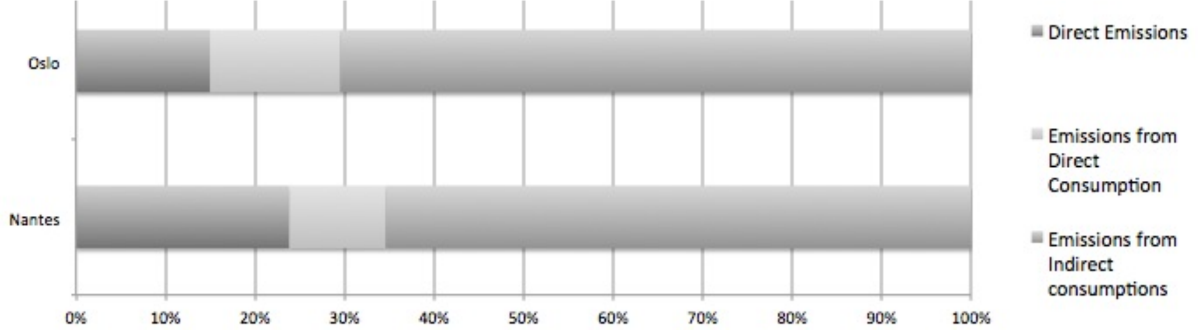
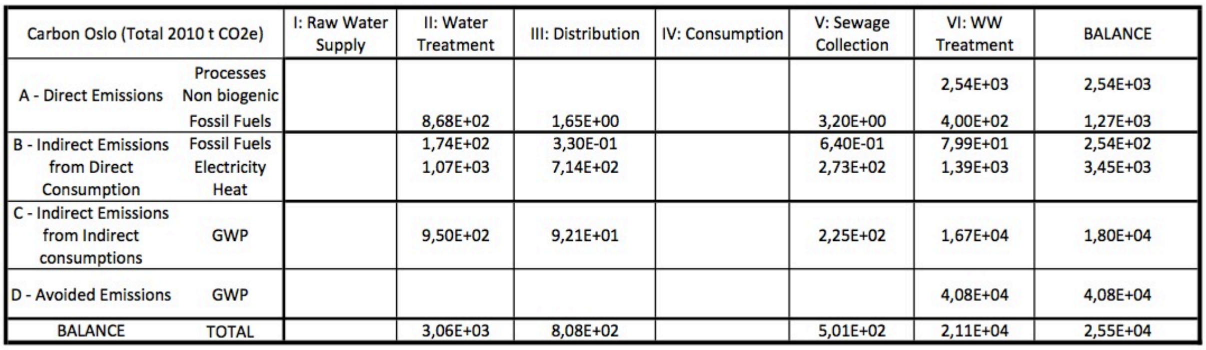


Figure 5-6: Repartition of GHG emissions in Nantes and Oslo

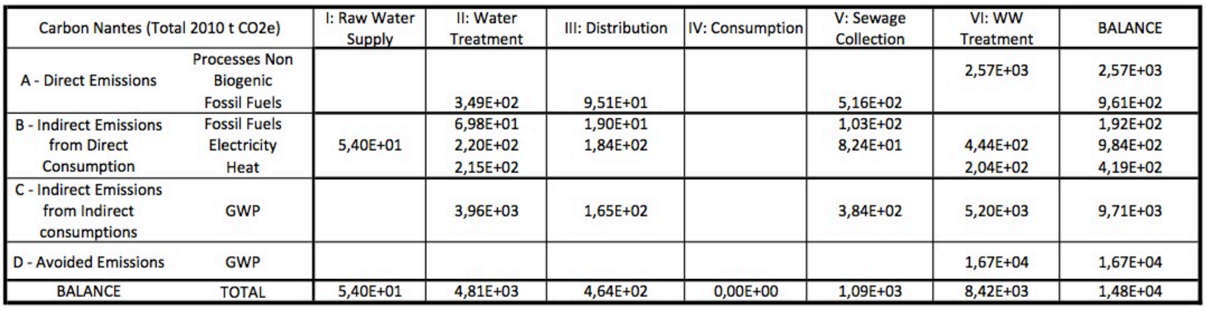
It is evident from Figure 5.6 that emissions in Nantes Métropole and Oslo occur mostly from indirect (upstream) energy consumptions (chemicals, materials for pipelines, transportation…). On the contrary, direct emissions and indirect emissions from direct consumptions of energy (electricity and heat) represent altogether 30% and 35% in Nantes and Oslo. For these, whereas Oslo ranks higher for indirect emissions (electricity and heat), Nantes has more direct emissions (diesel).

In order to analyse the sub-systems in greater detail, the following tables are handy.



Carbon Oslo (Total 2010 t CO2e)		I: Raw Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment	BALANCE
A - Direct Emissions	Processes Non biogenic						2,54E+03	2,54E+03
	Fossil Fuels		8,68E+02	1,65E+00		3,20E+00	4,00E+02	1,27E+03
B - Indirect Emissions from Direct Consumption	Fossil Fuels		1,74E+02	3,30E-01		6,40E-01	7,99E+01	2,54E+02
	Electricity		1,07E+03	7,14E+02		2,73E+02	1,39E+03	3,45E+03
	Heat							
C - Indirect Emissions from Indirect consumptions	GWP		9,50E+02	9,21E+01		2,25E+02	1,67E+04	1,80E+04
D - Avoided Emissions	GWP						4,08E+04	4,08E+04
BALANCE	TOTAL		3,06E+03	8,08E+02		5,01E+02	2,11E+04	2,55E+04

Figure 5-7: GHG emissions in Oslo in 2007 (tons CO_2e)



Carbon Nantes (Total 2010 t CO2e)		I: Raw Water Supply	II: Water Treatment	III: Distribution	IV: Consumption	V: Sewage Collection	VI: WW Treatment	BALANCE
A - Direct Emissions	Processes Non Biogenic						2,57E+03	2,57E+03
	Fossil Fuels		3,49E+02	9,51E+01		5,16E+02		9,61E+02
B - Indirect Emissions from Direct Consumption	Fossil Fuels		6,98E+01	1,90E+01		1,03E+02		1,92E+02
	Electricity	5,40E+01	2,20E+02	1,84E+02		8,24E+01	4,44E+02	9,84E+02
	Heat		2,15E+02				2,04E+02	4,19E+02
C - Indirect Emissions from Indirect consumptions	GWP		3,96E+03	1,65E+02		3,84E+02	5,20E+03	9,71E+03
D - Avoided Emissions	GWP						1,67E+04	1,67E+04
BALANCE	TOTAL	5,40E+01	4,81E+03	4,64E+02	0,00E+00	1,09E+03	8,42E+03	1,48E+04

Figure 5-8: GHG emissions Nantes in 2010 (tons CO_2e)

- **Water supply** accounts for a small share of the total systemic emissions. It consumes only electricity for pumping.
- **Water treatment** accounts for about 12% of Oslo's GHG emissions, and one third of Nantes'. This is due in Oslo rather to electricity consumption, and in Nantes to Indirect Consumption. Indeed, Nantes consumes 6 times more chemicals (in mass) than Oslo, and these chemicals require not only electricity for manufacturing, but often heat, and also transportation over several hundred kilometres. It is probable that this situation has now changed, due to the increase of chemical usage in Oslo.
- In the **drinking water distribution** subsystem, one can identify the same trends for carbon emissions as for energy. Emissions at this stage of the UWCS are higher in Oslo in total and per capita (50% higher), and about 50% lower per unit demand. When it is split up between the different the different impacting flows, it can be seen that Nantes has much higher impacts when it comes to direct emissions (diesel). 100 times more emissions occur in the pipelines replacement in Nantes Métropole than in Oslo, due to the different techniques. These emissions are counterbalanced to a certain extent by higher indirect emissions from direct consumption. The cause to this fact is the use of the Nordic electricity mix for Oslo, which has higher content of fossil fuels.
- The situation is somewhat different in **sewage collection**. Indeed, Nantes Métropole yields the largest carbon emissions to all respect (total, per capita and per unit

demand). This can be explained by the fact that concrete pipelines are particularly heavy (because bigger than pipelines in other materials) and lead to high emissions not only from manufacturing but also transportation and installation. In Oslo on the contrary, the use of epoxy allows sticking to lower emissions. The importance of materials at this stage can be seen by the relative lower impact of electricity, which represents only 1% of emissions in Nantes and 50% in Oslo, compared to 25% and 80% in distribution.

- When it comes to wastewater treatment, many impacts must be accounted for, as the numbers of flows and by-products is important. The total impact is higher in Nantes (8,400 tons CO_2e compared to 2,100 in Oslo), and in relation to demand and population, Oslo scores higher on the latter (37.7 kg CO_2e/cap v. 14.3 in Nantes) whereas Nantes has the highest impact per unit demand (0.27 kg CO_2e/m^3 in Nantes, 0.22 in Oslo). In both cases, the impacts occurring because of the upstream processes are the highest. As a matter of fact, chemical manufacturing represent respectively 55% and 76% of the emissions occurring in wastewater treatment in Nantes and Oslo. More particularly, the usage of HNO_3 and $FeCl_3$ in Oslo contributes to 75% the chemical manufacturing emissions. In Nantes, quicklime (CaO) contributes to 98% of them! These elements are thus contrary to the situation for the energy. Indeed, the use of chemicals did not entail as much energy as it emits carbon (when compared to direct use and emissions). As noted, the production of some of these chemicals is quite intensive on carbon emissions, both because of their own energetic requirements (fossil fuel and natural gas for example), but also because of processes emissions. It must be however noted that global values from the Ecoinvent database have been taken for the life-cycle emissions of the chemicals and differences may exist with reality. This remark also applies to the avoided emissions. Avoided energy only represented a share of the total energy in Nantes and Oslo, but it represents approximately 200% of the total GHG emissions in wastewater treatment subsystems, with a total offset of 157% and 113% of the total emissions in Oslo and Nantes respectively. This means that *theoretically,* the two utilities lead to net carbon sequestration. However, this is once again extremely dependant on three elements. Firstly, the actual carbon footprints of the fertilisers, which are not necessarily the same as is Ecoinvent. Secondly, the types of fertilisers used in France and Norway (the most common have been chosen, for Nitrogen and Phosphorus). Thirdly, there was no sufficient data available to make an interesting model of the sludge use as fertiliser, to know if for example 1kg Nitrogen in sludge replaces exactly 1kg Nitrogen in synthetic fertilisers in average. This element shall be part of the discussion chapter. Thus, even if these results of 'avoided carbon footprint' is interesting, and its order of magnitude probably more or less accurate, it will be considered with caution and not mixed with the carbon footprint of the utilities in the scenarios.

5.4. Scenario results

In this paragraph will be presented the results for the different scenarios, and analysed to the light of the elements that have been chosen for their development. We will firstly review the outcomes of the scenarios in terms of energy, before coming to the carbon results. The scenarios will be referred to as BAU (Business as Usual), WSQ (Water Safety and Quality), and EM (Energy Management) in some cases.

5.4.1. Energy

The energy scenarios are summarised on Figure 5.9 and Figure 5.10 below.

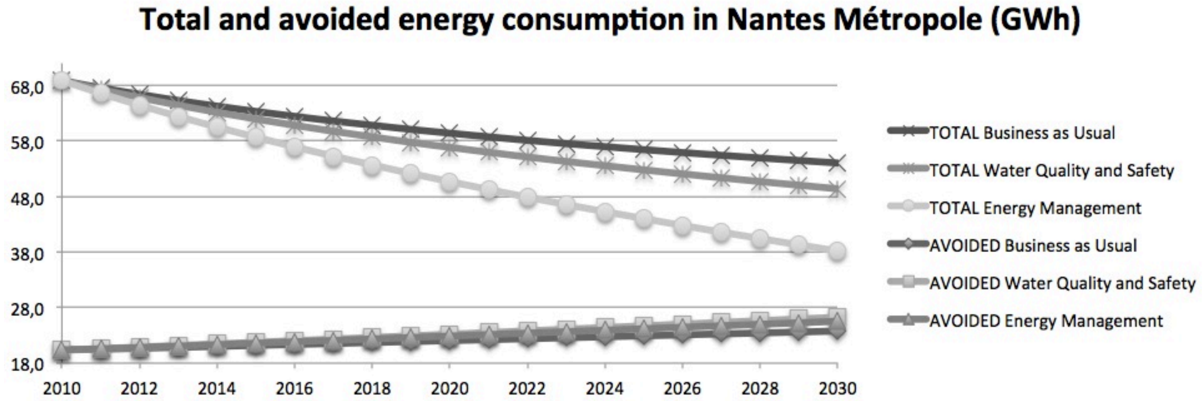


Figure 5-9: Energy scenarios for Nantes Métropole

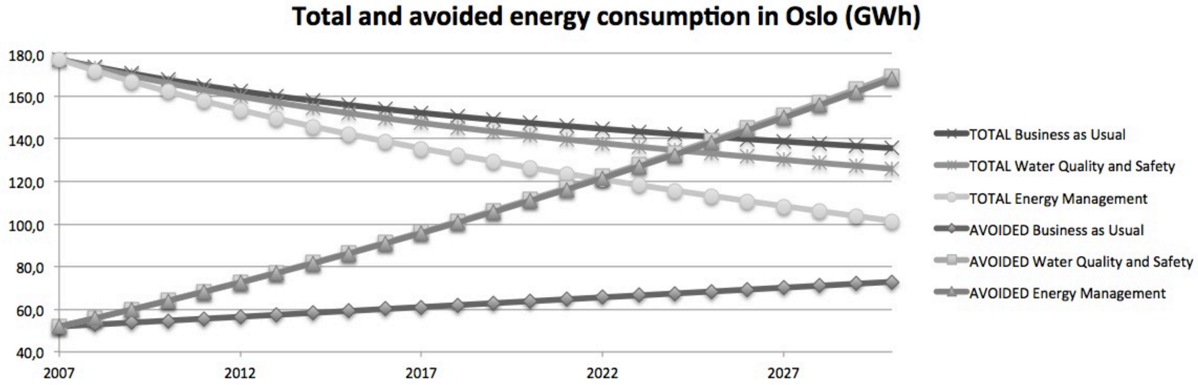


Figure 5-10: Energy scenarios for Oslo

Several elements can be noted and analysed for both figures.

- **Common trends**: In both cities, the global trends seen in the curves are the same. There is a global decrease of the energy consumption for all scenarios, and a global increase of the avoided energy for all scenarios. This can be explained by two facts. Firstly, the total energy consumptions are very much linked to the water demand in the model. In addition, the demand forecast has been developed based on foreseeable trends in the consumption of water by households and economy, which led to a global forecast of demand decrease (without taking into account any specific water management awareness campaign for the consumers). Thus, total consumption of energy steadily decreases in all scenarios. Secondly, the avoided energy through the by-products of the water utilities increases on the contrary to consumption. This is a consequence of the fact that avoided energy is strongly linked to the population. Indeed, the avoided consumption of energy results from the generation of biogas and from the recovery of nutrient, used in sludge as fertilisers, and these elements can be related to a good extent to the population’s waste (even if one consumes less water, one produces the same amount of waste in first approximation). Since Oslo and Nantes Métropole will experience important growth of their populations within 2030, the avoided consumption of energy will increase.

- **Particular trends in Nantes**: Concerning the total consumption side of the scenarios, there is a clear advantage for the Energy Management Scenario, which decreases by 30% the energy use by the utility (38GWh v. 54GWh in Business as usual by 2030). The main element backing this advantage is that the Energy Management Scenario plays to a very large extent on the upstream part of the UWCS: water treatment and drinking water distribution. In BAU, they both account for more than 30% of the energy consumption, whereas the EM scenario reduces them to 10% each. This also explains why Business as usual and the water safety and quality are so close for Nantes (the latter representing 90% of the first one): its major improvement is situated in the wastewater treatment with a decrease of quicklime use, which does not represent the same quantities of energy. The other elements modelled allow indeed efficiency improvements (WTP upgrading, distribution network management), but not as strongly as with water treatment decentralisation. On the contrary to these different values for energy use, the energy avoided by the utility (outside of the utility) is very similar in the three scenarios. This can be explained by the fact that no major change occurs for this element in Nantes Métropole. The biggest change is the decision to sell all the biogas as fuel from the Petite Californie WWTP. This is the smallest plant and biogas sales have less influence than the avoided consumption from sludge as a fertiliser (it accounts for only 10% of the avoided consumption). When we compare the overall results between consumed and avoided energy, the situation in 2030 allows offsetting in the best case (EM scenario) 67% of the consumption (25.5 GWh v. 38.2 GWh consumed), whereas BAU and WQS allow 44% and 53% recovery of the energy outside of the utility.

- **Particular trends in Oslo:** when it comes to the Norwegian utility, there is also a clear advantage to the EM scenario for the energy consumption, which decreases by 25% (101.5 GWh v. 135.6 GWh) compared to BAU. WQS only diminishes consumption by 7%, and the reasons to these evolutions are similar to Nantes Métropole. However, the evolution of avoided energy in Oslo is very different to Nantes. Indeed, both "new" scenarios allow recovery of more than all energy consumed by the utility throughout the UWCS. This is due to the biogas sales, which on the contrary to Nantes, is produced in both WWTPs. Moreover, heat recovery inefficiency at the plants is overcome by using the biogas as fuel. Thus, both scenarios are extremely close in terms of results (the only change is upstream in the recovery of energy from the distribution network and does not represent a significant amount of energy compared to biogas and sludge), and allow in the best case (EM scenario) a recovery of 168% of the total energy consumed (compared to 134% and 54%).

- **Compared trends**: The comparison between the two cities lead to a main conclusion, which shall be found for carbon as well. The choice of the wastewater treatment processes has indeed a very strong impact on the energy recovery, and allows to a certain extent to offset the energy consumed by the utility, which seems not to be the case where the wastewater treatment if majorly activated sludge.

5.4.2. Carbon

The scenarios regarding carbon emissions are summarised on Figures 5.11 and 5.12 below.

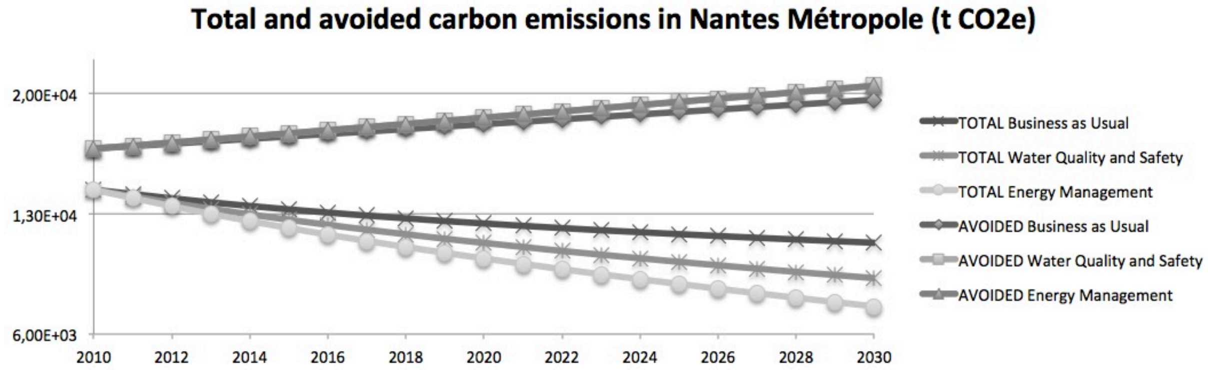


Figure 5-11: Carbon scenarios in Nantes Métropole

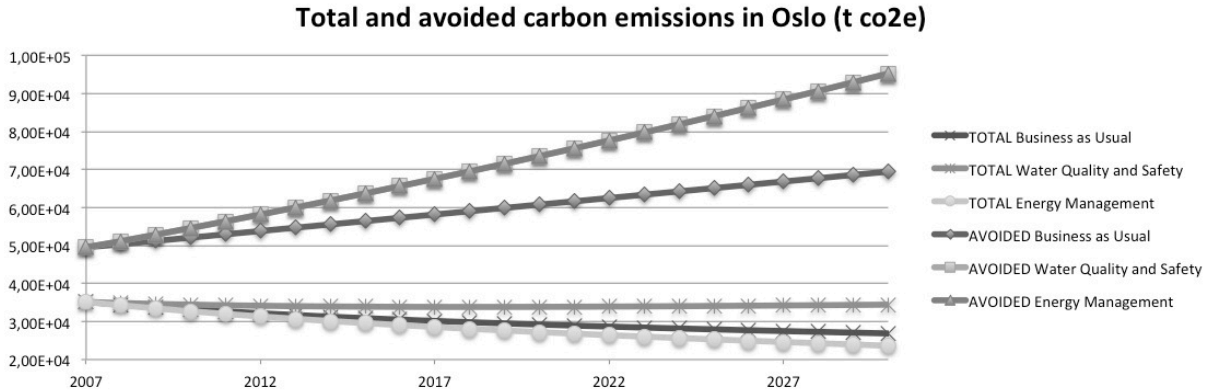


Figure 5-12: Carbon scenarios for Oslo

Before going into the analysis of the different values and trends, the attention of the reader must be drawn to a particular element (which shall be reviewed more in details in the Discussion chapter). The results of the carbon analysis are less sure than the results of the energy analysis. Indeed, as it has been mentioned in the analysis of the baseline years at previous stages of this chapter, the carbon emissions depend much more on the indirect consumption than energy consumption does. Thus, using average values from literature to calculate these emissions (as no data was gathered from the chemical manufacturers, for example) leads to high uncertainties in terms of results.

Nevertheless, it is possible to analyse trends and values for both cities and the different scenarios.

- ♣ **Common trends**: as seen earlier, two main trends can be identified from the graphs. Firstly occurs a global decrease of the total carbon emissions, due to the fact that the demand of water is likely to decrease over time, leading to lower requirements for direct and indirect energy, thus to lower carbon emissions. Secondly, an increase of the avoided carbon emissions thanks to the use of the utilities by-products such as sludge and biogas, linked to the increase of the population served by the UWCS.

- **Particular trends in Nantes**: as in the energy analysis, the EM scenario yields better results than the other scenarios in Nantes Métropole. By 2030, this scenario allows a reduction of emissions by 33% compared to BAU, with 7600 tons CO_2e emitted compared to 11300 tons originally. The "intermediary" scenario permits an 18% reduction of emissions. If the global results are similar to their energy counterparts, it is important to note that the scenarios impact nevertheless other elements in particular. This is the mere consequence to the fact that repartition of the impacts between the subsystems in the baseline models is different between energy and carbon. Thus the absolute biggest decreases occur in wastewater treatment. It is reduced by 23% between BAU and WQS (by 0.06kg CO_2e/m3 demand in 2030). This corresponds to the solar drying of sludge in this subsystem. As it was mentioned in the comments of the baseline years, sludge use in WWTP is the single most intensive process in Nantes in terms of GHG emissions and reducing the quantities of sludge used by solar drying allow decreasing the emissions, not only for quicklime manufacturing, but for transportation and for sludge transportation. The situation is the same between BAU and EM, but in addition to this impact on wastewater treatment, the situation changes dramatically in water treatment and drinking water distribution: it is reduced by an overall 63% and by an absolute 0.1 kgCO_2e/m3 demand in 2030). This means that despite the fact that wastewater treatment yields the highest impacts in GHG emissions, the changes in the management of the drinking water allow very large decrease of emissions at this stage. This can be explained by the fact that the model chosen for the EM scenario assumes a decrease of the chemical use in the drinking treatment. This opposes this scenario to WQS, which keeps high levels of chemical use in the water treatment, but stays still higher than Oslo's water treatment in the baseline year (giving a justification to the fact that this would be manageable in terms of water quality).

- **Avoided emissions in Nantes**: As was mentioned preliminary, the results from avoided emissions must be considered with caution because of the difficulty to estimate the actual emissions offset from sludge used as fertiliser. Thereby, it is more logical to compare the trends of the curves. They are also very close for the same reasons as for the total emissions, and because the quantity of biogas sold (leaving the system) is not important enough to have an impact compared to the fertilising results. In terms of total values, approximately three times the total emissions are offset in the best case (EM). Despite the uncertainty of the exact figure, the order of magnitude can probably be kept in mind.

- **Particular trends in Oslo:** In Oslo occurs a qualitative change in the scenario ranking compared to what has been seen elsewhere. Indeed, the BAU scenario does not rank last in terms of results for the carbon emissions, as the WQS has higher emissions. This is the direct consequence from the fact that important flows leave the system in the WQS scenario. All biogas is sold, and large quantities of electricity and heat must be bought to replace it, with the linked emissions. In the baseline scenario on the contrary, the emissions linked to the production of heat and electricity in the plant are directly embedded in all upstream emissions and give a quite low overall result. Nonetheless, the EM scenario overcomes the "bad" results from the WQS scenario. In this case, the improvement on the drinkability treatment and in the distribution have an important impact because decentralisation of the distribution allows very low energy use. Therefore, 12% of emissions are suppressed from the utility, whereas the Water Quality and Safety scenario leads to an increase by 28% of the emissions.

- **Avoided emissions in Oslo**: Commenting only the total emissions by the utility would be missing the interesting point, as the goal of selling biogas is to reduce emissions outside the utility's jurisdiction. When it is sold, biogas replaces fossil fuels for buses, and thus negates important emissions: biogas is carbon neutral, when fossil fuels are the world's carbon emissions biggest player. The results of this voluntary problem shifting can be easily seen from the graphs. Both WQS and EM scenario offset 37% more emissions than BAU. In addition should be mention the comparison of the growth rate of the scenarios: EM and WQS have a growth 2.29 higher than BAU. This remark is important because it allows overcoming the preliminary mention that has been made about the results of 'avoided emissions' due to sludge: all growths include the avoided emissions from sludge, therefore comparing growths negates the influence of this element. In terms of total results, almost 4 times of the total emissions are avoided in the best case. As in Nantes, the order of magnitude can be kept in mind.

6. Discussion

This chapter is the occasion to discuss the main results and their meanings. In order to do so, we shall first reflect upon the main findings that are the outcomes of the results. Then, must be presented some elements about uncertainties thorough a sensitivity analysis. Finally, the results will be embedded in larger contexts with insertion of figures from literature, and with a reflexion on their meaning for the case cities.

6.1. Main findings

As this thesis was based and articulated around several research questions, discussing the main results of the work means most importantly trying to answer them. In that optic, the three research questions can be found below:

1. At what energetic cost are urban water services delivered in Nantes and Oslo?
2. What is the carbon footprint of the utilities in Nantes and Oslo, as far as energy consumption (and generation) is concerned?
3. Can the energetic and carbon footprints be decreased in the future, and through which measures from the water utilities?

- **Answer to Research Question 1:**

As far as a quantitative assessment is needed, it is necessary to come back to the different indicators that were chosen in the Methodology chapter: total energy use, energy use per cubic metre demand, and energy use per capita. These three indicators yield different results for the two cities which are summarised in the Table 6.1 below:

	Nantes Métropole	Oslo
Total energy (GWh)	68.46	174.50
Energy per unit demand (kWh/m^3)	2.19	1.83
Energy per capita (kWh/cap.year)	116.03	311.61
Potential offset (kWh/cap.year)	-28.32	-49.88

Table 6-1: Energy use comparison in baseline years

The energy use of both cities is thus quite high in absolute values, but does in the end not represent very important quantities compared to other services one benefits from in cities. More particularly, the energy per unit demand is around 2kWh/m^3 in both cities but for different reasons: Nantes Métropole has more energy intensive water treatment and water distribution, respectively due to important chemical use in an old WTP, and to large energy requirements for water distribution.

On the contrary Oslo has high requirements for wastewater treatment, some of which are internally met by electricity and heat generation in the WWTPs. This approximate figure of 2kWh does however not represent an important energy quantity: 1000L of water are supplied with about 0.8% of the energy needed per surface unit (1m^2) in the average French home for one year (250kWh/m^2). When it comes to the per capita consumption, the influence of water demand is obvious, as Oslo inhabitants requirement almost 3 times more energy for their water needs. If one comes back to the comparison with floor heating, both figures are still quite low since Nantes' requirement are about 50% lower, and in Oslo it is 25% higher. However, when compared to the latest standard of house appliances (still in France) of 50kWh/m^2 for heating/cooling, Nantes Métropole's energy use per capita represent approximately 2.3m^2, and Oslo's are equivalent to 6.2m^2.

Finally, the water utility can also be seen as a provider of services for other sectors, notably agriculture. Both cities' utilities produce large quantities of sludge that replace to some extent the fertilisers used by farmers. In terms of energy use, 24% and 16% are thereby offset through the utility, which does not make it energy neutral.

- ♣ **Answer to Research question 2:**

As for energy, we can come back to the different indicators chosen for the work, in order to analyse the carbon emissions in both cities.

	Nantes Métropole	Oslo
Total emissions (t CO_2e)	14800	25490
Emissions per unit demand (kg CO_2e /m^3)	0.475	0.268
Emissions per capita (kg CO_2e /cap.year)	25.14	45.52
Potential emission offset (kg CO_2e /cap.year)	-28.26	-72.91

Table 6-2: Carbon emissions comparison in baseline year

Here again, the total quantities of carbon emitted are quite high in absolute numbers. However, when taken by inhabitant or unit demand, it must be acknowledge that UWCS does not yield the most important environmental effect when it comes to carbon, compared to other services. The emissions per unit demand, for example, represent around 0.5 and 0.3 kg CO_2e per cubic metre of final consumption. This difference is mostly due to chemical use. Nantes Métropole consumed in baseline years more chemicals than Oslo in water treatment especially, and this consumption leads to high upstream emissions, coming from the heat generation and fossil fuel consumption These figures can be compared to the worlds' carrying capacity of 3 GT CO_2e, that is about 430 kg per capita and per year (for 7bn people on the planet). The 1:850 and 1:700 proportions between them show indeed that there is margin to that respect.

However, water is not the only thing humans consume, and the per capita carbon emissions (included imported emissions from consumer goods) in France and Norway are about 13.1 and 14.6 tons CO_2e /cap.year in France and Norway (Hertwitch E. , 2009). Comparatively, water weights 0.19% and 0.32% in Oslo and Nantes of the total per capita emissions in both countries. Of course, one should not aim for the worst (current emissions) but for the best (carrying capacity), in which case total per capita emissions represent 6% and 10% of the total possible emissions in France and Norway. If we acknowledge the fact that many other types of consumption occur, and are likely to emit more carbon (food, housing, clothing, transport…), water consumption is consequently maybe not the most sustainable urban service.

On the contrary, when one compares the total emissions from the utility to the total emissions offset, the water sector is *theoretically and potentially* able to offset its own emissions, by avoiding fossil fuel consumption (from biogas), avoiding fertiliser use from agriculture (from sludge). More concretely, by recovering the three main elements (C, N, P) that are necessary to human activities.

- ♣ **Answer to research question 3**:

Scenario	Reduction by 2030 (in %)	Nantes	Oslo
Business as Usual	Total energy	20%	24%
	Per capita energy	32%	45%
	Total carbon	22%	24%
	Per capita carbon	33%	45%
Water Quality and Safety	Total energy	30%	29%
	Per capita energy	53%	49%
	Total carbon	36%	2%
	Per capita carbon	45%	30%
Energy Management and Enhanced Water Safety	Total energy	45%	43%
	Per capita energy	53%	59%
	Total carbon	47%	33%
	Per capita carbon	55%	52%

Table 6-3: Scenario improvements comparison

It appears from the table above that all scenarios will lead to an improvement of the results. It also appears that an important share of these improvements will come from elements that are independent from the utilities' internal policies and development. The drivers, population and demand, have as a matter of fact important effects on the overall results. This is why even BAU leads to reductions by 2030.
Nevertheless, alternative scenarios also make it possible to improve the baseline efficiency increases. The following elements are consequently leads on that matter, even if they are not the only ones.

- ♣ WTP efficiency improvement: the ageing of equipment is an important factor, as well as the size match between the plant and the demand.

- ♣ Distribution network management is also important. Not only should the leakage reduction and pressure by managed, but decentralisation of the water sources yields very large improvement.

- ♣ When it comes to processes and subsystems occurring after the water consumption, several elements are important: Heat recovery from the wastewater flow can be done, during times of the year when the difference in temperature is high especially. Biogas generation, as well as the sludge generation import even more.

6.2. Sensitivity analysis

It was mentioned throughout this work, in the Methodology and Results chapter particularly, that some elements were uncertain and could probably lead to important changes in the results if small changes were to be accounted for.

The main element quoted was the sludge use as fertiliser. In that case, two points will have particular importance. Firstly, two fertilisers (replaced by sludge) have been modelled thanks to the Ecoinvent process database and based on uses in France and Norway. But the requirements for these fertilisers might be very different than the ones accounted for in the database, which are average. Especially in terms of GHG emissions, because the use of one process rather than another for heating, or the phasing out of oil, can have large consequences. Secondly, the use made by farmers of the sludge has been calculated based on the equivalent replacement of the chemical elements. 1 N replaces 1 N, 1 P2O5 replaces 1 P2O5. But statistics about sludge use could actually not be found and used, and it is quite possible that farmers use for example more sludge (in terms of fertilising power) than they do with usual fertilisers. As it was seen in the results, the use of sludge in agriculture is the game changer for energy, but especially for carbon, because a reasoned use of sludge can actually offset emissions, and offset energy consumption to a certain extent

A second element that might have influence is the electricity mix in Norway. For this work was chosen the Ecoinvent Nordic mix (calculated with the ReCiPe method). But other values can be found (Schakenda & Nyland, 2011) for Nordic mix, and the Norwegian mix itself could be chosen.

Thus, the following Figures 6.1 and 6.2 have been made to track possible changes in terms of carbon emissions. In Oslo, three scenarios have been made:

- Nordic mix 2 (64 g CO_2e/kWh)
- Norwegian mix (2 g CO_2e/kWh)
- Sludge (36% decrease of the fertiliser carbon content – this change being the same as the variation from baseline to Nordic mix 2)

In Nantes, only Sludge was assessed.

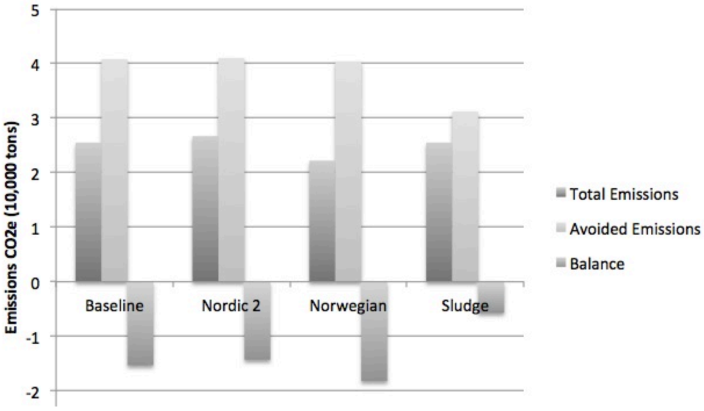


Figure 6-1: Sensitivity analysis Oslo

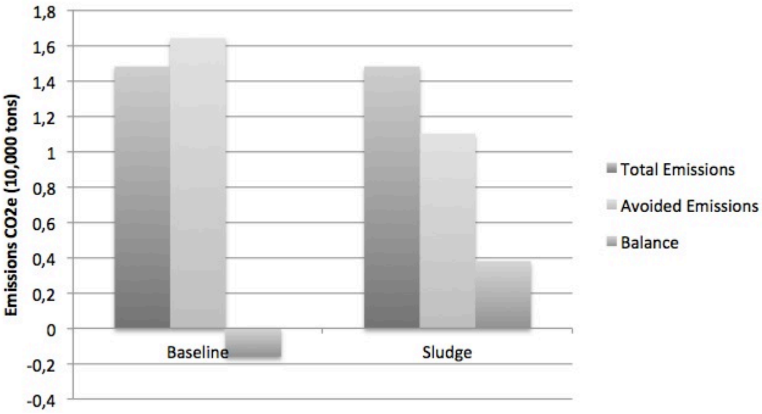


Figure 6-2: Sensitivity analysis Nantes

These two charts confirm the fact that the fertiliser use actually has very high impact on the total. In Oslo, the sludge scenario leads to a 25% reduction of avoided emissions (because avoided emissions from biogas remain), whereas in Nantes, a 33% decrease appears. Moreover in Nantes, a change of the fertiliser manufacturing/use leads to a change of status of the utility from net carbon capturer to net carbon emitter. If one considers that a 36% decrease of the net carbon content (hence manufacturing *and* use of fertilisers) might be below reality, it is possible that actually both cities are net carbon emitters when it comes to water use.

6.3. Results in the context of the case cities

In Nantes, we kan keep to main elements from this work. First of all, Nantes Métropole's water utility has very high requirements in terms of water treatment, and for drinking water distribution. In that context, going towards a higher decentralisation rate of the water supply would be interesting. Indeed, the rainfalls on the city would allow meeting several times to population's needs under the current conditions (and still in 2030). Consequently, energy requirements and carbon emissions could be decreased because: less treatment (hence chemicals) would be needed, less loss would occur, and the energy requirement for water transportation would dramatically decrease. It goes without saying that choosing such a scenario entails intense planning, and neighbourhood scale details to be as efficient as possible. This would also be an interesting way for Nantes Métropole to ensure its water safety, as it was mentioned in the Case Study Presentation chapter that no source has the same supply potential as the Loire, in case a major hygiene event would occur.

The second element to keep in mind is the potential of certain policies in wastewater treatment. Solar drying of sludge has now been planned on a larger scale in Nantes, and could possibly decrease the emissions of the WWTPs by a large share. When it comes to the treatment itself, Nantes Métropole has however not the same potential of resource recovery as Oslo: the biggest WWTP treats wastewater by activated sludge treatment, and no plan to change it has been made to date. But if the potential of nutrient recovery is considered, efforts could be made not towards energy recovery but P and N treatment.

In Oslo, the situation is a little different in that the utility requires more energy for wastewater treatment, even if some of it is met by internal production. Thus, the element that overweighs any other in the scenario projection is undoubtedly the choice of keeping biogas for internal demand or to sell it as bus fuel. If the first choice is made, the "official" energy and especially carbon footprint of the utility are decreased, as an important share of the energy is supplied internally. On the contrary, selling the biogas has a tremendous impact on the outside of the utility and allows it (without considering the fertilising sludge) to become carbon neutral or almost by extending its system boundaries.

On the contrary, Oslo benefits from low energy requirements in the drinking water production and distribution. Hence, a decentralisation of these subsystems does not impact the overall results as much as it does in Nantes: chemical usage is originally low, and the elevated position of the freshwater resources gives to the grid part of the energy necessary for the supply. Attention must nevertheless be drawn to chemical use in Oslo has been very much increased in the last years for drinking treatment, and is still below Nantes Métropole's usage on a per volume treated basis. It is hence possible to imagine that, driven by regulations or internal policies, chemical use increases, which could lead to a higher positive impact of a decentralised treatment.

6.4. Towards further research

The first and probably most important conclusion to draw upon this work is the reflexion on what more could be made in the direction that has been followed throughout this thesis. Indeed, it has been noted in the Results chapter and in this chapter that some elements were not certain enough. In addition, no extensive process model could be made, which would be entailed for an interesting forecast of wastewater treatment for example.

Thus, the following elements could be the subjects of further research.

- Sludge as fertiliser:

It has been pointed out that the actual effect of sludge in agriculture could probably not be evaluated better than its order of magnitude. To do so, work on two elements of importance must be undertaken. Firstly, a closer evaluation of the types of fertilisers used in agriculture could be made, possibly on the agricultural land reached by the sludge from both cities. This could lead to a better model of the requirement per element (N or P) through the evaluation of the energy and carbon emissions for manufacturing. In addition, it is of primary importance to evaluate the way sludge is used as fertiliser, if it replaces the exact same amount of nitrogen/phosphorus, if it replaces only part of it, or if farmers use lot more sludge fertilisers than necessary.

- Process emissions.

It is difficult to get any data for process emissions, especially in wastewater treatment. Nitrous oxide has a possibly high impact, but uncertainty is large. Consequently, a better model of process emissions ($N2O$, $CH4$) could be made. It could be used for investigating scenarios concerning the recovery and treatment of such flows.

- Wastewater treatment further scenarios

In this work has been evocated in the literature review the potential of emissions decrease, with new approaches such as grey water, black water and yellow water separation. It was not modelled, due to the complexity of the processes entailed, and also because of the important work it would lead on every single building in both cities. However, a closer look could be given to this possibility, which could allow treated lower flows in the WWTPs and recover at the same time the same quantity of carbon, nitrogen and phosphorus at a lower energetic cost. Such an approach would also need to propose solutions about the treatment of grey water. This wastewater comes particularly from kitchen use, showers, laundry washing… It holds many pollutants and eutrophication potential, from the detergents for example that have important concentration in N. Consequently, the choice of separating grey water from black water asks the question of decentralisation of grey water treatment or decoupling of treatments in the main WWTPs.

7. Conclusion

This thesis aims at avoiding what Industrial Ecologists name “problem shifting”. This term refers to any analysis where the specific focus on one particular element of a system leads to neglecting the rest of it. In order to avoid such an issue, methods such as Life Cycle Assessment and Material Flow Analysis have been developed and allow considering not only one phase, or one subsystem of the wished system, but its whole life cycle. In this work, such an approach was taken through use and development of a multi-indicator and thorough model of Urban Water Cycle Systems, based for example on Venkatesh (2011). The explicitly goal of the study was to develop an all-embedding system, in the water utilities of Nantes Métropole and Oslo.

The second main element, and the practical scope of the work was to investigate the water-energy nexus, the intricate relation that exists between water use in energy, and energy use in water, on the side of the latter relation. Indeed, literature review shows the importance of this relation and the necessity to reduce the impact from the water utility’s side, thus leading to exploring the cases of Nantes and Oslo. The case study was hence led in the idea of associating the identified flows to their energy contents and their emissions. To that respect, even if not every single flow could be identified, it has been possible to determine the significant ones, from literature and previous work. The outcome of this combined methodology is thus an overall energy/carbon system for both cities, which could be adapted to the forecast of future drivers, technologies, and trends.

When it comes to the specific results and their meaning, several important points can be identified. Firstly, the specific consumptions of energy throughout the urban water cycle is probably not the most important one when are considered all other services humans use. Indeed, they are respectively of 116 and 311 kWh/cap.year in Nantes and Oslo, numbers, which are far from the total energy used directly and indirectly by an individual in France or Norway. However, such figures and their values are by no means unimportant. They also reflect personal consumption of water services, three times higher in Oslo than in Nantes. This leads to an advantage in favour of the French conurbation, despite per volume energy requirements that are higher in Nantes: 2.19 kWh/m^3 final consumption versus 1.83 in Oslo. A direct consequence to this opposition is thus that it becomes possible not to stop at the total figures per capita and rather split it up. Then one can and aim for improvement, either on the requirement per unit volume, or on consumption trends.

Secondly, the carbon footprints associated to the consumption of water in Nantes and Oslo can also be viewed as not extremely high with regards to other services. The average user in Nantes is responsible of 25 kg CO_2e emissions in the baseline year, while the average user in Oslo emits 45.5 kg CO_2e. But it must be noted that the carbon impact related to the amount of energy used are quite high: 215 g CO_2e/kWh for the French utility and 145 g CO_2e/kWh for the Norwegian one. These two figures that correspond by analogy to electricity mixes with high share from fossil fuels: natural gas, diesel or coal. This fact depicts another important element for the UWCS: they are very dependent on indirect energy flows: chemicals, materials, transportation, which are heavily relying on fossil resources.

This brings to the next point about UWCS. Their role is not only to produce water but also to clean wastewater. they must comply with strict policies, and rely on more and more efficient technologies. Water utilities are hence able to recover the useful resources: carbonated elements for energy, nitrogen and phosphorus as nutrients, and the choice of use of these elements can offset a part of the energy used and carbon emitted.

Such an element has great importance, despite the uncertainty from which it suffers. As a matter of fact, the results of different scenarios show indeed that in a few years time, up to two thirds of the energy used by the utilities could be offset. For carbon, several times their emissions in carbon could be negated, if the by-products (biogas and sludge) are used properly. The outcome of this work is indeed that due to population and demand change, direct and indirect requirements are on a decreasing trend, while the 'avoided' energy and emissions are likely to increase. In order to make the change effective, the utilities have access to a span of different measures that they can use to create positive impacts on the environment. Thus, anaerobic wastewater treatment associated to biogas use as bus fuel, sludge use as fertiliser, are direct ways to offset this influence. Upstream flows before the consumer demand should on the contrary be investigated for more reduction measures, since resource recovery cannot be made before consumption. Decentralisation of the water supply and rainwater harvesting are hence major policy measures that can be implemented to decrease the reliance of UWCS on external resource.

As a conclusion, one statement by analogy can be made. Humanity has bent the natural cycles. Carbon, nitrogen and phosphorus have been used in large quantities outside of their normal dynamics. This situation has created enormous tensions on natural ecosystems and anthropic systems, which are now not always able to supply themselves for their basic needs, such as food and water. The urban water cycle systems are a perfect example of these human-made systems that cannot work any longer as they have. They must reduce their dependence on the linear economy of "make, use, waste" and work in closed loops. This can be done to a certain extent already today, with some of the scenarios and technologies that have been presented in this thesis. In that way, it is possible to bend back the natural cycles related to water use towards their original state, and extend such operations to other human activities, to make humanity a proper ecosystem.

Bibliography

Benyus. (1997). *Biomimicry: Innovation Inspired by Nature.*

BEVAS. (2007). *Årsrapport Bekkelaget Renseanlegg 2007.* Oslo.

BEVAS. (2009). *Årsrapport Bekkelaget Renseanlegg 2009.* Oslo.

BEVAS. (2010). *Årsrapport Bekkelaget Renseanlegg 2010.* Oslo.

Biekel, Cornell, & Wagner. (2010). Semicentralised supply and treatment systems: integrated infrastructure solutions for fast growing urban areas. *Water Science & Technology , 61* (11), 2905-29013.

Bogner, J., Ahmed, M. A., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., et al. (2007). *Waste Management, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Brattebø, B. S. (2009). Explorng built environment stock metabolism and sustainability using system analysis approaches. *Building Research and Information , 37* (5), 569-582.

Cohen, Henges-Jeck, & Castillo-Moreno. (2001). A preliminary water balance for the Colorado River delta, 1992 - 1998. *Journal of Arid Environments , 49*, 35-48.

Ehrenfled. (2002). Industrial Ecology: Coming of Age. *Environmental Science & Technology , 36* (13), 280A-285A.

Elkington, J. (1997). *Cannibals With Forks: The Triple Bottom Line of 21st Century Business.* Oxford: Oxford University Press.

FAO. (2006). *Overview of the hystory of water resources and irrigation management in the near east region .* United Nations. Iraklio: FAO.

Funamizu, Iida, Sakakura, & Takakuwa. (2001). Water Science and Technology. *43* (10), 277-285.

GIP Loire Estuaire. (2011). *Les prélèvements et rejets d'eau.* Nantes: GIP Loire Estuaire.

Höök, Sivertsson, & Aleklett. (2010). Validity of the Fossil Fuel Production Outlooks in the IPCC Emission Scenarios. (I. A. Geology, Éd.) *Natural Resources Research , 19* (2), 63-81.

Høibe, Clauson-Kaas, Wenzel, Larsen, Jacobsen, & Dalgaard. (2008). Sustainability assessment of advanced wastewater treatment technologies. *Water Science & Technology , 58* (5), 963-968.

Hawken, Lovins, & Lovins. (1999). *Natural Capitalism.*

Hawkins, H. H. (2007). A Mixed-Unit Input-Output Model for Environmental Life-Cycle Assessment and Material Flow Analysis. *Environmental Science & Technology , 41* (3), 1024-1031.

Hertwitch. (2005). Life Cycle Approaches to Sustainable Consumption: A Critical Review. *Environmental Science & Technology , 39* (13), 4673-4684.

Hertwitch, E. (2009). *Carbon Footprint of Nations*. Consulté le 2012, sur Carbon Footprint of Nations: http://carbonfootprintofnations.com/content/calculator_of_carbon_footprint_for_nations/

Houillon, & Jolliet. (2005). Life Cycle assessment of processes for the treatment of wastewater of urban sludge: energy and global warming analysis. *Journal of Cleaner Production , 13*, 287-299.

INSEE. (2011a). *Nantes Métropole pourrait gagner 100 000 habitants d'ici 2030.* Nantes: INSEE Pays de la Loire.

INSEE. (2011b, August 4). *Nombre d'établissements et effectifs salariés par secteur d'activité et tranche d'effectifs salariés au 31 décembre 2009.* Consulté le June 2, 2012, sur Institut National de la Statistique et des Etudes Economiques: http://www.insee.fr/fr/themes/detail.asp?reg_id=99&ref_id=etab-eff-sal-par-sates
Institut Français de l'Environnement. (2007). *La facture d'eau domestique en 2004 177 euros par personne et par an.* Orléans: Ifen.

Institut Français de l'Environnement. (2007). *Les services publics de l'eau en 2004.* Ministère de l'Ecologie, du développement et de l'aménagement durables. Paris: République Française.

International Energy Agency. (2010). *2010 Key World Energy Statistics.* OECD/IEA. Paris: OECD/IEA.

International Energy Agency. (2011). *World Energy Outlook 2011 - Executive Summary.* International Energy Agency. Paris: International Energy Agency.

IPCC. (2007). *Climate Change 2007: Synthesis Report.* IPCC.

Israel Ministry of Environment. (2010, 01 28). *Wastewater Treatment*. Consulté le 12 01, 2011, sur Ministry of Environmental Protection: http://www.sviva.gov.il/bin/en.jsp?enPage=e_BlankPage&enDisplay=view&enDispWhat=Object&enDispWho=Articals^l2089&enZone=Wastewater_Treatment

Keller, & Hartley. (2003). Greenhouse gas production in wastewater treatment: process selection is the major sector. *Water Science and Technology , 47* (12), 43-48.

Kenway, Priestlay, Cook, Seo, & Inman. (2008). *Energy use in the provision and consumption of urban water in Australia and New-Zealand.* CSIRO Australia and Water Water Services Association of Australia. Canberra: CSIRO and WSAA.

Lassaux, Renzoni, & Germain. (2007). Life Cycle Assessment of Water from the Pumping Station to the Wastewater Treatment Plant. *The International Journal of Life Cycle Assessment , 12*, 118-126.

Lazarova, Choo, & Cornell. (2012, April). Meeting the challenges of the water-energy nexus: the role of reuse and wastewater treatment. *Water21* , 12-17.

Letour.fr. (2011). *Tour de France 2011 - Etape par étape*. Consulté le May 18, 2012, sur letour.fr: http://www.letour.fr/2011/TDF/COURSE/fr/1400/etape_par_etape.html

Liu, B. M. (2011). Unearthing Potential for Decarbonizing the U.S. Aluminium Cycle. *Environmental Science & Technology* .

Lundin, & Morrison. (2002). A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. *Urban Water , 4*, 145-152.

Müller, Wang, Duval, & Graedel. (2006). Exploring the engine of anthropogenic iron cycles. *PNAS , 103* (44), 16111-16116.

Majeau-Bettez, G. (2011). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. *Environmental Science & Technology , 45* (10), 4548-4554.

McCann. (2012, April). Small-scale hydro shows promise for remote treatment stations. *Water21* , 18.

McNabola, Coughlan, & Wiliams. (2011). The Technical & Economic Feasibility of Energy Recovery in Water Supply Networks. *International Conference on Renewable Energy and Power Quality, Las Palmas de Gan Canaria, 13th - 15th April.* Las Palmas de Gran Canaria: Perez-Donsion.

Melbourne Municiplity. (2011). *Water recycling: Using recycled water*. Consulté le 12 01, 2011, sur Melbourne Water: http://www.melbournewater.com.au/content/water_recycling/using_recycled_water/using_recycled_water.asp

Menendez, & Veatch, B. a. (2010). *How we use energy at wastewater plants and how we can use less.* Consulté le May 10, 2012, sur NC AWWA-WEA

Ministère de l'Alimentation, de l'Agriculture et de la Pèche. (2010). *Etat, perspectives et enjeux du marché des engrais.* Ministère de l'Alimentation, de l'Agriculture et de la Pèche.

Montginoul, Even, & Verdon. (2010). *Comprendre l'évolution de la consommation d'eau potable dans l'agglomération nantaise.* Nantes: Cemagref, Nantes Métropole.

Nantes Métropole. (2012). Personnal communication with the personnel of Nantes Métropole.

Nantes Métropole. (2010). *Rapport annuel sur le prix et la qualité du service d'assainissement.* Nantes: Nantes Métropole Communauté Urbaine.

Nantes Métropole. (2010b). *Rapport annuel sur le prix et la qualité du service d'assainissement.* Nantes: Nantes Métropole Communauté Urbaine.

Nantes Métropole. (2008). *Rapport annuel sur le prix et la qualité du service public de l'eau 2008.* Nantes: Nantes Métropole Comunauté Urbaine.

Nantes Métropole. (2009). *Rapport annuel sur le prix et la qualité du service public de l'eau 2009.* Nantes: Nantes Métropole Communauté Urbain.

Nantes Métropole. (2010). *Rapport sur le prix et la qualité du service public de l'eau 2010.* Nantes: Nantes Métropole.

Nantes Métropole. (2010a). *Rapport sur le prix et la qualité du service public de l'eau 2010.* Nantes: Nantes Métropole.

Novotny, Ahern, & Brown. (2010). *Water Centric Sustainable Communities: Planning, Retrofitting and Constructing the Next Urban Environments.* Hoboken, NJ: J. Wiley & Sons.

Nowak, Keil, & Fimml. (2011). Examples of energy self-sufficient municipal nutrient removal plants. *Water Science & Technology , 64* (1), 1-6.

Oslo Kommune. (2011). *Årsberetning 2011.* Oslo.

Piednoir, F. (2008). *Pédaler Intelligent - La biomécanique du cycliste.* Creative Commons.

PRé Consultants. (2008). *Simapro.* Amersfoort: PRé Consultants.

Prof Arun Kansal, T. E., & Prof Shobhakar Dhakal, E. D. (2012, May). Personnal Communication in May 2012.

Racoviceanu, Karney, Kennedy, & Colombo. (2007). Life-Cycle Energy Use and Greehouse Gas Emissions Inventory for Water Treatment Systems. *Journal of Infrastructure Systems* , 261-270.

Retamal, Glassmire, Abeysuriya, Turner, & White. (2009). *The water-energy nexus. Investigation into the Energy Implications of Households Rainwater Systems.* Insitute for Sustainable Future. Sydney: UTS.

Rosso, & Stenstrom. (2008). The carbon sequestration potential of municipal wasterwater treatment. *Chemosphere , 70*, 1468-1475.

Sahely, & Kennedy. (2009). Water use model for quantifying environmental and economic sustainability indicators. *Journal of water resources planning and management , 133* (6), 550-559.

Sahely, Kennedy, & Adams. (2005). Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering , 32*, 72-85.

SBW Consulting, Inc. (2006). *Municipal Water Treatment Plant Energy Baseline Study.* Pacific Gas and Electric Company. San Fransisco: Pacific Gas and Electric Company.

Schakenda, & Nyland. (2011). *CO2-emissions associated with different electricity mixes.* SIMAPRO. (2012).

SSB. (2011, June 16th). *Population projections. National and regional figures, 2011-2060.* Consulté le May 20th, 2012, sur SSB.no: http://www.ssb.no/english/subjects/02/03/folkfram_en/

SSB. (2012). *StatBank Norway*. Consulté le June 4, 2012, sur Statistisk Sentralbyrå: http://statbank.ssb.no/statistikkbanken/Default_FR.asp?PXSid=0&nvl=true&PLanguage=1&tilside=selecttable/hovedtabellHjem.asp&KortnavnWeb=arealbruk

Statistics Denmark. (2012, June 2). *Final consumption of water and water intensity by industry and unit (DISCONTINUED)* . Consulté le June 2, 2012, sur Statistics Denmark: http://www.statbank.dk/statbank5a/SelectVarVal/Define.asp?Maintable=MREG5V&PLanguage=1

Stiglitz, J. E. (2009). *Report of the Commission of Experts of the President of the United Nations General Assembly on Reforms of the International Monetary and Financial System.* United Nations. New York: United Nations.

Ugarelli, Venkatesh, Brattebø, & Sægrov. (2010). Asset Management for Urban Wastewater Pipeline Networks. *Journal of Infrastructures Systems , 16* (2), 112-121.

Ugarelli, Venkatesh, Brattebø, & Sægrov. (2008). Importance of investment decisions and rehabilitation approaches un an ageing wastewater pipeline network. A case study of Oslo (Norway). *Water Science & Technology , 58* (12), 2279-2293.

Ugarelli, Venkatesh, Brattebø, DiFrederico, & Sægrov. (2010). Historical analysis of blockages in wastewater pipelines in Oslo and diagnosis of causative pipeline characteristics. *Urban Water Journal , 7* (6), 335-343.

United Nations General Assembly. (2000). United Nations Millennium Declaration. New York: United Nations.

United Nations. (1992). *United Nations Framework Convention on Climate Change.* UN, New-York.

VAV. (2006). *Oslo Water and Sewerage (VAV) 2006.* Oslo.

VEAS. (2008). *Årsmelding 2008.* Oslo.

VEAS. (2009). *Årsmelding 2009.* Oslo.

VEAS. (2010). *Årsmelding 2010.* Oslo.

Venkatesh. (2012). Personal Communication.

Venkatesh, G. (2011). *System performance analysis of Oslo's water and wastewater system.* NTNU. Trondheim: NTNU-Trykk.

Venkatesh, G., & Brattebø. (2011). Analysis of chemicals and energy consumption in water and wastewater treatment, as cost components: Case study of Oslo, Norway. (T. &. Francis, Éd.) *Urban Water Journal , 3*, 189-202.

Venkatesh, G., & Brattebø, H. (2011). Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway). *Energy , 36*, 792-800.

WHO and UNICEF. (2010). *Progress on Sanitation and Drinking Water, 2010 Update.* Geneva: WHO Press.

Wikipedia. (2012c). Consulté le 2012, sur pages for the different cities in Nantes Métropole, Oslo.

Wikipedia. (2012a). *Drinking Water.*

Wikipedia. (2011, 12). *Loire [les débits à St Nazaire]*. Consulté le 12 15, 2011, sur Wikipedia, the free encyclopedia: http://fr.wikipedia.org/wiki/Loire_%28fleuve%29#Les_d.C3.A9bits_.C3.A0_Saint-Nazaire

Wikipedia. (2012b). *Oceans.*

Wikipedia. (2011). *Wikipedia pages treating of water and wastewater treatment and supply.* Consulté le September to December 2011, sur Wikipedia, the free encyclopedia: http://en.wikipedia.org/wiki/Main_Page

World Council for Environment and Development. (1987). *Our Common Future.* Oxford: Oxford University Press.

Appendices

In the appendices, calculations of different results can be found, as well as the technical steps and hypotheses that were needed to perform them. Any result used in the main model is highlighted, for easier understanding and readability of the appendices.

Appendix 1: Water Demand by Agriculture in Nantes Métropole

There is very few information stating that there in any agricultural use of water. The annual assessments of water quality (Nantes Métropole, 2008) (Nantes Métropole, 2009) (Nantes Métropole, 2010) and the study of Oslo's UWCS by Venkatesh (2011) do not mention agriculture as an important consumer of water in the urban community. A research document (Montginoul, Even, & Verdon, 2010) states that only 6 subscribers to the services are registered as agricultural users, with consumptions under the average in Nantes Métropole. Moreover, other sources (GIP Loire Estuaire, 2011) on water withdrawals from the Loire in the Loire Atlantique department (administrative region of Nantes) mention particular spots around Nantes Métropole that are used for water supply to agriculture from the Loire.
Thus, one shall **neglect water use from agriculture** in both Nantes Métropole and Oslo.

Appendix 2: Calculation of Wastewater to individual sewage in Nantes

Another point of calculation is the wastewater that is treated in individual WWTPs, in parts of Nantes Métropole where sewage is not fully developed. The 2010 wastewater report (Nantes Métropole, 2010) states that 4427 non-collective wastewater treatment systems (WWTS) are installed on the territory. There are also 175,484 subscribers to sewage service, which in total gives 179,914 subscriptions, close to the 180,924 subscriptions to water services. We can calculate the wastewater produced by considering all the water consumed.

- 29.5Mm^3 are released into sewage
- 0.9Mm^3 are released through private WWTS.

Appendix 3: Calculation of rain content in the sewage system and WWTPs.

In this appendix is led the calculation of the rainwater flow repartition into both WWTPs.

Appendix 3.1: Nantes Métropole

- **1st stage: total rain on the territory:**

We use the total territory whose wastewater goes to the one or the other WWTP, from (Nantes Métropole, 2010) and Wikipedia for the surfaces. Total rainfalls were 690mm for 2010. From this we get the rain on the different territories, and combination of the elements permit calculation of rainfalls on each town.

	Tougas	Petite Cal.	
Rain (Mm^3)	**198.02**	**74.95**	**272.98**

Table 0-1: Rain on the territories

We have to consider that **not all this volume is recovered**: part of it will be lost in the non-urbanised part of those towns. There is **30% urbanised surface in Nantes Métropole** and we considered that the surface not considered for those WWTP is non urbanised (90% of the population lives on the surface considered that is 75% of Nantes Métropole). By retrieving this area, and the city of Nantes, considered as totally urbanised, we get a **urbanisation coefficient for the towns (except Nantes) that we consider: 28%.**
The total rainfalls recovered on the territories served by each WWTP can hence be calculated.

	Tougas	Petite Cal.	Total
Rain to WWTP (Mm^3)	**86.36**	**20.99**	**107.34**

Table 0-2: Rain flows treated in Nantes Métropole's WWTPs

- **2nd stage: rain recovery by the different types of pipelines**

Administrative sources provide with the lengths of the different types of pipelines (Nantes Métropole, 2010) serving each WWTP. It is hence possible to calculate the total rainflows going into each pipeline type thanks to a few hypothesis

Hypothesis 1: For each type of pipeline, we can use a coefficient that describes the amount of rainwater collected throughout the year per unit of linear length of pipeline.

Let k_m, k_s and k_r be respectively the recovery rates of mixed sewage, sewage and rain pipelines. (3 unknowns)
Let L_m, L_s and L_r be respectively the lengths of mixed, sewage and rain pipelines (0 unknown, figures above)
Let $V_{r,tot}$ and $V_{r,tp}$ be respectively the total volume of rain considered (after urbanisation coefficient) and the volume of rain going into the WWTPs.

We have:

(1) $$k_m*l_m+k_s*l_s+k_r*l_r = V_{r,tot}$$

(2) $$k_m*l_m+k_s*l_s= V_{r,tot}$$

With values calculated in the rest of the work it is possible to calculate $V_{r,tot}$ and $V_{r,tp}$.
Vr,tot =91.6 Mm^3 of water are collected and are sent back to the Loire through the normal storm pipelines, without entering treatments.

Hypothesis 2: The quantity of sludge produced by each plant is directly proportional to the "pure" wastewater received.

Notations:
- R, R_t and R_p are the rain flows, in total (recovered), to Tougas and to Petite Californie
- T_t and T_p are the total flows treated in Tougas and Petite Californie
- W_t and W_p are the total "pure" wastewater flows entering Tougas and Petite Californie
- S_t and S_p are the total quantities of sludge produced by Tougas and Petite Californie.

Equations
- $Wt/Wp =St/Sp$ (1) (hypothesis)
- $R = Rt + Rp$ (2) (mass balance of rain)
- $Tt = Wt+ Rt$ (3) (mass balance in Tougas)
- $Tp = Wp + Rp$ (4) (mass balance in Petite Californie)

Hence

$$R_p = \frac{R - T_p + \frac{S_t}{S_p}.T_p}{1 + \frac{S_t}{S_p}}$$

$$R_t = R - R_p$$

Numerically:

- $R_p = 3.0\text{Mm}^3$
- $R_t = 12.7\text{Mm}^3$

Hypothesis: The rainwater flow for each type of pipelines is directly proportional to the length of each type of pipelines

Notations:

- kw and km are the coefficients of rainwater infiltration for wastewater pipelines and mixed sewage pipelines
- Lwp, Lwt and Lm are the length of wastewater pipelines to Petite Californie, Tougas, and the length of mixed pipelines to Tougas.

Equations:

- Rp = kw.Lwp
- Rt = kw.Lwt + km.Lm

Numerical resolution leads to:

- kw = 5850 m^3/km
- km = 19220 m^3/km

Appendix 3.2: Oslo

The same approach is taken for Oslo. It was considered that the main hypothesis is still valid. In addition the same level of land use of 30% in Oslo municipality was calculated thanks to SSB statistics (SSB, 2012).

Thus, both kw and km could be kept and applied, with an additional linearization with respect to the rainfall, thus leading to renewed coefficients of

kw = 8.48 m3/km.mm; km = 27.86 m3/km.mm

With rainfalls of 937mm during 2007 in Oslo, and the data of 660km of mixed sewers and 792km of wastewater sewers, **the rainwater infiltration to the treated sewage flows could be estimated to be 24.59Mm^3 in 2007**

It is obviously difficult to estimate the quality of this calculation, but the other approach would have been to consider the mass balance between the consumption flow (considering no losses in consumption) and the inflows to both WWTP, giving a much smaller result (about 15Mm^3). When put into the perspective of the higher rainfalls and the larger mixed sewage network than in Nantes it seems hence more logical to go for the higher number (15Mm^3 being approximately the rainwater infiltration into Nantes sewage network).

The consequence of this is that a new "lost" flow is entailed from consumption to keep the mass balance. This flow is equal to 8.2Mm^3 in 2007, and could actually depict behaviour differences between Nantes Métropole and Oslo: in Nantes, people live less in private house, thus doing less gardening for example. Car washing could be also a reason to this difference.

In addition, based on the approach used for Nantes Métropole, and given the same level of urbanisation, it is possible to make an estimation of the total rainwater recovered by the stormwater collection pipelines. It will be of 30% (urbanisation rate) of the total rainfalls minus the recovered rainfalls: 103.0 Mm^3 rainfall to stormwater collection in Oslo in 2007

Appendix 4: Population Evolution

Both Nantes and Oslo are expected to experience population raise in the future. According to French and Norwegian Statistical Bureaux, Nantes Métropole will host 100,000 more inhabitants in 2030, and Oslo should have a total population of 786,000 inhabitants at the same date (INSEE, 2011a), (SSB, 2011).
As it difficult to predict the exact yearly variation of both populations, they will be modelled linearly:

$$P_{oslo}(year) = \frac{P_{oslo}(2030) - P_{oslo}(2007)}{2030 - 2007}.(year - 2007) + P_{oslo}(2007)$$

$$P_{nantes}(year) = \frac{P_{nantes}(2030) - P_{nantes}(2010)}{2030 - 2010}.(year - 2010) + P_{nantes}(2010)$$

Calendar year	NM	Oslo
2007		560,000
2008		569,826
2009		579,652
2010	590,000	589,478
2011	595,000	599,304
2012	600,000	609,130
2013	605,000	618,957
2014	610,000	628,783
2015	615,000	638,609
2016	620,000	648,435
2017	625,000	658,261
2018	630,000	668,087
2019	635,000	677,913
2020	640,000	687,739
2021	645,000	697,565
2022	650,000	707,391
2023	655,000	717,217
2024	660,000	727,043
2025	665,000	736,870
2026	670,000	746,696
2027	675,000	756,522
2028	680,000	766,348
2029	685,000	776,174
2030	690,000	786,000

Table 0-3: Population in Nantes and Oslo until 2030

Appendix 5: Water demand matrix

Appendix 5.1: Current situation

In Montginoul, Even, & Verdon (2010) the value of an average 85 to 86m^3 water per household was consumed in a sample of towns of Nantes Métropole in 2008 (representing the major share of its population), a figure in constant decrease. Thus, 84m^3 average was chosen for 2010. In addition, households were inhabited in Nantes Métropole by 2.3 people in 2010 in average. The total population in Nantes Métropole would hence represent 265,520 households. Consequently, total household consumption in Nantes Métropole in 2010 would be 21.55Mm^3, and the remaining 8.85Mm^3 are consumed by economy. This is a 71:29 repartition of the flows, not too far from the estimation (78:22) given in the 2009 institutional report (Nantes Métropole, 2009).

Danish water use statistics give the following table (Statistics Denmark, 2012):

Cubic metres per DKK million (2000-prices)	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Mining and quarrying	228	218	181	289	169	180	118	112	92	78	79
Manufacturing of food, beverages and tobacco	418	391	397	392	347	401	396	380	319	314	283
Industrial products manufacturing	438	364	412	444	380	444	453	480	324	343	291
Mfr. of basic metals and fabr. metal prod.	56	47	46	54	48	45	25	28	29	29	24
Construction	12	8	6	5	50	41	13	5	4	4	3
Wholesales, incl. vehicles	52	51	50	46	41	42	42	43	41	38	32
Hotels and restaurants	146	139	125	124	110	116	111	125	122	117	110
Transport	35	32	26	23	20	17	17	18	17	16	13
Post and telecommunications	6	7	7	7	7	6	5	5	4	3	3
Finance and insurance	9	8	7	6	6	6	5	5	5	4	3
Letting and sale of real estate	14	14	14	13	12	12	13	14	13	12	12
Public and personal services	103	97	92	87	89	84	86	78	75	70	66
Other services	118	109	99	96	103	90	81	84	78	74	73

Table 0-4: Water intensity of economy in Denmark, 1995-2005

We will assume the fact that European countries have more or less the same standards in terms of water use in the economy. Thus, Danish figures can be extrapolated to France or Norway. In order to apply these figures, economic repartition must be applied. To do so, the French GDP evolution (GDP being the sum of all value added in the economy) was aggregated since the end of WWII, along different sectors (INSEE, 2011a). By using the 2010 values, it is possible to calculate an average "per employee" value for each sector, and thus scale it to Nantes:

Sector (Nantes Métropole, 2010)	**Economic Share in NM, 2010**
Mining and quarrying	3%
Manufacturing of food, beverages and tobacco	1%
Industrial products manufacturing	5%
Mfr. of basic metals and fabr. metal prod.	1%
Construction	6%
Wholesales, incl. Trade and repair of vehicles	13%
Hotels and restaurants	3%
Transport	8%
Post and telecommunications	13%
Finance and insurance	9%
Letting and sale of real estate	14%

Public and personal services	20%
Other services	13%
TOTAL	100%

Table 0-5: Sectorial repartition of GDP in Nantes Métropole, 2010

From this starting point, and since the first calculation has given the total water consumption in economy in Nantes Métropole, it is possible to calculate the consumption of each sector and aggregate it to a more. In order to make the estimation for Oslo, elements found in Venkatesh (2011) are used, stating that 57% of the supply is used by households (54.2Mm^3). The economy, as in Nantes, can be adjusted thanks to the Danish statistics and economical statistics.

Sector Consumption	Nantes Métropole 2010 (Mm^3)	Oslo 2007 (Mm^3)
Industry	3.29	10,9
Construction	0.03	0,2
Commerce & Services	1.79	10,9
Admin	3.74	18,9
TOTAL ECONOMY	**8.85**	**40.9**
HOUSEHOLDS	**21.55**	**54.2**

Table 0-6: Repartition of water demand in Nantes Métropole and Oslo (baseline years)

Appendix 4.2: Perspectives towards 2030

Any possible evolution of the volumes consumed by economy will be the results of the interaction of two drivers: the economic growth and the water efficiency of the sector.

- Water efficiency improvement can be analysed on the statistics from the Danish Statistical Bureau (Statistics Denmark, 2012):

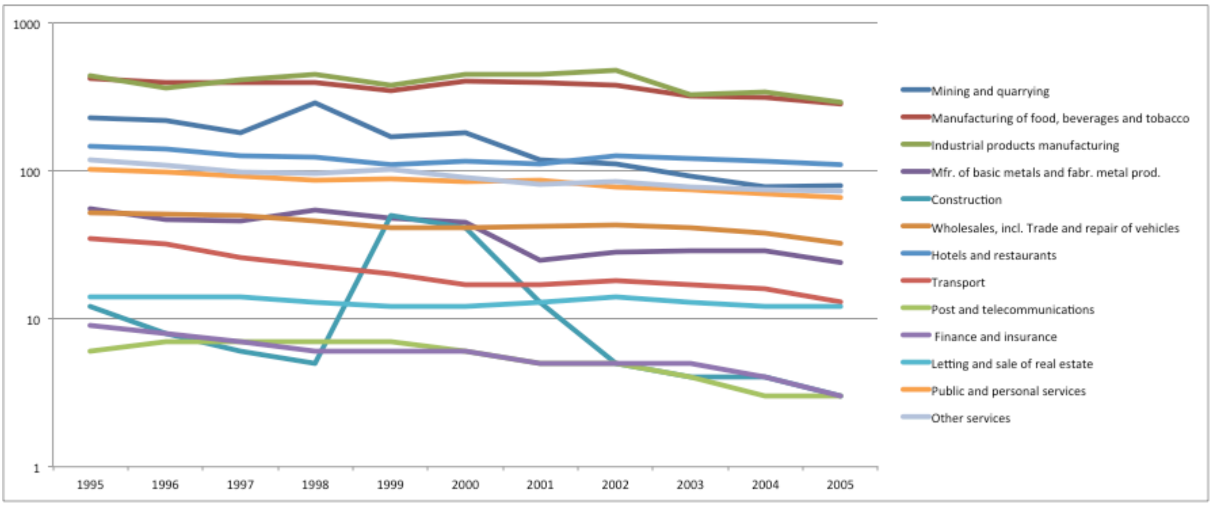


Figure 0-1: Evolution of water intensity of economy in Denmark, 1995-2005 (m3/DKK million-2010)

On this graph, which is displayed with a logarithmic scale, a clear tendency to water use decrease appears from 1995 to 2005. When aggregated to the wished sectors, we come to water efficiency improvements of 35% in Industry, 75% in Construction (despite a large variation around 2000), 45% in Commerce/Services, 35% in Administration over 10 years. We shall thus model further improvement on these trends between the baseline years and 2030 on this dynamics, considering that further improvements will be half of what they are now. For this, we can first notice that the curves on the figure above are almost linear when drawn on a logarithmic scale. Thus, a simple exponential model of the demand shall be made:

$$D = Do.e^{\frac{rt}{2}}$$
$$D(1995) = Do$$
$$D(2005) = Do.e^{10.r}$$

For each sector:

$$r = -\frac{1}{10}.\ln\left(\frac{D(1995)}{D(2005)}\right)$$

In addition, for the rest of the work, D_o shall be associated to the baseline years' demand for each sector, in order to keep close to the model.

As mentioned, another element needs to be accounted for to have a total estimation of the sectorial demand: the growth of each sector. Indeed, the results found for the baseline years are implicitly related to a certain economic situation, which can change.

Several trends are easily identified on the figure. Important growth until 1980-1985, then lower growth, and very low growth since 2008 (easily found on the top curve depicting the total). Thus, by doing the same type of analysis as for water demand and by considering that the different sectors shall remain on trends in between the two latest trends, we can identify the following approximate r coefficients for economy. The trend for Norway is chosen to be 1% higher than the trend for France, as Norway experiences higher economic growth than France, thanks to its natural resources.

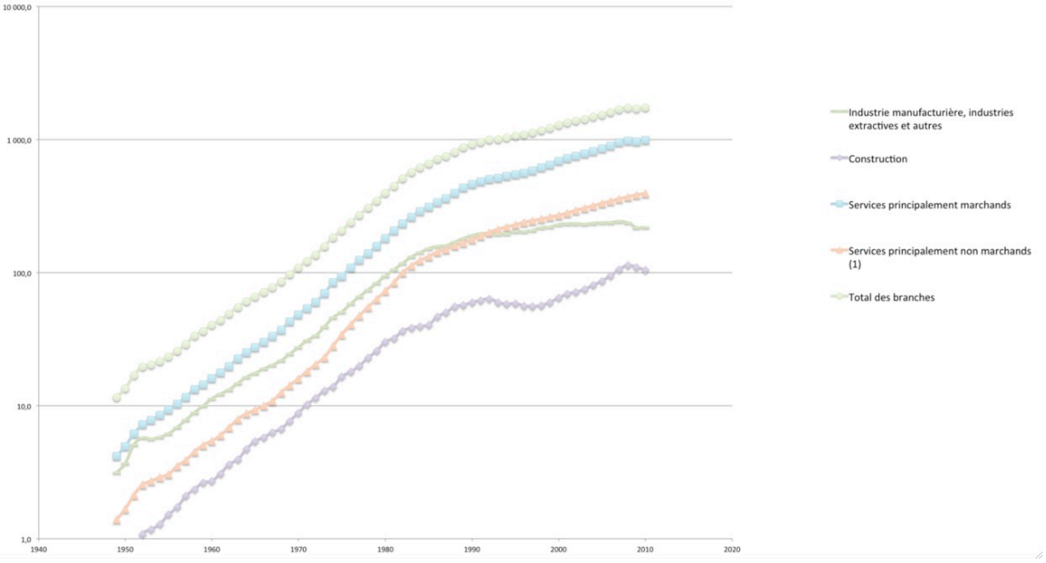


Figure 0-2: GDP evolution in France since 1945

The trend for household, which is not related to GDP but population, shall be taken to a decrease of 0.3m^3/year.cap in Nantes, and 1m^3/year.cap in Oslo. This choice has been made by using the estimations made in Montginoul et al. (2010).

$$D_{oslo-economy}(t) = D_{oslo2007-eco}.e^{(r+r_{no})t}$$
$$D_{nantes-economy}(t) = D_{nantes2010-eco}.e^{(r+r_{fr})t}$$
$$D_{oslo-hh}(t) = D_{oslo2007-hh}.\frac{pop_{oslo}(t)}{pop_{oslo}(2007)}.\frac{D/cap_{oslo}(t)}{D/cap_{oslo}(2007)}$$
$$D_{nantes-hh}(t) = D_{nantes2010-hh}.\frac{pop_{nantes}(t)}{pop_{nantes}(2010)}.\frac{D/cap_{nantes}(t)}{D/cap_{nantes}(2010)}$$

Consumption in Nantes (Mm^3/year)

	Industry	Construction	Commerce	Admin	Households	TOTAL
2007						
2008						
2009						
2010	3.29	0.03	1.79	3.74	21.55	30.40

2011	3.15	0.03	1.73	3.37	21.55	29.84
2012	3.02	0.03	1.67	3.04	21.56	29.32
2013	2.90	0.03	1.61	2.74	21.55	28.83
2014	2.78	0.03	1.56	2.47	21.55	28.38
2015	2.66	0.03	1.51	2.22	21.54	27.96
2016	2.55	0.03	1.46	2.00	21.53	27.57
2017	2.44	0.03	1.41	1.81	21.52	27.20
2018	2.34	0.03	1.36	1.63	21.50	26.86
2019	2.24	0.03	1.31	1.47	21.48	26.53
2020	2.15	0.03	1.27	1.32	21.46	26.23
2021	2.06	0.03	1.22	1.19	21.43	25.94
2022	1.98	0.03	1.18	1.07	21.40	25.66
2023	1.89	0.03	1.14	0.97	21.37	25.40
2024	1.81	0.03	1.10	0.87	21.33	25.16
2025	1.74	0.03	1.07	0.79	21.30	24.92
2026	1.67	0.03	1.03	0.71	21.26	24.69
2027	1.60	0.03	1.00	0.64	21.21	24.47
2028	1.53	0.03	0.96	0.58	21.17	24.26
2029	1.47	0.03	0.93	0.52	21.12	24.06
2030	1.41	0.03	0.90	0.47	21.06	23.86

Table 0-7: Final water consumption in NM until 2030, Mm^3/year

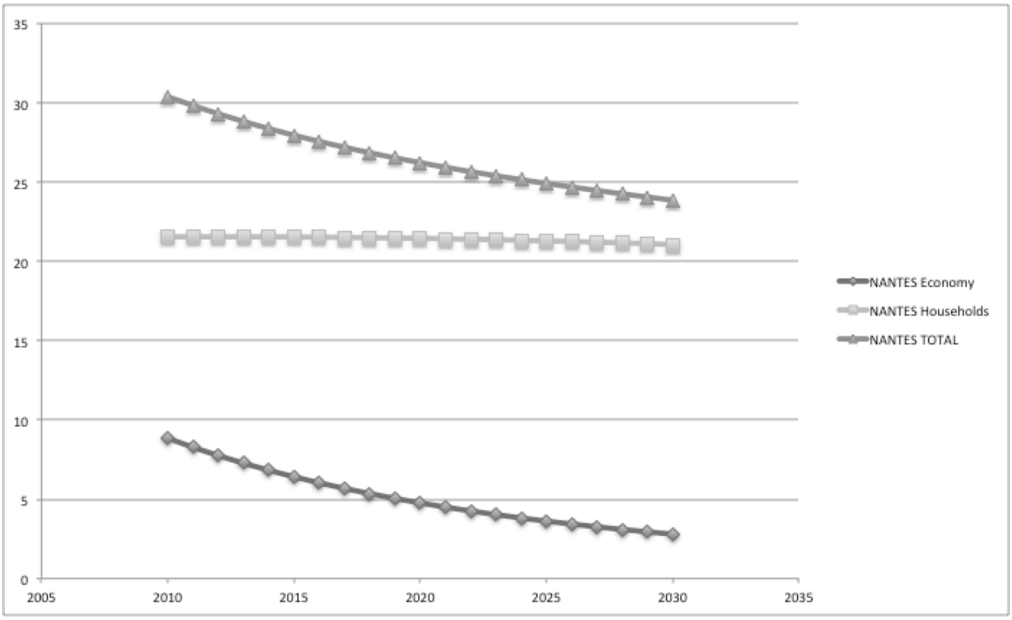


Table 0-8: Evolution of water consumption in NM, 2010-2030

Consumption in Oslo (Mm^3/year)

	Industry	Construction	Commerce	Admin	Households	TOTAL
2007	10.9	2	10.9	18.9	54.2	96.90
2008	10.55	2.02	10.64	17.20	54.58	94.99
2009	10.21	2.04	10.38	15.66	54.94	93.24
2010	9.89	2.06	10.13	14.26	55.28	91.62
2011	9.57	2.09	9.88	12.98	55.61	90.12
2012	9.27	2.11	9.64	11.81	55.91	88.74
2013	8.97	2.13	9.41	10.75	56.19	87.45
2014	8.68	2.15	9.18	9.79	56.46	86.26
2015	8.40	2.18	8.96	8.91	56.70	85.15
2016	8.14	2.20	8.74	8.11	56.92	84.11
2017	7.88	2.22	8.53	7.38	57.13	83.14

2018	7.62	2.24	8.32	6.72	57.31	82.23
2019	7.38	2.27	8.12	6.12	57.48	81.37
2020	7.14	2.29	7.93	5.57	57.62	80.55
2021	6.92	2.32	7.74	5.07	57.75	79.78
2022	6.69	2.34	7.55	4.61	57.85	79.05
2023	6.48	2.37	7.37	4.20	57.94	78.35
2024	6.27	2.39	7.19	3.82	58.01	77.68
2025	6.07	2.42	7.01	3.48	58.05	77.04
2026	5.88	2.44	6.84	3.17	58.08	76.41
2027	5.69	2.47	6.68	2.88	58.09	75.81
2028	5.51	2.49	6.52	2.63	58.08	75.22
2029	5.33	2.52	6.36	2.39	58.05	74.65
2030	5.16	2.55	6.20	2.18	58.00	74.08

Table 0-9: Final water consumption in Oslo until 2030, Mm^3/year

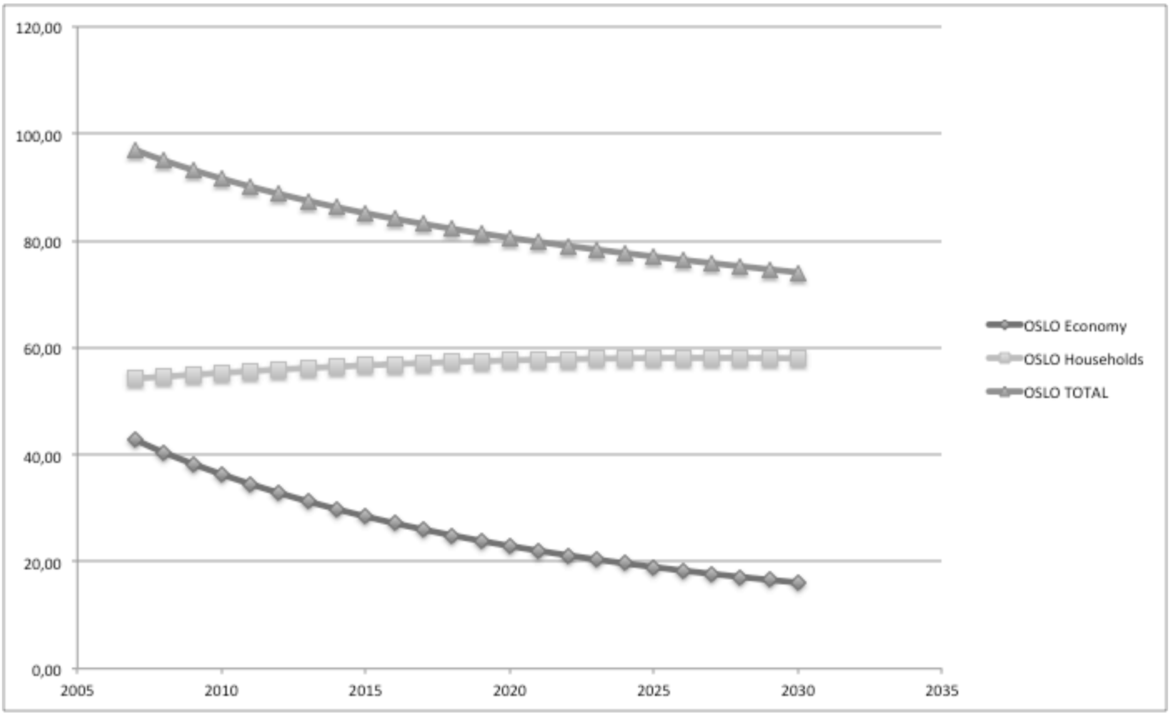


Table 0-10: Evolution of water consumption in Oslo, 2007-2030

Appendix 6: Baseline years models for energy and carbon

Here are given a few details in order to understand the calculations led in energy and carbon accounting for the baseline years in both cities.

- **Energy:**
  - Direct requirements: they have been directly collected from the sources mentioned in the thesis.
  - Indirect requirements: they are based on the energy requirements for chemical and material production, and the energy requirements for transportation. Grey values have been assumed on the basis of similar chemicals. Mass of pipelines material required was calculated based on the existing assets (lengths and diameters).
  - Avoided energy was estimated by calculating the total N and P_2O_5 equivalent generated by the sludge production, and calculating the total energy necessary to produce the mass of fertilisers with an equivalent fertilising power.

Indirect (reqt)	Chemical production (kWh/kg)		
	FF	el.	heat
FeCl3		1,22E+00	
Al2(SO4)3	2,50E-01	5,97E-01	
Polyacrylamide		1,03E+00	1,78E+00
NaOCl		1,13E+00	3,83E-01
NaOH		2,14E-01	6,19E-02
NaCl	6,19E-02	2,14E-01	
CaO	1,23E+00	6,36E-02	
Polymer		1,03E+00	1,78E+00
H2SO4	6,56E-02	5,50E-02	1,91E-01
AC (pow)		1,60E+00	3,67E+00
AC (gr)		1,60E+00	3,67E+00
AC (gr, renew)		1,60E-02	3,33E-01
CO2 l	1,41E-01	4,64E-01	8,06E-01
Ca(OH)2	8,61E-01	4,44E-02	
Polymer		1,03E+00	1,78E+00
HNO3		1,04E-01	1,66E+00
FeSO4		2,64E-01	
CH3OH		1,18E-01	2,14E+00
PAX		1,03E+00	1,78E+00
Cl2		1,82E+00	

Indirect (reqt)	Transportation (kWh/km)		
	FF	El	Heat
Truck	3,14E-04		
Ship	1,25E-05		

Indirect	Embedded energy (kWh/kg)		
	FF	el	heat
PEHD		23,61	
PVC		23,61	
Ductile Iron		10,61	
Concrete		0,56	
epoxy		23,61	

Ammonium Nitrate Manufacturing kWh/kgN	
FF	
el	0,45
heat	7,75

DAP Manufacturing kWh/kgP2O5	
FF	
el	0,59
heat	1,42

- **Carbon:**
  - Non-biogenic emissions have been directly collected from the utilities.
  - All emissions from direct energy consumption (direct and indirect) were calculated by using the life-cycle carbon estimation of the Ecoinvent database with the ReCiPe Midpoint (H) 1.06 Method. All heat has been considered generated by natural gas.
  - Emissions for material production has been collected from Venkatesh (2011).
  - Emissions for chemical production have been calculated from Ecoivent and the ReCiPe Method as well.

Direct Emissions	kgCO2e/kWh
Diesel, direct	0,360

kgCO2/kg active chemical (N or P2O5)	
NH3NOH	8,85
DAP	1,57

Indirect Emissions	kgCO2e/kWh
Diesel, indirect	0,072
Electricity, indirect (FR)	0,020
Electricity, indirect (NO)	0,047
Heat, indirect	0,256

Chemicals Manufacturing	kgCO2e/kg
FeCl3	2,00
Al2(SO4)3	0,49
Polyacrylamide	2,00
NaOCl	0,89
NaOH	1,10
NaCl	0,18
CaO	2,00
Polymer	0,47
H2SO4	0,12
AC (pow)	11,00
AC (gr)	11,00
AC (gr, renew)	1,17
CO2 l	0,82
CaOH2	0,76
HNO3	3,17
FeSO4	0,17
CH3OH	0,74
PAX	0,12
Cl2	1,06

Material Production	kgCO2e/kg
PEHD	1,93
PVC	2,01
Ductile Iron	1,48
Concrete	0,22
Epoxy	6,72
Transportation	**kgCO2e/tkm**
Truck	0,19
Ship	0,01

Appendix 7: Scenario modelling

Business as usual:

- Increase on chemical use in WTP, according to Venkatesh (2011) for Oslo
- Suppression of oil for electricity or heat for both cities.

Water Quality and safety:

Nantes:

- Renewing of Nantes' WTP. 35% of plant process improvement for energy, based on personal communication with Nantes Métropole (2012).
- Micro turbines: 5% of the water flow managed, 30 bars of head recovered, 60% efficiency. Based on McNabola, et al(2011) and Nantes Métropole (2012)
- Leakage and pressure management: 5% improvement on the water losses. Based on Nantes Métropole (2012)
- Solar drying: 60% decrease of the quicklime use. Additional energy use for ventilation has been assumed to be equivalent to the energy decrease for sludge process. Based on Nantes Métropole (2012)
- Total sales of biogas. Estimated from Nantes Métropole (2011)
- Includes Business as Usual.

Oslo:

- Micro-turbines, recovering 0.9GWh under the current conditions. Based on Venkatesh (2012).
- Losses improvement, equivalent to Nantes Métropole.
- Solar drying, equivalent to Nantes Métropole.
- Total sales of biogas. Figures estimated from Venkatesh (2011), VEAS (2010) and BEVAS (2010).
- Heat recovery from wastewater in winter. Assumption of 13°C for the incoming wastewater, 0° for the outside air, 4 months of efficiency, heat pump with COP of 4. Based on Funamizu, Iida, Sakakura, & Takakuwa (2001).
- Includes business as usual.

Energy Efficiency

Nantes:

- Water supply and treatment decentralisation: 75% of water supplied. Neighbourhood scale pumps of 0.06 kWh/m3 demand based on Nantes Métropole (2012). UV Treatment of 0.04 kWh/m3 demand (ibid.). Chemical use: Aluminium Sulphate, polyacrylamide and NaOCl used in the same quantities per unit demand as in La Roche WTP. No other chemical.
- "Normal" treatment: 25% of water supplied
- Include the Water Quality and Safety scenario

Oslo:

- Equivalent to Nantes, except: chemical use of aluminium sulphate, polymer and NaOCl in the same quantities as in the BAU scenario.

Scenarios combination

All requirements have been calculated on a per cubic metre demand of the baseline year basis, then extrapolated: energy and GHG emissions have been multiplied by the demand forecast of each year. Avoided emissions have been related to the population of each year.

All scenarios have been interpolated so that their value in baseline year is the value of BAU, and their value in 2030 is their final value.