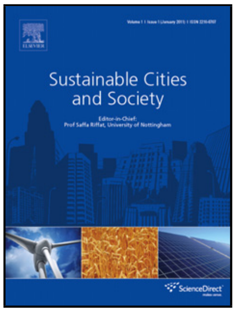

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Connecting the resource nexus to basic urban service provision – with focus on water-energy interactions in New York City

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Highlights

- Urban water and energy systems have essential and multiple interlinkages that should be considered when assessing the effects of efficiency and sustainability measures.
- A prototype *Reference Resource to Service System (RRSS)* framework is used to represent the urban water-energy nexus and linked impacts of measures.
- Indicative analysis based on example data for New York City reveals large variability in multi-resource and climate mitigation benefits.

Abstract

Urban water and energy systems are crucial for sustainably meeting basic service demands in cities. This paper proposes and applies a technology-independent "reference resource-to-service system" framework for concurrent evaluation of urban water and energy system interventions and their ‘nexus’ or ‘interlinkages’. In a concrete application, data that approximate New York City conditions are used to evaluate a limited set of interventions in the residential sector, spanning from low-flow toilet shifts to extensive green roof installations. Results indicate that interventions motivated primarily by water management goals can considerably reduce energy use and contribute to mitigation of greenhouse gas emissions. Similarly, energy efficiency interventions can considerably reduce water use in addition to lowering emissions. However, interventions yielding the greatest reductions in energy use and emissions are not necessarily the most water conserving ones, and vice versa. Useful further research, expanding the present analysis should consider a broader set of resource interactions, towards a full climate, land, energy and water (CLEW) nexus approach. Overall, assessing the impacts, trade-offs and co-benefits from interventions in one urban resource system on others also holds promise as support for increased resource efficiency through integrated decision making.

Keywords:

Urban service provision; Water-energy nexus; Integrated resource assessment; Urban sustainability; Multi-resource impacts; New York City

1. Context

Traditionally, urban service delivery systems are planned, developed and operated in silos. While improvements in water utility operations can improve the reliability and water-quality performance of a city’s water system, more advanced water treatment typically requires more energy (Pabi et al. 2013). Further, providing this energy requires water. The use of water in hydropower production can be significant (Destouni, Jaramillo, and Prieto 2013; Jaramillo and Destouni 2015a). Fuel extraction and processing require water before the fuel is put into electricity production (where additional water is used for cooling purposes) or used directly for heating or industrial processes. (Macknick et al. 2012a; Mekonnen, Gerbens-Leenes, and Hoekstra 2015; Mielke, Anadon, and Narayanamurti 2010). As a result, changes in a city's water system may alter the city's indirect use of both energy and water (Bazilian et al. 2011). Within the city the parallel water and energy systems have numerous interdependences (Kenway et al. 2015; Chini et al. 2016; Abdallah and Rosenberg 2014). Uncoordinated planning and management of these systems may therefore be suboptimal – with unaccounted for indirect impacts (Scott et al. 2011).

The importance of interlinkages in the supply chains of water, energy and food has been highlighted by the International Atomic Energy Agency (IAEA 2009), among others, emphasising the need for integrated management of Climate, Land use, Energy and Water (CLEW). Howells and Rogner (2014) further argue for the need to develop quantitative frameworks to support such integrated management and policies for increased efficiency and sustainability.

In recent years, CLEW, or *nexus*[1], studies have started to address various geographical scales: global (United Nations 2014), regional (Smajgl and Ward 2013; UNECE 2014), and national (Hermann et al. 2012; Howells et al. 2013; Macknick et al. 2012b; Sattler et al. 2012; Welsch et al. 2014). At sub-national level, Bartos and Chester (2014) point out missed opportunities from a lack of integrated handling of water and energy services in the state of Arizona, USA.

Available nexus literature at urban scale typically fall into one of three categories: comprehensive studies of single interactions, such as the energy footprint of a water utility's operations, or the energy and emission impacts of water conservation measures (Sanders and Webber 2015; Stokes, Hendrickson, and Horvath 2014; Xu et al. 2014); assessments of embedded resources in (and emissions of) water or energy supplies (Kenway et al. 2008; Plappally and Lienhard 2012; Sanders and Webber 2012; Sattler et al. 2012; Stokes and Horvath 2010; Zhou et al. 2013) or; more general reviews of urban planning practices (Yang and Goodrich 2014). By modelling the end-use consumption of water and energy, Rhodes et al. (2014) demonstrate the value of relevant data collection, including by use of smart meters. Other end-use focused studies regard correlated resource consumption patterns across

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[1] The *nexus* refers here to the interplay and interconnections between different societal or natural systems or resources. Most commonly found to cover water, energy and food, but also found to be joined by security, eco-systems, climate, sanitation, health and/or gender (see for instance (Beck and Walker 2013; UNECE 2014))

households (Abdallah and Rosenberg 2014) and potential economic and resource savings from shifts to high-efficiency residential appliances (Chini et al. 2016). Overall, however, as Nair et al. (2014) also points out, technology-general frameworks where centralized and decentralized solutions can be assessed concurrently for integrated urban resource planning and management, are still in their infancy.

This paper contributes to the development of such a framework for linked urban *resource-to-service systems*, focusing on the urban water-energy nexus in relation to meeting urban service demands. A specific case study, based on data for New York City (NYC), is used to exemplify the concrete application of this framework. Water and energy use impacts from a limited set of urban interventions are studied, with interventions grouped into two categories: (1) shifts to more *water and/or energy efficient household appliances* and (2) expansion of selected *urban water management measures*. By analysing different types of interventions (carried out by different actors in the city, motivated by different urban needs and linked to different parts of the city's energy and water infrastructure), we explore the usefulness of a, for this work developed, *Reference Resource-to-Service System* (RRSS) for informing the analysis of interlinked urban water-energy interactions.

2. Methodology

2.1 Framework

To map how resource supply chains are intertwined in the urban space, a conceptual RRSS schematic is developed that combines elements of a reference resource system (IAEA 2009; Weirich 2013) and flow diagrams for urban metabolism (Newman 1999). In the RRSS the demand side is placed at the centre, in order to capture how resource flows feed into urban service provision. Similarly to its predecessor for energy system analysis (the reference energy system – or RES (Seebregts, Goldstein, and Smekens 2002)), the developed RRSS schematic illustrates how a change in a single system link impacts other links, by simply following the arrow chains through the flowchart.

Figure 1 presents a prototype RRSS schematic developed for the case study of the NYC water and energy resource systems. Although currently based on NYC data, this RRSS framework can – with relatively small modifications – be applied to other cities. A more comprehensive RRSS schematic can also graphically capture how impacts from a broad range of urban interventions ripple through additional resource systems, such as land-use toward various end-use sectors.

The RRSS schematic is model independent by just illustrating the key elements of each resource system and how these are linked to form a system-of-systems (SOSys). Various models can be used to quantify the RRSS elements and links, as appropriate on a case-by-case basis. The schematic thus simply maps the interactions and models used to quantify them may range over different possible simulation, optimization, and/or accounting models. The illustrative case study described in this paper uses an accounting approach, with data describing marginal impacts of the studied interventions, based on an illustrative 'snap-shot' of NYC's resource-to-service water and energy flows in the year 2010.

2.2 Case study

NYC has a population of more than 8 million people (U.S. Census Bureau 2016) and is the centre of one of the world's top ten largest metropolitan regions. In 2010, the municipal water system supplied the city with one billion gallons (3.8 million cubic meters) of water each day, while 1.2 billion gallons (4.6 million cubic meters) of wastewater were treated in fourteen in-city wastewater treatment plants (NYC Department of Environmental Protection 2012). These volumes make the NYC Department of Environmental Protection the largest municipal water utility in the United States. The water system is characterised by mainly gravity-fed water supply and comprehensive watershed protection measures. The latter means that water filtration requirements can be evaded, thus relatively little energy is used for water treatment at the supply side (NYC Department of Environmental Protection 2011).

At the other end of the water system, stormwater and municipal wastewater share pipes in the city's combined sewers. Heavy rains repeatedly cause the city's sewers to overflow, releasing untreated wastewater to the urban watershed. The city actively aims to reduce these overflow events as part of its comprehensive PlaNYC2030, with green infrastructure and rainwater harvesting measures being important parts of the solution (City of New York 2007).

For electricity, NYC is connected to the United States Eastern Grid for electricity supplies. Yet, due to limited transmission infrastructure, the city is required to have an in-city production capacity of 80% of the projected summer peak demand (NYISO 2012). This capacity is normally not fully utilized. In 2010, in-city plants produced 45% (or 86 PJ) of the total 190 PJ of electricity consumed in the city. The city's second largest fuel use (in terms of source PJ), after electricity, is direct combustion for heating. Fuel oil boilers are being increasingly replaced, primarily by natural gas-fired alternatives. In 2010, natural gas contributed 62% (or 271 PJ) of the (non-electricity) fuel use in NYC buildings (City of New York 2012).

2.2.1 Studied water and energy interventions

Residential buildings account for close to 80% of the NYC's water use. Directly and indirectly, they account for a third of the citywide greenhouse gas emissions (NYC Department of Environmental Protection 2012). For these reasons, our analysis focuses on interventions related to the residential sector.

The RRSS aims to be technology-independent. As such, the number of urban interventions *possible* to assess in the RRSS framework should be close to the number of possible interventions in a city (i.e. countless). These could range from improvements in power plant efficiency, or water system leakage control schemes, to interventions relating to any existing or potential appliance using energy and/or water, including measures to recover waste heat or grey-water. In the present case study, only a limited set[2] of interventions is analysed.

The first category of interventions chosen for analysis regards different household appliances, including only water-using appliances (*toilets*), only energy-using appliances (*lighting*), and appliances that require both resources (*showers and washing machines*) (Table 1).[3] The second category of studied interventions is chosen to further capture indirect and decentralized interactions of the urban water-energy nexus, considering in particular an expanded use of *extensive green roofs*[4] on residential building rooftops and of *rain barrels* in single-family household gardens (Table 1).

Rain barrels are normally seen as 'water only' interventions and provide a low-cost point of comparison in the analysis. Rain barrels can reduce the use of municipal water use for

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[2] This set is not to be interpreted as comprehensive. Nor does it attempt to capture all of the most important interventions in NYC. Rather, the set is chosen as an initial example of a variety of interventions that can be studied in the RRSS framework.

[3] Other household services, such as space heating or food preparation can be significant water and energy users. The ambition of this study lies at illustrating the *variety* of interventions applicable (and comparable) in the RRSS framework. With a similar cost structure other service/appliance interventions can be assessed (including HVAC)

[4] Green roofs are vegetative layers grown on building rooftops. The vegetation scheme can vary from *extensive* – characterized by sheets of mosses or sedum – to *intensive* – characterized by larger plants or full gardens (U.S. Environmental Protection Agency 2011).

gardening in single-family households as well as decrease stormwater flows during heavy rains.[5]

Green roofs can have an insulating effect, decreasing the demand for heating and cooling in buildings (Berghage et al. 2009; NYSERDA 2012). They also reduce stormwater runoff, which is of particular relevance for NYC with its combined sewer system (NYSERDA 2012). In this study, the studied green roofs are considered to have minimal maintenance and irrigation requirements. Consequently, in the present numerical analysis, both the green roof and the rain barrel interventions have, limited direct resource use, once installed. However, they both have indirect impacts on the urban energy and water systems.

2.3 Quantifying nexus impacts

Available data on average annual conditions for year 2010 are used in the study, without taking into consideration intra- and inter-annual temporal variability. This variability may be important and can be considered in further studies and model developments. In this paper, we focus on developing and gaining insights from a first, internally consistent, multi-resource approach step for average conditions.

Seeking insights, rather than specific answers, in this way is a key use of models (Finn 2012). While the future changes of, e.g., climate, population and technology are unknown investigation of integrated resource scenarios with known present conditions is an important first step before further investigating possible future change scenarios.

Input data for investigating present conditions are compiled from a variety of publicly available sources of NYC data and relevant additional data for other cities and regions. Macro-information of citywide resource use is gathered and linked to estimated costs and indirect resource uses associated with each unit of direct water or final energy use. In order to allocate water and energy use to various end-use sectors and residential service demands, we employ a top-down approach. City-level data on direct water and final energy use are disaggregated by published percentage shares for each end-use sector, for NYC itself, a comparable city or based on national statistics. We acknowledge that all households and neighbourhoods in a city are not equal in their resource use (Gu, Sun, and Wennersten 2013). However, assessing the impacts of

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[5] Rain barrels are in this study by far the smallest-scale intervention (Table 1) - since the proportion of single-family households with a garden is relatively low in NYC. However, because this intervention most closely corresponds to an ongoing water management program in NYC (the "Rain Barrel Giveaway Program (NYC Department of Environmental Protection 2012)), it is considered a relevant point of comparison in the analysis.

residence variations is a contribution meriting publication in its own right and outside the scope of this paper. The share of the total resource use associated with each investigated service is estimated by collection and interpretation of appliance-level data from retailers' websites. More details on assumptions, input data and sources can be found in the supplementary material of this paper.

2.3.1 Indicative assessment of selected measures

A set of equations, assuming linear interdependencies, is developed and used to describe how each intervention would affect water use, wastewater load, energy consumption, indirect water consumption and carbon emissions. In addition, simple marginal cost and payback period equations are used to estimate the economic cost or benefit of each intervention.

Impacts on final energy use are disaggregated and categorised throughout the paper as: direct energy use reduction (energy use reduction of the studied appliance); indirect reduction of residential energy use (within the residential building, but not in the specific appliance analysed); and indirect, water utility related, energy use reduction (energy use change due to reduced need for water and wastewater treatment and transport).

Below, we present the most relevant equations employed in the numerical analysis. The full list of equations can be found in the supplementary material to this paper.

- For interventions that regard water using household appliances, the associated energy use change is calculated as the sum of changes in: direct energy use of the appliance *E(x,direct)*; indirect local energy use (e.g. for water heating) *E(x,local)*; and indirect energy required to treat and deliver the water used in the appliance and to collect and treat the wastewater produced *E(x,water system)*. These three variables are estimated as:

  $$E(x, direct) = DE(x) * x_{\#} * use(x) \,, \tag{1}$$

  $$E(x, local) = \sum_{i=1}^{n} [W(x) * HW\%(x) * E_{wh}(i)] \tag{2}$$

  $$E(x, water\ system) = W(x) * (E_{ws} + E_{ww} * Q) \,, \tag{3}$$

  where $x_{\#}$ is the number of appliances shifted, *use(x)* represents the estimated number of times each appliance is used and *DE(x)* is the direct energy used in each appliance. *W(x)* is the water use change from intervention *x*. *HW%(x)* is the hot water share of the changed water use. $E_{wh}(i)$ is the energy required to heat one unit of water (where *i* is the water heating technology). E_{ws} and E_{ww} represent the total electricity required to treat and transport one unit of water and to collect and treat one unit of wastewater, respectively. Q is a coefficient describing the relationship between the urban water supply and the wastewater production volume.

- For the light bulb intervention, only equation [1] is employed.

- For the rain barrel intervention, only equation [3] is employed.

- Impacts of green roofs on citywide energy use $E(gr)$ are calculated as:

$$E(gr) = SW(gr) * gr_{area} * E_{ww} + \sum_{j=1}^{m} [gr_{area} * E(gr(m^2)] \, , \qquad (4)$$

where $SW(gr)$ is the average annual stormwater retention capacity of one square meter of green roof, gr_{area} is the total area of installed green roof, and $E(gr(m^2))$ is the changed energy use of each fuel, j, per square meter of green roof (due to lower space heating and cooling needs).

- Emission reductions (in carbon dioxide equivalents) $CO_2e(x)$ from an intervention, x, directly relates to the reduction in final energy use, $E(x,j)$, of each fuel j, and is calculated as:

$$CO_2e(x) = \sum_{j=1}^{m} \left[E(x,j) * CO_2e\left(E_{NYC}(j)\right) \right] \quad , \qquad (5)$$

where $CO_2e(E_{NYC}(j))$ is the NYC specific emission factor for each fuel j.

- Impacts on consumptive water use related to energy production $ECW(x)$ from an intervention, x, relate to the intervention's impact on final energy use and is calculated as:

$$ECW(x) = \sum_{j=1}^{m} \left[E(x,j) * ECW\left(E_{NYC}(j)\right) \right] \quad , \qquad (6)$$

where $ECW(E_{NYC}(j))$ is the calculated NYC specific consumptive water use factor for each fuel j.

- The marginal cost, $M.COST(x)$, of a tonne of CO_2e emissions avoided is estimated as:

$$M.COST(x) = \left[CC(x) * x_{\#} - \sum_{k=1}^{life(x)} OC(x,k) \right] / [CO_2e(x) * \ life(x)] \, , \qquad (7)$$

where $CC(x)$ is the upfront capital cost of the intervention, $OC(x,k)$ is the estimated operational cost (or saving) in year k (subject to a 5% discount rate), and $life(x)$ is the expected lifetime of the intervention.

2.3.2 Data limitations and uncertainties

Limitations and assumptions relating to three aspects of the NYC case quantification require further discussion.

- First, to assess the overall impact of hot water use – and how that water is heated – two different water heating systems are considered. The first uses natural gas, the most prevalent fuel for water heating in New York State (U.S. Energy Information Administration 2011), in a conventional water heater that is relatively representative for NYC conditions. The second is a hypothetical case considering solar thermal water heaters with grid electricity back-up (an alternative water heating infrastructure that only few NYC residential buildings currently employ, but with potential to increase by the city's sustainability plans (Meister Consultants Group and City University of New York (2013)). In this paper, we make the conservative assumption that solar water heaters only contribute 50% of the total hot water production and the remaining 50% is heated with grid electricity (ACEEE 2012).[6]

- Second, to calculate and quantify benefits of green roofs, the available literature predominantly relates to specific sites and pilot studies, staying clear of generalisations regarding the amount of heating, cooling and stormwater runoff that some "generic" green roof may offset or reduce (Sailor and Bass 2014). In absence of such generalised data or guidelines, we here use a set of simple characteristics considered plausible for NYC conditions. Specifically, the green roof type assessed here is characterised as: extensive green roof, installed on previously black roofs of old residential buildings, with a Leaf Area Index of 1 and 6 cm Growing Media Depth (see available green roof literature for further details regarding these characteristics (Capozzoli, Gorrino, and Corrado 2013; Sailor and Bass 2014)). For this type of green roof, in combination with the NYC climate, irrigation and maintenance requirements may be minimal (Volder and Dvorak 2014) and are therefore neglected in the numerical analysis. For descriptions of

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[6] These two types of water heaters do not represent the full range of available water heating technologies, nor do they accurately represent current market shares in NYC, but they do provide examples of a relatively common and a relatively uncommon heating technology option and are therefore considered for comparative purposes. Other types of water heaters, such as efficient electrical water heaters, could be included in future studies but are, due to the illustrative purpose of this case study, not included here.

different types of green roofs, see for example Berghage et al. (2009); Carson et al. (2013) and Peck and Kuhn (2001).

- Third, assessments of water use for fuel and electricity production are wide-ranging and highly uncertain (Jaramillo and Destouni 2015b). This makes it difficult to conclusively estimate water required per each kWh of electricity or each cubic foot of natural gas used in NYC. Data for power plant specific water demands for cooling are regularly reported for U.S. power plants (U.S. Energy Information Administration 2016). However, these data do not include the water requirements during extraction or processing of the fuels being burned in the plant. Furthermore, the water use of hydroelectric power plants and in associated water reservoirs is not included in these data. Yet, available studies suggest that evaporative water losses related to the latter may be several orders of magnitude greater than the water consumption rates in thermoelectric cooling systems (Mekonnen, Gerbens-Leenes, and Hoekstra 2015; Mielke, Anadon, and Narayanamurti 2010; Fthenakis and Kim 2010).[7] Consequently, comprehensive assessment of the total “water footprint of energy” in a specific region requires extensive in-depth analysis of the energy supply chain and careful calibration of data (from an array of sources) on water use in each part of this chain. Examples of published assessments of the total water use associated with the energy supply of a specific region include the studies of Rio Carrillo and Frei (2009) and Fthenakis and Kim (2010). However, such comprehensive investigation of the water-energy nexus of energy supply lies outside the scope of the present work and its focus on urban water and energy end uses. To account for these upstream indirect resource interactions in an applicable and, for the present analysis, internally consistent manner, we use here consistent water consumption factors from a single source (Mekonnen, Gerbens-Leenes, and Hoekstra 2015) for all the energy resources included in the analysis (electricity and direct fuel use). The water consumption factor for electricity use in New York City is then calibrated by combining fuel specific consumptive water data from this source with the reported fuel mix of electricity consumed in NYC (City of New York 2011).[8] The water consumption factor for natural

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[7] It is acknowledged that many reservoirs have multiple uses and evaporative losses should not only be assigned to power production. However, published estimates suggest that water use associated with hydropower production is several times larger than that of thermo-electric cooling technologies (e.g. Torcellini et al. 2003)

[8] The calculated “water consumption for electricity” factor lies within the range of reported average consumptive water footprint for electricity and heat in US and Canada (Mekonnen, Gerbens-Leenes, and Hoekstra 2015).

gas is further obtained directly from reported consumptive water use in the processing of natural gas.[9]

To better understand the effects of uncertainties and possible inconsistencies in the used input data, a sensitivity analysis is carried out, considering a simple triangular distribution of uncertainty up to 20% around each input variable. Complementing this, a detailed analysis of payback periods' sensitivity to fuel prices and capital costs is performed as a first-order test of the robustness of results. Further details on the sensitivity analysis can be found in the supplementary material of this paper (Annex D).

We thus again emphasise that the snap-shot (assumed average) analysis carried out here is primarily an illustrative application example. While it is based on data for New York City, it does not aim to be a full representation of city conditions. Rather, it is used to exemplify a concrete application of the RRSS framework for integrated water-energy nexus assessment in a city setting.

3. Results

3.1 NYC water-energy impacts quantified

System-wide effects on water, energy and associated carbon emissions of each studied city-scale intervention are calculated based on available NYC data and displayed in Table 2. Energy demand reductions are reported in final[10] energy units. Figure 2 shows disaggregated reductions in energy, emissions and water use for each intervention, based on where in the system the reduction occurs.

Different patterns emerge for the studied interventions' impacts on energy, water and emissions. Where hot water use is a component (showers and washing machines) this represents the by far greatest energy use reductions of those interventions (green bars in Figure 2). Emission reductions are further more than twice as large for water heated by natural gas

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[9] It is noted that this approach to calculate upstream water consumption simplifies our analysis. However, while published data on water consumption for energy supply varies greatly for reasons beyond geographical differences, and while the purpose of our analysis is illustrative, using a single source allows our results to be *comparatively* consistent without significantly reducing the accuracy.

[10] Since this paper reports results in final energy use, the reader should consider that the generation of electricity is subject to efficiency losses, which increases the relative (and primary) use of fuel for the system.

than by solar water heaters. These results are expected and consistent with those of Sanders and Webber (2015).

Impacts on indirect consumptive water use (for energy supply) display an opposite pattern to those for energy use. For the shower head intervention in the case of solar water heating, the indirect (upstream) water use is greatly reduced by the associated reduction in electricity use[11] (due to reduced need of hot water). In the present analysis, this indirect water use reduction may be up to ten times greater than that associated with the same intervention connected to a gas water heater (Table 2), even though the latter has greater impact on total energy use and emissions. Overall, there is hence no single intervention that maximizes reduction in both emissions and indirect water use.

The studied shift to low-flow toilets and use of rain barrels exhibit the lowest impacts on all resource uses. Nevertheless, although neither of these interventions affect energy use directly, they still yield an observable reduction in energy use, emissions and indirect water use. More remarkably, shifting to efficient light bulbs, a measure that only reduces electricity use directly, yields the greatest reductions in indirect water use of all studied interventions. As such, both the “energy only” and the “water only” interventions clearly demonstrate how employing a *nexus* approach reveals indirect resource use reductions.

PlaNYC includes investments in green roofs explicitly as a (storm)water management measure (City of New York 2007). It is therefore interesting to note that the wastewater load reduction of the green roof intervention (from decreased volumes of stormwater entering NYC’s combined sewers) is marginal compared to that of all other studied interventions, with the exception of rain barrels. In contrast, the energy use reduction of green roofs is close to comparable to that of the light bulb intervention in the present analysis. 3.2 The economics of studied interventions

Table 3 shows the calculated total cost (capital cost plus discounted operational cost) impacts of all interventions, in units of “marginal cost of emissions avoided”. Due to their relatively low capital cost and significant negative operational costs (in effect savings) , low-flow shower heads, CFL light bulbs and green roofs display negative marginal cost values.

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[11] Electricity is used as backup when the solar heating is insufficient.

The toilet and rain barrel interventions yield inconclusive results as marginal costs span from positive to negative within the uncertainty range of the present analysis. The cost ranges for these two interventions are also significantly greater than for any of the other studied interventions.

Washing machines cost more than they save over their lifetime regardless of water heating technology. This result differs from that in another recent assessment (Chini et al. 2016) where efficient washing machines were found to have negative lifetime costs. These result differences may be explained by differences in indirect water use definitions and in the considered time points (year represented by input data) between the two studies. Specifically, the present study only explicitly accounts for indirect water use in the energy production, while Chini et. al (2016) also consider water leakage as an indirect water use. In the RRSS framework, water leakage is external to the presently studied interventions and could instead be subject to its own "leakage control" intervention. Moreover, the NYC water supply and wastewater systems were subject to a set of upgrades between 2010 and 2015, which overall increased their energy intensity and cost of operations (NYC Department of Environmental Protection 2011). The present analysis use data for 2010, when the NYC water system was still one of the most energy efficient systems in the US. Energy and cost reductions from the studied interventions are hence expected to increase with increasing energy intensity of the urban water system. The discrepancies in results of different studies nevertheless highlight the importance of the spatial and temporal specifics of any analysis. Complementing the marginal cost calculations, *payback periods* of each intervention are calculated and depicted in Figure 3. Low-flow shower heads, light bulbs and green roofs are again found to be economically beneficial. These interventions do not only have shorter payback periods than their respective lifetimes, but are comparable to conventional energy efficiency measures (solid red line in figure 3). The interventions of toilets, rain barrels and washing machines have longer payback times. When considering uncertainty ranges from the sensitivity analysis, the toilets and rain barrels may in some cases be paid back before the end of their lifetime, but are far from competitive from an energy efficiency perspective.

Figure 3 displays three payback times for each intervention, accounting for: a) only residential direct and indirect energy use impacts, b) additional water utility related impacts, and c) additional impacts of accumulated emission reductions based on a hypothetical CO_2 price of USD50 per tonne. For all interventions, the payback period decreases with each additional system component, as expected.

At present, a carbon tax is not in place in NYC, but Figure 3 shows that, if implemented, the economics of these interventions would improve. However, the impacts of a tax on CO_2 are too small to alone motivate any of the analysed interventions.

With volatile fuel prices and the cost of water expected to increase, the sensitivity of payback periods to energy and water price and to capital cost are distinguished and compared for each intervention. Results show that increased capital cost by 10% increases payback periods from 10% to 25%, depending on intervention. In contrast, increased resource cost (electricity, natural gas and water) by 10% reduces the payback periods between 9% and 17%. These result ranges represent payback periods when accounting for changes in both direct and indirect water and energy use (payback periods considering only direct resource use vary less). Similar to the results of the general sensitivity analysis, the payback periods of interventions with higher impacts on resource use (showers, light bulbs and green roofs) are less sensitive to cost uncertainties than those of interventions with lower resource use impacts (toilets, washing machines and rain barrels).

Detailed results of these sensitivity analyses can be found in the supplementary material.

4. Discussion

The present analysis of interventions on selected household appliance and water management measures indicates water and energy interlinkages that are both traceable and quantifiable at a large urban scale. In isolation these insights are not new, but the RRSS framework enables consistent analysis and comparison between different (categories of) urban interventions and their nexus effects, which has not been previously demonstrated.

Water and energy efficiency potentials differ greatly between the studied interventions and potential reductions in direct and indirect water use, in final energy use and in emissions do not follow a uniform pattern. A citywide shift to low-flow shower heads (primarily a water efficiency measure) may reduce energy use as much as a citywide light bulb switch, at costs comparable to those of conventional energy efficiency measures. However, this is not the case for a shift to low-flow toilets. Furthermore, impacts on indirect water use from interventions where hot water is a component are greater if that water is heated by electricity than if it is heated directly by natural gas.

Efficient shower heads reduce the direct water use in a home. Through this effect, they indirectly reduce the energy needed in the home to heat water. As water needs decrease, pumping and treatment needs in turn also decrease – together with their respective energy requirements. However, in this analysis the energy impact of lower residential water heating dwarfs the energy reductions resulting from lower water demand. These results point in the same direction as those found by Ren et al. (2016), in their detailed modelling of behavior and appliance efficiencies connected to household water services – and their related energy requirements.

When calculating the marginal cost (for emission reductions) of each intervention, the need to replace conventional appliances (or roofing) "naturally" as their lifetime is reached has not been accounted for. Accounting for such replacement needs would likely improve the economic case for all interventions[12], and may make low-flow toilets more interesting from an energy efficiency or climate mitigation perspective.[13] This is also true for the rain barrel intervention. Payback periods for these interventions are in this study comparable to their expected lifetimes, although subject to large uncertainty (Figure 3). In cities with higher energy use in their water supply and greater outdoor water use for gardening, the effects of this type of rain barrel intervention may be greater in terms of both resource efficiency and economics. As exemplified by Lam et al. (2016), both the per capita use of water and the energy required to provide that water to urban users can vary greatly between cities, even in the same country. This may be due to varying local resource availability, climate conditions and/or urban water management strategies. Further, shown by as Noiva and Wescoat (2016), where water use exceeds the available local climatic water budgets, the corresponding energy requirements are likely to be high.

Green roofs are viewed as strategic measures for reducing stormwater flows in NYC (City of New York 2007). Yet, the present assessment indicates that the benefits of green roofs may be even greater for energy use reduction. This result may be especially important for a city like NYC, experiencing both hot summers and freezing winters with associated high energy demands.

In general, interventions with smaller resource use reductions are found to be more sensitive to input data uncertainties. An extended sensitivity analysis is therefore needed when applying the modelling framework to real-world decision-making where marginal impacts need to be

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[12] This could also make results more readily comparable to those of Chini et al. (2016).

[13] It should be noted however, that as effluent concentrations increase with decreased water use, there will be important impacts on purification costs and implications. This is not taken into account in this analysis, but should be analyzed in the case of potential large scale shifts.

assessed with certainty. The uncertainties in calculated payback periods for the studied interventions do not reveal greater sensitivity to fuel price variation than to capital cost uncertainty. However, with fuel prices likely to be more volatile over time than most appliance performance and cost indicators, further assessment of the impacts of fuel cost variation may be needed in forthcoming studies.

In terms of methodological uncertainty, the RRSS framework developed and applied in this paper deliberately simplifies the urban water-energy system, its cost structure and emission sources in several ways. Some limitations to consider in further work include:

- The study assumes linear relationships between direct resource uses, indirect resource uses and system costs. It is, however, not necessarily the case that a reduction in, for instance, wastewater load translates directly into a corresponding decrease in energy use at the wastewater treatment plant. On short timescales, it is rather likely that these types of systems operate most efficiently at a certain (dimensioning) load. Changes in water and wastewater flows from this load level may then alter, and likely lower, the efficiency level. If, on the other hand, the measures aim to keep wastewater levels constant as population grows, such non-linear efficiency effects may be less important.
- The impacts on indirect water use for energy supply accounted for in this analysis are subject to particularly high levels of uncertainty. Using a single data source for indirect water use per unit of energy use that is not specific to NYC conditions contributes to this uncertainty. An in-depth assessment[14] of the water footprint of NYC energy use (perhaps similar to the city’s greenhouse gas inventories) may contribute to reducing this uncertainty. However, a possibly even larger source of uncertainty in this context stems from the lack of established and standardized methods for quantifying the consumptive water use for all forms of energy supply (Jaramillo and Destouni 2015a,b). Until scientific consensus is reached, this uncertainty range will remain large, and should be acknowledged.
- All cost calculations presented in this paper are made from a city system perspective. This does not take into account that savings from, for example, reduced water use most likely benefit municipal water or wastewater utilities, while the cost of more efficient

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[14] For example, for electricity, indirect water consumption should in fact be calculated from the dispatch of the power plants in the NYC power system as a function of marginal reductions in demand. This will identify the specific power plants whose operation (and therefore water use) is affected by the interventions modeled.

appliances are most likely borne by the end user (residential consumer) or landlord. In the case of green roofs, the costs of installing them are likely to be borne by the building owner, while the savings are likely to benefit the tenants. The importance of assessing stakeholder requirements when implementing sustainability retrofits is emphasized by Menassa and Baer (2014). As such, incentivizing building owners to make such investments may be both necessary and, on a city level, economically efficient.

- Marginal costs and payback periods are calculated with a simple discount rate of 5%. More sophisticated assessments of the variability of intervention value over time would require account of additional parameters, which may further increase rather than decrease result uncertainty.
- In real-world applications for decision support, it may be important to acknowledge possible conflicts among interventions. Green roof installations, for example, may compete with solar-powered water heating systems for the same roof space, and may also reduce the rain harvesting potential of rain barrels connected to the building.

While the scope of the present NYC case study is limited to a few hypothetical interventions, it illustrates how the RRSS framework *can* be employed. As such, it exemplifies how an RRSS-based analysis enables “cross-category” comparison of the impacts of interventions as different as low flow toilets and extensive green roofs. We acknowledge that several highly relevant water-energy related interventions for NYC have not been included in the present analysis. Future research should therefore expand the analysis to consider additional aspects, such as local resource recovery, more space- and water heating options and additional green infrastructure options, to name a few possibilities.

5. Conclusions

To our best knowledge, this paper presents a first attempt to conceptualize, quantify and compare integrated impacts of alternative city-scale interventions on water and energy use. This is done for a set of hypothetical interventions based on a limited snapshot of data (for the year 2010) for New York City. Considering the possible total combined changes in water and energy use associated with a limited pick of residential service demands, this paper provides a start for further CLEW nexus studies targeting an urban scale, adding to the body of examples compiled by the United Nations (2014).

The graphical *reference resource-to-service system* (RRSS) framework developed in this paper, albeit simple, connects not only the urban energy and water systems, but also couples these to the urban services they provide. A framework that in this way centres on urban service provision enables rational prioritization of interventions that are not commonly compared - or even subject to decision by the same urban authority.

All studied interventions reveal simultaneous impacts on water use, energy use and emissions. The magnitudes of these impacts vary greatly, however. Interventions with the greatest potential for reduction of greenhouse gas emissions are not necessarily the most water conserving ones, and vice versa. Still, some interventions commonly motivated by water sector goals can also contribute to meeting energy efficiency and climate mitigation targets.

Our efforts here have focused on developing and exemplifying the application of an internally consistent multi-resource analytical approach to seek nexus insights. Temporal changes to the nexus conditions may be significant, due to climate, population, technology and other changes – and we do not account for such change in this initial work. While the future is unknown, the ability to assess integrated scenarios consistently – even as snapshots – is a modest but important step forward. Next steps would include: the ability to incorporate a greater multitude of interventions, additional analytical techniques (such as multi-objective optimization), expanding the framework to include additional resource interactions and targeted data collection and stakeholder engagement to further understand the potential utility of the approach.

6. Acknowledgements

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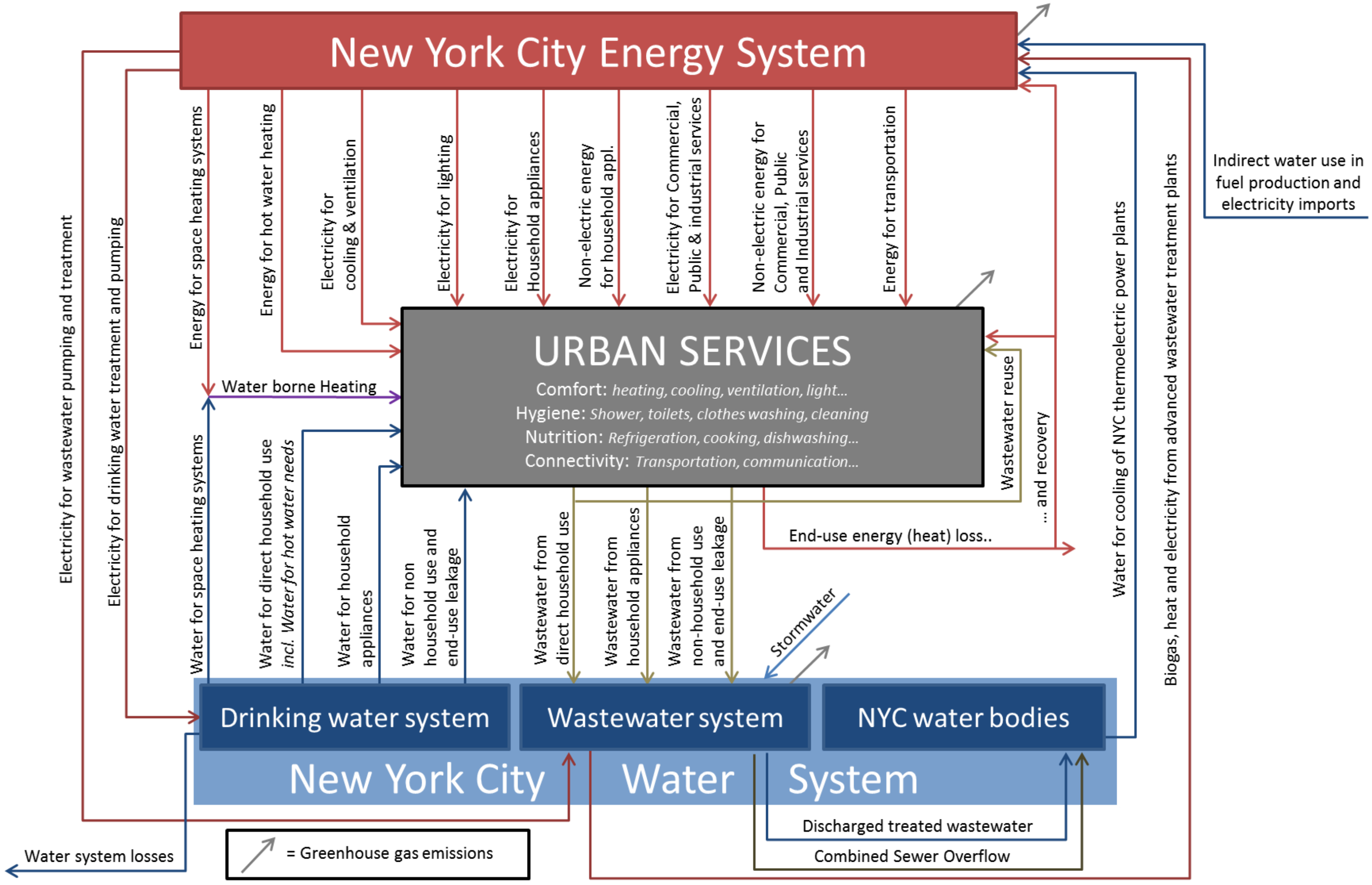
New York City Energy System
URBAN SERVICES
Comfort: heating, cooling, ventilation, light...
Hygiene: Shower, toilets, clothes washing, cleaning
Nutrition: Refrigeration, cooking, dishwashing...
Connectivity: Transportation, communication...
Electricity for wastewater pumping and treatment
Electricity for drinking water treatment and pumping
Energy for space heating systems
Energy for hot water heating
Electricity for cooling & ventilation
Electricity for lighting
Electricity for Household appliances
Non-electric energy for household appl.
Electricity for Commercial, Public & industrial services
Non-electric energy for Commercial, Public and Industrial services
Energy for transportation
Water borne Heating
Water for space heating systems
Water for direct household use incl. Water for hot water needs
Water for household appliances
Water for non household use and end-use leakage
Wastewater from direct household use
Wastewater from household appliances
Wastewater from non-household use and end-use leakage
Stormwater
Wastewater reuse
... and recovery
End-use energy (heat) loss..
Water for cooling of NYC thermoelectric power plants
Biogas, heat and electricity from advanced wastewater treatment plants
Indirect water use in fuel production and electricity imports
Drinking water system
Wastewater system
NYC water bodies
New York City Water System
Discharged treated wastewater
Combined Sewer Overflow
Water system losses
= Greenhouse gas emissions

Figure 1: The *reference resource-to-service system* (RRSS) diagram developed for the New York City (NYC) case study, illustrating the interlinkages between the urban water and energy systems and between these resource systems and urban residential service demands.

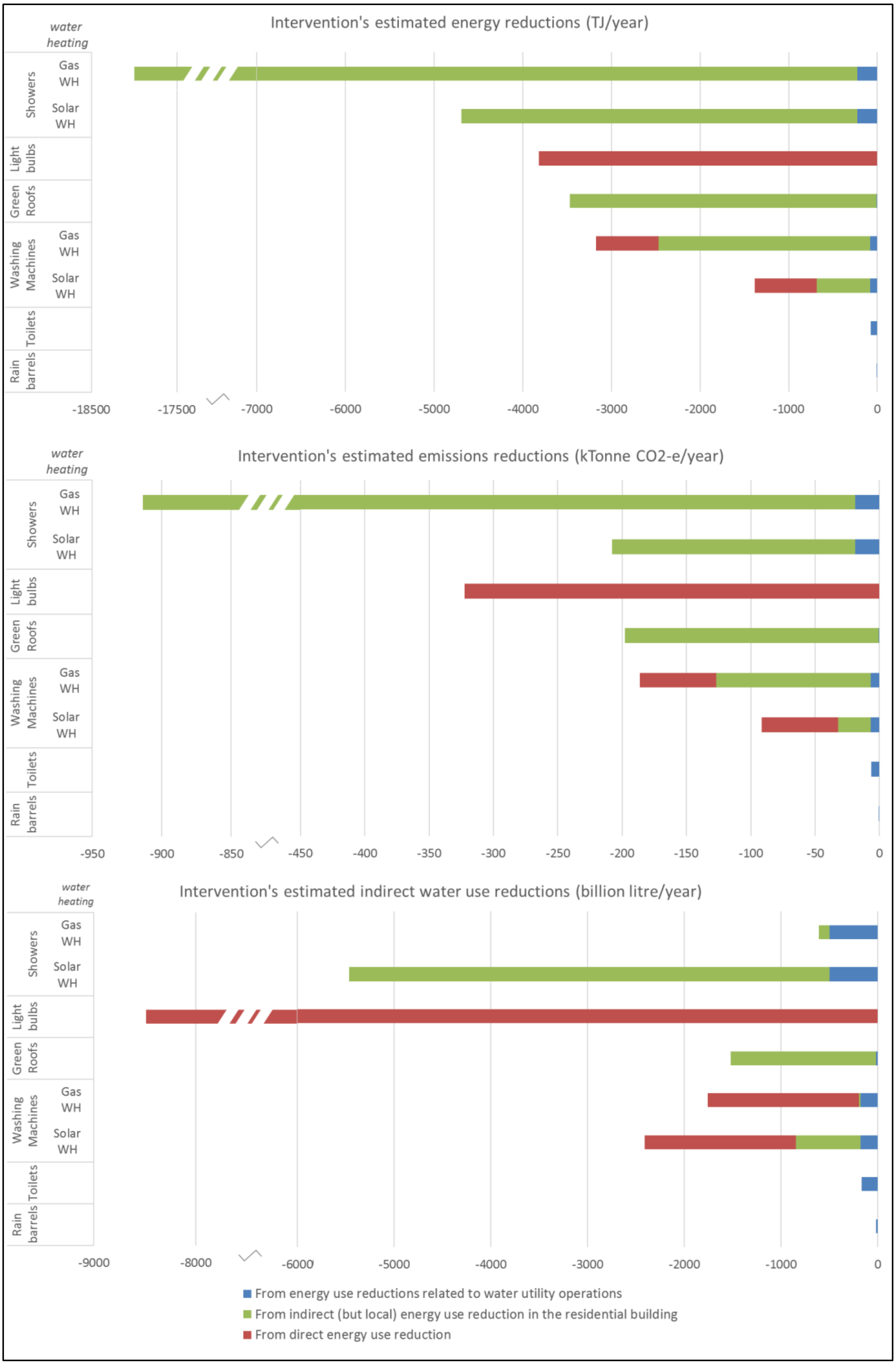

Figure 2: Calculated final energy, emission and water use reductions split by direct (at appliance use) reduction, indirect residential reduction, and indirect water utility related reductions. *Note: The emission*

factor for electricity use in NYC is 85 kg CO$_2$e/GJ (final energy) and for Natural Gas 50 kg CO$_2$e/GJ (City of New York 2012). *Indirect water use for NYC electricity generation is estimated to 2.2 litre/GJ and for natural gas to 0.006 litre/GJ* (Mekonnen, Gerbens-Leenes, and Hoekstra 2015).

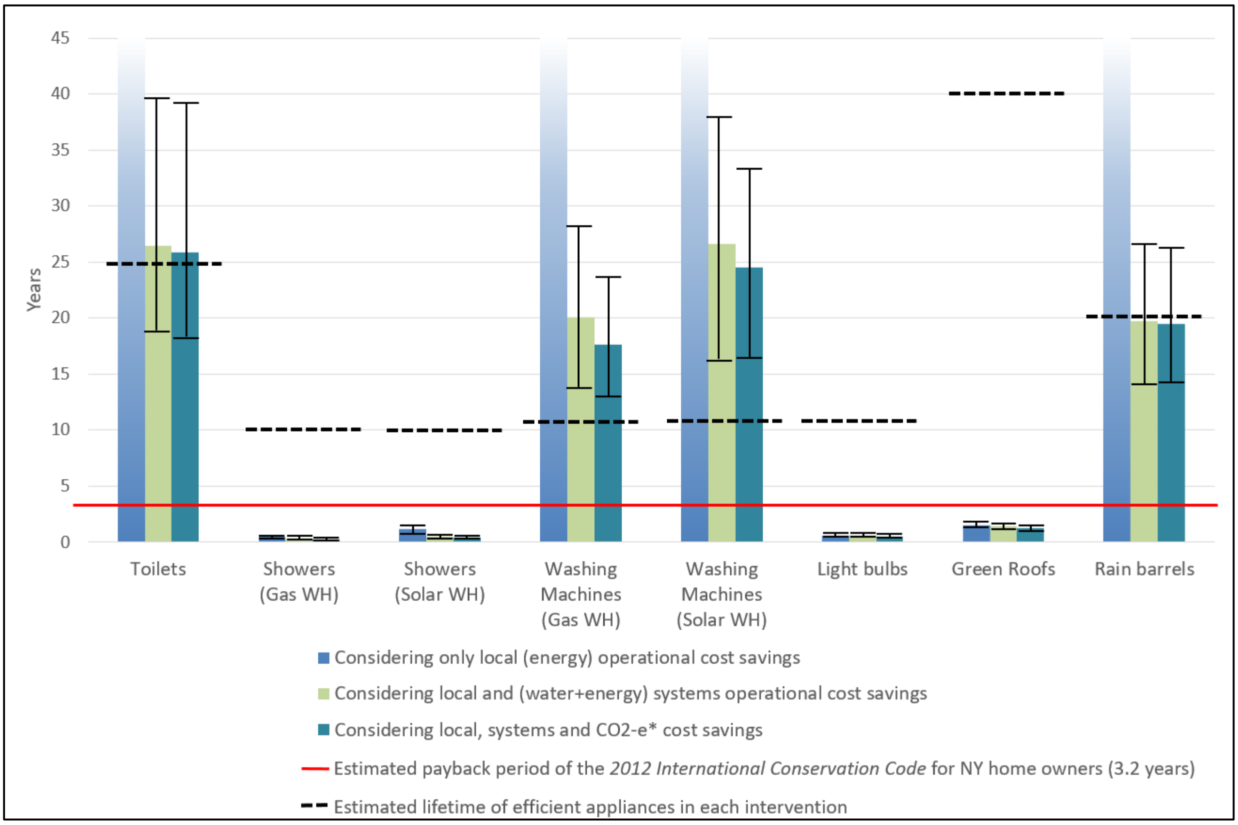

Figure 3: Payback Periods for the interventions compared to expected appliance lifetimes and average *International Energy Conservation Code* payback time for New York homeowners **(U.S. Department of Energy 2012)**, with sensitivity bars included. All results are calculated based on a 5% discount rate. The third (dark turquoise) bar for each intervention illustrates payback times when cost savings from reduced emissions, with a hypothetical CO$_2$ price of USD50 per tonne, are added to the total system cost savings. Currently in the U.S., there is no price on carbon emissions, however other nations have started employing carbon taxes. For reference, in Sweden the carbon tax has exceeded USD150 per tonne CO$_2$ since the mid 1990's **(IEA 2008)**.

Table 1: Summary of interventions assessed in the NYC case study. Highlighted linkages in the RRSS for each intervention can be found in the supplementary material (figure D1).

	Appliance studied	**Secondary resource use**	**Scale of intervention (numbers rounded down to the closest 100 000)**
Household appliances	Low flow toilets	Indirect, water system related, energy use (energy required to treat and transport water and wastewater)	All "conventional" appliances are shifted to low-flow options. Estimated to 2.1 million toilets
	Low flow shower heads	Indirect (water system related) energy use and energy use for water heating	All "conventional" shower heads are shifted to low-flow options. Estimated to 3.9 million appliances.
	ENERGY STAR labelled washing machines	Direct, indirect (water system related) energy use and energy use for water heating	All "conventional" washing machines are shifted to ENERGY STAR labelled machines. Estimated to 2 million appliances.
	Compact fluorescent lighting	Direct energy use only	50% of all incandescent bulbs are shifted to CFL bulbs. Estimated to 38.9 million bulbs.
Water management measures	Extensive green roofs	No direct resource use. Multiple impacts on both energy and water systems.	10 % of total residential roof area. The intervention assumes that extensive green roofs are installed on old residential buildings only, where the insulation effect can be considered greatest. Estimated to 10 million m^2
	Rain barrels	No direct resource use.	Considers rain barrels with a 55-gallon volume (similar to those offered to single-family households as part of the "Rainbarrel Giveaway Program" in NYC) and assuming that every 1-2 family NYC housing units installs one rain barrel. Estimated to 900 thousand.

Table 2: Calculated water, energy and emissions impacts of the six considered interventions in NYC. Ranges cover 90% of the calculated results when input data are varied up to 20%.

		Shifts to low-flow toilets	**Shifts to efficient shower heads**		**Shifts to ENERGY STAR washing machines**		**Shifts to CFL light bulbs**	**Shifts from black roofs to extensive Green Roofs**	**Increased number of rain barrels**
			Gas water heater a)	**Solar water heater a)**	**Gas water heater a)**	**Solar water heater a)**			
Input parameters	Number of appliances (or m^2) considered available for intervention	2 100 000	3 900 000	3 900 000	2 000 000	2 000 000	38 900 000	10 000 000	900 000
	Capital cost of intervention (million $)	$ 728	$ 117	$ 117	$ 1 500	$ 1 500	$ 102	$ 100	$ 63
	Estimated lifetime of intervention (years)	25	10	10	11	11	11	40	20
Calculated ranges of system wide impacts	Direct Water use reduction (billion litre/year)	40 – 52	121 – 155	121 – 155	43 – 59	43 – 59	n/a	n/a	4 – 6
	Indirect reduction in water use from fuel and electricity production (billion litre/year)	150 – 200	500 – 740	4000 – 6660	1460 – 2130	2050 – 2820	7390 – 9400	1210 – 1710	13 – 21
	Wastewater load reduction (billion litre/year)	42 – 55	127 – 163	127 – 163	45 – 61	45 – 61	n/a	4 – 6	4 – 6
	Final energy use reduction b) (TJ/year)	65 – 92	14400 – 22500	3540 – 5470	2560 – 3800	1130 – 1590	3450 – 4050	3070 – 3830	6 – 9
	Emission reductions (kTonne CO_2-e/year)	5 – 8	721 – 1156	161 – 253	149 – 216	74 – 105	279 – 367	177 – 220 c)	0,5 – 0,8

Notes: a) Gas WH and Solar WH in the shower and washing machine columns represent two different water heating technologies: a common natural gas fired heating system and solar powered water heating system (with grid electricity back up), respectively. b) The reader should consider that the generation of electricity is subject to efficiency losses, which increases the relative (and primary) use of fuel for the system. c) Avoided emissions from the green roofs do not include potential effects of Green Roofs as a CO_2 *sink.*

Table 3: Marginal costs of the six interventions in NYC, when considered as climate mitigation strategies (in units of USD per tonne CO_2-e emissions avoided). Ranges cover 90% of the calculated results when input data are exposed to uncertainties of up to 20%.

	Shifts to low-flow toilets	**Shifts to efficient shower heads**		**Shifts to ENERGY STAR washing machines**		**Shifts to CFL light bulbs**	**Shifts from black roofs to extensive Green Roofs**	**Increased number of rain barrels**
		Gas water heater a)	**Solar water heater a)**	**Gas water heater a)**	**Solar water heater a)**			
Emission reductions (kTonne CO_2-e/year)	5 – 8	721 – 1156	161 – 253	149 – 216	74 – 105	279 – 367	177 – 220 b)	0,5 – 0,8
Marginal cost of emissions avoided (USD per Tonne CO_2-e)	-$467 – $1089	-$368 – -$277	-$1076 – -$779	$124 – $395	$421 – $948	-$482 – -$339	-$170 – -$130	-$829 – $976

Notes: a) Two scenarios with different water heating technologies are represented: a common natural gas fired heating system and solar powered water heating system (with grid electricity back up). b) Avoided emissions from the green roofs do not include potential effects of Green Roofs as a CO_2 *sink.*