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Building a Water-Energy Nexus Modelling tool for New York City

Development of a NYC WaterMARKAL model

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Abstract

Building a Water-Energy Nexus Modelling Tool for New York City

Rebecka Segerström

Increasing demands for energy and water from a growing urban population challenges resource availability and infrastructure capacity in cities worldwide. Planning for infrastructure systems development to meet growing demands has traditionally been done separately, not regarding that these systems are in many aspects interlinked. New York City has well developed systems for supplying these basic needs, but they are among the oldest in the country and may not suffice the needs of a growing population. Meanwhile, ambitious city-planning documents recognize opportunities for holistic planning focused on resource efficiency and long-term sustainability. This thesis aims to develop a foundation for quantitative modelling of how water and energy consumption may be affected by political decisions in New York City. The MARKAL (MARKet ALlocation) framework, commonly used to model long-term energy systems developments, is expanded to include the NYC's water system. Relevant water system technologies are quantified with economic parameters, energy input and greenhouse gas emissions to give an as realistic as possible description of the entire water system. When combined with the existing MARKAL-model over NYC's energy system, the test runs of the model clearly shows impacts on energy consumption from water system regulations. These preliminary results are not applicable to support urban policy-making at this stage. However, with further development of the model as well as improvements in data quality it is perceived that this integrated water-energy model has the potential to become a powerful decision support tool for joint planning of water and energy systems developments in New York City.

This Master thesis has been conducted in collaboration with the Energy Policy and Technology Analysis Group of the Sustainable Energy Technologies Department at Brookhaven National Laboratory, U.S.A.

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Populärvetenskaplig Sammanfattning (Summary in Swedish)

I takt med att befolkningen växer i världens städer så ökar även behoven av våra mest grundläggande resurser för överlevnad. Fungerande vatten- och energisystemen är en grundförutsättning för stadens tillväxt och befolkningens välmående. Att dessa system på många sätt är beroende av varandra har lett till att många städer strävar efter samplanering och ett holistiskt perspektiv i sin stadsplanering. New York City har sedan 2007 arbetat efter ett plandokument – PlaNYC2030 – som binder samman initiativ för hur land, vatten, luft, klimatförändringar och energi ska hanteras och utvecklas i staden. I och med att delar av stadens infrastruktur för vatten och energiproduktion är över ett sekel gamla finns det både stora behov och uppenbara resurseffektiviseringsvinster i att uppgradera och bygga ut dessa system.

Efter oljekrisen på 1970-talet började forskare vid Brookhaven National Laboratory, USA (i ett samarbete mellan the United States Departement of Energy och the International Energy Association) att utveckla en matematisk modell för att modellera hur energisystem kan komma att utvecklas över tiden beroende på råvaru- och bränslepris, teknikutveckling och politiska beslut. Dessa modeller, vilka går under förkortningen MARKAL-modeller, har sedan dess utvecklats och används idag i över 100 länder för att modellera den långsiktiga utvecklingen av energisystem på regional, nationell och multinationell nivå.

I detta examensarbete har en befintlig MARKAL-modell över New York Citys energisystem byggts ut för att även kunna modellera vattenflöden genom staden, från dricksvatten- reservoarerna norr om staden, via distributionskanaler och konsumtion i hushåll, kommersiell sektor och energiproduktion, till stadens 14 avloppsreningsverk och vidare ut i Hudsonfloden och East River. Syftet med arbetet har varit att bygga ett modelleringsverktyg med kapacitet att modellera hur både energi- och vattensystemen påverkas av politiska initiativ i staden – i synnerhet sådana som främst är tänkta att påverka enbart det ena systemet.

Genom en detaljerad studie av New York Citys vatteninfrastruktur identifierades och kvantifierades 82 specifika ”vattensystems-teknologier”, som antingen finns i det befintliga systemet, eller spås komma in i systemet de närmsta decennierna. Denna kvantifiering bestod i att knyta kapacitet, effektivitet, energibehov och investeringskostnad till varje teknologi – från snålspolande toaletter till den dricksvattenreningsanläggningen som har kapacitet att rena 90% av New York Citys dagliga behov av dricksvatten. En majoritet av det dricksvatten som levereras till New York City varje dag går till hushållen, medan energiproduktionen står för den största konsumtionen av råvatten (det vill säga vatten som används direkt från vattendrag och inte är direkt drickbart). Dessa förhållanden ledde till att hushållens och energisektorns behov av vatten modellerades mer detaljerat än övriga sektorer.

Trots att MARKAL-modellering kräver en stor mängd kvantitativ data har fokus för denna uppsats legat på de kvalitativa resultat som modellutvecklingen genererat. Systematiska skillnader mellan ett vatten- och energisystem – som att det som i energisystem modelleras som slutkonsumtion i fallet med vatten konsumeras i ”mitten” av systemet, för att sedan behandlas av ett avloppssystem i flera steg – kräver exempelvis att vissa parametrar i MARKAL-modellen används på nya sätt. När en första testmodellering genomfördes visade det sig att modellen valde att aggressivt investera i de mest vattensnåla teknologier som fanns i modellen. Detta kunde också förutses av manuella beräkningar av hur mycket driften av vattensystemet sammantaget kostar per droppe (eller det amerikanska volymmåttet ”gallon” som använts genomgående i uppsatsen).

För att testa den utbyggda modellens förmåga att modellera beroenden mellan New York Citys vatten och energisystem modellerades därefter ett alternativt scenario, där snålspolande toaletter inte tilläts komma in på marknaden i samma takt som i den första modelleringen. Resultaten visade att utöver en direkt förändring i vattenkonsumtion så påverkades både energikonsumtionen och koldioxidutsläppen i New York City – vilket tyder på att modellen har den kapacitet att modellera kopplingar mellan vatten- och energisystemen som var syftet med modellutvecklingen.

Innan den i detta arbete utvecklade vatten-energi-modellen kan visa pålitliga resultat för hur New York Citys energi- och vattensystem kan komma att utvecklas över tid krävs både justeringar av datakvalité och en ytterligare utbyggnad av modellen. Dock visar examensarbetet att MARKAL-verktyget kan vara ett användbart hjälpmedel för att synliggöra kopplingar mellan energi och vatten resurs användning, någonting kan komma att bli allt mer nödvändiga att ta hänsyn till i stora städer där begränsade vatten och energiresurser måste räcka till en allt större befolkning och deras behov.

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A final thanks to my mother for her endless loving support and to Tobias for always pushing me to the top and never letting me fall.

Content

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Glossary – Terms and Abbreviations

AAS	– Aerated Activated Sludge (wastewater treatment process)
BAU	– Business as Usual
BNL	– Brookhaven National Laboratory
Cat/Del	– Catskill/Delaware (the watersheds that jointly provide 90 % of NYC water)
CSO	– Combined Sewer Overflow
DEP	– New York City Department of Environmental Protection
DOE	– (U.S.) Department of Energy
EIA	– Energy Information Agency
EnergyStar	– EPA and DOE joint program, marking energy (and water) efficient products
EPA	– U.S. Energy Protection Agency
EPRI	– Electric Power Research Institute
IEA	– International Energy Agency
MARKAL	– Market Allocation Model
MG	– Million Gallons
MGD	– Million Gallons per Day
NYC	– New York City
NYCDCP	– NYC Department of City Planning
NYISO	– New York Independent System Operator
NYSERDA	– New York State Energy Research and Development Authority
O&M	– Operation & Maintenance
RES	– Reference Energy System (in MARKAL)
RWS	– Reference Water System (in MARKAL)
USGS	– United States Geological Survey
WPCP	– Water Pollution Control Plant (term primarily used for the NYC plants)
WWTP	– Wastewater Treatment Plant (occasionally used instead of WPCP)

1. Introduction

In traditional infrastructure development, water planning has been carried out under the assumption that energy will always be available for water projects. Simultaneously, energy planning has historically assumed that water will always be available for energy projects. Realizing that both energy and freshwater availability is limited – and to a great extent by how much of one is available to the production of the other – demands a new approach to planning of how these resources are utilized and how the systems we build to access them are developed. Adding urgency to the issue, it is estimated that climate change will increase stresses on both the energy and water systems in the future, further adding to the need for joint resource management and planning.[1]

In the urban environment it is not only resource availability that challenge water and energy deliveries. Infrastructure constraints are looming in most of the big cities in the developed world as many systems are ageing beyond their designed lifetime and projected population growth cause demand to hit system capacity limits. For these reasons, urban sustainability is no longer an issue pushed by environmentalists alone, but is increasingly seen as the economically sensible approach to long-term urban challenges. In New York City (also referred to as NYC throughout this report), political initiatives to accommodate population growth and economic development are focusing explicitly on long-term sustainability. The interlinked nature of urban resource flows is also acknowledge in city planning. As the NYC's Department of Environmental Protection (DEP) Commissioner Cas Holloway puts it:

> *...without clean, plentiful water, dense cities with great transportation networks and low carbon footprints can't exist.*[2]

A defining step on the path towards such urban sustainability was taken on Earth Day, 2007, when the Mayor of NYC announced the "PlaNYC 2030" (hereafter PlaNYC), a comprehensive development plan aiming to make NYC a more environmentally, socially and economically sustainable city by the year 2030.[3] The plan takes up all major aspects of the physical condition of the city, ranging from Land Use to Climate Change Adaptation, with Water, Transportation, Energy and Air Quality in between. Although each of these sectors are presented in a chapter of its own, linkages between them are actively sought throughout the plan and goals in one sector is formulated taking potential consequences in other sectors into account. This holistic approach to urban planning has been emphasized by the institutions behind the PlaNYC as something that sets it apart from previous plans, since traditionally the agencies have planned the development in silos.[4]

The potential benefits of co-planning water and energy resources, especially in urban areas, has been recognized also in the scientific community. In 2008, researcher at Brookhaven National Laboratory published a pilot study for a decision-support tool for long-term planning of water and energy in New York City. It was concluded that the MARKAL (MARKet ALlocation) model – commonly used to model long-term scenarios for regional or national energy systems (see more on MARKAL in chapter 3) – could be an appropriate tool for such integrated decision-making. A pilot version of a NYC WaterMARKAL model was developed around a couple of specific water/energy

[1] New York Regional Energy-Water Workshop (2004)
[2] Speech: Holloway, C (2011)
[3] NYC DEP website [1]
[4] *PlaNYC 2030* (2007), p. 11

scenarios and showed promising results. Water was in this model depicted as a material flow in the energy system. Among the recommendations for future research was a suggestion to develop a model with a more detailed water system description.[5]

In 2010, a full-scale NYC-MARKAL-model that modelled the electricity flows in NYC was updated and used at BNL to model how peak electricity demand in the city could be mitigated.[6] To comprehensively investigate how water and energy (electricity) is interacting in NYC using MARKAL, a new WaterMARKAL-model, that adds the full water system to the model, needs to be created. One way of doing so would be to model the water system in itself, changing the focus and giving water technologies energy inputs instead of only providing water inputs to the energy system.

1.1 Thesis Objectives

The objective of this master thesis is to explore the possibility to model the NYC water system with the existing MARKAL modelling tool. This is based on combining three types of information:

- publicly available information about the New York City water system – its present condition as well as present and future demands on the system,
- a systematic description of present and emerging technologies for supplying, treating and using water (and wastewater), specifically in the urban environment,
- knowledge on how the MARKAL-model works, what type and format of data the model needs and what kind of results it can generate.

By combining these types of information, the applicability of a new *WaterMARKAL-model* as a tool for modelling long-term development of NYC water and wastewater system is analysed.

A "no constraints" scenario, where the model is given free hands to find the most efficient solution to providing the city with it's water needs is compared with a scenario where a water related technology constraints is added. The impact on city-wide water use, energy consumption and carbon emissions is then analysed then analyzed to determine if the model really captures the interconnection between water and energy in the city.

The extended *WaterMARKAL model* is developed with the aim to be able to investigate several more policy-scenarios than the one tested. To limit the scope of this thesis, the scenario used was chosen primarily to test the NYC-WaterMARKAL and provide some indication of the applicability of the model. More comprehensive analysis of this and other policy-scenarios are left to future research.

1.2 Delimitations of the study

Although this thesis aims to build a model that can study Water-Energy linkages in NYC, the focus lies heavily on describing and modelling only the water system. This is due to the fact that the modelling tool used in this thesis, MARKAL, was create for energy systems analysis and an existing NYC's energy system model could be used in this work. The data used in the 2008 pilot version of NYC WaterMARKAL was no longer available, but some of the qualitative aspects of this model helped to build the foundation of this work.

Much published literature on both water supply and wastewater systems focus on chemical, biological and environmental aspects of these resources and systems. Although the chemical composition of both the water resources and the discharged water are well documented (and largely

[5] Bhatt, V. et. al (2008)
[6] Bhatt, V. et. al (2010)

affect the cost and the energy needs of the systems that treat these waters) this is left outside the scope of this study. This study hence include only technical, financial and energy-related aspects of the urban water system and the included present and planned treatment technologies comes with embedded water quality assurance.

The thesis aims to demonstrate the methodology of modelling long-term water and energy systems development and the potential such a model can have in supporting urban policy development. The data used in this study has been carefully selected but indirect sources provide in many cases the only available data. Improvements in input data quality is expected to improve the quality of the outputs of the model. However, the aim of this thesis is foremost to develop and showcase the model and not to provide a perfect depiction of the water system today and in the coming decades.

The area of investigation of this work is the City of New York.[*]

1.3 Work Process and Disposition

To gain sufficient knowledge on the water-energy nexus research field, and on New York city as a case study area for modelling long-term policy scenarios, a background study initiated this thesis work. Following this work was an iterative data collection process where all necessary information for the quantitative scenario building was gathered. This was limited on the one side by data availability and on the other by the input data variables that the MARKAL modelling demands. The third phase of this work consisted of formatting and inserting the data into the MARKAL framework – creating a specially designed NYC WaterMARKAL, modelling the test scenario and analysing the results. Learning how MARKAL works and how it can be adjusted and applied in this thesis has been an ongoing process in parallel with all the other phases.

A large part of the contribution of this work is its efforts in methodology development, where the MARKAL methodology has been analysed and expanded to incorporate the special characteristics of a water system – and the NYC water system in particular. For this reason, this report does not contain a separate methodology chapter where each step in this process is described. Instead, a more detailed description of the work process of each phase is given in the introduction to each chapter. Further, the methodological development of the MARKAL-model is thoroughly presented in Chapter 3 and 4.

Chapter 2 contains a review of scientific literature on the water-energy nexus in general, that is followed by a presentation of NYC and its water and energy infrastructure.

In Chapter 3 the conceptual framework of MARKAL-modelling and MARKAL methodology is presented.

Chapter 4 presents the model adjustments made, the practical data collection process along with limitations encountered and system boundaries redefined, to create the new Water-MARKAL model

In chapter 5, some pre-modelling results based on the collected data is followed by attained results from running the ”no constraints” scenario as well as the adjusted scenario in the developed NYC WaterMARKAL.

Chapter 6 contains a concluding discussion of the applicability of the extended MARKAL model as a support tool for integrated energy and water planning. The potential of developing the model further and some suggestions on future research is concluding the chapter and the report.

[*] The geographical area of the five boroughs: Bronx, Brooklyn, Manhattan, Queens and Staten Island (and their respective Counties: The Bronx County, Kings County, New York County, Queens County and Richmond County).

1.4 Relevant definitions

Water system – refers to the technical systems built to treat and transport water. If not otherwise specified, this includes the water supply system and the wastewater system.

The NYC Water System – refers to the whole water system that delivers municipal water to NYC, including the reservoirs and treatment facilities outside the city. Consumers of this water outside the city have been eliminated. The NYC water system also includes direct self-supply of water in industries and the thermo-electric power sector.

Energy system – refers to the whole chain of technologies and infrastructure from extracting the raw energy source, through transforming it to electricity or fuel or heat and distributing it through electricity grids or other distribution systems to the end users where the energy comes to use in everything from domestic lighting to wastewater pumping.

The NYC Energy System – refers to the part of the energy system that is geographically located within the NYC boarders. This system has embedded characteristics from the greater energy system that it is linked to outside the city, but when it comes to e.g. water consumption in the NYC energy system only the in-city part of the energy system will be intended.

2. Water and Energy consumption – in general and in New York City

This chapter aims to present a background on both the water-energy nexus as a growing research filed and on NYC as the case-study area of this thesis.

Available literature related to the whole or a part of the water-energy nexus. Numerous reports of calculated water footprints of different energy production technologies can be found and more are constantly being added. The water-energy nexus section of this literature review presents the general concepts together with descriptions of selected water-energy issues found to be relevant in the NYC setting. As far as possible, the sources to this literature review has been sought in the U.S. When gaining a broader picture of how New York City is supplied with its needs for energy and water, a couple of resources contributed significantly, including the PlaNYC, DEP's website and *the Works* by Kate Asher.[7] More detailed information were largely found in more specific sources, such as reports on city sub-systems published by that sub systems' operating authority or Environmental Impact Assessment Reports for major system upgrades.

The chapter is divided into two sections: The Water Energy Nexus – includes Water in the energy sector and Energy in the water sector. Following this is a presentation of New York City’s water and energy systems, where the present system is described together with development plans and opportunities.

In literature on NYC, the nexus perspective is not predominant and descriptions of water system sections commonly do not focus on energy inputs in particular (and vice versa). Water-energy nexus issues in NYC are therefore identified by combining information from the first and second part of this chapter.

2.1 The Water-Energy Nexus

Recognition of the finite nature of our fossil energy sources and their contribution to an unwanted global warming through its emission of greenhouse gases, along with the often high financial and physical thresholds to exchange them with renewable sources, has made energy planning an important priority to governments, cities and industries. Simultaneously, the pace in which we are depleting our freshwater resources is increasing. As groundwater tables around the world are dropping the need for sound and integrated water management is becoming increasingly clear.[8]

Realizing that these resources, and the systems we have developed to make them available to us, are also interlinked has in the last decade created a new field of research that focuses on the nexus where water and energy meets. Measures to convert our energy systems to lower their green-house gas emissions have often been paid with increased water consumption. Bio energy is a one of the most studied examples as it has been proven to have an alarmingly high ”water footprint” due to the amounts of water needed for fuel crop irrigation. [9] Likewise, the further we have to look for clean water, in terms of both distance and quality level, the higher runs the energy needs to make it clean and accessible to us. Desalination plants are giving us the opportunity to tap the enormous potential of converting seawater to a drinkable source, but the energy prize even in the most advanced plants is still high.[10] Recognizing these interconnections is at the core of the water-energy nexus.

[7] Ascher, K (2005)
[8] UN-water (2006), p. 4
[9] Gerbens-Leenes, P.W. et. al. (2008)
[10] Presentation: Koschikowski, J. (2011)

2.1.1 Why the "Nexus" perspective

It is not only water and energy that has been described in the terms of interdependence. Research on the food/energy nexus, where bio-energy has a central role, and the water/food/trade nexus are two other examples. Common for "nexus"-oriented research is the realization that challenges in one field can not be solved in isolation. Especially when it comes to necessities such as water, food and energy, a joint perspectives can be argued to be the only way to ensure resource security in the long run.

According to Allan (AAAS 2011) security in its traditional sense has since the end of the cold war slowly been redefined. From being a matter of protecting the national sovereignty it has shifted towards securing our possibility to survive on the planet. Access to water, land, food and sustainable energy supply are examples of these new types of security considerations. Others are ensuring our life support system in means of ensuring stability in our climate and health in our eco-systems. On top of the challenges each of these security types present, they are in many ways conflicting and competing.[11]

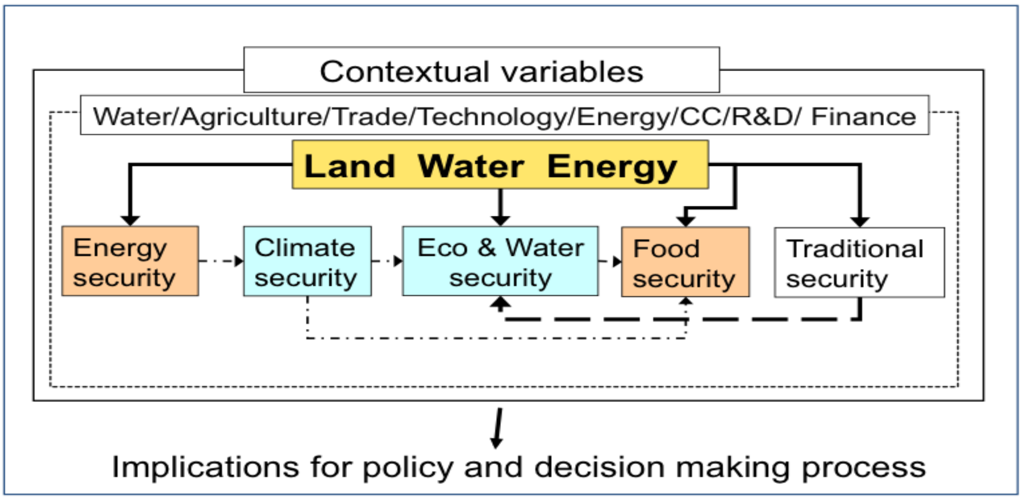

Figure 1: An example of "Nexus-thinking": A schematic view of the *Land-Water-Energy-Food-Climate Change Nexus*. Source: Allan, T. (2011)

From this perspective, ensuring sustainability to our civilization demand that we have a nexus perspective that include, but are by no means limited to, the water-energy nexus.

Central to "nexus" research is the aim to increase foresight in decision-making processes, in business as well as the public sector. Awareness of the implications in the water sector from a decision on an energy project (and vice versa) is essential in the creation of ambitious and sustainable policy-making.[12]

2.1.2 Embedded energy in Water

When looking at our blue planet from space, it is clear that we will never run out of water in an absolute sense. It is therefore important to define that when discussing water scarcity, it always refers to *freshwater* scarcity and, although often only implicitly, the lack of *easily accessible* freshwater. We can transform saltwater to drinkable water through desalination technologies, pump water from deep groundwater reservoirs or from long distances on land to get the water we need when the local freshwater sources are depleted. In a sense, water availability is a function of energy and cost. This specification poses other challenges than absolute water scarcity and in a report from 2004 the Electric Power Research Institute (EPRI) posed the question "Will there be sufficient electricity available to satisfy the country's need for fresh water?". Their results showed that

[11] Presentation: Allan, T. (2011)

[12] See for example: National Conference of State legislature website [1]

electricity availability is not likely to constrain water systems on a national level. However, posing the question shows that this is a real concern and although the nation is not expected to be severely constrained, certain locations may be.[13]

Energy embedded in water can be defined in two categories. The first is energy directly consumed during treatment and transportation of water to its end users and during the collection and treatment of wastewater before discharge to the environment (when no recirculation is employed). The second is the energy embedded in the infrastructure. This includes the energy needed to manufacture pipes, water treatment plants and chemicals added to the water during treatment. Both these energy consumptions are included in life cycle assessments of the water system, where all energy consumed during the whole life time of the system is included.[14] In this thesis, it is primarily the direct energy needs that are taken into account.

The electricity needed to provide clean drinking water and collect and treat wastewater represents around 4 % of the total electricity demand in the United States but constitutes around 80% of the total municipal cost related to treating and transporting water.[15] These figures only include the embedded energy in the water and does not take into account the energy use that is related to water use activities, such as water heating and washing. The latter has been estimated to be as high as 8% of the total energy use in the country's building sector – which in turn stands for 40 % of the national total.[16]

According to EPRI, the following parameters are most significantly impacting the amount of (electric) energy needed in a water system:

- the age of the water delivery infrastructure: with system age, friction in piping fixtures increase, efficiency of pumping decrease and the energy need rises

- water consumption restrictions (voluntary or mandatory) that may apply to end users: can cause energy demand in the system as a whole to go down, but could also increase the energy need per unit of water

- water quality standards, both for drinking water and for treated wastewater discharge to the environment – and the associated increased treatment required to reach that water quality

- the water quality of the raw water source: as source quality decrease, more treatment (and energy) is needed

- treatment technology largely affect the energy needs of treatment, as does the size of the treatment facilities from an *economy of scale* logic.[17]

2.1.2.1 Energy consumption in water supply systems

Most of the US water supply comes from surface water and around 70% of the water withdrawn is freshwater.[18] Table 1 lists estimated general (electric) energy need for collection and treatment of water up to drinking water standard based on the water source.

Surface water generally needs more treatment than groundwater, but the collection of groundwater requires pumping, causing groundwater to most often be a more energy demanding water source over all. Where freshwater, neither from the ground or surface, is not available to meet water demands, communities and cities are in increasing numbers developing desalination facilities to tap into the abundant resource of seawater. This is however a very energy intensive process. Although the theoretical minimum amount of energy needed to obtain one m^3 of freshwater from seawater is

[13] EPRI (2002) p. 1-1
[14] See for example: Fok, S. et. al (2002)
[15] EPRI (2002) p. 1-2
[16] Novotny, V. (2011), p. 186
[17] EPRI (2002) p. 1-2/1-3
[18] USGS (2009), p. 38

about 0,7 kWh, in reality the most efficient plants using reverse osmosis technology today use around 2,5 kWh (corresponds to the 9700 kWh/MG shown in table 1).[19]

Table 1: Embedded Energy in Water Supply, based on water source

Water Collection and Treatment	kWh/MG*	kWh/m^3
Surface Water Treatment	220	0,06
Groundwater Treatment	620	0,164
Brackish Water Treatment	3900 – 9700	1,030 – 2,563
Seawater Desalination	9700 - 16500	2,563 – 4,359

* MG = Million Gallons.

Source: Stillman et. al, *Energy Water Nexus in Texas*, 2009 (p. 22) and own calculations.

2.1.2.1.1 Energy for Water Distribution

On a U.S. national average, 80 % of the electricity that goes into the water system is used for moving water but this varies greatly depending on the topography of the distribution area and its distance to the water source. Whenever it is possible to use gravity to convey the water this reduces the need of pumping and thereby the energy demand. Many water supply systems work with high water pressure to reduce the risk of contaminants entering the water from cracks in the distribution pipes or to eliminate energy consumption (from pumping) when transporting water between two high-lying areas separated by a valley. Pressurized water tunnels however require more robust piping structures than non-pressurized.[20]

2.1.2.2 Energy consumption in Wastewater Treatment

The amount of energy consumed in wastewater treatment depends primarily on the level of treatment required and what quality the treated water needs to reach. In the U.S. a majority of the wastewater treatment facilities can be divided into four groups of treatment systems: trickling filter treatment, activated sludge treatment, advanced wastewater treatment and advanced wastewater treatment with nitrification. Activated Sludge Treatment (often called Aerated Activated Sludge, hereafter AAS) and Advanced Treatment with Nitrification are being deployed in New York City and will therefore be briefly described.

2.1.2.2.1 AAS – Aerated Activated Sludge Treatment

In AAS treatment, oxygen is added to the wastewater through fine bubble aeration, allowing for the growth of aerobic micro organisms. These digest most of the organic material remaining in the wastewater after the first treatment steps with bar screens and primary settling has removed larger particles. Both before and after the aerated tanks, sludge is removed in settling tanks. Some of this sludge is recirculated back to the aerated tanks to feed the micro organisms. The rest is pumped to a sludge treatment process where it is anaerobically digested to remove organic material. In this step large quantities of biogas is produced that can be used for on-site electricity and heat production. The remaining sludge then goes to a dewatering step where the sludge becomes biosolids and remaining water is recycled back to the headwork of the plant.[21]

Below is a schematic description of an AAS treatment facility.

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[19] Shiffer, M. (2004), p. 5 and Stillwell, A.S. et. al. (2009), p. 22

[20] Boot, J.C. and Gumbel, J.E. (2007)

[21] Description drawn from: New York City Department of Environmental Protection (2007) and EPRI (2002)

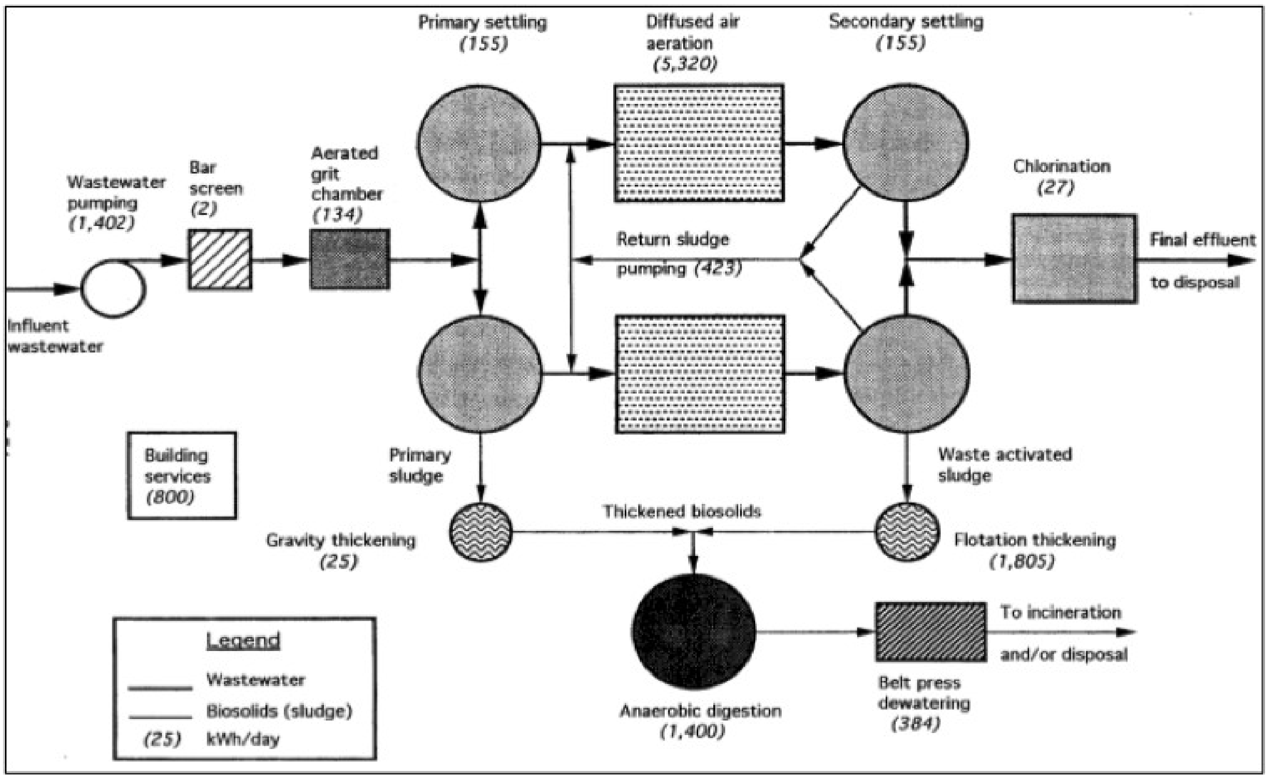

Figure 2: Representation of an ASS Wastewater Treatment Process Sequence, for a plant with typical 10 MGD treatment capacity (with Energy Consumption in perentheses) Source: EPRI (2002)

2.1.2.2.2 Advanced Treatment with Nitrification

More advanced treatment include additional steps after the AAS-treatment. With a chemical treatment step, remaining substances, and phosphorus in particular, can be removed. Biological nitrification enhances the nitrogen removal when bacteria specific for nitrification are artificially added to the AAS-treatment step. Coupling aerated tanks with anoxic tanks can further enhance nitrogen removal as bacteria that thrive in oxygen free zones help break up the nitrogen molecules. This naturally takes up more space than the traditional AAS-treatment.[22]

The majority of the energy consumption in AAS, both with and without nitrogen removal, occurs in the aeration tanks. Pumping wastewater, from a lower level sewage intake (which is a common solution since it lets sewage flow to the wastewater treatment plant by gravity) and between treatment steps, together with mixing (e.g. to dissolve chemicals) are two other major energy consuming activities.[23] Table 2 gives estimated aggregated energy needs for wastewater treatment plants (WWTP) with flows from 10 MGD and above.

Table 2: Unit (electric) Energy Consumption for publicly owned water treatment works

WWTP average water flow:	10 MGD (kWh/MG)	20 MGD (kWh/MG)	50 MGD (kWh/MG)	100 MGD (kWh/MG)
Activated sludge	1203	1114	1051	1028
Advanced treatment with nitrification	1791	1676	1588	1558

* MG = Million Gallons

Source: EPRI Technical Report, *Water & Sustainability (Volume 4)*, 2002, p. 3-5. Edited by Author.

[22] Kjellén, B.J. and A.C. Andersson (2002), p. 8
[23] Pitas, V. et.al. (2010)

2.1.2.2.3 Emerging technologies - Side-stream Nitrogen Removal

Several alternative technologies to decrease the amount of nitrogen in effluent water are emerging on the market that promise to be both less costly and less energy demanding than the conventional process described above. Two of these technologies are included in this study.

The SHARON-process (Stable reactor system for High activity Ammonium Removal Over Nitrate) removes nitrogen from the return flow from the dewatering step, which is many times more nitrogen rich than the water running through the main plant. Although the flow is only 1% of the plant's total hydraulic load, treating this water can reduce the plant's total nitrogen load by up to 30%. By calibrating the temperature, the SHARON-process creates a beneficial bacterial growth for a simplified nitrogen removal process, which uses shorter retention time, uses less oxygen and less carbon than conventional treatment.[24]

The Ammonia Recovery Process – ARP – is also placed on the side-stream from the dewatering in a WWTP. It is a chemical-physical process that uses vacuum and ion exchange to rapidly remove ammonia from the water. Both ARP and SHARON are physical-chemical processes in contrast to the conventional biological treatment process (described in 2.1.2.2.2). Many plants that install these new processes already have some basic biological nitrogen removal in the main stream of the plant.[25]

2.1.2.3 Energy needs coupled to water use

Water users are commonly divided into domestic, commercial, industrial, power generation related and agricultural users. Where water is supplied through a public supply system and discharged to a public sewer all water will typically be delivered at drinking water quality and all wastewater treated to the same level regardless of how the water is used in between. All these user sectors can however to a portion be self-supplied with water. The embedded energy in the water (the energy needed to treat and transport the water to the user and process the wastewater) will in those cases differ depending on the quality required by each user sector. Today the difference in embedded energy between user sectors are nominal compared to the differences depending on for example water source. This could grow however, if different water qualities for different uses were employed to a greater extent.[26]

Adding to this embedded energy is the direct energy used when water is used. For residential sector, this includes the electricity needed to run dishwashers and clothe washers, energy needed to heat water for both hot water use and space heating. Depending on the age and quality of an appliance, water and energy consumption can vary greatly in these uses. Energy is also often consumed during water-intensive industrial processes as well as in commercial food services.[27]

[24] Mulder, P. W. et. al. (2006)
[25] Presentation: Pugh, L. (2010)
[26] EPRI (2002), p. 1-4
[27] *Energy Star Data:* [3] and [4]

2.1.3 Embedded Water in Energy

The concept of embedded water, or virtual water, was defined[28] in the 1990's and describes the water that has been consumed in the manufacturing process of goods and services. Water footprints have been calculated for most agricultural products, including whole dietary preferences. In recent years it has also been used to calculate water footprints of energy carriers. Reports on water embedded in electricity is dominating the water-energy nexus research field.[29]

2.1.3.1 Direct and local water consumption – Water for Thermo-electric cooling

Many water footprint assessments of energy systems calculates the water needed in all steps of the energy production, from extracting and processing the raw energy resource to transforming it to electricity and distributing it to the end users. All of this water is considered to be direct water embedded in the electricity. When investigating the sustainability of an energy system from a global perspective, as has been done for e.g. bio energy systems, the water needed for fuel processing is as important as the water needed for cooling in the thermo-electric power plants.[30] However, many research articles and reports focus on the thermo-electric generation when calculating the local sustainability of an energy system, in which case emphasis lie on the local water footprint.[31] The water footprint of energy systems varies therefore depending on the research question. In this thesis, when investigating the linkages between water and electricity production in NYC, it is the "local" water footprint that is most relevant.

2.1.3.1.1 Water Withdrawal vs. Consumption

Water *withdrawn* refers to the amount of water that needs to be temporarily removed from the water body to cool the steam in the steam cycle after it has gone through the turbine. Most of this water is usually released to the same water body it was withdrawn from and is therefore not considered to be consumed. Water *consumed* is the part of the water withdrawn that is consumed by in the cooling system, most commonly through evaporation in cooling towers. This water eventually returns to some water body and can be used again, but the conventional divide between water withdrawn and water consumed is that consumed water is not returned to *the same* water body and can therefore not meet other local water needs.[32]

The impact of large withdrawals on available water sources is largely dependent on a) the amount of withdrawn water that is consumed and b) the quality of the water that comes back to the water body after being used. If vast amounts of water is withdrawn but it is all returned to the same water body without substantial quality reduction (in purity or changed temperature) it is less unsustainable than if the quality is seriously altered (e.g. in desalination plants, where the salt level is increased significantly, or in nuclear, where the temperature is significantly increased). Data on water withdrawals is therefore most useful when accompanied by information about how the water is altered in the cooling system. Unfortunately this is still very difficult to estimate.[33]

2.1.3.1.2 Cooling technologies

Knowing a power plants water withdrawal is important from the perspective that this is the amount of water the plant needs to operate. If sufficient water is not available, power plant operations are inevitably constrained.

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[28] by professor Tony Allan, for which he received the Stockholm Water Prize in 2008 (Stockholm International Water Institute's website [1])
[29] See for example: Glennie, P. et. al. (2010), Gerbens-Leenes, P.W. et. al. (2008) or; Fthenakis, V. and H. C. Kim (2010)
[30] See for example: Gerbens-Leenes, P.W. et. al. (2008) or; Fthenakis, V. and H. C. Kim (2010)
[31] See for example: Feeley, T. J. et. al (2008) or Fisher, J. and Ackerman, F. (2011)
[32] Glennie, P. et. al. (2010), p. 4
[33] Allan, T. (2011)

There are two main cooling water system technologies in use in thermo-electric power plants today: *once-through cooling* and *recirculated cooling*. In once-though cooling water is withdrawn from an adjacent water body, circulated to cool the close-looped steam systems as it leaves the turbine and then returned to the same water body. The most common circulated cooling systems are cooling towers, where heat is released from the cooling water to the atmosphere in large cooling towers before being recirculated to condenser where it can be used to cool steam again. The second most common wet cooling system in the U.S. is the cooling pond, where heat exchange to the atmosphere takes place in an artificial pond instead of in a tower. Once-through cooling withdraws large amounts of water, while consuming very little of it. Cooling Tower systems withdraws substantially less, but due to inevitable water evaporation in the towers the consumptive water use is bigger. Emerging in the U.S. but still very minor (making up 0,9 % of total US: generating capacity in 2007) are cooling systems that does not require any water, commonly referred to as *dry cooling*. These are either direct cooling systems, where air is passed at high flow rate outside steam condensing tubes, or indirect, where a closed water cooling system condenses the steam, but is in turn cooled by air without evaporation losses.[34]

2.1.3.1.3 Thermo-electric Water Footprints

Water footprints from each of these cooling systems have been calculated by numerous reports. The results vary depending on methodology and power plant data used. Table 3 provides a weighted U.S. national average estimate of water use for some of the most common power plants, based on work by T.J Feeley et. al. (2008). According to the U.S. Geological Survey (USGS), the aggregated national (U.S.) average water consumption per kilowatt hour (kWh) of electricity is estimated to between 23 and 25 gallons, based on data from year 2005.[35]

The thermoelectric industry is an example of where degraded – and not up to drinking water standard – water could be used. 99% of all U.S. cooling withdrawals come from surface water and more than a quarter of these use saline water. Reclaimed wastewater is also being used in thermo-electric power plants, although so far primarily in arid states.[36]

Table 3: U.S. National average cooling water withdrawal and consumption for fossil fuel based thermo-electric plants (based on 2005 year data)

Fuel and generation technology	Cooling system	Water withdrawal (gallons/kWh)	Water consumption (gallons/kWh)
Coal [Subcritical and *Supercritical*]	Once-through	27,0 *22,6*	0,07 *0,06*
	Wet Cooling Tower	0,5 *0,6*	0,39 *0,46*
	Cooling Pond	17,9 *15,0*	0,74 *0,04*
Nuclear	Once-through	31,5	0,14
	Wet Cooling Tower	1,1	0,62
Oil and Natural Gas (steam cycle)	Once-through	22,7	0,09
	Wet Cooling Tower	0,25	0,16
	Cooling Pond	7,9	0,11
Natural gas Combined Cycle (NGCC)	Once-through	9,0	0,002
	Wet Cooling Tower	0,15	0,13
	Cooling Pond	5,95	0,24
	Dry Cooling	0,004	0

Based on: T.J. Feeley III et al., *Water: A critical resource in the thermoelectric power industry,* 2008.

[34] Feeley III, T. J. et. al (2008)
[35] USGS (2009) p. 38
[36] Ibid, p. 38

2.1.3.2 Indirect water needs in the energy sector

Manufacturing the building materials in power plants and grid poles demands water and energy that is important to consider in a global water use perspective but that is not included in this study.

2.1.3.2.1 A note on indirect impacts on water by the energy sector through climate change

It is often stated that water is the media through which climate change will be manifested.[37] A changed climate threatens to disturb the hydrological cycle resulting in more rainfall in some parts of the world while less in others and glaciers that provide water to millions of people have been observed to decrease rapidly.[38] On the other side of climate change a majority of the scientific community acknowledges that global warming and is largely caused by green-house gas emissions, that to a large part comes from burning of fossil fuels.

As the complexity and uncertainties of today's climate change models are still big it is impossible to quantify this link between energy and water and it is not included in the scope of this study. Nevertheless, recognizing that the water-energy nexus spans from the local to the global level shows how central this nexus is in the sustainability discourse.

[37] See for example: UN-Water (2010)

[38] Bates, B.C. et.al (2008), p. 3

2.2 Water and Energy in New York City – Physical reality and Political ambition

New York City is one of the worlds largest cities (ranking between 4th and 17th depending on how the metropolitan area is defined and what indicators are used) and by far the most populous metropolitan area of the OECD countries. The city of New York - the centre of this metropolitan area - is made up of the 5 city boroughs: Manhattan (New York County), Brooklyn (Kings County), the Bronx (the Bronx County), Queens (Queens County) and Staten Island (Richmond County), and holds a population of over 8 million people on 305 square miles (approx. 790 km^2).[39] This population is expected to increase to over 9 million people in the next 20 years (see table 4 below).[40]

Table 4: New York City Population by Borough, 1950-2030*

Borough	1950	1960	1970	1980	1990	2000	2010	2020	2030
Bronx	1 451 277	1 424 815	1 471 701	1 168 972	1 203 789	1 332 650	1 401 194	1 420 277	1 457 039
Brooklyn	2 738 175	2 627 319	2 602 012	2 230 936	2 300 664	2 465 326	2 566 836	2 628 211	2 718 967
Manhattan	1 960 101	1 698 281	1 539 233	1 428 285	1 487 536	1 537 195	1 662 701	1 729 530	1 826 547
Queens	1 550 849	1 809 578	1 986 473	1 891 325	1 951 598	2 229 379	2 279 674	2 396 949	2 565 352
Staten Island	191 555	221 991	295 443	352 041	378 977	443 728	491 808	517 597	551 906
NYC	7 891 957	7781984	7 894 862	7 071 559	7 322 564	8 008 278	8 402 213	8 692 564	9 119 811

* Unadjusted decennial census data 1950-2000; projected populations, 2010-2030

Source: NYCDCP Population projection report, table 6.[41]

Both the water system and the energy system of NYC are among the oldest in the United States. The oldest parts of the drinking water distribution system dates back to the second half of the 19th century and most of it was constructed around mid 20th century.[42] Many of the power plants along the shores of the city were taken into operation in the 1950's and 1960's.[43] The challenge of delivering stable and reliable water and energy in the amounts that the city today demands lies to a great extent on securing that this infrastructure continues to function. Leakage reduction, construction of a third in-city water tunnel – that will give the water supply system its first level of redundancy – along with upgrading power plants and investing in distributed power generation are examples of measures that the city is planning to secure that the delivery of electricity and water can be sustained well into the future.[44]

The City of New York's PlaNYC2030 contains 96 initiatives with concrete goals on how to make New York city more sustainable: to make the land able to hold an increasing population; to ensure that water and air is clean enough for peoples' – and the environments' - health to be upheld; to find solution to traffic congestion; and make sure that peaking energy demands don't lead to green-house-gas emission bursts that makes it impossible for the city to meet its target to reduce emission by 30% below 2005-levels in 2030.[45]

The following sections gives a brief description of the city's physical water and energy systems. It describes in more detail where and how energy and water resources are needed in the water and energy systems respectively. Each section is concluded with future development plans in that sector, taken from PlaNYC and other NYC planning documents.

[39] New York City Department of City Planning website [1] and [2]
[40] *PlaNYC 2030, Update 2011* (2011), p. 5
[41] New York City Department of City Planning (2006)
[42] *PlaNYC 2030* (2007), p. 64
[43] *US-EPA Database – eGRID* [1]
[44] All the plan's goals are summarized in *PlaNYC 2030* (2007), p. 143-145
[45] *PlaNYC 2030* (2007), p. 108 & 134

2.2.1 The NYC Water System

To understand the water system of NYC the city borders needs to be crossed. Water supply travels up to 125 miles to reach New York City from upstate watersheds. Likewise, not only does the discharge water from the city's sewer system flow downstream out into the Atlantic Ocean, but much of the biosolids produced in the city's wastewater treatment plants are also transported out of the city and used as nutrients for agricultural purposes as far away as Colorado and Florida.[46]

The water supply and wastewater treatment system is operated and managed by New York City's Department of Environmental Protection (hereafter DEP).

2.2.1.1 NYC water supply

Around 1 Billion Gallons of water travels from upstate reservoirs to the city each day to serve 8,4 million peoples water needs as well as the commercial and industrial sectors and public demands. The city relies on three water systems for its drinking water, the Delaware, Catskill and Croton systems, providing roughly 50%, 40% and 10% of the city water supply respectively.

The water in the Delaware and Catskill systems are closely connected in an overlapping watershed area that spreads over 5 counties west of the northern part of Hudson River.[47] The water in this watershed is so pristine that the city was given a renewed Filtration Avoidance Determination for this part of its water supply system by the U.S. Environmental Protection Agency (EPA) in 2007, a distinction it shares with only four other large cities in the country.[48] This makes the combined Catskill/Delaware System one of the largest unfiltered surface water supplies in the world.[49]

Only 10% of the water supply comes from the city's oldest system, the Croton system, but all water flowing into the city passes the Croton watershed in aqueducts and tunnels. 19 reservoirs and 3 regulated lakes, 14 of which lies within or in the vicinity of the Croton watershed.[50] In the downstream end of the Croton system lies Jerome Park Reservoir and marks the point where the Croton water enters the city (for the Catskill/Delaware water system this connection takes place at Hillview Reservoir, a few miles further north). The in-city distribution system is made up of two water tunnels, both dating back to the first half on the 20th century, and a third water tunnel that is one of the largest capital projects in the city's history and was initiated in 1970.

Most of the water supply, both in the upstate water systems and in the in-city distribution tunnels travel by gravity, giving New York City's water supply system an unusually low energy consumption (considering that most of its water supply is also unfiltered). For this reason, the Croton system typically supply only low-lying areas of the Bronx and Manhattan, but there are two pumping stations in the Croton System that makes it possible for the Croton system to supply areas that lie higher in the event that the Delaware/Catskill system would not be able to do so. [51] Thanks to pressurized water mains the water supply reaches up to the 6th floor in most of buildings in the city without additional pumping and less than 5% of the city water distribution requires pumping.[52]

[46] New York City Department of Environmental Protection (2007), p. 10
[47] *PlaNYC 2030* (2011), p. 64
[48] US-EPA (2007b) and *PlaNYC 2030* (2011), p. 65
[49] New York City Department of Environmental Protection (2010b), p. 1
[50] *PlaNYC 2030* (2011), p. 64
[51] New York City Department of Environmental Protection (2004), p. 4
[52] Ascher, K. (2005) p. 159

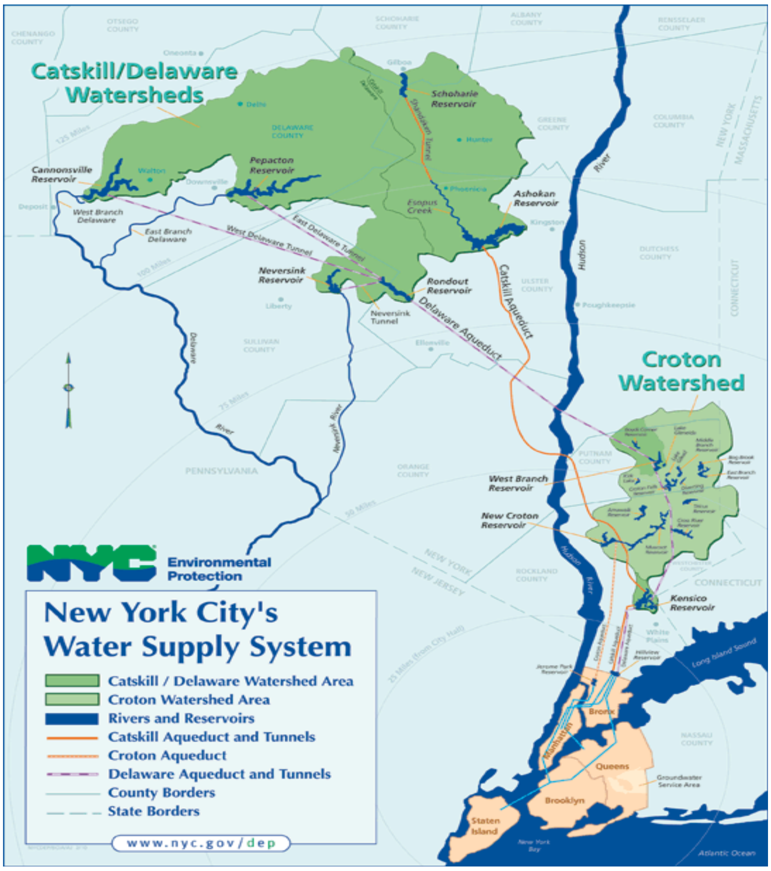

Figure 3: Map over New York City's Water Supply System
Source: NYC DEP website (www.nyc.gov/dep, 2011-07-21)

2.2.1.1.1 Large-scale projects underway in the water supply system

The treatment of the water that flows into the city from the three water systems has to date been limited, this is however changing. In the Croton system a new filtration plant is currently being built. It is expected to reduce colour levels, lower the risk of microbiological contamination and comply with stricter water standards.[53] Up until now the Croton water has been chlorinated to reduce colour and bacteria, but new health regulations have prohibited some of the by-products of this chlorine use. Instances of high turbidity in the Croton water in 2002 is another underlying reason for the new filtration plant.[54] The plant is being built at the Mosholu Golf Course in the Bronx and is expected to be complete in 2012, with a capacity to treat 290 MGD.[55]

Following this development in the Croton System, the *Catskill/Delaware UV facility* (hereafter the Cat/Del UV-plant) is being built to disinfect the water coming from these watersheds, with a maximum capacity of 2,4 billion gallons per day. The plant will be a supplement to the existing microbial disinfection carried out by the DEP in the Catskill/Delaware supply systems and is an initiative to meet upcoming health regulations. The plant is expected to be completed in 2012.[56]

The Water Tunnel No. 3 is one of the largest capital projects in New York City's history. It was initiated in 1970 and is currently at its second stage, which is projected to be completed and operating by 2012. There will be a third and fourth stage of this huge tunnel project before Water Tunnel No. 3 is completed – at which point New York City for the first time will have full redundancy in its water supply.[57]

[53] New York City Department of Environmental Protection (2009) p. 4
[54] New York City Department of Environmental Protection (2004), p. 6 & 8
[55] *PlaNYC 2030* (2007), p. 67
[56] New York City Department of Environmental Protection (2009), p. 4
[57] *PlaNYC 2030* (2007) p. 69

2.2.1.1.2 Water supply issues facing New York City

As stated above, much of the water infrastructure in New York is very old and in urgent need of repair. The USGS estimates that as much as 1.7 trillion gallons of water are wasted each year in the U.S. due to main breaks and leaks.[58] DEP estimates that 5% of the water is lost in leakages, but also states that up to 21% of total water delivered is unaccounted for, when water going to fire hydrants and all other unmetered water use in the city is added to the leakages.

Developments in the watershed area upstate from the city is another issue of concern for DEP, especially in the Catskill/Delaware watershed that is presently excepted for filtration. Increasing upstate urbanization threatens to cause pollution of the water.[59]

A rising issue of concern is the conflicting interests in the areas of the watershed where shale gas is found, a natural gas resource that is being rapidly exploited as conventional fossil fuels are depleted.[60] The Delaware watershed has been identified as a rich shale gas area but today's technique of extracting the gas from the shale rock is dreaded to have potential hazardous impact on the local environment and in particular water resources. Emerging regulation is trying to balance the risks of water contamination with the potential gains from large-scale domestic gas production and is still being negotiated.[61]

2.2.1.2 Water Uses in NYC

In the U.S. as a whole, about 58% of the water delivered through the public supply went to domestic use in 2005.[62] In NYC this figure is close to 70%. The rest is estimated to largely go to commercial users and public needs. Only a small portion of the public supply can be found in the industrial sector and for power generation.[63]

Within the domestic sector water use is typically split between: toilets, faucets, showers, clothe washers, dishwashers and outdoor use. Although several studies have published estimates on how water use is split between these uses, non have been found for NYC.[64]

Among self-supplied water users the thermo-electric sector stands out as it stood for 95% of total water withdrawals in the five boroughs in 2005, amounting to over 2500 MGD out of which more than 80 % was saline water.[65] Worth noting when analysing these figures however, is the fact that practically all of the municipal water is imported – and therefore not accounted for in the in-city withdrawals.

2.2.1.2.1 Issues linked to Water Use in NYC

Water supply is abundant today, but there are still many good reasons for water conservation and the city of New York and DEP continues to work to try to "slow the flow"[66].

- Domestic leakage is an issue of rising concern – not the least when water treatment and distribution is becoming increasingly energy-intensive and costly. One way of tackling this concern from the city government is a newly initiated program on leakage alerts.[67]

- Low flow appliances are encouraged as a means of lowering the domestic water consumption.

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[58] US-EPA (2007a), p. 2
[59] New York City, Department of Environmental Protection (2011a), p. 24
[60] See for example: Hehl, F. (2010)
[61] DEP testimony on the public hearing on hydro-fracking, New York City Hall, March 2011 (found on NYC DEP website [2])
[62] USGS (2009), p. 1
[63] Calculated based on *USGS data* [1]
[64] See for example: Mayer, P. W. et. al. (1999), p. xxvi
[65] *USGS data* [1]
[66] Slogan from DEP website (NYC DEP website [3])
[67] New York City Water Board (2011), p. 2

With the U.S. Clean Water Act there is for example now a limit on the amount of water used per flush in a toilet put into law.[68] In NYC the DEP has been giving away rain barrels to single-family households to collect water for gardening purposes since 2008.[69]

2.2.1.3 New York City's Wastewater System today

In NYC around 30 % of the wastewater from the city's water users go to separate sewer systems where only wastewater is collected. The remaining wastewater flows into the combined sewer system which is shared with storm water run off from the streets of the city every time it rains.[70]

14 wastewater treatment plants (often refereed to as Water Pollution Control Plants, or WPCPs, in the NYC literature) around the 5 boroughs treat approximately 1.3 Billion Gallons of wastewater every day before discharging it to the waterways around the city. The city plants are all AAS plants that include sludge treatment. Only 8 of the plants have sludge dewatering facilities, why the remaining plants ship their digested sludge to these plants.[71] In the spring of 2011, the last upgrades to meet secondary treatment standards was completed (at Newtown Creek WPCP). As a result, all the city's wastewater treatment plants now meets required federal treatment standard.[72] 7 plants are estimated to have some basic biological nitrogen removal.[73]

The preliminary treatment, where large item such as newspapers, bottles and rags are removed from the flow by large vertical bar screens, occurs several stories underground in the city treatment plants. This makes it possible for practically all water entering the sewers to flow by gravity from the drains to the WPCPs. The wastewater is then pumped up to surface level where it goes through the remaining treatment steps.[74]

2.2.1.3.1 Large-scale projects underway in the wastewater system

As with most parts of the public water system, the infrastructure is ageing and both sewers and wastewater treatment plants are in continuous need of upgrade.[75]

In addition to this, the high level of nutrients in the discharged water from the WPCPs is found to cause degradation of the natural eco-systems in parts of the city harbour. A number of wastewater treatment plants will in the coming years therefore be equipped with full-scale nitrogen removal facilities to meet tougher regulations on water quality in the Long Island Sound and Jamaica bay (two water bodies that are most impacted by high nitrogen levels, that together receive the discharge from 8 of the WWTPs and approximately 60% of the city's total wastewater discharge). SHARON and ARP are the two most discussed options for these upgrades.[76]

2.2.1.3.2 Wastewater issues facing New York City

Combined Sewer Overflow (CSO) happens in the city each time there is more storm water entering the sewer system than can be processed by the city's wastewater treatment plants. Instead of creating a backward flow in the sewer system – which could cause untreated sewer to rise in the drains or on the streets – the city has built CSO-outlets along the shores of the city where untreated wastewater is released instead.[77]

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[68] US-EPA (1995), p. 23
[69] New York City Department of Environmental Protection (2011b), p. 10
[70] NYC DEP website [4]
[71] New York City Department of Environmental Protection (2007), p. 8
[72] New York City, Department of Environmental Protection (2011a), p. 36
[73] New York City Department of Environmental Protection (1998), p. 1
[74] New York City Department of Environmental Protection (2007), p. 7
[75] New York City, Department of Environmental Protection (2011a), p. 26-31 in particular
[76] New York City, Department of Environmental Protection (2011a) and data from
New York City Department of Environmental Protection (2010c)
[77] NYC DEP website [5]

To mitigate CSO's, the DEP is launching several stormwater retention projects. These include both conventional CSO retention facilities and “green infrastructure” initiatives. Conventional CSO storage is typically underground tanks where wastewater is retained when WPCP capacity is exceeded, to be treated when the wastewater flow decreases. With green infrastructure, the city aims to retain stormwater from entering the sewers in the first place. Planned projects include green roofs, blue roofs (non-vegetated), retrofitting parking lots and sidewalks with enhanced tree pits and infiltration swales that can retain more stormwater than conventional ditches and tree pits.[78]

Both the CSO incidents and high nitrogen concentration in the controlled WPCP discharge have negative impact on the NYC harbour water quality. The harbour water is already improving and is now cleaner than it has been in a century. As nitrogen removal treatment is taken into operation and CSO mitigation projects are implemented this trend is expected to continue.[79]

2.2.1.4 Energy in the New York City Water Systems

All treatment and pumping of water demands energy. Having a largely gravity fed supply and sewer system and up until now limited treatment of the water supply, puts the DEP below the national average when it comes to energy consumption. However, the wastewater treatment facilities are old and therefore more energy consuming than new facilities. 86% of all DEP energy use (including energy for non operation facilities such as offices) is consumed by the wastewater treatment plants.[80] This is projected to change as the new water supply treatment facilities will begin to operate and as city population is expected to increase over the coming decades. To meet this increased energy need the DEP plans to implement an aggressive demand-side management program.[81]

At four of the city’s wastewater treatment plants fuel cells have been installed by one of the city’s larger energy companies. They have a total capacity of 800 MW and are fuelled by biogas produced during the sludge digestion process.[82] The energy produced by these fuel cells together with heat produced from bio-gas boilers at most of the treatment plants are used internally at the WPCPs to lower the need of external energy.[83] In addition to the conventional treatment process upgrade at Newtown Creep WPCP, there are plans on utilizing the methane gas produced during the plant's anaerobic sludge digestion for more than just this internal use. In an newly initiated cooperation with one of the energy utilities in NYC – National Grid – the Newtown Creek WPCP will start supplying digester gas that National Grid purifies and distributes to gas customers through their regular natural gas pipes.[84]

In 2009, 19% of the city's municipal greenhouse-gas-emissions came from operation of the wastewater treatment plants.[85]

2.2.1.5 PlaNYC on Water and DEP plans

Much of the information given in the two previous sections is collected from the PlaNYC. The list below concludes what the plan says about the *development* of these systems in the coming years.

- Ensure the quality of the city’s drinking water, through continued watershed protection and through the completion of the two drinking water treatment facilities

- Create redundancy for aqueducts to New York City, through maximization of existing facilities as well as evaluation of new water sources

[78] New York City Department of Environmental Protection (2010a)
[79] NYC DEP website [6]
[80] Fiore, A. (Personal communication, June 26, 2011)
[81] New York City, Department of Environmental Protection (2011a), p. 58
[82] New York Power Authority website [1]
[83] NYC DEP website [7]
[84] Fiore, A. (Personal communication, July 18, 2011)
[85] Dickinson, J. and R. Desai (2010) p. 29

- Modernize in-city water distribution, for example through completion of Water Tunnel No. 3

- Continue implementing infrastructure upgrades.

- Pursue proven solutions to prevent stormwater from entering the system

- Expand, track and analyse new Best Management Practices – making CSO reductions a priority for all relevant city agencies, introduce new treatment methods in the harbour and enhance the green infrastructure.

- Keep pursuing water conservation and encourage lower consumption by end users.[86]

[86] *PlaNYC 2030* (2007), p. 63-83 and *PlaNYC 2030, Update 2011* (2011), p. 78-87

2.2.2 The NYC Energy System

Energy in New York City is produced by a handful of utility operators and delivered to end users by one of them, Con Edison Inc. Since this system has already been modelled with MARKAL, it is only briefly described in this section.

2.2.2.1 The Energy System today

New York City is connected to the Eastern Grid in the US, which spans over more than half the U.S. all the way to the border of Texas. Although the interconnected area is large, due to limited transmission infrastructure, the New York State Reliability Council and New York Independent System Operator (NYISO) require that 80 % of the New York City's projected summer peak demand can be met by in-city resources.[87]

In-city power is generated by more than 40 large and small fossil fuel burning thermo-electric power plants, with the vast majority employing once-through cooling.[88] 95% of these power plants are primarily burning natural gas, either as the single fuel or as the primary fue1 in dual-fuel plants.[89] Renewable energy production is still small but growing rapidly, especially when it comes to solar energy. Last year the installed capacity of solar photo voltaic energy doubled from 3 to 6 mega watts (MW).[90]

In the NYC MARKAL project carried out in 2008, the distribution and end consumption of electricity is thoroughly described and will therefore not be presented here.

In addition to electricity, energy in New York City also flows in the form of Steam and Gas that provide heating and cooling of buildings. The latter is also the most common energy supply for cooking.[91]

2.2.2.2 Water in NYC Energy System

A large portion of the water that is withdrawn in New York State goes to thermo-electric power plant cooling (see figure 4) and as stated in sector 2.2.2.2 this portion is even more dominating on the city level. This level is extreme compared to the national level of around 40 %,[92] but can largely be explained by 1) the absence of agriculture in the city – which nationally withdraws almost a third of total water withdrawals and 2) the public water supply collects its water outside the city.

Recently (and after this data was collected), the first power plants with closed-loop wet- and dry-cooling were taken into operation in NYC and a couple more are planned. They will be taking the water they use from the public water supply system.[93]

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[87] NYISO (2011)
[88] Data from previous MARKAL-models and *USGS Data* [1]
[89] NYISO (2008), p. 3-3
[90] *PlaNYC 2030, Update 2011* (2011), p. 113
[91] Ascher, K. (2005) p. 110
[92] USGS (2009)
[93] *US-EIA Data* [1] and [2]

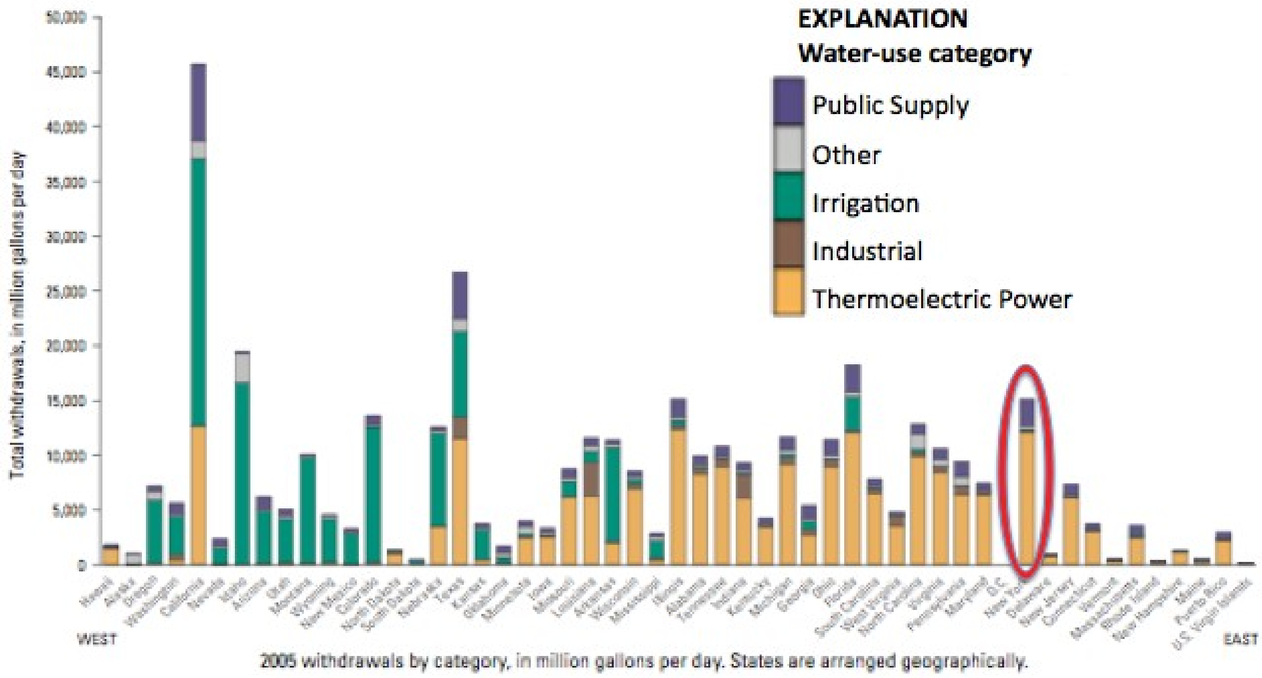

Figure 4: 2005 Withdrawals by category, in million Gallons per Day for all U.S. states. New York State is circled, Thermo-electric water withdrawals are marked in yellow.
Source: USGS, Summary of Estimated Water Use in the United States in 2005. Edited by Author

2.2.2.3 PlaNYC on Energy and other energy plans

The first energy related goal of PlaNYC is to establish a New York City Energy Planning Board. Since this was done in 2008 the Planning board is working on realizing the remaining goals.[94] These include:

- Reducing NYC’s energy Consumption, including an expanded peak energy demand management and promotion of energy efficiency through institutional development,
- Expanding the city’s clean power supply, including fostering a market for renewables,
- Modernizing electricity delivery infrastructure.
- Support cost-effective repowering or replacement of our most inefficient in-city power plants.[95]

On a state-level, regulations against large water withdrawals are in the process of being passed. This is generally thought to be aiming at potential gas companies seeking to extract the shale gas that is embedded in underground rock-formations across large areas in the North East regions of the U.S. However, it might have consequences for other large water users, such as the thermo-electric power plants. If the regulation is strict enough, several plants might need to evaluate the benefits and costs of retrofitting the cooling system to use wet-towers or dry-cooling instead of once through systems.[96]

[94] New York City Energy Planning Board (2008)
[95] *PlaNYC 2030* (2007), p. 103
[96] Campbell, J. (2011). See also: New York State Assembly's website [1]

3. MARKAL methodology – the Conceptual Framework

MARKAL (an acronym for MARKet ALlocation) is a mathematical modelling tool for energy systems on local, regional or national level that was first developed at Brookhaven National Laboratory (BNL) in collaboration with the US Department of Energy (DOE) and the International Energy Agency (IEA), following the oil embargo in the 1970s.[97] Today MARKAL is used by nearly 100 institutions in more than 55 countries and is used to model systems from a town-level up to multi-regional and global systems.[98]

This paper showcases how MARKAL can be expanded to also model an urban water system. Before demonstrating how this expansion was created, and discussing how the NYC water system was formulated to fit the MARKAL format, this chapter gives an overview of the characteristics of MARKAL and the data needed to make it work.

3.1 MARKAL for Energy Planning – overview of the MARKAL's "original" use[99]

Mathematical energy modelling can traditionally be divided into two categories, that are distinguished mainly by the degree of detail with which the systems are represented in the model. They can be summarized as:

- *Top-down models* depict an energy system in its external environment and takes macro-economic variables that go beyond the energy sector into account, such as wages, consumption patterns and interest rates.

- *Bottom-up models* create detail rich representation of all available (at present and in the future) technologies in an energy system and focus on the interlinkages and competition between them.

MARKAL is a technology-explicit, *bottom-up* model where each important energy-using technology is identified by a detailed description of its inputs, outputs, unit costs, and several other technical and economic characteristics. However, MARKAL also incorporates some of the impacts from the entire economy on the energy system modelled, making it closer to a *top-down* model than traditional *bottom-up* energy models. The main objective of MARKAL is to compute an optimization of resource use and technology employment that minimize the total cost of the system (or maximize its surplus), over an up to 50 year time-horizon (which will be further explained in section 3.1.3).

3.1.1 MARKAL Structure: Components, connections and the Reference Energy System

A MARKAL-representation of an energy system is typically dominated by *technologies* and *commodities*.

- *Technologies* transform the energy from one form to another (or transport it from one place to another).

- *Commodities* are the thing being produced or consumed by each technology.

When modelling an energy system, technologies are typically power plants or air-conditioning units and commodities are typically all energy carriers such as fuels, electricity or heat. In addition to commodities and technologies, *energy sources* and end-users' *service demands* are needed in order for MARKAL to represent the entire system.

[97] Bhatt, V. et. al (2010)

[98] Lee, J. (MARKAL-briefing July 27, 2011)

[99] If not otherwise noted, this entire section is based on Luolou, R. et. al. (2004).

- *Sources* are typically Oil imports, Biomass produced, Uranium extracted or any other energy source that can create a *commodity* in the energy system.

- *Service demands* are the "commodity-free" but energy consuming end-use demands.

The latter can be "vehicle miles travelled" or "commercial space cooling", and are incorporated in every technology describing ways to meet these service demands. These are not to be formulated as "gasoline needed to travel X miles" or "electricity required for space cooling", since that would limit the flexibility of the system in choosing technology and commodity paths to meet that demand.

Flowcharts that depict the networks of technologies and commodities that make up the energy systems with all its alternative paths from source to end-use are called a *Reference Energy Systems* (RES). These systems can be seen as the backbone of the MARKAL model, where all commodities and technologies are mapped in relation to each other. Figure 5 gives a partial view of a typical RES. Technologies are depicted as rectangular boxes while commodities are the arrows connecting the boxes, and the oval shaped sources and service demands (in this simplified example only "home space heating").

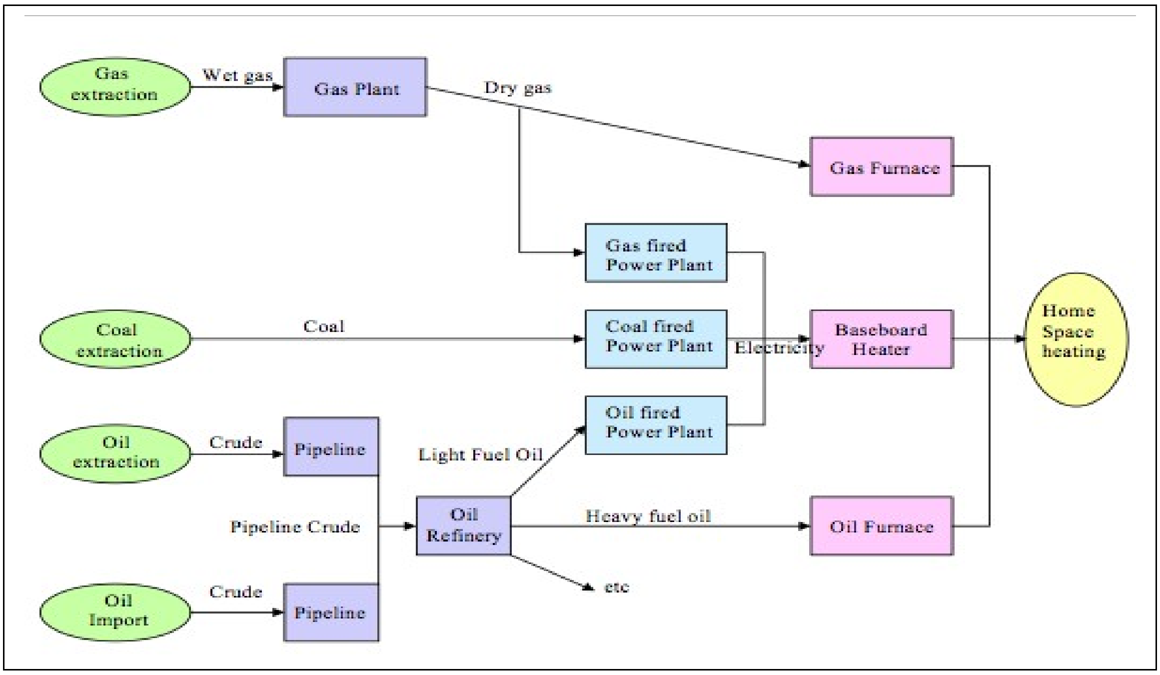

Figure 5: Partial view of a simple Reference Energy System
Source: *Documentation for the MARKAL Family of Models* Luolou et. al. (2004), page 14

Most technologies used in the system – for extraction, distribution or transformation of energy from source to end-use – are represented with several technological alternatives. When the model choose what equipment to employ, both the characteristics of the alternative technologies and the economics of the primary resource supply is taken into account.

3.1.2 Data Parameters in MARKAL

While the structure of an energy system can be similar in several regions, data* input is largely what differentiate one system from another. An energy system is explicitly described in MARKAL by the user-provided input data, which consist of both qualitative and quantitative data.

* Data in this sense refers to parameter assumptions, technology characteristics, projections of energy service demands, etc. and does not refer to historical data series.

- The qualitative data includes: the list of technologies in use or determined to be potentially applicable in the system over the chosen time horizon; a list of available energy carriers/commodities; as well as the environmental impacts to take into consideration.

- The quantitative data contains all technological and economic parameters specific to each technology (and time-period). This include investment costs, energy conversion efficiency, greenhouse gas emissions per unit of electricity produced, etc.

Some examples of this: For process technologies, quantitative data often includes up to 4 types of costs, energy and materials input and output, lifetime of equipment and some pollution entity such as greenhouse gas emissions. Service demand data include a quantified "amount of service needed per year", the seasonality of the demand (how it varies over the year) and price-elasticity (indicating the allowed variations for this demand). Some Energy Carriers have input data that couples it to its end-use, such as diesel fuel for agriculture or for residential space heating. This allows policy incentives to be aimed at only parts of the use of these commodities but not the other (e.g. if the policy aims to phase out the use of diesel in boilers but not in tractors).

Costs of each source is in conventional MARKAL described with classic micro-economic supply curves, with the available quantities of the source at various prices. Similarly, each service demand is depicted with a demand curve of service demanded at different prices of that service.

To summarize, a MARKAL model typically consist of:

- *process, conversion, transmission* and *end-use* technologies;

- *energy carriers, electricity* and *low-temperature heat* commodities;

- *energy resources* or *imports* as sources;

- and *energy consuming services as* demand services.

Depicted as commodities are also *environmental emissions* and *materials*. The second refers to all non-energy commodities going in and out of the technologies in the energy system. In a traditional MARKAL model, water needs in the energy system would be depicted as a material – and can be depicted at varying levels of detailed depending on the purpose of the model.

In addition to these components, the model contains *system-wide attributes* that describe how the system will be modelled in terms of time horizon, population growth etc. All quantitative data is given in units of commodity produced/consumed per year.

3.1.3 Adding it together and running the MARKAL

MARKAL is a dynamic modelling tool, meaning that all investment and operational decisions are made with "perfect foresight" – full knowledge of future event. Allowing the model this unrealistic feature is crucial to generate a solution that optimizes the market allocation of energy production and consumption so that costs for the total time-horizon modelled is minimized.

Mathematically, MARKAL is based on linear, dynamic programming where the main objective is to compute an optimization of resource use and technology employment that minimize the total cost of the system (or maximize its surplus), over an up to 50 year time-horizon.

The mathematical problem can be summarized as maximizing (or minimizing) one linear function while satisfying a number of constraints. A (simplified) matrix formulation of this is given below:

$$Min[G(y)] = by \text{, when } \quad yA \geq c \quad \text{and} \quad y \geq 0 \qquad ^{*}$$

[*] This equation is commonly referred to as the "Dual" of the first – called "Primal" – equation.

where *y*-variables are called *decision variables* – the variables that the model calibrates to reach its optimal solution. *G(y)* is the *Objection function*, the expression that is sought to be minimized. This linear function adds together all costs in the system and can contain many thousands of variables in a full MARKAL model. $yA \geq c$ contain the *constraint equations* (or more often inequalities). Here the limitations to the model are defined by the user, that must be satisfied in the optimal solution of the system.[100]

Adjustments to this "minimization of costs" can be made by internalizing some of the external costs of a technology, or by adding or changing the user-defined *constraints*. Constraints in the energy system can range from limits to market penetration for a specific technology to regional greenhouse gas emission targets, but also define simple systems characteristics such as that an air-conditioning unit can only remove heat from a room by consuming electricity as energy carrier. In general, MARKAL *constraints* are the physical and logical relationships that needs to be satisfied in the model. They have to be defined by the user and are often many, but are crucial to make a realistic representation of the system modelled.

The time-horizon is typically set to 45 or 50 years into the future, divided into time-periods of 5 years. MARKAL creates an "inter-temporal partial equilibrium" for each time-period where the price of each commodity is fixed to the level where suppliers of that commodity produce exactly the quantity demanded by the consumers of the same.

One of the crucial tasks when creating the structure of the MARKAL-model is the calibration of the base-data – the data that describes the first time-period and determines the "present" condition of the energy system. This description cannot be changed by the model and it is only the development beyond this baseline that is the model can optimize. Important parameters in the base-data are description of existing technology, both data on their activity (production or consumption levels and emissions from this) and the total initial existing stock of each technology. A parameter describing the lifetime of a technology is especially important, since a technology affects all future time-periods until its end of life (since investment costs are already "swallowed" it may be profitable to keep using an old system instead of investing in a new and more resource efficient one).

In one sentence, MARKAL is a technology-explicit, partial equilibrium model that assumes competitive markets with full foresight.

[100] Lee, J. (MARKAL-briefing July 27, 2011)

3.2 Previous NYC MARKAL models

As mentioned in the introduction, MARKAL-models have been developed for NYC in recent years. When possible, this thesis had made use of the models already created and the following section therefore presents these models briefly.

3.2.1 The WaterMARKAL Pilot in 2008

One of outcome recommendations from the New York Regional Energy-Water Workshop on *Energy-Nexus Issues in the metropolitan region*, held in NYC in 2004, called for the development of an analytic decision-making tool to address the complex economic, environmental and energy-water interactions of short- and long-term planning.[101]

Based on this, a pilot study to develop such a decision-support tool was undertaken and completed by 2008 as a part of the DOE's Energy-Water Nexus Program. The study found that it was more suitable to develop an existing decision making tool already in use in energy or water planning than to develop a whole new tool. The choice fell on expanding an earlier version of the NYC-MARKAL, and on incorporating water and waste-water flows, infrastructure, water demands and associated energy use and economic considerations into the existing MARKAL-model. In the WaterMARKAL and similarly to this thesis, the application of an earlier developed NYC-MARKAL was extended to incorporate NYC water and wastewater systems as well as some water using data. The RES of the NYC-MARKAL was expanded to a REWS – a Reference Energy *Water* System – where water and wastewater flows were depicted within the original NYC-model. [102]

A schematic view of a REWS-system is shown in figure 6.

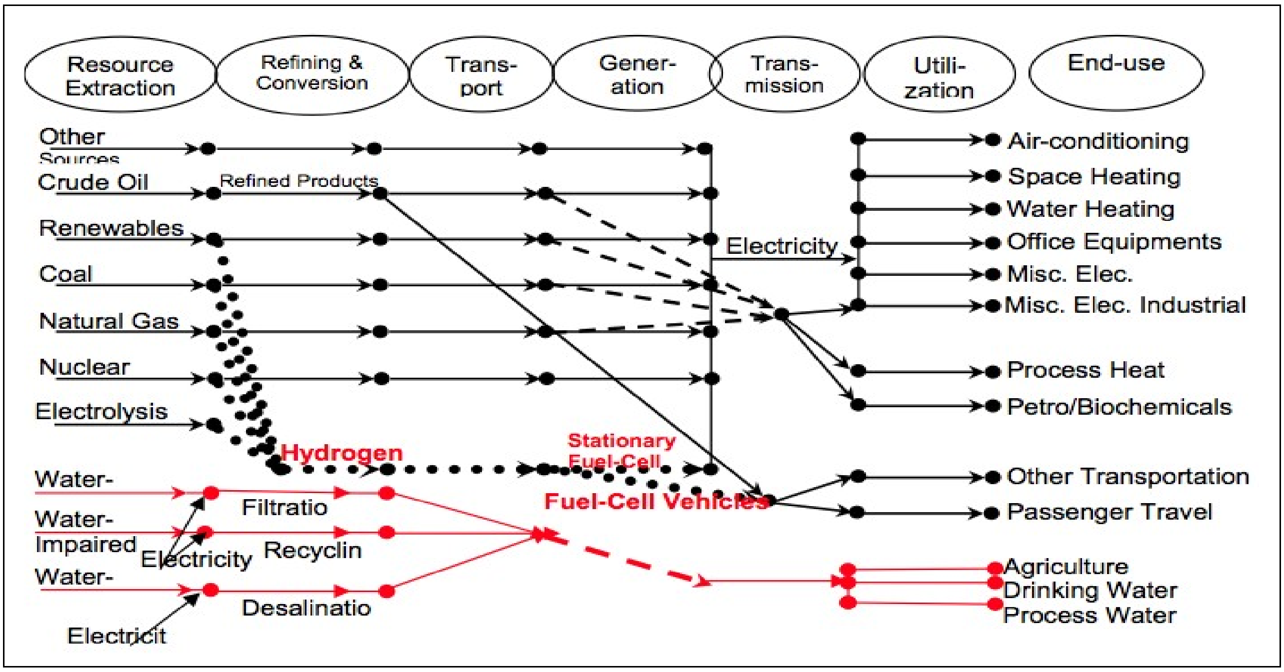

Figure 6: Generalized Reference Energy-Water System in the Pilot water-MARKAL
Source: V. Bhatt et al. (2008)

The purpose of building a WaterMARKAL-model in 2008 was to demonstrate that such a tool could facilitate decision-makers to take the water-energy nexus issues in New York into account in their

[101] New York Regional Energy-Water Workshop (2004)
[102] Bhatt, V. et. al (2008)

policy work. Data from this study was not available to use as a base in this thesis, but the conceptual framework and some hints towards water-energy nexus issues have been used in the development of the new model. For a full description of the WaterMARKAL pilot, see the report "New York City Energy-Water Integrated Planning: A Pilot Study" (V. Bhatt et.al. 2008).

3.2.2 The NYC-MARKAL – modelling electricity in NYC

When developing the most recent city-MARKAL over NYC the focus was on investigating how lower Manhattans' peak electricity demand could be lowered. It was also a showcase of how MARKAL could be used to support decision-making and cost-efficient planning of low-carbon cities.

Since the NYC-MARKAL was investigating electricity consumptions, model components included all electricity producing units in the city as well as imported energy through the grid. MARKAL was in the scenario analysis coupled with *Urban Heat Island*[103] mitigating efforts. End-use technologies that satisfy "space cooling" demands in the city were therefore in focus. Both conventional electricity consuming technologies to cool buildings and alternative technologies to those appliances were inserted in the model. In the analysis, "green roofs" and similar unconventional "building retrofitting" technologies were found to have the potential to reduce peak electricity demand significantly, since the cooling service they provide come without a corresponding energy input. Another conclusion of this work was that a broader systems approach to address e.g. waste minimization and pollution control could be supported by adding further material flows to the model. Implicitly, water and wastewater are mentioned as examples of such materials.[104] For full documentation of this process, see Bhatt, Friley and Lee (2010).

After developing the new WaterMARKAL model in this thesis, it will be combined with this NYC-MARKAL model to demonstrate some preliminary uses for the combined Energy-WaterMARKAL.

[103] The concept that cities retain heat in a way that makes dense urban areas reach significantly higher temperatures during hot days than the surrounding environment. (See for example: NYSERDA (2006))

[104] Bhatt, V. et. al (2010)

4. Building a MARKAL-model of New York City's Urban Water System

In this chapter, the MARKAL framework is extended to incorpoate a new WaterMARKAL model. It is based on both the previous chapter's MARKAL description and the NYC water system presentation in Chapter 2. Concluding this chapter is a short discussion on the overall capability to describe New York City’s water system in MARKAL, with a focus on MARKAL's demands on data and the experienced data limitations.

The aim of this thesis is to apply the MARKAL tool to describe the water system in New York City, with the overarching ambition to – in combination with the NYC-MARKAL – find optimal development paths for water and energy use in this urban area.

The process to create the water systems model was conducted in four phases. First, the water flows in the city was mapped and the Reference *Water* System (RWS) for the NYC model was created. Second, the qualitative data was determined and compiled, which consisted of identifying all relevant technologies and the parameters needed to sufficiently describe each of them in order to model the water system realistically in MARKAL. The third phase was obtaining quantitative data to populate all parameters identified in the second phase. Lastly, the data was calibrated, which included converting everything into the appropriate unit and making rationality checks on relevant parameters aggregated to the system level. Throughout this process the model was continuously revised and updated as new knowledge was gained, or due to experienced limitations in data availability.

Rather than depicting water as a material input (or output) in the NYC energy system, this thesis chose to build a WaterMARKAL model where water is the main commodity, and energy is depicted in material input (and output) flows. This gives water a more dominant role and makes it possible to include water related activities in NYC that does not have a direct energy component.

This chapter presents how the WaterMARKAL structure was created. It also goes thorough how data was collected to populate the model.

4.1 Creating a Referens Water System based on the RES framework

In RES, the *commodities* in the system are the energy carriers, which are followed from extraction to end-use, changing along the way from raw fuel, to electricity, to space cooling service (for example). In the RWS, the commodity is water, and it only changes in terms of quality as it passes through the system, in terms of concentration of contaminants, temperature, etc. These changes have not been explicitly expressed in the water commodity description. Instead *constraints* are put on the system so that for example outputs from a wastewater treatment plant can not be a direct input in domestic showers.

Below is a schematic figure of the model RWS, including water flows in Million Gallons per day (MGD). This is a “historic” RWS, based on 2005 data.

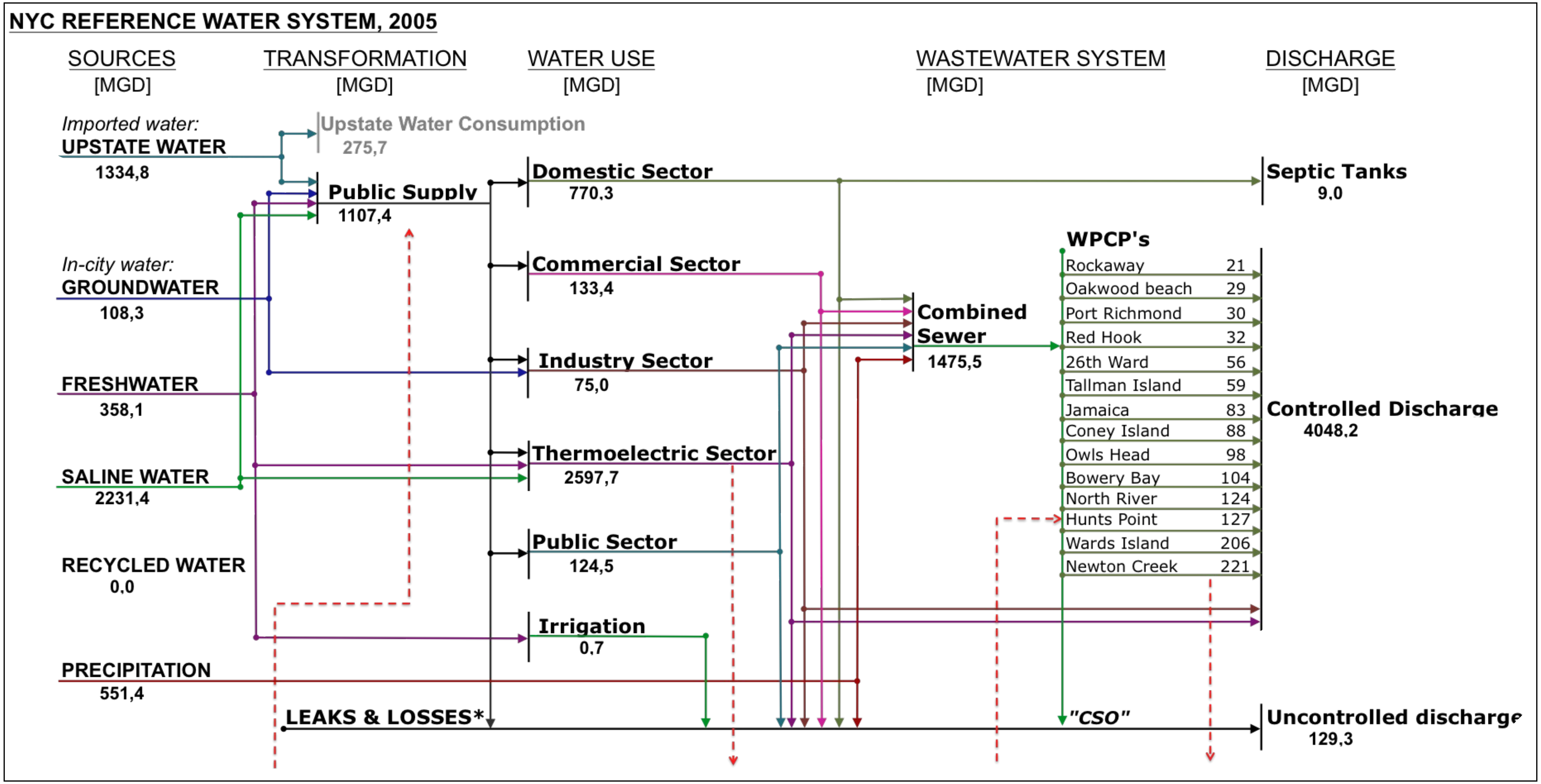

Figure 7: The New York City Reference Water System, used as a base to develop the new WaterMARKAL model. Including water flows in Million Gallons per day (MGD) for year 2005 – USGS data + calculations (see app. B). Created by the author.

The dotted lines in figure 7 indicates major net energy flows – where energy is produced (an output) or consumed (an input) in the water system. This RWS does at this stage not yet include the specific technologies employed in the system but shows all parts of the water and wastewater system as well as the water using sectors. Corresponding to what was presented in chapter 2, the RWS shows that the domestic sector is using almost 70% of the publicly supplied water, while the by far largest over-all water consumer is the thermo-electric sector (using more than 65% of the total water flowing through the system). The total water quantity flowing through the system each day was calculated to a 2005 average of 4300 million gallons.

4.2 Technologies included in the WaterMARKAL

This RWS was then populated with technologies with the common denominators of having a water inputs and outputs and being realistically used in an urban area such as NYC within the coming decades.

Since the MARKAL model uses an up to 50 year horizon, a key feature in gathering data for the model was to describe alternative and "not yet in place" technologies. Some of these alternatives might not be feasible in a base-line scenario, but comes into play as the policy-scenarios are run. All thinkable alternatives could naturally not be included.

4.2.1 Treatment Technologies

For the water supply as well as the wastewater system, the level of detail the system were chosen to be represented on was at plant level, or "complete treatment" level. This meant that all the processes involved in one treatment facility transforming water from the raw water source to potable quality are treated as one technology in the model. As a result, supply treatment technologies constituted: "Current disinfection treatment", "Croton Filtration Plant treatment", Catskill/Delaware UV-plant treatment" and so on. As alternative technologies, Reverse Osmosis facilities for desalination of seawater and for treatment of recycled wastewater to potable quality were put in the model. Based on the ongoing debate on hydro-fracking near the up-state water supply reservoirs, a technology describing a full-scale (conventional) treatment of all Catskill and Delaware water was also included.[*]

14 "municipal wastewater treatment technologies" were created, one for each of the 14 WPCPs in NYC. In addition, both "Nitrogen Removal" technologies (conventional, SHARON-process or ARP) and "Digester Gas to Energy" technologies (fuel cells, micro-turbines, combustion engines or "gas to grid") were created and coupled to the wastewater treatment plant technologies. As many of these "coupled" technologies can only come into play in the future – and it is uncertain if they will – additional alternative technologies were not added to the wastewater treatment technologies in this version of the model.

4.2.2 Distribution Technologies

In between these treatment technologies, only 2 public water supply distribution technologies – "delivered" and "unaccounted for" – and only one municipal sewer technologies – "public sewer" - were created ("septic tanks" and "self controlled discharge (industrial)" are included, but does not describe municipal water flows). The reason for this was that there were found to be no realistic technology options for either of these piped public systems connecting treatment facilities with end-use technologies: Both run practically by gravity and both consist of infrastructure buried under the

[*] If Hydro-fracking was to contaminate these water bodies, it is expected that conventional treatment is needed at minimum. (Source: NYC DEP website [2])

streets since many decades and is only subject to continuous reparation and maintenance. Constructing a new "competitive" sewer system is not a reasonable option and the fact that there are *no* alternative "transmission" technologies can in a way be seen as one way of adjusting the model to describe the water system.

4.2.3 Water Use Technologies

Due to constraints in data availability and time limitations, not all water-using sectors could be modelled with explicit technologies. Only water using technologies in the domestic sector and the power-generating sector were included. These are the sectors using a majority of the public water and "total" water respectively (as noted from the RWS-figure). The power sector was also naturally prioritized for the sake of depicting water-energy nexus issues in NYC. In addition, data on commercial and industrial water use was found to be scarce and it was therefore not possible to reliably describe these sectors in detail for the NYC system.

Data for the water use in the domestic and power sectors was not always available for the New York City conditions in particular. Water using technologies included in these sectors were therefore determined by 1) general technologies found to be in use in NYC today or explicitly mentioned in city planning documents or in other ways indicated as emerging on the market and 2) data availability.

For domestic use, the technologies correspond to those presented in Chapter 2: toilets, faucets, showers, clothe washers, dishwasher and outdoor use, as well as domestic leakages and a category representing miscellaneous water use in the domestic sector. Leakage control measures were not possible to quantify and were therefore not included. Various ways of heating water, from conventional gas storage to solar heating systems, are depicted as water heating technologies in the model.

For the power-generating sector, only water-technologies (cooling systems) for Natural Gas/Oil fueled power plants are modelled in the WaterMARKAL. They were considered to represent all power plants currently being used in NYC today and it has been assumed that this will remain the case also in the future. Although the share of electricity generated from natural gas is expected to grow, this is not modelled to affect the water needs, since cooling water needs for oil and gas fired plants are considered to be equal in the general case in their water use (see table 3). Further, recirculated water cooling systems using ponds have not been included in the model, based on the notion that ponds need to be of sufficient size to work as cooling sources and that this area is not expected to be available in NYC at a reasonable cost. The technological alternatives in the model are therefore restricted to natural gas or oil fired steam plants or combined cycle plants with once-through cooling, wet towers or dry cooling. It is estimated that renewable energy, particularly in form of solar PV and wind power could increase in NYC in the future. The water needed for maintenance (cleaning) of these systems are therefore also included as technologies in the model.

The user sectors not represented with specific technologies – the commercial, industrial and public sectors (agricultural water use is considered to be negligible) – were depicted as a single technology each, simply containing the total water flow going into and out of that sector.

Table 5 lists all 82 technologies included in this study. All parameters needed in the model is further described in the next section.

Table 5: Technologies included in the Model to depict New York City's Water System from sources to wastewater discharge. Created by the author.

WATER SUPPLY TECHNOLOGIES			**DEMAND TECHNOLOGIES**			**WASTEWATER SYSTEM TECHNOLOGIES**		
			Residential Sector		*Energy Sector*			
Water Source	**PRE-Use Treatment**	**In-City Distribution**	**Water Heating**	**Toilets**	**Steam plant Cooling**	**Sewers**	**WPCPs**	**Nitrogen Removal**
Cat/Del Water	Cat/Del 1 -	Public - Delivered	Conventional	Conventional	Once Through	Public Sewer System		Conventional BNR
	U.V. Treatment Plant	Public - Unaccounted	gas storage	Pre-1980 (conventional)	Wet Tower (forced draft)		Rockaway	SHARON-process
Croton Water				Low-flow	Dry Cooling	Setic Tanks System		ARP
	Cat/Del 2 -		High-efficiency	Ultra Low-flow			Oakwood beach	
Ground Water System	*Full Treatment*		gas storage		**CC-plant Cooling**	Self-Controlled		**Digester Gas**
(Public Supply)				**Showers**	Once Through	Discharge (Industries)	Port Richmond	**to Energy**
	Only Disinfection		Condensing	Conventional	Wet Tower (forced draft)			Micro-turbines
Rainwater Harvesting			gas storage	Low Flow (aerated)	Dry Cooling		Red Hook	Fuel Cells
(for Gardening)	Croton Filtration Plant							Combustion Engine
			Demand gas 5	**Faucets**	**Renewable Energy**	**CSO Mitigation**	26th Ward	"Gas to Grid"
Ground Water				Conventional	Solar PV Cleaning	Grey infrastructure		
(Industrical self-supply)	*R.O. Plant 1 -*		Conventional oil-	Low Flow (aerated)	Wind Turbine Cleaning	Green Infrastructure	Tallman Island	
	Seawater Desalination		fired storage					
NYC Harbor - Freshwater				**Clothes Washing**			Jamaica	
(for Power Plants)	*R.O. Plant 2 -*		Minimum efficiency	Conventional [El. Dryer]				
	Wastewater re-use		electric storage	Conventional [Gas dryer]			Coney Island	
NYC Harbor - Saline water				Conventional [no dryer]				
(for Power Plants)			High-efficiency	Low Flow [El. Dryer]			Owls Head	
			electric storage	Low Flow [Gas Dryer]				
Recycled Water				Low Flow [No dryer]			Bowery Bay	
			Electric heat pump		*Other Sectors*			
			water heater	**Dish Washing**	**Comm. Water Use**		North River	
				Conventional				
			Solar heating with	Low Flow	**Ind. Water Use**		Hunts Point	
			electric back-up	By hand, full basin				
				By hand, tap running	**Public Water Use**		Wards Island	
				Outdoor Water			Newton Creek	
				Domestic Leakage				

4.3 Parameters needed to portray the technologies

These technologies then needs to be describe by user-defined sets of parameters that are then given data values. To describe the water flow in NYC accurately, parameters had to be adjusted for the WaterMARKAL. The following list presents the basic parameters used to describe each water system related *technology*:

- Water quantity available (for water system technologies and sources) – in BG/year[*].

- Water quantity consumed (for water consuming technologies) per "appliance" – e.g. "gallons of water needed"/"clothe washing load" (for each type of washer), or "gallons of water needed for cooling the steam in a power plant"/"MJ of electricity produced" (for each type of thermo-electric cooling system)).

- Investment costs for every given technology option – in $/BG/year [to tie the cost to the installed capacity] for water system technologies, or in $/"1000 appliances" for water consuming appliances.

- Operation & Maintenance (O&M) costs for every given technology option (excluding the water cost and electricity cost for water use technologies since they are accounted for in the water and energy systems) – in $/MG[**] produced, treated or consumed.

- Energy input for each water unit produced or consumed (both water system technologies and water use technologies) - in MJ/MG[***] of water produced or consumed.

- Existing stock, quantity of appliances (esp. important for water use technologies where several options exist) – in "no. of facilities" (for water system technologies) or "1000 units" (for water using appliances (and rain barrels)).

- Direct Green-house-gas emissions. Since the energy generation related emissions are captured in the pre-existing NYC (Energy) MARKAL, only the water system (water supply and wastewater treatment system) and the water heating appliances have direct emissions parameters tied to them in the WaterMARKAL model – in Metric Tons/year of CO_2, CH_4 and NO_X.

An exception from this "parameter recipe" is the energy input parameter for the cooling systems in the power plants, which was exchanged to a parameter of the overall plant efficiency. The cooling systems energy consumption is often not reported and is considered to be nominal in comparison to the impact the choice of cooling system has on overall energy production efficiency.[105] Further, the water quantity parameter used for the power sector refers to the water *withdrawn* (and not *consumed*) and is also extended with an indication of the water source from which the water quantity is withdrawn, with the basic notation of "self-supplied" or "public supply". All once-through cooling systems are considered to be self-supplied with water (considering the amount!) while all recirculated systems (wet towers) are assumed to be served by municipal water.

Another exception to these parameters are that not all technologies have energy input. For example, since all transmission technologies in the NYC are "gravity fed", these technologies do not have an energy parameter. The same goes for toilets, outdoor domestic water use and all water using sectors not explicitly modelled (commercial, industrial and public).

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[*] Billion gallons per year

[**] Dollars per million gallons of water

[***] Megajoules per million gallons

[105] Politis, S. (Personal Communication, May 2011)

In this created NYC-WaterMARKAL model, two sets of parameters described in Chapter 3 were to be simplified. First, the cost variables were simplified to 2 instead of 4 and only fixed costs (not supply/demand curves) were inserted in the system. Second, the only material flow included in the model was energy. The simplification of these parameters are a consequence of the choice to include a large number of technologies in the system.

4.4 Water Using Service demands

Service Demands were not included in the table of technologies in the previous section. For the WaterMAKRAL they are considered to be closer to what could be called simple "system parameters" than to complex technologies.

To de-couple the city's *demands for services that (commonly) use water* from the *technologies available to meet these demands*, service demands were formulated with one single, "water-independent" parameter. An example of this is the domestic needs for showers, described only by "minutes per day" that an average shower is in use in NYC.

It is in the service demands that the surrounding society (NYC) is most explicitly present in the water system model. To determine the total number of "loads per year" of clothes that are cleaned in NYC every year, population data (and expected growth) was a crucial input. To realistically model the demand for outdoor water use, knowledge of the number of single-family households was needed and to estimate the cooling need in the thermo-electric power plants, it was crucial to have a good approximation of the number of plants in operation and their respective and total electricity production. The unit of the service demand was determined largely by the unit of the demand technologies tied to that demand. For the power sector demand technologies, cooling systems water quantity is described in MG/MJ (million gallons withdrawn per Mega joule of electricity produced). The service demand in this sector is therefore MJ/year of electricity output. The service demands in the water model is hence tightly linked to energy system changes and the power sector "water related service demand" is one of the ties through which the interactions between the energy system and water system can be most obviously modelled in the combined NYC-WaterMARKAL model.

4.5 Constraints

MARKAL can include two types of constraints. The first is the constraints depicting the present system, where water can not flow from industrial use straight to domestic toilets and similar. These are constraints that makes the system work logically. The second type are constraints that depict regulations and limitation forced on the system by everything from the city government, to international convention, to cultural norms. One such identified constraint placed by the city government is the 30% reduction in green-house-gas emissions by 2030. Due to the limitations of this thesis, this second type of constraints were not implemented in the model at this stage of the process. Constraints protraying social and behavioral aspects related to adoption of new technology also needs to be explicitly implemented, since the model logic assumes that all customers are completely informed actors that always acts rationally. How this impacts the model will be both visibe and further addressed in chapter 5.

4.6 Adding NYC data to complete the NYC WaterMARKAL

Populating the model with reliable quantitative data proved to be the most challenging work of this thesis. In many cases, NYC specific data was not available and the city conditions could not easily be estimated by looking at U.S. averages or even New York State averages. For one, agriculture is practically absent in the city water system and the industrial sector is very small compared to national data. In addition, it does not compare well with many other metropolitan areas. It is one of the worlds largest cities – and by far densest in North America – but has a much slower population growth than most urban areas where resource availability is studied. When it comes to water efficiency schemes on a city level, existing examples are almost exclusively from arid regions while NYC at present have plentiful water resources. In sum, finding good estimates for the New York City case demanded careful consideration of all these aspects when actual city-data was not available.

4.6.1 Data collection

Much of the data collection work has naturally been closely linked to the literature review and background research presented in Chapter 2. In practice, all general data of water footprints of the energy sector is taken from recently published reports within the water energy nexus field. Many figures on the particular flows of energy and water in New York City was available in conjunction with reports from the state or the system operating agencies – sources that were also valuable for understanding how the water and energy systems in the city works (section 2.2). All data sources are listed in Appendix A.

Different data was found at different sources, and costs and energy demands for a particular water technology were not always found at the same source:

- *Water withdrawal data* was primarily gathered from the United States Geological Survey (USGS), where data from 2005 was the latest available.

- *Water treatment and transmission data*, such as daily flow rates through the distribution tunnels and aquifers, leakage estimates, came from the DEP. Through online material and published reports, the DEP also provided most of the data needed to describe the flows in the combined sewer system and through the wastewater treatment plant.

- *Water demand data* came from a variety of sources. From technical specifications of domestic water consuming appliances from the industry (e.g. washing machines, toilets and water heaters) to operation data from power plants, specifying water needs in the cooling system of the thermo-electric power plants in the city (see EIA form 860 and F767[106]). General Conversion factors[107] from fuel burning were used to estimate emissions from non-electric water heating technologies.

- *Water system components technological data*, were usually not all found at one source and can broadly be divided in four sub-categories:

  - *Energy data* were only partially available from DEP. To fill the gaps, scientific articles, technical documentation of other U.S. water systems and EPRI publications (in particular the series on “Water and Sustainability” vol. 1-4) were used.

  - *Cost data* were largely available in the fiscal year reports from the *NYC Water Board* (a part of DEP). For specific end-use technologies and alternative treatment technologies, brochures and articles from suppliers were useful. To complete the picture, scientific articles comparing water treatment technologies from e.g. a life-cycle perspective or reviewing emerging technologies, were employed.

  - *Greenhouse Gas Emissions* from the water system were found in material from the City of New York and the DEP such as the *NYC Greenhouse gas Inventory*[108] and the *DEP strategy 2011-2014*[109].

[106] *US-EIA Data* [1] and [2]
[107] Supple, MIT Energy Club (2007)
[108] Dickinson, J. and R. Desai (2010) p. 29
[109] New York City, Department of Environmental Protection (2011a)

- *Existing Stock* of each technology was either found in the technology specific data sources or calculated based on population characteristics in NYC.

Since a majority of the base data needed was not available specifically for NYC, an extensive number of approximations, assumptions and estimations were carried out. These were based on a combination of literature from other parts of the U.S. or other industrialized countries and statistical data on NYC – such as population size and growth rate. Much of the NYC specific economic data available to describe the water system technologies only provided total investment costs and O&M costs for an entire system section (such as "Water Pollution Control"). As far as possible, these sums were broken up into pieces and allocated to each technology in that system section before turning to more general sources that describes costs in an urban water system. When it came to investments for larger upgrades such as the water tunnel no. 3 which is not depicted as a technology of its own, these were also divided and allocated proportionally to the relevant water system technologies. All assumptions made are described in Appendix B.

All the data described up until this point has been the base-data, used to create the first time-period of the MARKAL-model. Being the base of the model, it is important that this is described with as much detail and accuracy as possible. Projecting how the data changes over time is by nature a more uncertain part of building a MARKAL model. To make this as uncomplicated as possible and avoid misleading assumptions based on vague trends, data series into the future were in this first version of the model calibrated with only population growth and already planned system changes (such as the retirement of old power plants and the opening of the new water treatment facilities).

Since the Energy MARKAL for NYC was already in place, data updates were limited to adding new power plants that had come into planning since 2005 (last model's base year) and taking away retired plants. In two cases this included changing from once-through cooling to closed-loop and in a third to building a new closed-loop cooling power plant.[110]

4.7 Conversions and Calibrations to tackle specific data inconsistencies

When sufficient data had been collected to give a reasonable estimate to each of the hundreds of parameters included in the model, the data was organized in excel spreadsheets sorted by technology type and parameter (e.g. capital costs for water supply treatment technologies). All data points were then recalculated to the units described in chapter 4.3, to be on the format compatible for the WaterMARKAL model.

4.7.1 Water Balances

Before inserting the data collected into MARKAL, water balances were calculated for the entire system. In every section of the system, the sum of water flows had to add up to the total water flow to ensure a completely balanced system – as described in Chapter 3. Even in modelling cases when the data available has been comprehensive, this is generally difficult to attain.[111] In the case of the New York city water system, levels of leakage in all parts of the system was kept reasonably flexible for the balance of the water supply side. For wastewater flow balance, two parameters were given more flexibility. The first was the amount o stormwater entering the sewers. The other was "imported" wastewater from the large commuting population – who work (and create wastewater) in the city, but live (and consuming most of their water supply) elsewhere. These flexible parameter largely helped to balance the water flows.

[110] *US-EIA Data* [2]

[111] Bhatt, V. (Personal communication, April, 2011)

4.7.2 Water flows in the Power Sector

The 2005 USGS data on water withdrawals to the thermo-electric sector in NYC counties was significantly higher than the calculated sum of all power plants cooling water need (based on the general water withdrawal figures presented in chapter 2). Reasons for this discrepancy could be explained by: a) NYC power plants are old. 12 plants out of the 30 plants explicitly modelled were put online before 1975.[112] Although many plants have been upgraded, it is reasonable to assume that the water footprint calculations found in other literature are based on more modern – and therefore more water efficient – plants, and b) 6 power plants produce steam in addition to electricity.[113] The electric output does therefore not relate directly to the total cooling needs of the plant.

In addition, several plants have moved from once-through to recirculated cooling since 2005 (based on data showing that up to 19% of total capacity installed is now using municipal water as its primary energy source).[114] Due to the fact that the most recent USGS data on thermo-electric water withdrawals in NYC dates 2005, these numbers do not cover this shift towards recycled cooling.

For both these reasons, and to make "alternative technologies" (not present in the NYC power generation sector today) comparable in the model, literature figures on water quantity in the power sector were used. The data put into the model was chosen after analysing multiple sources. Figure 10 illustrates how literature results vary on thermo-electric water withdrawals.

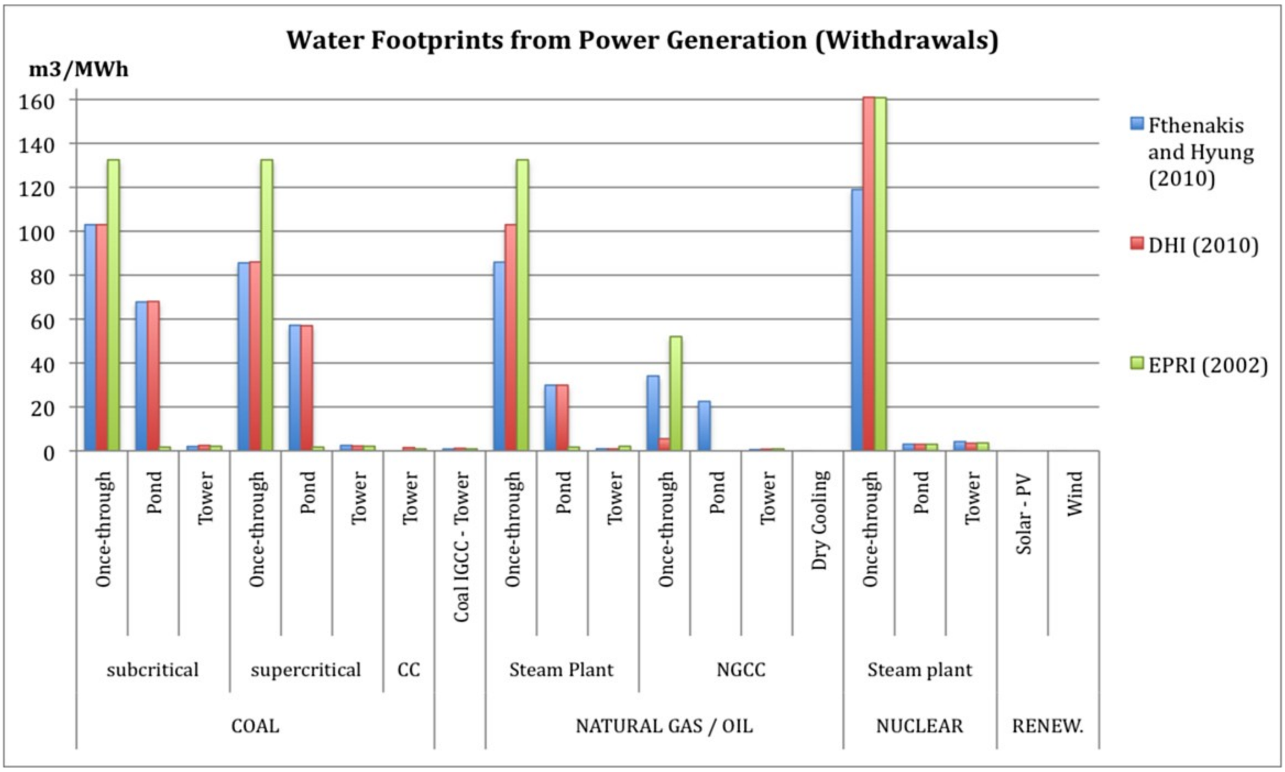

Figure 8: Summary of water footprints from electricity production. Published by V. Fthenakis & Hyung (2010), DHI (Glennie, P. et. al. 2010) and EPRI (2002).

The Fthenakis & Hyung results are recently published, are calculated based on U.S. plants and correspond closely to the data presented in chapter 2 (T.J. Feeley III et al, 2008). This data does not have any unexpected peaks and follows the generally accepted pattern that water withdrawals

112 *US-EPA Database – eGRID [1] (column AO)*
113 ConEdison (2010)
114 *US-EPA Database – eGRID* [1] (column AO)

decrease as cooling-system shift from once-though to pond, and from pond to tower. This source was therefore chosen to depict the NYC Thermo-electric water use in the model.

4.7.3 Ensuring Reasonable Cost Data

A particular issue of concern when combining data from a wide range of sources was the "capital cost" data for both water treatment technologies and thermo-electric cooling technologies. NYC-specific cost data was consistently found to be significantly higher than the general cost estimates. The reason for this could not be thoroughly investigated, but possible explanation could be the density of the city, making construction work more costly there than where land is more abundantly available. Another explanation could be that some O&M costs are incorporated in the reported investment cost. For the power plant cooling technologies, several "general" sources were found to be converging in terms of costs and there was only a single NYC-data point available – a point that was notably higher. For this reason, the NYC data was not used. For water treatment technologies, NYC specific cost data was found for most existing and soon to be implemented technologies, and in this case the NYC data was used.

4.8 Summary of the constructed WaterMARKAL model

With a quantitative description of 82 technologies, the NYC water system has been depicted from water source to wastewater discharge in the MARKAL-framework. For the water system technologies, emphasis was put on describing existing and emerging treatment technologies. Water sources and transmission of water and wastewater were not given any energy inputs, but has been depicted with economic inputs and water flow capacities. When modelling the water use in NYC, the domestic and thermo-electric sectors were prioritized and represented with explicit water consuming technologies. The industrial, commercial and public sectors have also been represented in the model, but only as water consuming units in the system. Constraints on the system were limited to logical constraints to make the system behave realistically. Data used to populate the model came from many different sources and have been weighted and calibrated to depict the conditions in New York City.

Table 6 gives a summary of the type of technologies and parameters that have been included in the NYC WaterMARKAL model. It also list the sources where most of the data for these parameters were found.

Table 6: Examples of data required to build the NYC water-MARKAL model.

System Section	Technologies (examples)	Parameters (examples)	Data Sources (examples)
Water Supply	Source Protection Conventional Filtration Plant UV-Filtration Plant	Total Water Available Total Water Extracted Cost of Treatment Energy Consumption	USGS Data NYC DEP reports City of New York Capital Strategy Environmental Assessment Reports of NYC Water Treatment Plants Scientific Articles
Water Use – Domestic	Toilets Clothe-washers Faucets Outdoor Water Showers Water Heating	Water Use per appliance Appliance Cost Energy Consumption per appliance Existing No. Of Appliances in NYC	Product Fact Sheets from home appliance industry Energy Star Data & Calculators Scientific Articles & Research Papers EPRI ACEEE
Water Use for Energy	Oil/Natural Gas Steam Plant with Once-through Cooling Cleaning of Wind Turbines	Water Withdrawal Power Plant Efficiency Retrofit costs of changing cooling syst.	Exciting NYC-MARKAL EIA Data Scientific Articles and Research Papers
Water Service Demands	N/A	Power plant energy production requirement No. of Showers per year per person	Scientific Report EIA power plant specific data US Census Bureau
Wastewater System	Septic Tanks Public Sewer System Rockaway WPCP North River WPCP SHARON Treatment Process Fuel Cells for Digester Gas Recovery	Wastewater Flow Wastewater Treatment capacity Investment Cost Retrofit costs (for Nitrogen removal or Digester gas recovery technologies) GHG emissions	NYC DEP Reports City of New York Capital Strategy Environmental Impact Assessments of NYC WPCPs Scientific Papers Reports from the Wastewater Industry

N/A – Not applicable, Service demands are by their nature non-technology specific.

Source: Created by the Author (See Appendix A for the complete table of data sources).

5. Evaluating the new WaterMARKAL Model

To analyse the strengths and weaknesses of the developed NYC WaterMARKAL model in more detail, the model was tested, both manually and with a simple test scenario. Although it will take several iterations to get the model adjusted and applicable for full-scale and more complex energy-water scenario modelling, these results gives some indication of how the model works.

5.1 Pre-Modelling Results drawn directly from the final data

As explained in chapter 3, each data point is described explicitly in the MARKAL model, to allow the model to have full flexibility in its path to find the least cost solution to provide for the city's water-related needs. To determine if the created WaterMARKAL depicts the present NYC water system realistically however, some of the collected base-line data was manually aggregated to the city level. These calculations revealed the broader energy demand and cost of each part of the water system – which can be seen as some of the most direct water/energy-linkages in NYC.

5.1.1 Power sector Water use

Based on the large discrepancies found in data on water use in the NYC Power sector, this was explicitly calculated to get an idea how the model depicted this parameter. NYC specific data on number of power plants, their specific cooling systems and their respective electricity produced was attained from the a central database administered by the EPA (these were also included in the NYC MARKAL that the water model is paired to).[115] Together with the chosen ”water footprint data”, total water withdrawals in NYC power sector could be calculated. A figure of water needs and power produced based on cooling system (and water source) is given in figure 11 & 12.

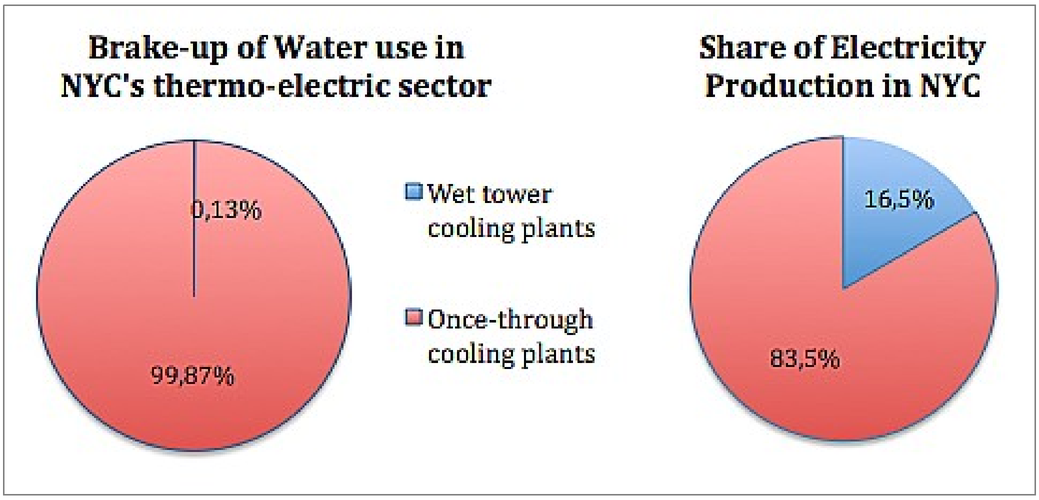

Figure 9: Calculated break-up of water withdrawals and percentage of electricity produced based on cooling-system. Once through cooling systems are assumed to use self-supplied water while recycled systems, such as wet towers, more often rely on municipal water supply.

Interesting to note is the significant difference between percentage of electricity produced and the percentage of water withdrawn by plants with recycled cooling systems. As the background literature has already portrayed, once-through cooling requires many times the amount of water that recycled system needs. Even as the popularity of recycled cooling is increasing, the water need for recycled cooling stays nominal in comparison to the once-through cooling systems.

[115] *US-EPA Database – eGRID* [2]

5.1.2 Costs and Energy Demand in the Water System

5.1.2.1 Aggregating Operational costs in the Water System

Rough calculations of the Operation and Maintenance cost data over the water flow data in the present water supply states that it costs around $1.6 to treat and deliver every 1000 gallons of water to the NYC consumers. In 2015 this figure is $3.7, but again investment costs are not included.[116]

As presented in chapter 4, the sewer system is in this study not considered to have an energy component. Although a small amount of pumping is estimated to occur, this is negligible and in practically all sewage flow by gravity to the WPCPs. In the NYC WaterMARKAL-model it is still represented, but only as one technology and with only water quantity and cost figures. Adding together the O&M costs for the sewers together with the O&M costs calculated for the WPCPs gives every 1000 gallons of wastewater handled by the system a price-tag of $2.14. In 2015, this number is expected to be $3.15.[117]

An example of what these calculations implies can be formulated as follows: If these numbers, and the corresponding water supply "embedded costs" are accurate, it could be argued that any investment that saves 100'000 gallons over its expected life time, compared to present technology and costs less than $350 today ((1,6 + 2,14) *100 >350), or less than $650 ((3,7+ 3,15) *100 >650) in a few years when the new treatment plants are operating, would lower the total cost of the water system.

5.1.2.2 Embedded energy in the water system

To get an idea of where in the water system the NYC water-energy nexus is most significantly manifested the embedded energy of the water was calculated for both the water supply and wastewater. The result is shown in table 7.

Table 7: Embedded energy in the NYC Water System

Part of System		2010	2015*	2020
Water Supply	(kWh/MG)	42	735	271
Wastewater System	(kWh/MG)	1420	1897	1897
Total	(kWh/MG)	1462	2632	2168

** When parts of the Delaware Aqueduct is taken out for service for repair – sometime between year 2011 and 2019 – the supply from groundwater and Croton Water will be increased. Here these sources are estimated to deliver at full capacity - resulting in only 56% of the water coming from the Catskill/Delaware system (compared to 90% during normal conditions).*

The majority of the energy-consumption is happening in the wastewater system. This corresponds to estimates made by the DEP that approximately 86% of all the departments energy is consumed at the wastewater treatment plants. When nitrogen removal processes are introduced the WPCP energy consumption rises further, although the proposed technique for the NYC WPCPs – the SHARON-process – is expected to use 25% less energy than conventional nitrogen-removal processes. This may explain why the energy consumption does not increase more than ~1'700 MJ/MG.

Further, the calculated numbers in table 7 are largely in the same range as the theoretical levels of embedded energy in the water system presented in chapter 2. Initially (year 2010 in table 7) the

[116] Appendix B
[117] Appendix B

gravity based non-filtrated water supply demands much less energy than the average water supply, as is expected. The following peak in energy need in 2015 comes at a point where the most efficient treatment technology is limited due to reparation work and groundwater sources and Croton water is utilized at maximum capacity. The wastewater treatment's energy requirement lies slightly higher than the theoretical data, which may be a consequence of the age, and thereby inefficiencies, of the infrastructure.

The energy *produced* at the WPCP's is not included in these calculations.

5.1.2.3 Highest energy consumption during the use of water – the Clothe washing example

Calculations of the energy demand of water using appliances in the residential sector reveal much higher consumption "per drop" of water than the embedded energy in the water system, if measured in MJ/MG: around 150'000 MJ/MG for a conventional clothes washer. Worth noting is that the absolute water flow to one appliance is nominal compared to total system water flow. Also, "energy per drop" of water in this water use sector does not capture the energy efficiency in many low-flow appliances, since the energy consumed in water-efficient appliances are divided over a smaller volume of water. Still, since roughly 70% of the public supply goes to the residential sector, and 10%-18% of this water is used in clothe washers, total energy consumed tied to water use for clothe washing is still significant.

5.1.3 Water Flows in the Domestic Sector

NYC Water flows were generally already in balance when the RWS was created. There was however one sector that needed to be calibrated to reach a point where total water delivered to the sector was realistically allocated to all water using technologies in use.

In the domestic sector the water quantity figures going to each technology type (toilet, shower etc.) put in the model, were calculated based on data on domestic water use from NYSERDA[118], DEP[119], EnergyStar[120], AWWA[121] and a recently published report on urban water systems in Australia[122]. Since neither of these sources were picturing the domestic water use in NYC, they were weighed together and a unique share of water uses was calculated for NYC (see Appendix B for more details). The calculated water use are depicted below for multi-family and single-family housing units respectively.

In these tables, as in the model, simplifications have been made when dividing water to single-family and multi-family households. Most obviously, it has been considered that single-family households correspond to households with a garden – and hence a need for outdoor water. Due to the small size of many multi-family household units in NYC, it has further been estimated that both clothe washers and dishwashers are not standard appliances. Although present in many multi-family units, roughly half of the multi-family households have been assumed to clean their clothes in a commercial Laundromat (adding to no domestic water consumption) and wash their dishes by hand (adding substantially to the domestic water consumption). This explains why the percentage of water going to clothe washing is lower here than in single-family units, and why water consumption for dishwashing is higher.

118 NYSERDA (2008)
119 NYC DEP website [8]
120 *Energy Star Data:* [1] and [2]
121 Aquacraft Inc. (2009)
122 Kenway, S. (2008)

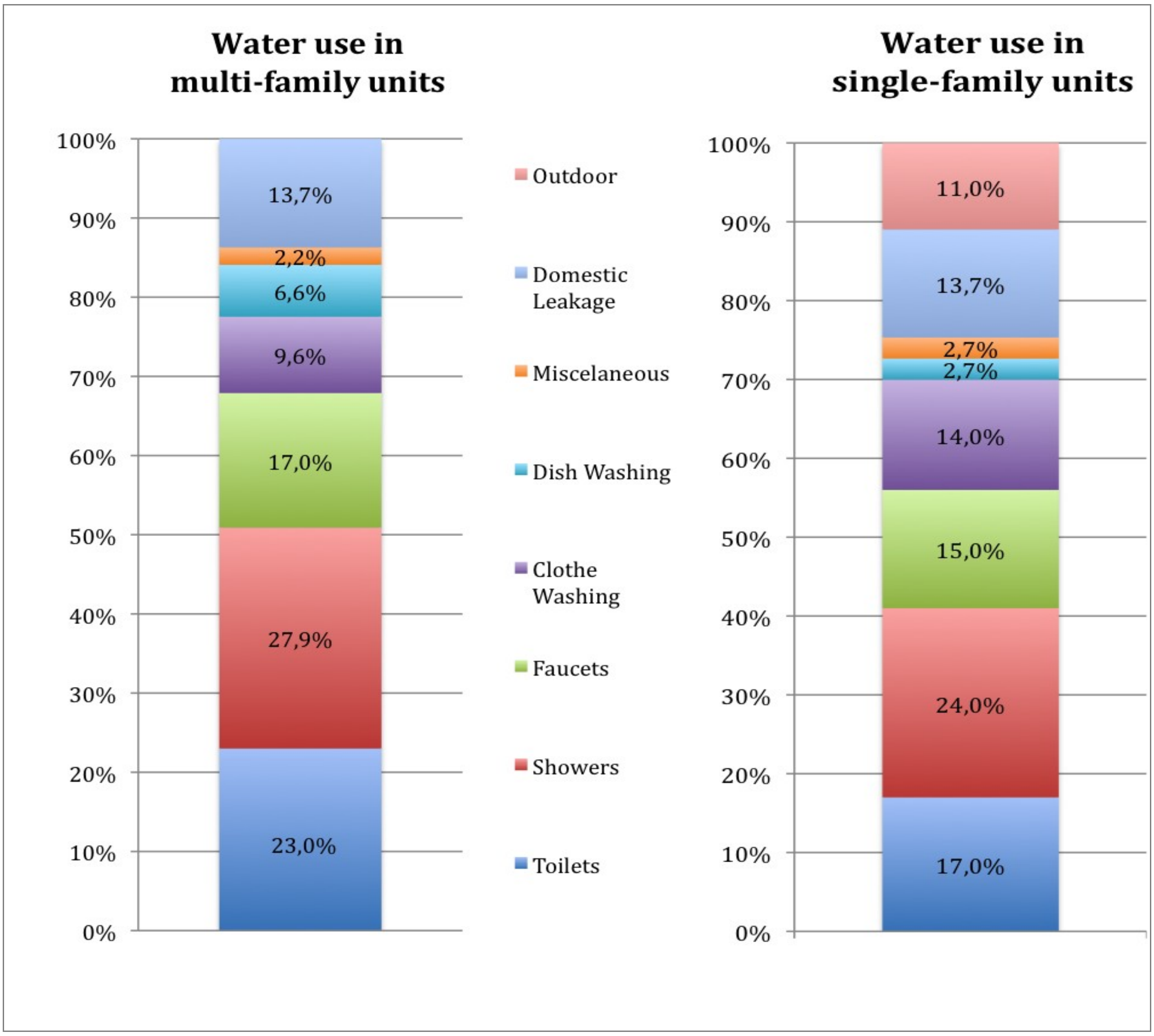

Figure 10: Water use in the New York City's residential sector, calculated based on collected input data

Leakage in the residential sector is estimated to be 13.7% of total water used, almost as high as toilet water use in the single-family households. This high level of leakage corresponds to the results from an EPA study from 1995. That study did not look specifically at New York City. However, when comparing these figures with table of cumulated water losses from dripping faucets and running toilets published at the DEP website, this level of water losses are found to be reasonable: One steadily dripping faucet in one out of 7 households will result in larger losses, roughly 14% of total water consumption in these 7 households.[123] This level of leaking appliances are therefore considered to be reasonable and can also justify the city's initiative to lower water losses in their leakage alert program. As mentioned in chapter 4, this initiative was not quantifiable in this work and could therefore not be included in the model.

[123] For calculations, see Appendix B.

5.2 Preliminary Modelling Results

The purpose of expanding the NYC MARKAL model to include complete water flows is ultimately to run scenarios of how NYC's water and energy consumption is projected to change in the coming decades, and how the systems may impact each other. Although the aim of this thesis is limited to developing a first version of this model and not to draw results from its runs, two test runs were conducted to give a preliminary idea of how the model works. The following section presents some of the results obtained when the WaterMARKAL-model was added to the existing NYC-MARKAL and tested. To make a robust MARKAL-model, technologies and sections of the system are added in pieces, dynamically testing how the model responds to the new additions. At the time for these first test runs, only the water supply was fully included in the model, hence the results in this section are not including the dynamics of the wastewater system. Consequences of this will be lifted at the end of this chapter.

5.2.1 ”No Constraints” scenario results

The first run of the WaterMARKAL model showed that after starting out at levels corresponding to the water distribution presented in Chapter 2, public water flow increased in all parts of the system that has not been explicitly described with detailed demand technologies. Counteracting this development, the residential sector's water consumption drops dramatically over the initial years, bringing down total water consumption level substantially before increasing again as the model approaches 2050. Figure 12 shows how public water supply (in Million Gallons per Year) is allocated between the water using sectors from 2010 to 2050.

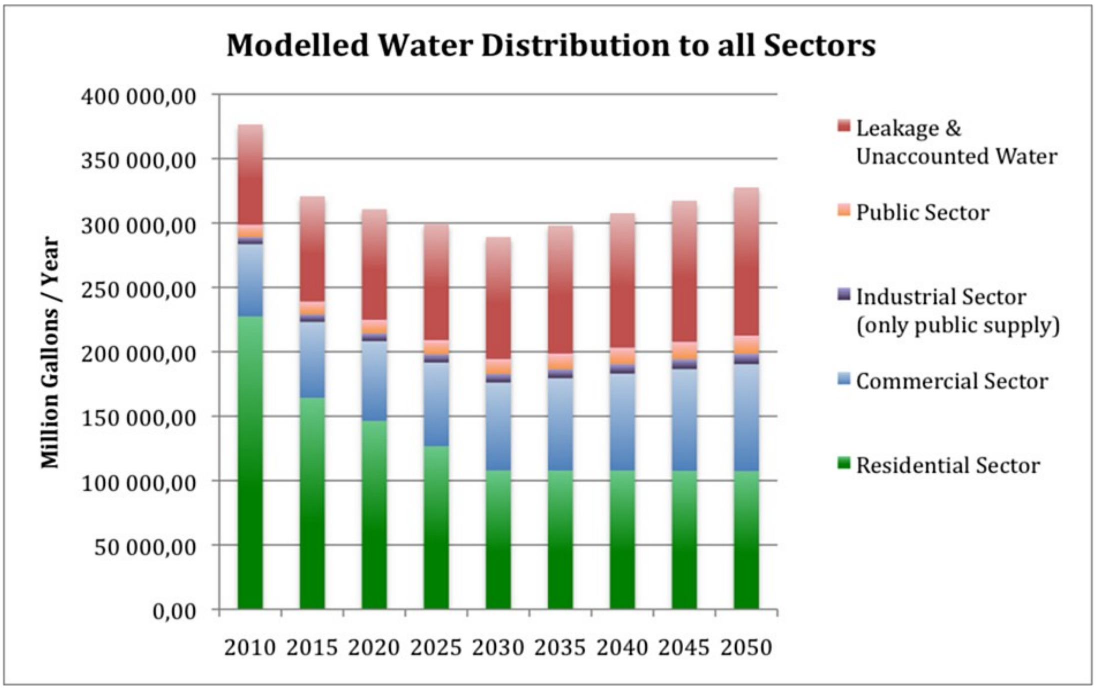

Figure 11: Modelled Water Consumption by sector in NYC 2010-1050 (million gallons per year)

The sole thing impacting the water flow in the non-residential sectors at this version of the model is the growth of the city and a slow but steady growth is therefore to be expected. The city government has expressed a goal to keep total water consumption constant even as population increase and has explicitly estimated that the industrial sector will decrease. Due to lack of concrete and detailed plans on how this is achieved, this has not been included in the model and is therefore also not shown in the results.

When it comes to the residential sector, the demand for *services using water* is increasing, following population growth, but with the explicit demand technologies included in the system, the actual *water use* is dramatically decreasing as the model seems to invest aggressively in low flow appliances. This behaviour suggests that the overall cost of providing water is in most cases higher than the marginal cost of changing to a more water efficient appliance (and all the water conserving appliances included in this version of the model meets the criteria calculated in section 5.1.2.1). Looking into the residential sector further, figure 13 and 14 shows where the decrease in water consumption is greatest. Most striking, water going to toilets are reduced by close to 90% in the multi-family households, and almost 85% in the single family homes. Water used in faucets and for dishwashing is also decreasing by more than 50%. Depending on the number and range of technology options included in the model for each residential service demand the water consumption has decreased in varying degree in different water needs in the residential sector. The toilet technologies included in the model represents the greatest variety in water use, where the most water efficient technology consumed only 6% of the least efficient toilet in place in the city today.

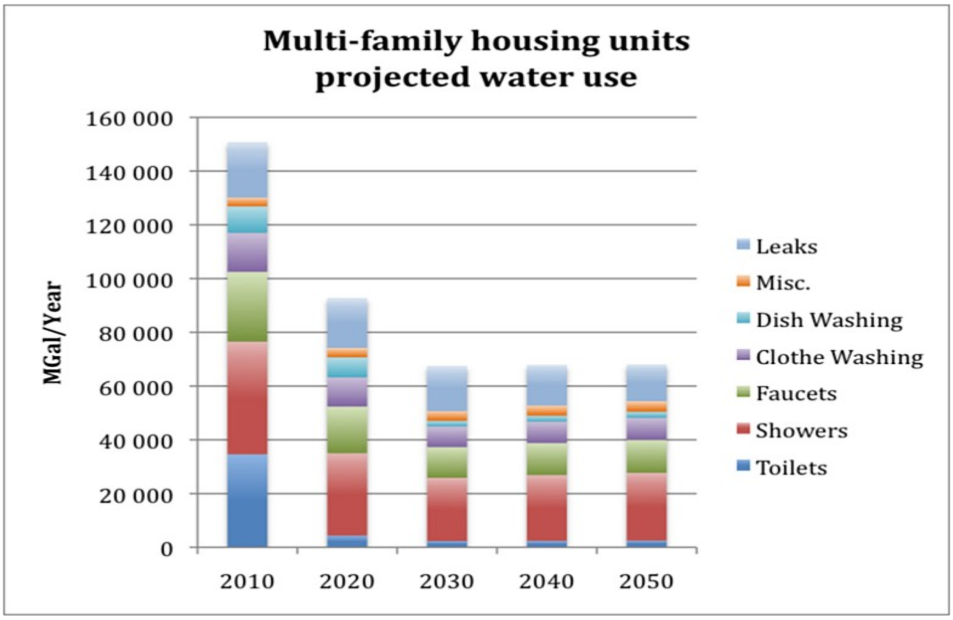

Figure 12: Modelled Multi-family Residential Water Use (million gallons per year)

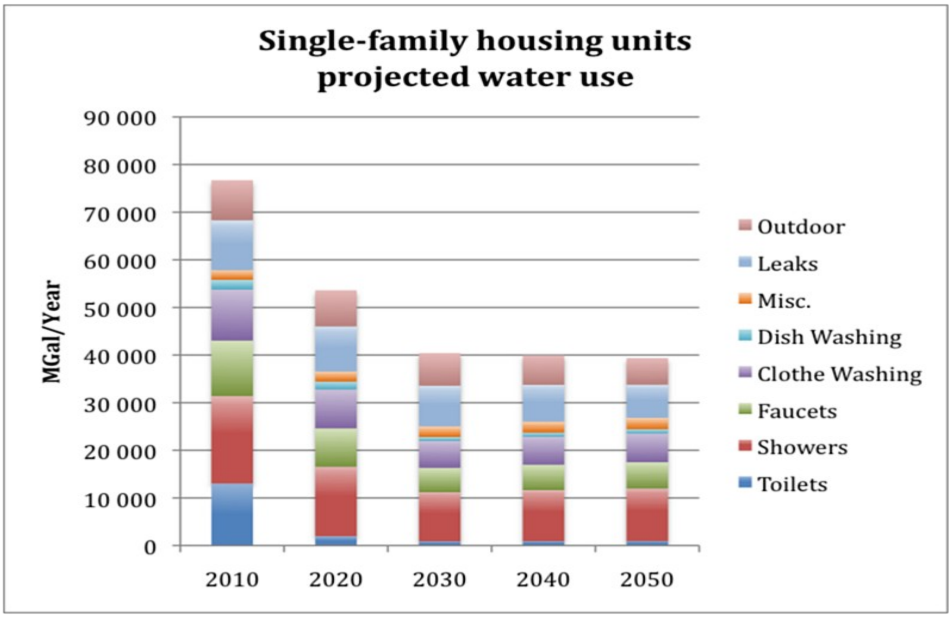

Figure 13: Modelled Single-family Residential Water Use (million gallons per year)

5.2.2 Developing an alternative Scenario to test the WaterMARKAL-model

The number of policy scenarios that could be develop for a MARKAL-model depicting water and energy in NYC are endless. For the purpose of testing the model dynamics and investigate if linkages between water and energy are portrayed realistically in the model, a very simple test scenario was developed.

Based on the results in the ”no constraints” scenario, it became clear that the model consequently chose the most water efficient residential appliances when new investments were made. This was obvious by the graphs depicting how residential water use develops and is confirmed in figure 15 and 16 below (also showing how the demand for appliances, or the service they provide, are increasing, following population growth, even as water consumption levels drop).

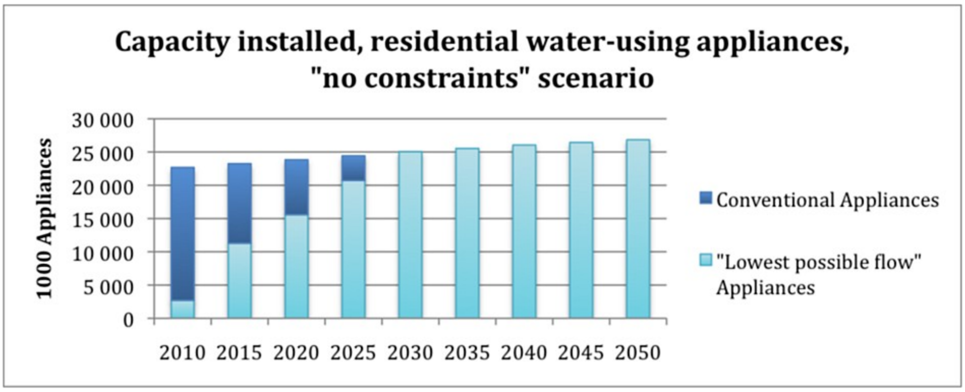

Figure 14: Illustration of how water-efficient appliance come into the market in the ”no constraint” modelling scenario.

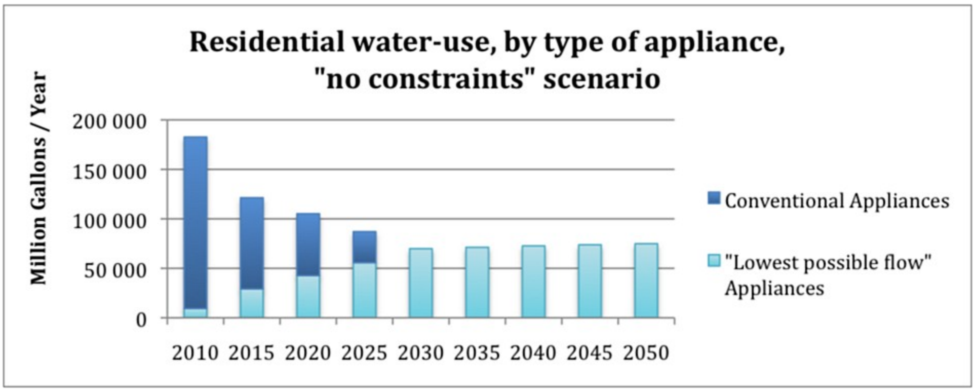

Figure 15: Illustration of how the introduction of water-efficient appliances affect residential water consumption in the ”no constraint” modelling scenario.

Putting a upper bound on the level of investments allowed each year for the most efficient appliances would slow down this development and should thereby slightly alter, or more specifically increase, the water use as less efficient appliances were forced to remain on the market. The most water-efficient toilet included in the WaterMARKAL-model uses on average 0.8 litre, or 0.21 gallons, per flush.[124] As seen in figures 13 and 14, this toilet is quickly out-competing all other toilets in the residential sector in the ”no constraints” scenario results. A more realistic scenario would be letting this technology enter the market more slowly over the coming decades as the acceptance and thereafter the demand for this technology gradually increase. Changing the model input data to simply constrain the number of these ultra low-flow toilets available on the market each year was therefore chosen as an appropriate, simple test scenario. With this change, it is

[124] Wostman Ecology Product Website [1]

expected that the model will both balance the water consumption pattern in the residential sector and, when compared with the first run, show if water consumption variety effects the energy consumption in the model the way it was designed to. Since energy is not directly consumed when either the conventional toilets or the ultra low-flow toilets are used any impact on the energy consumption would validate that the model both links the water used in one end of the system with the energy required to provide or treat it in another, and also show that the developed WaterMARKAL, when combined with the NYC-MARKAL energy model, can portray interlinkages between water and energy – the overall aim with this thesis.

5.2.3 Comparing the ”no constraints” run with a simple ”slow market” scenario

To first make sure that the altered water model is computed correctly, a graph showing what technologies are on the market was produced (figure 17). Low flow appliances are still coming into the market quickly, but some conventional appliances are forced to stay in operation and there is a clear difference in appliance mix when compared with the results in figure 15.

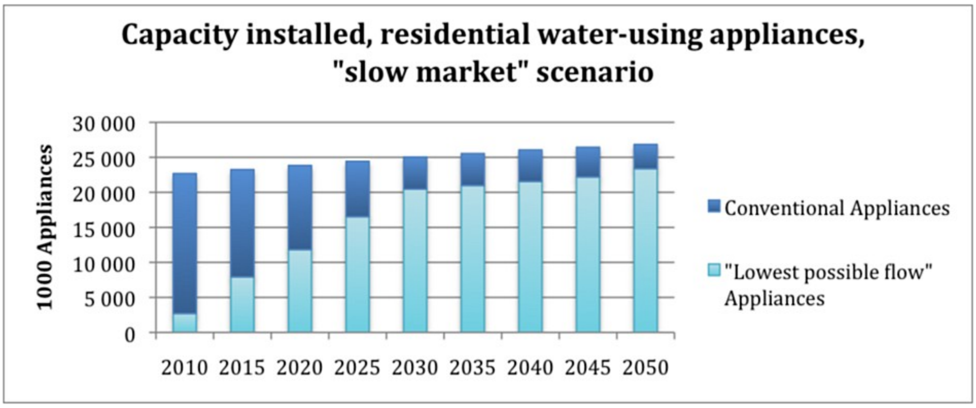

Figure 16: Illustration of how water-efficient appliance come into the market in the ”slow market” modelling scenario.

When the two scenarios are then modelled in parallel it is possible to test if coupling the water and the energy parts of the model really makes it possible to depict water and energy linkages in the city. The adjustments made in the ”slow market” scenario should directly impact water consumption, but is also expected to have indirect impacts on energy consumption and green-house-gas emissions, if the model is operating correctly, due to the embedded energy in the water system. Figures 18 to 20 shows the change in city-wide water consumption, energy consumption and CO_2-emissions in NYC between the 2 scenarios.

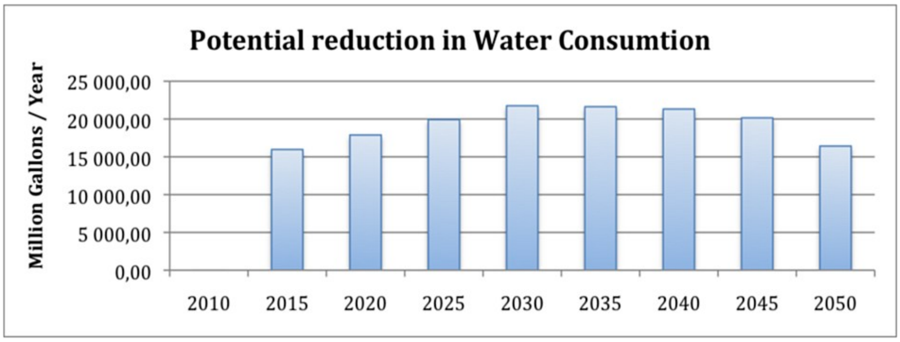

Figure 17: Change in water consumption when the market for low-flow toilets is constrained and not constrained in NYC 2010-2050

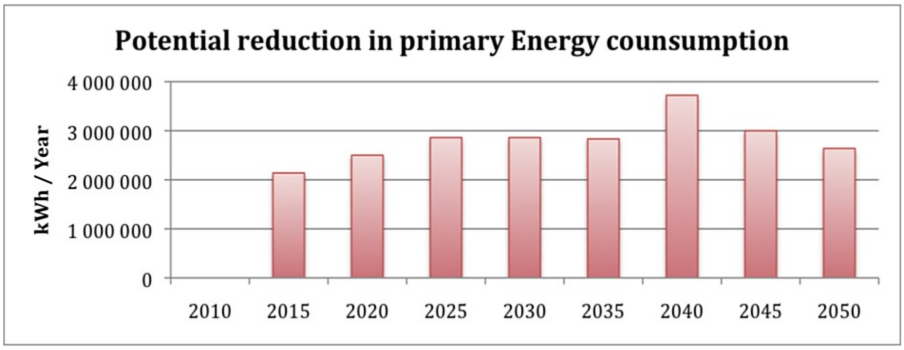

Figure 18: Change in energy consumption when the market for low-flow toilets is constrained and not constrained, predictions up to year 2050

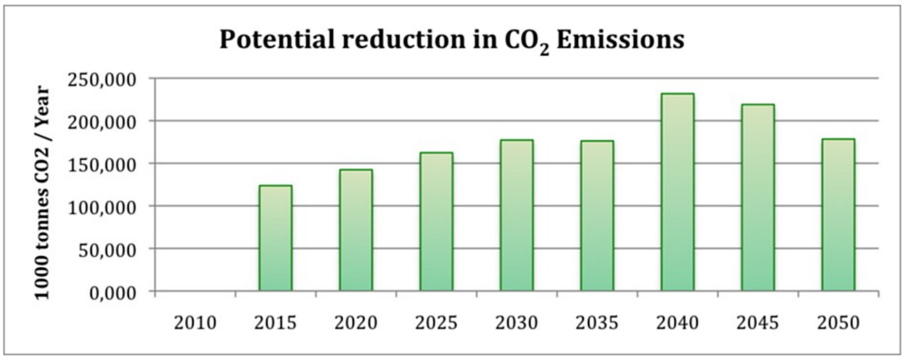

Figure 19: Change in CO_2-emissions when the market for low-flow toilets is constrained vs. not constrained, predictions up to year 2050

The graphs show a clear increase in both water and energy consumption as well as in CO2-emissions when older, less water efficient toilets remain in operation in the city. Inverting the meaning of these results, it shows the potential reduction in water and energy use and emissions if a rapid change to ultra low-flow toilets would be imposed by e.g. the city government. This is however in many ways an unrealistic scenario, and such a policy recommendation is not what this test scenario aims to provide. Instead, simply showcasing that energy and CO2-emissions both *are affected* by a water-conservation measure, and in the direction anticipated, gives validity to the developed NYC-WaterMARKAL model and shows its potential for modelling more realistic water-energy policy scenarios in New York City as it is further developed.

Due to the preliminary nature of these results, and since the wastewater system was not incorporated at the time of these model runs, the quantitative levels of change in water, energy and emissions levels will not be analyzed here. Instead, this thesis stops at the conclusion that all three graphs display similar curves of change and are therefore highly – and by visual examination almost linearly – interlinked. These linkages are likely to be even more emphasized in results from completed model, where the full wastewater flow is included, since a majority of the energy is consumed in that part of the water system.

6. Concluding discussion

In this thesis, a MARKAL model was expanded from its original energy-systems boundaries to in detail portray the water systems in New York City. The created WaterMARKAL-model, in its first version, includes all major parts of the system from a technological and economical point of view. Preliminary results from modelling runs of parts of the system shows promising results, including clear water-energy interlinkages. The applicability of the model on New York City policy issues is still limited, but further development is expected to make this WaterMARKAL model over NYC a useful tool to support long-term energy and water planning.

6.1 Achievements and limitations in the model building process

In order to start creating the Reference Water System for the WaterMARKAL model rigorous knowledge of the water system and the technologies included was required. The literature study showed a complex system with many ambitious city planning initiatives in the pipeline.

One of the most striking differences between the NYC water system and a general energy system – as usually modelled in MARKAL – was the fact that water systems have their ”end-use” in the middle of the system. In traditional MARKAL-modelling the commodity flow (of energy) ends with the user. The service that the energy carries out and the excess heat produced is not recovered. In the water system on the contrary, the water continues as a wastewater flow that is recovered and treated and there is even a potential for creating a closed loop if wastewater is treated to potable standards that could never occur in the energy system. With the issue of reoccurring combined sewer overflows in NYC and resulting contamination of the harbour water, not only the potential of wastewater reuse but also the overall challenge with wastewater management comes into the WaterMARKAL model.

Another difference noted during the model building was the substantial leakage found in the water system. Although energy is being lost in the form of low-temperature heat in many processes, it is not perceived to reach the levels found for water leakages in this study. The fact that over 20% of the water flowing into the system is not being used – or the use is not being accounted for – shows a clear difference between the water and energy system and perhaps also between how energy and water is valued in our societies.

As for the quantitative description of the NYC water system, appropriate data often proved to be difficult to find. Although reports and data from the DEP provided good guidance, to complete the model other sources of information had to be used and the discrepancy in the data material was at times high. Most predominantly, the investment costs for new water or energy system facilities and the water use in the NYC power plants were far apart when NYC data was compared with more general figures. Since the reliability of the results from a MARKAL model is directly proportional to the quality of the input data, these data weaknesses clearly limits the applicability of the created model.

While all physical parts of the water system described in chapter 2 has in some way been included in the model, many of the future plans were not possible to quantify and were therefore left outside this first version of the model. Nevertheless, this thesis shows that it is possible to build a MARKAL structure that depicts the water system technologies and that links to the energy system both for inputs and outputs of energy and water. Although it may not be possible to pull reliable and detailed results from the developed model at this stage, having this model structure in place provides a good base for further developments of the model.

A fully developed NYC WaterMARKAL model, with a sophisticated set of constraints, is expected to make it possible to model and quantify system limitations in the combined urban water-energy system that ”single-system” models would not do. Especially scenarios that do not allow imports from outside the city to ”solve the problem” would be suitable to model with this kind of model. An example of such a scenario could be the effects of the potential regulation on once-through cooling-systems water withdrawals, since this is expected to cause an increase in public water demand while the city's powerplants still need to meet their requirements of producing 80% of the city's peak demand.

6.2 Reflections on the Results from data and from model test run

The manual calculations of the model input data corresponds to the literature stating that energy used in the NYC water system is almost entirely consumed in the wastewater treatment plants today. This is only expected to change slightly when the more energy consuming Croton Filtration Plant and Cat/Del UV-plant is taken into operation. Opportunities for energy production at the wastewater treatment plants could therefore potentially significantly reduce the total energy need in the public water system. An interesting energy-water link that is more difficult to quantify or address with a single strategy is the energy needed when water is consumed in the residential sector. Clothe-washing was calculated to be many times more energy intensive (per drop) than the operations of the water system as a whole. This is assumed to be true for other equipments as well. Both in the manual calculation of energy consumption in the water system and in the results from the modelling runs it is clear that the combined NYC WaterMARKAL model have embedded interlinkages between water and energy consumption that a ”single-system model” is not expected to have. The test run of the model showed close to linear changes on both energy consumption and CO2-emissions to the air to those in water use from an adjustment in available water using appliances. In contrast to tools such as ”water footprint calculators” - that are very useful to account for the direct and indirect water that has gone into a product up until it is consumed - the MARKAL tool only takes into account direct water and energy consumption, but has in turn been shown to identify in-city linkages between seemingly independent sub-systems and effects from purely water-related changes in the energy consumption.

The economic calculations shows that operating the water system is quite costly. This is also confirmed when the model is tested as more expensive but less water consuming appliances are consistently chosen as the most economical solution by the model – unless constrained by the modeller. To make a thorough analysis of the marginal cost of water in NYC, cost figures would need to be further analyzed and fine-tuned. Still, the fact the that New York City water operations are largely funded by the city government – and not the residents using most of the services it brings – could potentially be a factor impeding the market for low-flow appliances in the city.

In sum, the results shows that the anticipated system dynamics between water and energy are in place in the mathematical algorithm behind the developed WaterMARKAL model. The scenarios tested in this thesis are not meant to provide any policy guidance on Water-Energy Nexus issues in New York City, but clearly shows that more balanced and realistic scenarios have great potential to give interesting modelling results as this NYC-WaterMARKAL model is further developed. Expanding the model to include more technologies, more realistic constraints and elasticity in prices as well as fine-tuning the input data is therefore believed to make the model a useful decision-support tool for policy makers on the city level.

6.3 Opportunities and Recommendations for Future Research

This thesis has provided a first showcase of a model that predicts how water and energy in NYC interact and can be affected in the coming decades. In addition to the already mentioned incremental improvements in input data that is continously needed in most MARKAL models, there are numerous possibilities to develop the model further and countless policy scenarios that could be investigated. A few of these are discussed below.

Adding technologies to the existing model could include describing the Commercial Sector, Industry and Public Sector with explicit demand technologies and corresponding service demands. This would enable the model to balance the water needs and the development of technology alternatives in the different sectors in a way that thus far has not been possible. It could also include adding more alternative technologies to all sectors of the system and possibly go into component level at the water treatment plants.

Adding more constraints to the model have already been mentioned as a development option throughout this report. Such constraints would ideally regard everything from green-house gas emissions to social behaviours (in a more sophisticated format than the one used in the test scenario). Additional interesting parameters to add to the water system and to put constraints on in the model are water pollutants. As mentioned in the introduction of this report, chemical and biological aspects of water treatment lies outside the scope of this thesis, but is dominating the literature and often driving the development of more advanced treatment. If these substances were captured in the model as pollutants from the water discharge, it would be possible to also model the development of water treatment facilities under different levels of water pollution regulations.

When it comes to scenarios to test with an enhanced version of the created model a few examples are given below. They all tie to issues or plans mentioned in chapter 2 that were not included in this version of the model:

- Effects on the urban water and energy system from water withdrawal constraints in the power sector. As mentioned previously, this is expected to affect public water consumption dramatically, but exactly how would be interesting to test with the model.

- Investigating the Green Infrastructure potential on both energy and water system sustainability. The dual service from urban green areas of giving both Urban Heat Island mitigation – as was investigated by the NYC MARKAL in 2010 – and stormwater retention – that is one of the prioritized CSO mitigation efforts by the city – could be interesting to investigate with MARKAL.

- Transforming the NYC WPCPs into energy producing units – going into more detail on the potential to make WPCPs energy self-sufficient or even net producers of electricity.

- Investigating impacts from Shale Gas extraction in the upstate Water Supply – Looking into how MARKAL could depict both direct and indirect ties between energy and water in the natural gas extraction technology of hydro-fracking in the upstate watershed.

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[5] http://www.nyc.gov/html/dep/html/stormwater/combined_sewer_overflow.shtml (2011-08-08)
[6] http://www.nyc.gov/html/dep/html/harborwater/index.shtml (2011-07-26)
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[8] http://www.nyc.gov/html/dep/html/residents/wateruse.shtml (2011-09-08)

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New York Power Authority website:

[1]http://www.nypa.gov/services/fuelcellprojects.htm (available 2011-04-13)

New York State Assembly's website:

[1]http://assembly.state.ny.us/leg/?default_fld=&bn=A05318&term=2011&Summary=Y&Memo=Y (2011-09-12)

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Energy Star Data (a United States Environmental Protection Agency and U.S. Department of Energy initiative):

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(http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/CalculatorConsumerClothesWasher.xls (2011-09-06))

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Vatsal Bhatt, Brookhaven National Laboratory, informal advisory talk, April 8, 2011

Anthony Fiore, Chief of Staff, Operations, New York City Department of Environmental Protection, Interview, June 22, 2011 and follow up phone interview, July 18 2011

John C. Lee, internal MARKAL-briefing Session, Brookhaven National Laboratory, July 27, 2011

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Appendix A

This following is a list of all sources used to gather input data the WaterMARKAL-model. For more information on what data was collected, please contact the author.

Reports, Presentations and Datasets:

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http://www.homewyse.com/services/cost_to_install_toilet.html (2011-05-20)
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Appendix B

Assumptions made throughout the data collection work as well as calculations made to aggregate final data for make pre-modelling analysis are described in this appendix.

1. Water Flows

1.1 It is generally assumed that 90% of the NYC Public Water Supply (DEP System) comes from the Catskill/Delaware Water system and 10% comes from the Croton System.

1.2 Leakage and system losses are not measured, but the assumption that is used by DEP is 5% of total water supply.[1] The unaccounted for water however, reaches 21% of water distributed to the city by DEP. This includes water for fire fighting and other fire hydrant uses (sometimes used as cooling sprinklers for residents during the summer) leaks in the system and unmetered water.[2] For all of these "unaccounted" uses apart from leakage, it is assumed that the water goes into the sewer system. Since the 21% figure can not be disaggregated further, the 5% leakage figure is used when calculated the water flow that is lost and *not* reaching the sewers.

1.3 This leakage is assumed to be largely offset – from a water balance perspective – by a 5% increase in wastewater creation from all activities and people migrating into the city during the workdays. This "5% imported wastewater" assumption is used by the DEP.[3]

1.4 With roughly 1 Billion Gallons per day (BGD) of water flowing into the city through the water supply system, but roughly 1,3 BGD flowing out and passing the water pollution control plants, it has been assumed that the additional 0,3 BGD or 300 million gallons per day can be allocated to storm water runoff to the combined sewer. This assumption is built up by the following arguments:

- New York City is one of few large cities who has a combined sewer system for much (~70%) of its wastewater – meaning that storm water (rainwater) is largely diverted from the city through the same sewer pipes as wastewater and ends up in the WPCP.[4]
- The average annual precipitation over New York is 45 inches. Multiplying this by the total land area of New York City (305 square miles or 790 km^2)[5] and distributing it evenly over the year this amounts to around 550 million gallons per day. 70 % of this is just below 400 MGD.
- Parks and green areas of the city are not expected to create any storm water runoff since the water is retained and absorbed by the soil and vegetation.

1.5 For 2010 water delivery data, the DEP report *Water Conservation Plan, annual Update* for 2011 has been used. Due to the 21% unaccounted for water, the water shares are shifted to: Residential: 61%, Non-residential: 15% (Internally estimated to be split as: Commercial = 13,5%, Industrial+Thermoelectric = 1,5%), Public/Government Use: 3%. Thermo-electric public water use is estimated to be higher than in 2005 due to a couple of new or upgraded plants using cooling towers instead of once-through cooling and consequently moving from direct self supply to municipal water.[9] Simultaneously the total industrial municipal water use is estimated to have declined, in coherence with a declining sector.[10]

1.6 Data on public supply deliveries to each sector of the city was not available for the year 2005. Only the domestic share, accounting for 58% of this water use, was available. The remaining 42% has been allocated as follows: Public Use: 11%, Industrial Sector: 1% (see assumption 1.6), Thermo-electric Sector: <1%, Water losses: ~4%, Commercial Sector: 25 %. This is based on USGS data for 2005[6] and the distribution of an average American publicly owned water supply from EPA.[7]

1.7 The self-supplied water to industries in New York City in 2005 amounted to 60 MGD.[8] The industrial sector is generally assumed to get 80% of its water needs from self-supplied systems and the remaining 20 % from a municipal supply, which would equal to around 15 MGD in NYC in 2005. 15 MGD is slightly more than 1% of the total daily water supply through the public system, why this percentage was chosen for the 2005 base year.

2. Water System Economic Figures

2.1 Calculating the Upstate Water Supply:

Based on Table 1.A&B, 4.A&B and 8.A&B in New York City Water Board's *Report on the Cost of Supplying Water to Upstate Customers for the 2009 Rate Year*[11] and *Report on the Cost of Supplying Water to Upstate Customers for the 2011 Rate Year*[12] the cost for maintaining the Croton and Catskill/Delaware Water Supplies were calculated by adding together:

"OTPS Costs – all" + "Personal Services Costs – Watershed Security" + "Personal Services Costs – Hillview Reservoir" + "Facilities North of the City - Debt Service/ Capital Costs" + "Facilities North of the City -Misc, Costs".

These were then split between the water supplies: 90% to Catskill/Delaware and 10% to Croton. For the Croton System "*Personal Services Costs – Watershed East of Hudson*" was then added.

2.2 Catskill/Delaware UV Facility:

Based on the same tables as assumption 5.1, the O&M costs for the facility was calculated by adding together:

"OTPS Costs – UV Facility" + "Personal Services -UV Facility"

2.3 Operational costs per drop of water:

The below table was used created when calculating operational costs for the entire water and wastewater system – per 1000 gallons of water.

Table B 1: Calculated operational cost per gallon of NYC Water

	2010	2015
Cost of supplying 1000 gallon of municipal water:	1,5888	3,7348
Cost of treating 1000 gallon of municipal wastewater:	2,1463	3,1539

The water supply figures were reached by adding together O&M cost data for all water sources, water disinfection (for 2010) or Croton Plant and Cat/Del UV-plant (for 2015) and conveyance - divided over the amount of water going to each of these technologies. The wastewater was similarly calculated by taking the O&M-costs for sewer system and the total wastewater treatment system and divide them over the total water flow.

3. Water System Energy Assumptions

3.1 Water Sources - apart from Groundwater and Recycled Water – are not estimated to have any energy consumption.

3.2 Water Demand Technologies that does not have an electrical component – such as toilets, faucets and shower heads – are not estimated to have any energy consumption. All energy consumption related to domestic hot water is captured by the domestic hot water demand technologies.

3.3 Catskill/Delaware UV Plant and Croton Filtration Plant energy requirements for treatment was calculated based on figures in their respective FEIS-reports. First the required power (kW) at average load – times 24 to get a full days operation – was divided by the average water flow (MGD). The same thing was done for maximum load figures. These figures were far apart and did not correspond to other estimations for general plants in the literature. Therefore the same calculation was made for the marginal power increase and the marginal water flow (from average to maximum). These figures corresponded much better to other literature sources and are capturing the power requirements for every additional drop of water.

3.4 WPCP Energy Demand – based on treatment technology:

All WPCP's in NYC have AAS-treatment, 7 of them also have a basic step nitrogen removal. [13] 5 plants out of these 7 plants, plus 3 plants that does not yet have any specific nitrogen removal steps in their treatment process, are scheduled to have advanced nitrogen removal before year 2020. One plant, the 26th Ward WPCP in Jamaica bay, will be the first plant to get ARP treatment to its side-stream.[14] Wards Island is under upgrade to get full scale SHARON treatment of the water returning from the dewatering facility.[15] The remaining 6 plants scheduled for nitrogen removal are in the base case scenario expected to get conventional full-scale nitrogen removal.

The energy input for these different kind of wastewater treatments are summarized in table B.1

Table B 2: Energy Input, Investment Cost and Operation & Maintenance (O&M) Cost, estimates for the WPCP treatment alternatives in NYC.

	Energy Input	Inv. Cost	O&M cost
Treatment process	**MJ/MG**	**$/(BG/year)**	**$/BG**
Advanced Activated Sludge Treatment (AAS)	3701[1]	N/A[2]	N/A[2]
AAS + Basic Nitrogen Removal	4277[1]	N/A[2]	N/A[2]
AAS + Full-scale Nitrogen removal (conv.)	5609[3]	1 610 959[4]	632 731[5]
...with SHARON	4207[6]	597 227[7]	550 005[6]
...with ARP	4767[8]	321 414[8]	316 365[9]

1 EPRI (2002b) Water and Sustainability - Volume 4, p. 3-5

2 Not available, these costs are either already invested or are based on actual data from the NYC WPCPs.

3 Calculated based on Grontmij estimate (se comment in cell) and EPRI, Water & Sustainability - Volume 4, p. 3-5

4 From EPA: Biological Nutrient Removal Processes and Costs, June 2007, p. 10

5 Based on Plant-wide (BSM2) evaluation of reject water treatment with a SHARON-Anammox process, by E.I.P. Volcke et.al. IWA Publishing 2006. (London), p. 7

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9 Est. from the 'Frost & Sullivan' *Movers and Shakers* interview with ThermoEnergy representatives, Nov 18 2005 (published at: http://www.frost.com/prod/servlet/exec-brief-movers-feature.pag?mode=open&sid=53501427)

4. Water Use Assumptions

4.1 Residential Water Demand data was provided of 4 different types.:

4.1.1 Total water quantity delivered to residential sector (mainly from DEP and USGS) and average daily water use per household and/or capita (from various sources).

4.1.2 Residential water use split up in percentages going to toilets, faucets etc.

4.1.3 Data on the number of times an appliance is used per cap/day, per appliance/day or per household/day together with technology-specific data on how much water each appliance use, from conventional clothe washers in gallons/load to aerated faucets in gallons/min.

4.1.4 Some approximation on the split between conventional and efficient appliances for the base year 2010.

Description of how this data was used:

These assumptions were weighed together to arrive at a reasonable approximation of total number of appliances for all different needs in the residential sector. Total water quantity going to the residential sector, data on number of uses per day and technology specific Gallons/flush etc. were kept constant. Firstly, data of type 4 was reworked to fit New York City. This included allocating at least 1.3 million toilets to being "low flow" in accordance with the city's various toilet replacement project conducted between 1993 and 2005.[16] It further included making reasonable approximations regarding how many showers, faucets and toilets there are per capita in NYC – since these figures were only provided in per capita units.

The percentage of water going to each residential water use sector was then modified to better represent NYC conditions and was done separately for multi-family and single-family residential unit. The below table shows how the daily water use has been divided in the respective residential unit types.

Table B 3: Estimated residential water consumption, by use

	AWWA Research Foundation[125]	NYC Multi-family Unit		NYC Single Family Unit	
Water Use Area	*%*	%	Gal/Day	%	Gal/Day
Toilets	*26,70%*	*23,00%*	*41,0*	19,09%	41,0
Showers	*16,80%*	*27,90%*	*49,7*	26,95%	57,9
Faucets	*15,70%*	*17,00%*	*30,3*	16,85%	36,2
Clothes washers	*21,70%*	*9,64%*	*17,2*	15,72%	33,8
Dishwashing	*1,40%*	*6,56%*	*11,7*	3,00%	6,4
Miscellaneous	*3,90%*	*2,20%*	*3,9*	3,00%	6,4
Leaks	*13,70%*	13,70%	24,4	15,39%	33,0
Water Use for one Household in Gallons per Day:					
Total Indoor			178,08		214,67
Outdoor			0,00		26,42
Total			*178,08*		*241,10*

The basis of the division of water between different appliances in the household was taken from a study on residential water use carried out by the American Water Works Associations (AWWA) Research Foundation in 1999. This was then manipulated to describe the particular water use conditions in NYC. For single-family units, who was given a total annual water

[125] P. W. Mayer, W. B. DeOreo, *Residential end uses of water*, AWWA Research Foundation, 1999, p. Xxvi

consumption of 88000[18] gallons, a share of this water was allocated to outdoor use. This is estimated to be 22,81 gallons/day per household (averaged out over the full year) from the estimate that up to 40% of water is used outdoor during the summer months[19], and assumed that summer comprises one quarter of the year. This is suspected to be a slightly too high estimate for only gardening purposes, but as other outdoor uses such as car washing are not explicitly described in its own category this “outdoor water use” data is considered to be a good enough estimate for the purposes of this study. No outdoor water was allocated to multi-family households.

Multi-family households in NYC are not estimated to have clothes washers in the same numbers as in the AWWA data, considered to be closer to average U.S. conditions. Commercial Laundromat facilities are common in the city and when residents use these the water is metered as commercial water use. For dish washing, it is assumed that many households do not have a dishwasher installed but do their dishwashing by hand. The water consumed when dishes are washed by hand are several times that of conventional dishwashers, why the share of water going to dish washing is significantly higher than what the literature suggests. The single family households are closer to the AWWA shares but are also slightly adjusted. The amount of water going to toilets are lower than the AWWA suggests much due to the city’s toilet replacement program described earlier. Showers on the other hand is given more water, based on DEP data on amount of water used per person for showering in NYC.

The last step in the calculation was to match the total amount of water going to each use segment with the water use per appliance. For dish washing and clothes washing data was available per appliance, but for the other main uses, toilets, faucets and showers water use was only given in per capita numbers. These were therefore transformed according to the following approximations: 2 people per toilet; 1 people per faucet; I,7 people per shower.

4.2 Calculating domestic leakage:

To make sure the domestic leakage level is reasonable, the 13,7% leakage estimation was tested in the following way. As calculated above, one household is expected to consume between 178 and 214 gallons of water per day. If roughly 13% of this is to go directly to leakage, sufficient number of appliances needs to leak. On the DEP website[20] the following leakage estimations are found:

Table B 4: NYC DEP General Leakage factors[126]

Faucets:	
Slow Drip	36 Gallons
Steady Drip	180 Gallons
One Quarter Open	684 Gallons
One Half Open	1620 Gallons
Full Open	3600 Gallons
Toilets:	
Seeping	30 Gallons
Leaking	250 Gallons
Constantly Running	6000 Gallons

Approximating total household water use to 180 gallons/day and leakage should be 13%, an equation to calculate how number of households can be ”counted” for one leaking appliance could be:

[126] www.nyc.gov/html/dep/html/ways_to_save_water/waterleak_wide.shtml, (2011-05-20)

$$x = \text{Leakage}/(180*0,13)$$

where x is the number of households. For the slow dripping tap, this is 1.5, for the seeping toilet it is 1.3, and for a steadily dripping tap it is 7.7. In other words, one steadily dripping tap in every 7th household will create more than 13% total domestic sector water losses. For slowly dripping taps and toilets, if 2 appliances are dripping in every 3 households, the leakage would come close to 13%. By looking at the table, it is clear that more severe leakages can occur in one out of many households to create the same total effect. The 13,7% water leakage level is therefore estimated to be high but realistic for NYC domestic sector.

References for Appendix B:

[1] Interview with Anthony Fiore, June 22, 2011

[2] DEP Water Conservation Plan, Annual Update, June 2011, p. 19

[3] Interview with Anthony Fiore (2011-06-22)

[4] New York City's Wastewater Treatment System, DEP report from ____?

[5] NYC Department of City Planning (http://www.nyc.gov/html/dcp/html/landusefacts/landusefactshome.shtml)

[6] *Estimated Water Use in 2005, by County,* NYS counties spreadsheet.

[7] EPA, *Cleaner Water From Conservation*, 1995, p. 8

[8] *Estimated Water Use in 2005, by County,* NYS counties spreadsheet

[9] EPA Form 860, with 2009 data for New York State Plants

[10] See e.g. figure in PlaNYC (1st edition), p. 6.

[11] New York City Water Board and Amawalk Consulting Group, 2008 *Report on the Cost of Supplying Water to Upstate Customers for the 2009 Rate Year*

[12] New York City Water Board and Amawalk Consulting Group, 2010 *Report on the Cost of Supplying Water to Upstate Customers for the 2011 Rate Year*

[13] Acc. to DEP's Nitrogen Control Action Plan 6th annual report, 1998, executive summary, p. 1

[14] *ThermoEnergy: Back from the dead?*, article in American Water Intelligence (AWI), Vol 2, Issue 4 (April 2011)

[15] *Removing Nitrogen in One Step – The first U.S. installation of SHARON technology reduces energy and BOD demands, saving money and space*, Biosolids Technical Bulletin, May/June 2010, Volume 16, Number 3. Water Environment Federation

[16] DEP, Water Conservation Report, Annual Update, June 2011, p. 15

[17] P. W. Mayer, W. B. DeOreo, *Residential end uses of water*, AWWA Research Foundation, 1999, p. Xxvi

[18] Average between 2009 and 2011 figures published by DEP (see *NYC Water Board Blue Book 2010* and *NYC Water Board Blue Book 2012*) for water consumption estimates by sinlge-family households, 100'000 and 80'000 gallons/year respectively.

[19] From DEP Press Release (DEP 2011a)

[20] www.nyc.gov/html/dep/html/ways_to_save_water/waterleak_wide.shtml, (2011-05-20)