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Exploring the Transferability of Market, Technical, and Regulatory Concepts from the Electricity to the Water Sector

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Notes

A scientific article based on this report has been submitted to *GAIA – Ecological Perspectives for Science and Society* and is currently under review. For reference purposes, the article's status is: in review.

Abstract

This report investigates relationships between the water and electricity sectors, emphasizing their shared challenges in the context of climate change and urbanization. As both sectors are crucial for modern society, their evolution towards sustainability is increasingly vital. The report begins with a historical overview of each sector, illustrating how the electricity sector has pioneered innovative approaches that can inform the water sector's transition.

The analysis identifies three key concepts – smart meters and dynamic pricing schemes, legal instruments such as cap-and-trade schemes, and extended sector coupling – that have proven effective in the electricity sector and evaluates their potential applicability to the water sector. Smart meters, which enable real-time monitoring and efficient demand management, could enhance water usage efficiency, while dynamic pricing models could incentivize conservation behaviours. Additionally, the exploration of legal instruments like cap-and-trade schemes may provide new frameworks for managing water resources more effectively.

The report also discusses the potential for extended sector coupling, where the integration of water and energy systems can optimize resource use and improve resilience. This approach highlights the importance of viewing water not just as a utility, but as a resource that can contribute to energy management and sustainability.

Despite the opportunities for innovation, the report acknowledges the challenges faced by the water sector, including its regulatory constraints and the fragmented nature of its market. These factors contribute to a slower adoption of new technologies compared to the electricity sector. However, the potential benefits of adapting successful strategies from the electricity sector are significant, with implications for resource management, regulatory compliance, and system integration.

In conclusion, the report advocates for further research and pilot projects to explore the feasibility and impact of these concepts within the water sector. By leveraging lessons learned from the electricity sector, stakeholders can enhance the resilience, efficiency, and sustainability of water systems, ultimately contributing to a more sustainable future for both sectors.

Contents

1 Introduction

In a world increasingly shaped by climate change and urbanisation, our reliance on robust water and energy systems is more critical than ever. These sectors, though distinct, face common challenges and opportunities. The energy sector has pioneered several innovative concepts towards a sustainable transition, offering valuable lessons that the water sector can learn from. This report explores the potential for cross-sectoral learning, assessing how successful innovations in electricity can be adapted for the water sector.

The following sections delve into the historical evolution of these sectors: first, the water sector (1.1), then the electricity sector (1.2). Section 1.3 outlines the aim and structure of this report, setting the stage for an analysis of transferable concepts.

1.1 Historical development of the water sector

The evolution of the water sector is closely linked to the development of human civilisations. Ever since the first human settlements flourished thousands of years ago, infrastructure for irrigation and drinking water was built. As the population density of settlements increased due to improvements in agriculture, sanitation became a bigger concern. Consequently, sewage systems were constructed, and water of better quality was transported over longer distances by aqueducts. In some cities, such systems appeared as early as 4 000 years ago. (Grant 2016a)

The technology to treat and transport water remained fundamentally unchanged for most of human history (Grant 2016b). It was until the beginning of the 19th century where modern water supply and sewage systems appeared in industrialised nations, a time where the expansion of cities was so drastic that significant changes were needed (Hansen 2024; Lemon 2024). These advances include the use of chlorination and filtration for drinking water treatment and sedimentation and filtration in wastewater treatment.

Today, not only urbanisation poses a threat, but also climate change. Extreme weather events such as intense rainfall and prolonged droughts increase in magnitude and occurrence, threatening the infrastructure's reliability and security. For instance, in 2021, the western United States experienced severe drought conditions, leading to water shortages that affected millions of people and agricultural activities. The Colorado River, a vital water source for seven U.S. states, saw its lowest levels in decades, prompting emergency measures and interstate water agreements to manage the crisis (Garcia et al. 2019). Similarly, in South Africa, Cape Town faced a "Day Zero" in 2018, where the city nearly ran out of water due to prolonged drought. This crisis highlighted the importance of proactive water governance, as stringent water-saving measures and effective communication with the public played crucial roles in averting disaster (Madonsela et al. 2019). Meanwhile, in Germany, the drought of 2018-2020, one of the most severe over the last centuries, caused significant losses in the agricultural and forestry sector (Conradt et al. 2023).

The need to adapt has driven innovations in the water sector. For most of the 20th century, the hydraulic paradigm was the norm, characterised by big, centralised engineering projects (e.g. dams) to ensure water supply. This paradigm is challenged by the rise of new concepts, such as water-sensitive logic and water market logic (Fuenfschilling and Truffer 2016).

In the hydraulic paradigm, surface and groundwater bodies were the main sources of water, leading sometimes to overuse. Due to new regulations like the Water Framework Directive (European Parliament 2000) and the German Water Strategy (BMU 2023), the sustainable use and the protection of water bodies became a top priority. These regulations promote the renaturation of watercourses (e.g. by dam removal), water circularity (e.g. by reusing greywater or treated wastewater), and the use of alternative water sources (e.g. collecting rainfall).

Some of the main innovations in the water sector over the last decades have been achieved in (waste-)water treatment technologies (O'Callaghan et al. 2020). Despite the progress, research expenditure on water is still far behind the energy sector (European Commission. 2016). Innovation adoption in the water sector is a slow process compared with other industries; the water sector itself is necessarily conservative, and regulation-bound (O'Callaghan et al. 2020; Wehn and Montalvo 2018).

According to the author (O'Callaghan et al. 2020) "The fragmented nature of the global water market, long replacement cycles for existing technologies and the market growth dependence on population increases and new regulation all contribute to the slow technology diffusion rates and low disruption in the water sector."

The next section will discuss the development of the electricity sector, where market and economic efficiency principles have shaped the innovation of this sector.

1.2 Historical development of the electricity sector

Compared to water, electricity is a relatively recent resource. While static electricity was recognized in ancient times, the systematic study and formal understanding of electrical and electrotechnical principles only began in the late 17th century. The discovery of electrical charge, currents, and electromagnetism paved the way for innovations like the battery, telegraphy, and generators.

The widespread adoption of electric lighting, which replaced gas lighting, played a crucial role in bringing electrification to the general public. Simultaneously, the electric motor triggered the Second Industrial Revolution, displacing steam engines in factories. The introduction of the first electric railway in 1879 further revolutionized urban transport, influencing city planning and development. Electric mobility also briefly became significant in personal transportation, capturing notable market shares.

These technological advancements necessitated the creation of an extensive supply infrastructure, leading to the establishment of large-scale and regional transmission networks. This development marked the beginning of the electricity industry's history, necessitating state regulation of these natural monopolies. A key regulatory shift was the liberalization of the industry, separating energy generation, trade, and distribution from network operations. This aimed to prevent market distortions and foster a free market, ultimately contributing to the formation of an integrated European electricity market. Unlike the water sector, this allowed for consumer choice and the ability to switch providers.

As the energy transition becomes a central political and societal goal, renewable energy sources are increasingly important. Wind power and photovoltaics are expected to be the primary pillars of future electricity supply, with their expansion in Germany being supported by regulatory and financial incentives. This shift is leading to a decentralization of the energy landscape, which was previously dominated by large fossil fuel power plants.

The growing integration of sectors through new consumption technologies, such as heat pumps and electric mobility, presents new challenges for the future energy system. Electricity demand is rising, while generation is becoming more volatile. The proliferation of private photovoltaic and storage systems is also driving the trend toward localized generation, transforming consumers into "prosumers" who both produce and consume energy. To ensure the secure operation of power grids, enhanced communication and control of installations will be required to efficiently and economically leverage existing flexibility in a grid-friendly manner.

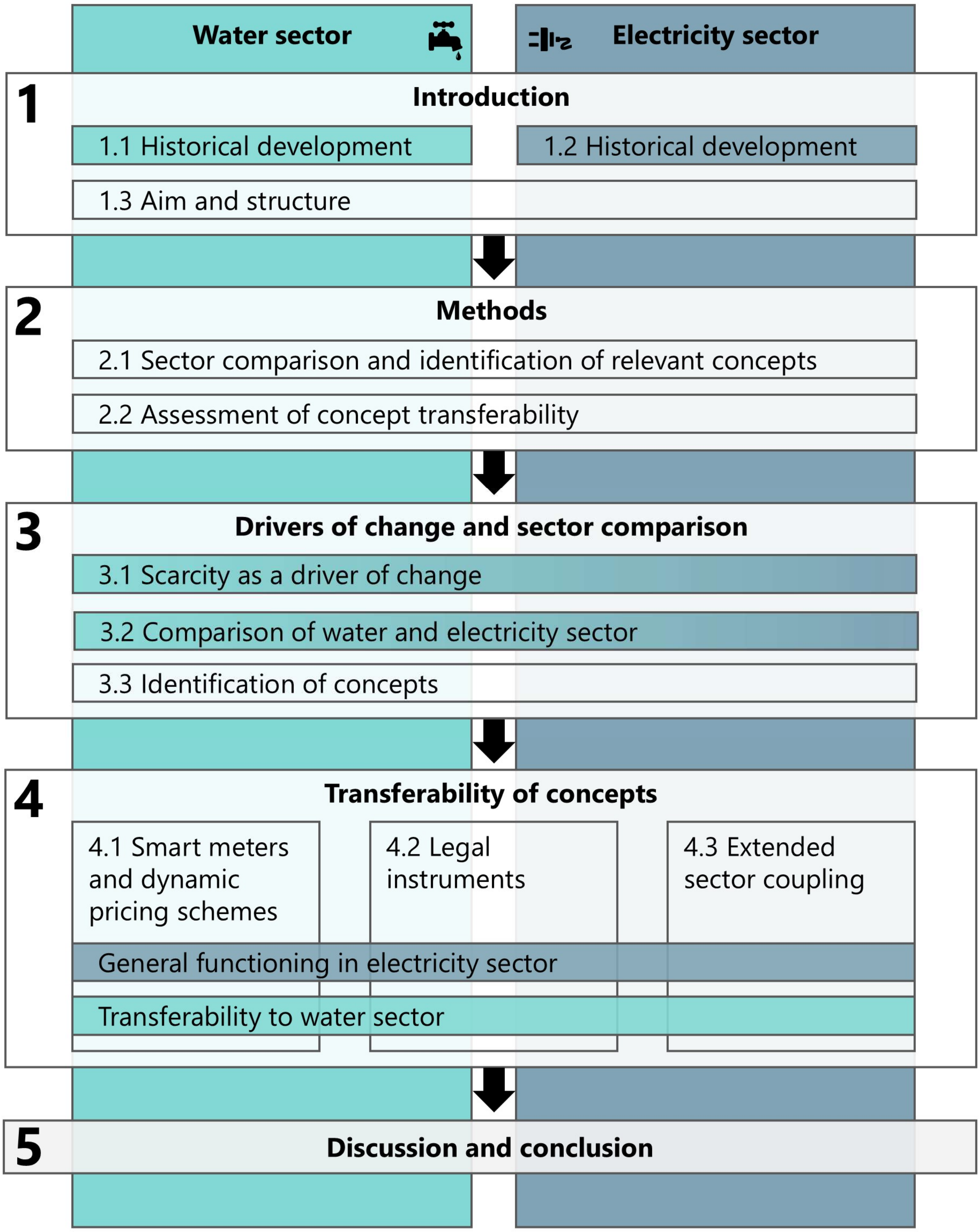
1.3 Aim and structure of this report

Both the water and the electricity sector are essential for meeting our daily needs. Climate and demographic changes (e.g. urbanisation), are underlining our reliance on the two sectors while posing transformational needs. Despite obvious differences, the water and the electricity sector share some analogies. At large scales, both systems need large infrastructure networks, characterised by long lifetimes and high fixed costs (Schleich and Hillenbrand 2019). The efforts to plan, construct, operate, maintain and decommission these networks typically require large investments. Perhaps one of the main differences between electricity and water sectors are the drivers of innovation. While innovation in the electricity sector was presumably largely driven by politics and the market, innovation in the water sector was - historically - mainly driven by demographic changes (especially urbanisation) and regulatory framework. The fragmented nature of the global water market, long replacement cycles for existing technologies and the market growth dependence on population increases and new regulation all contribute to the slow technology diffusion rates and low disruption in the water sector (O'Callaghan et al. 2020).

Against the background of transformational needs, given the shared challenges and potential for innovation in both the water and electricity sectors, this report posits that there are valuable lessons to be learned from the electricity sector's innovative strategies that could be adapted for the water sector. Specifically, we will examine the transferability of three concepts: smart meters and dynamic pricing schemes, legal instruments such as cap-and-trade schemes and water saving obligation schemes, and extended sector coupling using the example of decentralised districts.

We divided this publication into five chapters (see **Fehler! Verweisquelle konnte nicht gefunden werden.**), including this introductory chapter. Chapter two is concerned with the methodology used for this study. The third section presents a deeper look into shortage situations as a driver of change, provides a comparison of electricity and water sector, and explains the three concepts that were chosen for closer analysis. The fourth section lays out the transferability analysis of these three concepts. For each of the three concepts, we present the general functioning in the electricity sector followed by the analysis of feasibility, economic, environmental and social impacts when applying it to the water sector. Finally, the conclusion gives a brief summary and critique of the findings.

Figure 1: Structure of report



2 Methods

This study has been carried out in a process encompassing several steps. First, a general comparison of water and electricity sector has been elaborated, followed by the identification of expedient concepts from the electricity sector. Finally, the potential for transferability of these concepts from the electricity to the water sector has been assessed. In our research, the term 'concept' can refer to a variety of different approaches aimed at improving sustainability in one of its environmental, economic or social dimension. A concept can for example be a technological solution, a market-based approach or a legal instrument.

For this research to be fruitful, thorough expertise regarding approaches in the electricity sector has been as paramount as the consideration of relevant specificities of the water sector, in order to ensure proper transferability. Therefore, the research has been carried out in the framework of an interdisciplinary cooperation between researchers from four research groups, focusing on the topics of Energy Efficiency, Demand Response and Smart Grids, Energy Policy, and Water Resources Management, respectively.

The following paragraphs provide further information on the research approach.

2.1 Sector comparison and identification of relevant concepts

In a first step, water and electricity sector have been systematically compared. To do so, a comparison framework has commonly been elaborated covering a variety of facets, such as fundamental aspects including infrastructure functioning and constraints, how supply and demand form, price setting mechanisms as well as aspects pertaining to market structure and regulatory framework.

The comparison has been developed in an iterative process, with electricity and water researchers first providing key information, details, and specificities of their respective sector based on literature analysis. In a second phase, the other sector’s perspective to all points brought up in the previous phase has been elaborated, to generate a comprehensive direct comparison between energy and water sector.

Based on the resulting common understanding of the distinctive features of both sectors, a series of brainstorming sessions have been carried out, in order to identify prevalent concepts of the electricity sector, which have not yet been tested or rolled out in similar form and on a larger scale in the water sector.

2.2 Assessment of concept transferability

Each identified concept has then been assessed by the energy researcher closest to the matter, describing the general functioning in the energy sector. In cooperation with a water researcher, the sustainability of transferring the concept (or aspects of it) to the water sector have been examined. The more detailed procedure is described in the following paragraphs.

The general functioning of the analysed concept is first described, looking at its purpose and how it is designed within different contexts. Moreover, resulting benefits in the energy sector are explained.

Then, the approach to apply the innovation to the water sector is elucidated. This includes the description of a fruitful design, learning from the application of the innovation to different contexts within the electricity sector.

Finally, the transferability of identified concepts to the water sector is assessed, covering aspects such as environmental sustainability, social sustainability, economic sustainability, and feasibility of implementation.

Within the dimension of ecological sustainability, the environmental impacts of the energy-related concepts being considered for transfer to the water sector can be assessed. Depending on the type of concept, this can entail evaluating factors such as the availability of renewable resources, responsible sourcing practices, and the potential impact on biodiversity. Additionally, the influence of these concepts on water consumption can be examined, considering water usage efficiency, conservation practices, and the potential for water pollution or depletion. Furthermore, the raw material and energy consumption associated with the infrastructure required for implementing these innovations can be analysed, focusing on resource utilization efficiency and potential environmental impacts.

In terms of social sustainability, the influence of the energy-related concepts on the price of water within the water sector can be considered. Factors such as the affordability and accessibility of water, as well as potential disparities in water pricing that may affect different social groups can be examined. Additionally, the social distribution effects of implementing these concepts can be evaluated, considering their impact on vulnerable or marginalized groups, equity in access to water resources, and social inclusivity.

Regarding economic sustainability, the efficiency of the systems associated with the transfer of energy-related concepts to the water sector can be assessed. This involved analysing factors such as cost-effectiveness, resource optimization, and overall economic viability. Additionally, the overall societal costs associated with implementing these innovations can be considered, including both direct and indirect costs, as well as potential long-term economic impacts.

Finally, the feasibility of transferring energy-related concepts to the water sector can be evaluated. This can include assessing the legal feasibility by considering compliance with relevant laws, regulations, and overarching principles related to energy and water management. Moreover, the administrative burden associated with the transfer process can be examined, including permits, regulations, and administrative complexity.

3 Scarcity as a driver of change and sector comparison

Scarcity, as a crucial driver of change, is first examined through the lens of electricity and water shortages. The exploration then expands into a comprehensive comparison of the energy and water sectors, scrutinizing their technical, market, and regulatory aspects. This detailed analysis paves the way for the identification of key concepts, which hold the potential to address scarcity-induced challenges and enhance system resilience and efficiency. These concepts will serve as the focal point in the subsequent chapter with the transferability of concepts.

3.1 Electricity shortage

3.1.1 Types of electricity shortages

The German energy system is said to be very safe and reliable. In addition to risk analysis, experience and lessons learned from the past, other important components are redundancies (Bundesnetzagentur and Bundeskartellamt 2022; Erlach 2024).

In electricity systems there are different types of power failures. Due to local construction work there can be a planned power shut-down (Geier and Lauwe 2024). A power outage is defined as unexpected, but local and limited in time (Geier and Lauwe 2024). Several reasons for power outages may occur. Infrastructure breakdowns may arise, when transmission lines, substations or power stations fail. Beside natural disasters destroying infrastructure like extreme weather (storm, tornado, hurricane, flooding), earthquakes, wildfires, and extreme temperatures may occur. Breakdowns may also arise because of technical faults and human errors, cyber-attacks, terrorism or due to political and regulatory variables. A blackout is also unexpected, but extensive and long-lasting (Geier and Lauwe 2024). In a "black system event" or cascading black out, the electricity system collapses after an initial failure due to interlinked power transmission (Patel 2024). This occurs, when failures spread over a large area of the network (Patel 2024). The event may then affect all consumers in the grid, with the exception of those with an emergency power supply (Patel 2024). However, a brownout is defined as a situation, where the supply cannot be (fully) provided, because not enough electricity can be produced (e.g. due to fuel shortage, low generation capacity), the result is a reduction in demand (Geier and Lauwe 2024). Another term for this is a load shell, where a rolling/controlling/automatic shutdown is carried out (Patel 2024).

3.1.2 Countermeasures in case of electricity shortage

To prevent these situations in long-term, a certain overcapacity is existing in the electricity system. The n-1 principle ensures that there is always one more power line than required (Erlach 2024). Plus, the dimension of operating resources are in such a way, that they are utilized well below the permitted maximum in normal operation and there are always reserve services, which need to be in parts functional even without digital communication (Erlach 2024). Countermeasures in the network may be more battery storage systems, demand-response-systems or involving the public through prosumers (Geier and Lauwe 2024). Other preventing measures are decentralised power plants, microgrids, virtual power stations or insular networks with several suppliers (power plant and renewable energies) (Geier and Lauwe 2024). This is complemented by safe and secure digitalization and using AI to help predict situations. In addition, grid operators are allowed to reduce the electricity consumption of newly installed, controllable heat pumps, charging stations/battery storage systems and air conditioning systems in an emergency from 2024 on (Bundesnetzagentur 2024). However, the system is not regulated down completely, but to a minimum of 4.2 kW (Bundesnetzagentur 2024). There are interim regulations for existing systems (Bundesnetzagentur 2024).

When the supply cannot be (fully) provided in short-term a brownout or load shell, where a rolling/controlling/automatic shutdown is carried out. This is a preventive measure to reduce the grid load in order to maintain the grid balance between electricity generation and consumption to prevent voltage instabilities, voltage dips or cascading power failures (Patel 2024). There may be short-term shutdowns of a few minutes to a few hours, in which certain consumer groups are taken off the grid on a "rolling" basis (Patel 2024). If the demand for electricity is generally higher than the supply a long-term rationing leads to regular load sheds for consumers or the rationing of 4-10 % of annual electricity consumption (Patel 2024).

If an emergency situation occurs, there are different existing emergency concepts. In a top-down strategy the power grid is resupplied with the help of a neighbouring grid (Puleo et al. 2024). Following the bottom-up strategy, the power grid supplies itself again from its own resources (Puleo et al. 2024). A so-called blackstart is possible, if a power plant can start itself without external energy supply (Puleo et al. 2024).

3.2 Water shortage

There are different terms used to describe problems concerning water availability. Water shortage refers to a local and generally short-term imbalance between water availability and water consumption. Water stress is generally broader. It refers to the ratio of water withdrawals to water availability. The withdrawals encompass urban, industrial and agricultural water use. This term is generally used to describe the situation for larger areas (e.g. river basins) and can be used both in short- and long-term contexts. Finally, water scarcity generally describes a persistent long-term problem where the supply cannot meet the demand. This is generally associated to climate change, urbanisation, increasing need for irrigation and environmental degradation (UN Water 2024; Kummu et al. 2016).

In this section, the terms water shortage (short-term) and water scarcity (long term) will be illustrated in the context of residential drinking water networks. In centralized infrastructure systems, drinking water is transported in pipelines. Drinking water must be provided in the right quality, amount and pressure (BMU and UBA 2017). The quality must meet the requirements stipulated in the Drinking Water Ordinance. The amount can vary significantly from location and uses, in average, a citizen in Germany consumes 121 Liters per day (BMU and UBA 2017). According to several technical guidelines (i.e. DIN, DVGW), the pressure must vary between 2 to 8 bars.

Shortages in the water sector have a different picture compared to the electricity sector. First, water quality issues can cause temporary shutdowns of the network. Long stagnation times and high temperatures in the supply networks can increase the risk of bacterial growth, among others.

Short-term problems concerning amount and pressure are generally not an issue. In contrast to electricity, water can be stored easily (if microbial issues are addressed properly). Storage systems are a common measure to address hourly and daily flow fluctuations in the system. Pressure drops are common at times of high demand, however, this does not damage the equipment, and in case this problem appears frequently, it can be solved by increasing the pressure locally, for example, using a pump. High pressure can damage the system, but this can be easily solved by technical measures.

In the long term, however, water scarcity can become more critical. Despite its generally gradual nature (e.g. declining groundwater levels, degrading water quality, etc.) water scarcity requires large investments and long periods to be solved. In essence there are two approaches to solve scarcity, either the availability is increased, or the demand is reduced.

The former, known as water supply augmentation, traditionally consists of big engineering projects like dams or wells to increase water supply. Cost-efficiency is key here, since in many cases, it is easier to bring water of good quality from distant regions than treating (i.e. improving water quality of) local water sources. This phenomenon means that water must be transported over longer distances. This is already the case in many big cities in Germany like Munich, Frankfurt or Stuttgart. Other examples of supply augmentation are desalination technologies (Ahmed et al. 2020) and aquifer storage or managed aquifer recharge (Henao Casas et al. 2022; Sprenger et al. 2017; Yuan et al. 2016).

The latter, known as water demand management, is another approach. Solutions vary from simple to complex. Rationalisation, for example, consist of distributing water in selected time intervals or in smaller amounts. During the "Day Zero" of Cape Town in 2018, an amount of 50 litres per person per day were distributed (Madonsela et al. 2019). According to the World Health Organization, approximately 50 litres of water per person per day are needed to ensure that most basic needs are met while keeping public health risks at a low level (United Nations Education, Scientific and Cultural Organization 2019). In emergency situations the quantity of water is defined at least 5 litres per day (World Health Organization 2017).

Other measures include leak detection, maintenance of the network, sensibilisation campaigns and the installation of water-saving utilities in households. All of them were perceived as effective according to the evidence from Tallin, Berlin, Zaragoza and Copenhagen (Stavenhagen et al. 2018). More complex measures are the adjustment of water pricing schemes and the introduction of water markets. The debate as to whether or to what extent these solutions lead to positive outcomes and the discussion on which circumstances are adequate for the adoption of those measures is still debatable and fairly hard to answer (Wheeler and Xu 2021; Wheeler 2021; Quentin Grafton et al. 2016; Griffin et al. 2013; Quiggin 2021; Ann Wheeler and Garrick 2020).

Finally, water circularity has gained relevance over the last decades to face water scarcity (Afghani et al. 2022). Examples of this are the reuse of rain- and greywater and the use of treated wastewater for irrigation purposes. However, this last approach is still not widely implemented as it is subjected to legal, political, economic and social constraints (Fuenfschilling and Truffer 2016). It was only until 2023 when the European Water Reuse Ordinance became valid in all EU-member states. However, there are big differences concerning the implementation of water reuse. For instance, in Spain, water reuse technologies are more widely used than in Germany.

4 Comparison of water and electricity sector

We structured the comparison of water and electricity sector into technical, market and regulatory aspects. Comparison tables for each of the three aspects can be found in the respective section. Technical aspects (Table 1) are subdivided into infrastructure, supply and demand – each with further subcategories. Market aspects (Table 2) are divided into those related to design and those related to price formation. Regulatory aspects (Table 3) are divided into laws and standards – on EU, national and if applicable regional level.

4.1 Technical aspects

In the technical aspects, both sectors have key infrastructure components which are influenced by various factors affecting their design. The water sector uses a combination of extraction, treatment, pumping, pipe networks, storage, and utilization components, while the electricity sector primarily uses generation plants, cables and lines, substations, and measurement and monitoring technology. Transport losses are a common feature in both sectors, with the water sector experiencing about 6.8% losses in Germany (BMU and UBA 2017). The electricity sector suffers losses during transport, which vary depending on the method of transmission and distance.

Storage in the water sector is used to balance daily variations in water demand and must comply with DIN EN 1508, while in the electricity sector, storage is possible only through conversion and with losses. Quality and contamination are critical issues in the water sector, with water quality measured based on physical, chemical, and biological parameters. In contrast, the electricity sector does not face devaluation through "consumption".

Supply in the water sector comes from surface water or groundwater and depends on precipitation patterns which vary seasonally. In the electricity sector, supply comes from various renewable and non-renewable energy sources. Both sectors face challenges in predicting supply, influenced by factors like climate change and land use changes. The water sector has the potential for decentralization via rainwater harvesting, grey water reuse, and local wells, while the electricity sector is experiencing increasing decentralization through smaller systems (see Table 1).

Table 1: Comparison of technical aspects of water and electricity sector

	Water sector	**Electricity sector**
Technical aspects		
Infrastructure		
Components		
	a) Extraction (groundwater: spring water, wells. Surface water: reservoirs, bank filtrate and groundwater recharge); b) treatment (waterworks); c) pumping (pumping station); d) pipe network (various materials and diameters); e) storage (tanks); f) utilisation (e.g. taps, other appliances) (DVGW 2024) Factors affecting design: a) Extraction (local conditions like hydrology, geology, population and water consumption); b) treatment (water quality); c) pumping (topography, pressure losses); d) pipe network (costs, flow/speed ratio); e) storage (daily or seasonal fluctuations in water consumption).	The electricity infrastructure includes key components such as generation plants that produce power, cables and lines for transmission, and substations with transformers and switchgear to adjust voltage levels. Measurement and monitoring technology tracks electricity use, with detail varying by grid level. Additional elements include storage systems (e.g., batteries) for managing renewable fluctuations, smart grid technologies for better integration of decentralized energy, and control centres for coordinating grid stability.
Transmission system and transport losses		
	Water distribution system is the sum of the above-mentioned components. There are 6000+ water suppliers in Germany. The networks are generally independent (not interconnected), but there are exceptions. Transport distance varies from approx. 1 to 150 km. Remote water distribution ("Fernwasserversorgung") refers to the transportation of water over long distances. This is crucial for many cities, especially for big cities like Frankfurt, Munich or Stuttgart. System losses in Germany are very low (approx. 6.8%) compared to other countries. Less than 20% is already good. The main design parameters for the system are flow, pressure, velocity. Strong oscillations in the water pressure	The electricity transmission system is made up of several key components, including generation plants, substations, and transmission lines. There are multiple interconnected grids across Europe, allowing for cross-border electricity exchange. The transport distance for electricity can vary significantly depending on the region and infrastructure. System losses in Europe generally range between 0.99% and just under 4% (Council of European Energy Regulators ASBL 2025). The main factors influencing the transmission system are voltage levels, transport distance, and load. Losses are minimized through regular maintenance and optimization of the grid. High-voltage transmission lines are typically either alternating current (AC) or direct current (DC), with AC lines

	can cause cracks in the pipe, leading to higher water losses. Maintenance of the system is therefore very important. (BMU and UBA 2017).	commonly used for shorter distances and DC lines more efficient for long-distance transport.
Storage		
	Storage is used to even up the hourly or daily variations in water demand. The design of this facilities must comply with the DIN EN 1508. Water can be stored in water closed containers (above or underground). The design must guarantee that the water quality remains drinkable. One of the main issues is microbial growth. To avoid this, air and water circulation are important. Sunlight must be avoided and insulation must be used to avoid temperature oscillations. Note: Reservoirs or aquifer storage go beyond the water supply system; thus, is not included here. However, it is important to mention that these bodies can store larger volumes that can compensate for seasonal imbalances in the supply/demand.	Storage in the electricity sector is achieved through conversion processes, which inevitably involve some level of loss. Short-term storage is primarily provided by pumped storage power plants and batteries, both of which allow for the temporary storage of electricity for later use. Pumped storage plants are particularly effective in balancing supply and demand over shorter timeframes, while batteries offer rapid response times for smaller-scale storage needs. Long-term storage options, though still evolving, are critical for managing fluctuations in renewable energy generation, such as from wind and solar. Storage systems also play a vital role in ensuring grid stability and security, particularly during blackouts, by providing backup power and helping to quickly restore supply to affected areas.
Quality and contamination		
	Definition: Water quality is measured according to physical, chemical and biological parameters and is regulated by the Drinking Water Ordinance (TrinkwV 2001) The drinking water quality may degrade from the waterwork to the tap. Problems: Corrosion, substance migration, microbial growth. Influencing factors: surface/volume ratio of the pipework, temperature, stagnation times, pH value. Monitoring plays an important role in the entire chain (see components). (BMU and UBA 2017).	In the electricity sector, there is no devaluation of the product through "consumption" as it remains immediately usable for its intended purpose. Once electricity is consumed, it cannot be repurposed or stored for future use without conversion. Unlike other resources, there is no residual product left after consumption.
Supply		
Sources		
	In a traditional drinking water supply system water comes either from surface water or groundwater (or both). All water originated from precipitation. Different physical (or hydrological) processes (explained in the water cycle) allocated water in different places. Water is renewable, but its renewal rate can vary immensely. The list below gives the residence time depending on the source. [average values] - Water in the atmosphere: 9 days (van der Ent and Tuinenburg 2017) - Surface water: 2.5 weeks (Oki and Kanae 2006) - Groundwater: depending on depth profile and geology the residence time can vary from days, years, centuries and even millennia (The groundwater project 2020) The residence time equals the storage volume of the body over the water flow. Note: The use of alternative sources has gained popularity in recent decades. In some parts of the world, sea-, rain- and wastewater can be treated, used and distributed as drinking water.	The electricity supply sector relies on a diverse mix of renewable and non-renewable energy sources, each with distinct properties and performance characteristics. Renewable sources like wind, solar, hydro, and biomass provide environmentally friendly alternatives but can be intermittent, requiring backup solutions or storage systems. Non-renewable sources, such as coal, natural gas, and nuclear, offer more stable and reliable power generation, though they often come with environmental and sustainability concerns. Despite their differing characteristics, all these energy sources ultimately deliver the same product with indistinguishable quality into the grid.
Seasonality and intermittency		
	Rain patterns vary seasonally and between years. The phenomena “El Niño” and “The Niña” affect precipitation patterns over the world.	The seasonality and intermittency of supply present significant challenges in the electricity sector. Renewable energy sources, such as wind and solar, do not offer constant power generation potential, as their output depends heavily on weather conditions and fluctuates throughout the day. Historically, power production followed total demand, as it was mainly controlled by conventional, dispatchable sources. Today, however, controllable generation follows the residual load, which is the difference between overall demand and the fluctuating output from renewable energy sources. This shift requires a more flexible and responsive grid to balance supply and demand efficiently.
Prediction		
	Determination by hydrological models for surface water. Hydrogeological models, geophysical investigations, and other methods for groundwater (Balsubramanian 2007). Important factors: climate and land use changes.	Supply prediction in the electricity sector relies on accurate load and renewable energy forecasts. Influencing factors include weather conditions, short-term demand fluctuations, and long-term factors like climate change and political decisions.
Decentralisation		
	A system can become decentral if it can harness rainwater, treat and reuse greywater or use the water from a local well. Common practices are the use of cisterns to collect rainwater and apply it where a lesser quality than drinking water is allowed, e.g. toilet flushing.	The decentralization of supply is increasing with the rise of smaller systems in large-scale distribution. Decentralized concepts are being implemented at lower grid levels, where additional measurement and control technologies are becoming more relevant. This trend also includes the growing presence of smaller generation plants in private ownership, driven by efforts toward self-sufficiency. As more individuals and communities generate their own energy, the overall structure of the electricity grid becomes more distributed and flexible.

Demand	
Consumption patterns	
Specific drinking water consumption in Germany is 121 litres per capita per day for households and small businesses (BMU and UBA 2017).	Electricity consumption patterns fluctuate throughout the day, with demand typically peaking in the morning and evening due to residential and commercial activity. In Germany, Standard Load Profile (SLP) customers exhibit this typical consumption pattern, while Registered Load Measurement (RLM) customers, such as industrial users, may show more variable demand based on production schedules.
Short- and long-term demand response	
Forecasts go hand in hand with population trends. Meeting the supply in the short term is generally unproblematic, since one can simply extract more water from the reservoir or the aquifer. However, if the water utilisation index (a.k.a. water stress), which equals water withdrawals (demand) over renewable water supply (UBA 2022) exceed a critical point, causing ecosystem degradation, demand management or supply augmentation measures (i.e. infrastructure projects) must be taken.	Short- and long-term demand response strategies are essential for managing electricity consumption. In the short term, to cover demand, power plants can be ramped up, redispatch can be used, and demand response potential can be activated if available. In the medium and long term, solutions include expanding power lines and generation capacity, increasing energy efficiency, and reducing overall energy demand. However, new consumers with high outputs and unique characteristics, such as electric vehicles (EVs) and heat pumps, pose additional challenges in balancing supply and demand due to their variable consumption patterns and growing market presence.
Digital solutions	
Smart metering can play a role	Digital solutions in the demand sector optimize electricity consumption through ICT, enabling real-time price signal transmission and consumption adjustments. Smart meters and smart grids provide detailed insights into energy use, improving demand response. Decentralized energy management systems allow prosumers to manage both generation and storage, enhancing flexibility. The integration of electric vehicles, heat pumps, and home energy storage helps coordinate activities based on grid conditions and pricing signals. Finally, AI and machine learning predict consumption trends and optimize energy use, offering advanced demand-side management solutions.

4.2 Market aspects

In terms of market aspects, the water sector is a natural monopoly while the electricity sector in both Germany and the EU is a fully liberalized and unbundled market. The price formation in the water sector is based on the cost recovery principle, with prices influenced by factors like settlement density, geographical location, and hydrology. In the electricity sector, price formation is based on the merit order, with prices increasingly influenced by the rise in renewable energy generation and decentralised PV systems (see Table 2).

Table 2: Comparison of market aspects of water and electricity sector

	Water sector	Electricity sector
Market aspects		
Design		
Type	Natural monopoly (BMU and UBA 2017)	The electricity market is fully liberalized and unbundled, with legal separation between networks and providers, offering a complex range of products and trading platforms. While new products, particularly related to flexibility, are expected to emerge in the future, there are currently no dedicated platforms for marketing these innovations.
Involved stakeholders	Water supplier and competent authorities in change of regulating the service (water price and fees, water quality, etc.). Additionally, environmental agencies and water offices may also have influence on e.g. granting water rights, expanding infrastructure or other type of measures. Other actors may also be involved in the management of the catchment area ("Trinkwassereinzugsgebiet")	The electricity market involves a wide range of stakeholders, including generators, grid operators, electricity traders, end customers, regulatory authorities, and policymakers. With the rise of decentralization, new participants and forms of involvement have emerged, such as self-supply, tenant electricity, community-based energy supply, and citizen energy companies. This shift is fostering greater independence through community organizations and service providers, reshaping the landscape of market participation.
Level of privatisation	Water supplier: public vs. private (AG, GmbH, KG)	Electricity supplier: public vs. private (AG, GmbH, KG)
Price formation		
Principle & geographical scope	Cost recovery principle according to the European Water Framework Directive. This means, that the actual costs are considered (no subsidies). Factors affecting price include settlement density, geographical conditions, hydrology, topography, etc. This means that the water supply companies incur different levels of costs, which must be covered by locally applicable water prices. In 2022, an average German household with a consumption of 93 m^3 per year will pay € 262,39 for drinking water. € 91,97 for the basic fee (independent of consumption) and € 1,83 per every cubic meter (DESTATIS 2023). For public water suppliers, drinking water prices are regulated by the municipal charging law (*"Kommunaler Gebührenrecht"*). Cost recovery, equal treatment and equivalence principles apply. For water suppliers under private law the antitrust law (*"Kartellrecht"*) applies. The same cost recovery principle applies, only in this case the prices are compared with water suppliers operating under similar conditions, and in case additional measures are required, a price increase can be justified and the verifying authority may allow it (BMU and UBA 2017).	Electricity price formation in Germany is based on the merit order principle on the electricity exchange, where power plants are dispatched according to their variable costs. Within the national bidding zone, standardized prices ensure competition among market participants, while physical connections to foreign countries allow cross-border electricity trading and integration into wider European networks. However, physical grid restrictions are only accounted for downstream through redispatch measures, which help to stabilize the system when bottlenecks occur. As the share of renewable energy continues to grow, particularly with the expansion of decentralized PV systems and prosumers, the simultaneity of generation leads to more pronounced price fluctuations and an increasing influence of renewables on market dynamics.
Allocation	Approximately 75% of the actual costs are fixed and 25% are variable. However, in reality roughly a quarter of charged fees is fixed and three-quarters variable. (VkU 2017)	The allocation of electricity costs is composed of procurement and sales, taxes, allocations, and profit, all shaping end consumer prices. Traditionally, fixed retail electricity prices have provided stability but lacked flexibility. With the introduction of dynamic tariffs and price components, prices can now better reflect real-time market conditions, encouraging more efficient consumption.
Price Elasticity	The price elasticity of residential water consumption is relatively low, about 4,2% in the short term and 13% in the long term (Schleich and Hillenbrand 2009, 2019).	In the household sector, electricity demand remains largely unresponsive to price changes in the short term (Csereklyei 2020). However, studies indicate that industrial consumers tend to react more sensitively, even on an hourly basis (Hirth et al.). External factors such as population density, temperature, and policy measures also play a role in shaping electricity consumption.

4.3 Regulatory aspects

Regarding regulatory aspects, both sectors are regulated by EU laws such as the European Water Framework Directive and the Renewable Energy Sources Act. They also have national laws in place. In the water sector, the Federal Water Act (Wasserhaushaltsgesetz - WHG) and national guidelines from DVGW & DIN apply, while in the electricity sector, the Energy Industry Act, Combined Heat and Power Act, and Building Energy Act are relevant. The water sector also has regional laws in the form of municipal bylaws on compulsory connection and use (see Table 3).

Table 3: Comparison of regulatory aspects of water and electricity sector

	Water sector	**Electricity sector**
Regulatory aspects		
Laws		
EU laws	European Water Framework Directive (EU-WFD): Ongoing implementation and updating of the necessary management plans and programmes of measures to reach good status in all water bodies in the European Union. Specific implementation steps are carried out every 6 years. Each cycle corresponds to a separate management period. The federal states are primarily responsible for implementing the WFD. Urban Wastewater Treatment Directive (EU-UWWTD): Aims to protect the environment from adverse effects of wastewater discharges from urban sources (towns over 2.000 inhabitants) and specific industries. The implementation must be reported every 2 years. Drinking Water Ordinance: Requirements for drinking water quality. Is valid throughout the entire water supply system. Besides municipal and federal state authorities in change of monitoring the drinking water quality, this ordinance is also valid for houses, since their installations also belong to the supply system (BMU and UBA 2017). Ordinance on water reuse in agriculture: This ordinance sets the minimum water quality standards for water reuse in the agriculture. Is the newest of the list, valid in the Member States of the European Union since 2023.	The most important EU legislation shaping the energy market includes: The Renewable Energy Directive (RED) establishes the framework for the promotion of renewable energy across the European Union, aiming to increase the share of renewable energy in the EU's energy mix. Its goal is to ensure a sustainable, greenhouse gas-neutral energy transition by setting binding renewable energy targets for each member state and promoting the integration of renewable sources such as wind, solar, and biomass into the energy market. The European Electricity Market Design (EMD) aims to create a fully integrated and competitive internal electricity market in the EU. It sets rules for electricity trading, system operation, and the integration of renewable energy sources, while also ensuring security of supply, fair competition, and price transparency across borders. The EMD facilitates cross-border electricity exchanges, optimizes the use of existing infrastructure, and supports the development of a flexible, decarbonized energy system. Directive 2012/27/EU on energy efficiency sets binding measures to help the EU achieve its energy efficiency targets. It outlines requirements for member states to establish national energy efficiency action plans and implement strategies to reduce energy consumption. The directive focuses on improving energy performance across various sectors, such as buildings, transport, and industry, and includes measures like energy audits, energy management systems, and efficiency obligations for utilities.
National laws	Water resources act *("Wasserhaushaltsgesetzt" oder WHG):* Provisions on the protection and utilisation of surface waters and groundwater, as well as regulations on the development of water bodies, water management planning and flood protection. Specific rules for the federal states are laid down in state water laws. Besides, guidelines from DVGW & DIN may apply for technical aspects like pipework materials, operation and installation of systems, maintenance practices, monitoring of water quality, etc.	National laws play a key role in regulating the German energy market. The Energy Industry Act (EnWG) has governed the functioning of the German energy market since 1935, aiming to ensure a secure, affordable, consumer-friendly, efficient, environmentally sustainable, and greenhouse gas-neutral energy supply for the public. It focuses on regulating and ensuring effective, undistorted competition through mechanisms like notification and authorization obligations, unbundling (to ensure transparency and non-discrimination), and grid regulation and access. The Federal Network Agency holds powers to enforce these rules, which are further detailed in various ordinances such as the NAV, StromNEV, and StromNZV. The Combined Heat and Power Act (KWKG) promotes the simultaneous, efficient generation of heat and electricity, supporting sector coupling and enhancing the integration of energy systems. The Building Energy Act (GEG) establishes requirements for the most efficient use of energy in buildings, including standards for electricity, heating, and cooling, along with regulations for heating and air conditioning technologies. The Renewable Energy Sources Act (EEG) regulates the privileges, obligations, and remuneration for the generation and utilization of electricity from renewable energy sources. Its goal is the transformation towards a greenhouse gas-neutral electricity supply, entirely based on renewable energies.
Regional laws	Municipal bylaws *(„Kommunale Satzungen"), e.g. on compulsory connection and use.*	

5 Identification of concepts

Based on the detailed analysis of the electricity and water sectors, we have decided to further analyse the following three concepts:

Smart Meters and Dynamic Pricing Schemes: The utilization of smart meters is evident in both sectors, especially in electricity where it's crucial for managing demand-response systems and controlling the time of recharging for vehicle charging stations. In the water sector, smart metering can provide valuable data for managing water demand. Additionally, dynamic pricing schemes, which are more prevalent in the electricity sector, can be explored for the water sector to incentivize efficient water usage and manage demand.

Legal Instruments (Cap-and-trade schemes and Water Saving obligation schemes): The electricity sector operates under various legal instruments such as the Renewable Energy Sources Act and the Energy Industry Act. Similar legal instruments in the water sector like the European Water Framework Directive and the Water Resources Act are in place. The exploration of cap-and-trade schemes, which have been successful in managing emissions in the energy sector, could be a potential solution for managing water resources. Similarly, water saving obligation schemes could possibly enforce more efficient use of water.

Extended Sector Coupling: Both sectors are experiencing increasing decentralization. In the electricity sector, this is evident with smaller systems in large-scale distribution and private ownership of increasingly smaller generation plants. The water sector shows potential for decentralization through practices such as rainwater harvesting, greywater reuse, and the use of local wells. Exploring extended sector coupling in these evolving frameworks can potentially enhance the resilience and efficiency of both sectors.

These concepts were chosen based on their potential to address key challenges in both sectors such as managing supply and demand, reducing losses, and improving system efficiency and resilience. Furthermore, they offer opportunities for cross-sector learning and innovation.

6 Transferability of concepts

This part of the report delves into the potential application of strategies from the electricity to the water sector. It considers how smart meters, dynamic pricing schemes, and legal instruments might be used in this new context. It also explores the idea of sector coupling, which integrates energy, water, and material flows at a neighbourhood level.

6.1 Smart meters and dynamic pricing schemes

The energy transition is not the only development induced and triggered by climate change; the increasingly tense situation of water scarcity is also noteworthy. Altered precipitation patterns, heatwaves, and escalating dry spells leading to droughts are becoming more frequent and must be addressed more intensively in the future. Although approaches like smart meters and dynamic pricing schemes aren't new concepts in general, the implementation in Germany is still in an early phase and not obligated for all customers. Nevertheless, their potential in the electricity sector has been recognized. The following section aims to show use cases in which these approaches can be transferred to the water sector.

Smart meters

Smart meters are advanced energy meters that record real-time electricity, gas, or water usage and communicate this information directly to utility providers. Unlike traditional meters, smart meters enable two-way communication, allowing for remote readings, system monitoring, and updates.

Key benefits include accurate billing, energy usage insights for consumers, and improved grid management for providers. They also support integration with renewable energy sources and facilitate dynamic pricing, encouraging energy use during off-peak hours. By promoting efficiency and sustainability, smart meters could be an essential part of modern energy infrastructure.

Dynamic pricing

Dynamic pricing is a flexible pricing strategy where the cost of goods or services fluctuates based on real-time supply and demand conditions. In the energy sector, dynamic pricing adjusts electricity rates throughout the day to reflect grid demand and energy availability.

This approach incentivizes consumers to shift energy usage to off-peak hours, reducing strain on the grid and lowering energy costs. Dynamic pricing benefits utilities by balancing demand and supporting renewable energy integration while helping consumers save money through informed energy management. It's a key tool for promoting energy efficiency and sustainability.

6.1.1 General functioning in electricity sector

Smart meters are intelligent measuring systems and will be a central component of a digital energy system in the future. They consist of a digital electricity meter and a communication unit, allowing real-time data transmission between consumers, energy suppliers, network operators and other service providers. Thus, they form the basis for a powerful smart grid, where robust digital infrastructure is a prerequisite for integrating a growing share of renewable energies.[1]

One significant characteristic of wind and solar energy is their fluctuating supply, resulting in a highly variable generation profile throughout the day. Conventional and controllable power plants cannot simply follow the predicted demand as before but must cover the residual load, the difference between demand and renewable generation. Consequently, baseload power plants are displaced and the need for flexible power plant capacity increases.

The altered structure of the power plant fleet not only leads to more production of green electricity but also to more volatile electricity prices. Due to marginal costs close to 0 €/MWh the electricity price drops significantly during hours of high renewable generation and can even become negative.

Demand Response and Demand Side Management are tools on the consumer side to respond to corresponding price signals from the market. Processes can be shifted to hours of lower electricity prices or storage can be charged or discharged based on price signals to serve inflexible processes. This leads to a reduction in both CO_2 emissions and electricity procurement costs.

Metered capacity measurement is already an established standard for large consumers, where, in addition to an energy charge for consumed energy, a capacity charge must be paid as well. The maximum demand peak plays a crucial role in calculating grid fees, as it serves as a measure for required network capacity and thus future expansion needs.

In the future smart meters can also provide households with this price information, enabling flexible consumption in this sector as well. Thus, electricity-intensive processes such as operating washing machines, heat pumps, or charging electric vehicles (EVs) can be shifted to off-peak hours. In this way the grid will be relieved and can prevent expensive redispatch measures.

Although smart meters are an essential component of new tariff options, including Real-Time Pricing, end consumers must be able to sensibly adjust their consumption alongside the offering of time-dependent tariffs by electricity suppliers. Technological and financial barriers to the availability of flexible technologies, as well as informational barriers and adjustment efforts, can hinder a price-induced flexibility of households. Nevertheless, smart meters can initially promote transparency and awareness of one's own consumption and costs.

6.1.2 Transferability to water sector

Although water is a utility transported through pipes and shares similarities in measuring consumption volumes and billing, a straightforward transfer of the mechanisms outlined above is not readily feasible for various reasons.

While in the electricity sector, demand and production must be always balanced for grid stability reasons, this strong temporal dependence does not exist for water. In contrast, water can be stored much more easily in reservoirs, towers and tanks. Even the infrastructure itself can serve as storage in the short term. Due to these options, demand and supply don't have to meet each other as strictly as in electricity. Fluctuations appear on bigger time scales and therefore must be addressed differently. Nevertheless, metering plays a crucial role in monitoring and pricing water consumption also.

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[1] Bundesnetzagentur, Messeinrichtungen/Intelligente Messsysteme, https://www.bundesnetzagentur.de/DE/Vportal/Energie/Metering/start.html

The use of smart meters in the water sector is still rare and simple water meters and annual billing are the standard. Where they are used, they mainly serve to simplify and automate meter reading. The main benefits of smart meters (Smart Water Magazine) will be discussed below.

Metering & Billing

Smart metering technologies offer real-time, high-resolution monitoring of water consumption, providing users with detailed insights into their usage patterns. This allows consumers to identify inefficiencies and adjust their habits. Increased billing frequency made possible by smart meters gives users timely feedback on their water use, encouraging more mindful consumption. Also, the processes of reading water meters by the utility provider are simplified. Although smart metering does not play a crucial role within the water sector for now, there are some examples of stakeholders that already implemented them to digitalize and simplify the metering pro. For example, in Germany there are Gelsenwasser (Gelsenwasser AG; DVGW) and the Wasserzweckverband Inn-Salzach (Christian Zenger et al. 2019), where in America San Deigo aims to deploy smart meters for the whole city (Inside San Diego) .

Additionally, smart meters enable rapid detection of leaks and anomalies in the water supply network, allowing for quick maintenance and reducing water loss. This proactive approach conserves resources and cuts costs for utility providers.

Awareness

Although price-driven control of water consumption throughout the day does not have the same relevance as with electricity, smart meters can also create transparency and awareness here initially. It can be understood how much water a bathtub or washing machine requires and encourage a more rational water use. By reconsidering certain routines and unconscious behavioural patterns, water demand and costs can be influenced (Sønderlund et al. 2016; Tian and Chen 2022), which is relevant especially to the fact that many people underestimate their personal water consumption (Seelen et al. 2019).

In addition, it is possible to incentivize the reduction of water by providing information on the current situation of water supply without changing prices. For example, a “drought indicator” could show the status of the local water supply and the severity of the drought. This would also be possible without individual smart metering systems but requires a different channel for informational flow. Raising public awareness of water shortages can motivate people to voluntarily reduce their water consumption, as they are more likely to act when they understand the impact on the community. By combining a drought indicator with practical water-saving tips, responsible behaviour can be encouraged without relying on financial incentives. Such non-price measures are particularly effective in regions where price adjustments are difficult to implement or politically sensitive.

Tariff design

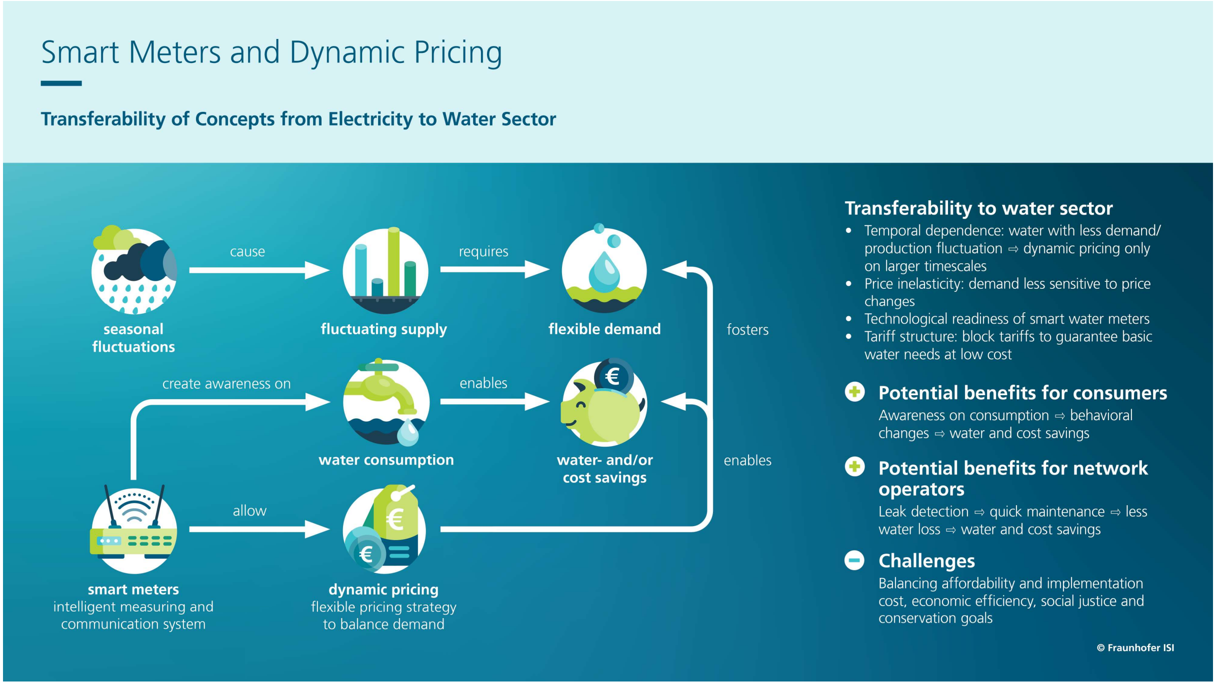
Water is essential for basic needs like hygiene, cooking, and cleaning, making a large proportion of its demand relatively inelastic to price changes, except when prices reach a certain threshold. This characteristic should be considered when adjusting water prices (Schleich and Hillenbrand 2009). The introduction of smart meters facilitates more frequent billing and enables innovative pricing models, such as progressive pricing through Increasing Block Tariffs (IBT). In this system, water is priced in tiers, with the base rate covering a defined essential volume, and higher rates applied to usage beyond this level (Dale Whittington et al. 2002). This approach encourages water conservation and discourages excessive use. However, it’s important to incorporate social factors – like household size and income – and to ensure access to water as a basic human right at an affordable cost (Barnett et al. 2020). The effectiveness of IBTs depends on the timing of billing cycles (monthly, annually, etc.) and the design of the pricing tiers, which can help achieve various policy goals. Smart meters play a crucial role in accurately tracking and billing usage over time. Digital data transmission through smart meters also allows for the flexibility to implement different tariff options in the short term. For instance, tariffs can be adjusted based on weather conditions or forecasts of anticipated droughts and therefore directly coupled with a drought indicator as mentioned above. However, there are challenges with block tariffs. Policymakers must carefully consider the structure of the blocks in terms of volume and price to balance affordability, economic efficiency, social justice, and conservation goals. This requires further research and a thorough review of existing studies.

Conversely, real-time pricing, which is already an option in the electricity sector, seems not suitable for water management. Unlike electricity, water supply does not experience strong short-term fluctuations, and shortages develop over longer periods, requiring different management approaches.

While higher water prices may have a limited impact on reducing consumption due to its inelastic nature, informed consumers are generally more responsive to price changes. This raises questions about the effectiveness of pricing as a tool for water conservation and whether alternative strategies, such as awareness campaigns and providing more information, could achieve similar results with less effort.

Except from providing general information on a community wide level like scarcity indicators all measures mentioned above require smart metering. This change in metering structure arises the question of feasibility. The costs and wide availability of such metering systems are significant factors to consider, as the implementation of smart metering requires substantial initial investment in infrastructure and technology. Additionally, the widespread adoption of these systems depends on the readiness of the local utilities and the affordability for consumers. The installation and maintenance costs, along with the need for robust data management and security protocols, may pose challenges for some regions or stakeholders. Furthermore, ensuring equitable access to smart metering technologies across different socio-economic groups is crucial to avoid creating disparities in water management. Despite these challenges, the long-term benefits in terms of water conservation, operational efficiency, and cost savings make the adoption of smart metering a worthwhile consideration.

Figure 2: Smart Meters and Dynamic Pricing – Summary and Impact



Smart Meters and Dynamic Pricing

Transferability of Concepts from Electricity to Water Sector

Transferability to water sector

- Temporal dependence: water with less demand/production fluctuation ⇨ dynamic pricing only on larger timescales
- Price inelasticity: demand less sensitive to price changes
- Technological readiness of smart water meters
- Tariff structure: block tariffs to guarantee basic water needs at low cost

Potential benefits for consumers

Awareness on consumption ⇨ behavioral changes ⇨ water and cost savings

Potential benefits for network operators

Leak detection ⇨ quick maintenance ⇨ less water loss ⇨ water and cost savings

Challenges

Balancing affordability and implementation cost, economic efficiency, social justice and conservation goals

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6.2 Legal instruments

Legal instruments can address the demand or the supply side. For electricity, a typical supply-side instrument is a cap-and-trade scheme. Instruments to steer electricity demand a rarer, with one example being energy efficiency obligation schemes, which are a way to ensure a certain volume of energy savings each year. However, both instruments target energy more generally rather than electricity specifically. Thus, in this chapter, instruments in the energy sector rather than the electricity sector are assessed.

Cap-and-Trade Schemes

Cap-and-trade schemes are market-based instruments used to limit the consumption of a finite resource and ensuring an adequate allocation through economic incentives. In the energy sector, a governing body sets a 'cap' or maximum limit on the volume of total permitted emissions. Companies are then issued emission permits, which they can trade among each other. If they want to emit more than their allocated amount, they must buy permits from others. Conversely, if they emit less, they can sell their unused permits. Thereby, incentives to reduce consumption of the relevant resource are steered by the market.

Energy Efficiency Obligation Schemes

Energy Efficiency Obligation Schemes are a concept obligating energy suppliers to achieve a specified amount of energy savings over a given period. Certificates are acquired by implementing measures that improve energy efficiency, often among their customer base, such as heating replacement or building retrofitting. In addition, third parties can also generate savings and trade the respective certificates with obligated parties, either bilaterally or through dedicated trading platforms. The obligated companies are allowed to pass on the costs of these measures to their customers, providing a market-based approach to improving energy efficiency, given the competition to other suppliers.

6.2.1 Cap-and-trade schemes

This scheme is quite common in energy policy and is among others used in the European emission trading system (EU ETS) or its equivalent in California. In this section, the applicability in water resource conservation is assessed, inter alia drawing conclusions from the implementation of the scheme in Australia’s Murray-Darling Basin.

6.2.1.1 General functioning in energy sector

Generally, a total number of allowances is defined and actors on the market can trade these allowances freely, often receiving a certain number for free. As a result, they have an interest in consuming as little of the resources as possible, in order to be able to sell remaining allowances or avoid having to buy additional ones.

A frequent point of discussion, are the free allowances for actors in the market. Although there is still an incentive to save as much of the resource as possible, the exploitation within the budget remains a non-internalised externality, since no additional costs accrue. This is not particularly problematic in case the total budget to be exploited is sustainable. However, since the budget is often defined as a practical limit that does not restrict market actors too much, costs to cover damages still accrue (Heinmiller 2007). Yet, with the issuance of free allowances, funds are missing to counteract the negative externalities.

Moreover, precise monitoring of resource exploitation is necessary, with illegal consumption of the resource jeopardising the integrity of the related market and the system in general.

In the specific case of the EU ETS, one of the largest and most complex cap-and-trade schemes, several safeguards mainly comprised in the so-called Market Stability Reserve (MSR) are in place to ensure that prices are neither skyrocketing nor too low (European Commission 2021; Perino and Willner 2016). In addition, in order to uphold incentives to save carbon in spite of free allowances, a benchmark system is in place to reward actors that are already spearheading their sector in terms of sustainability (Sartor et al. 2014).

6.2.1.2 Transferability to water sector

Given its scarcity in dry regions of the world, the concept of trading schemes for water has gained traction in the last decade. This concept has already been implemented in Australia to restrict water consumption for agricultural use in the Murray-Darling Basin with groundwater shortages.

In practise, every farmer in the relevant region receives a certain water budget. The total budget should constitute a sustainable quantity of water to retrieve from the groundwater source. Then, farmers having more allowances than necessary can sell their remaining water allowances to those needing more water than their budget. This rewards farmers using water carefully and investing in water saving infrastructure. Moreover, these costs incentivise measures to save water that would otherwise not be economically viable (Heinmiller 2007).

In Australia, water allowances are divided into water access high-reliability and general-reliability entitlements. According to these entitlements and seasonal water availability (depending on water levels in water bodies and dams), water is allocated to entitled rightsholders, with high-reliability entitlements allocated in 95% to 100% of cases and general-reliability entitlements allocated according to remaining water (Burdack et al. 2014).

An issue with cap-and-trade schemes is the need for all actors to be located within the same catchment area. While this can be very vast for emissions, catchment areas for water are typically way smaller. As a result, the number of market actors can be quite limited, resulting in comparably low market efficiency (Burdack et al. 2014).

A key difficulty lies in implementing this in regions, where customers supplied by a single water supplier account for a major share of water consumption, as this comes with major market power and tends to result in a significant market distortion.

In addition, a political setting able to enforce all actors' adherence to the scheme as well as providing the financial capability to address potential hardships stemming from a proper implementation of the scheme are paramount, in order for actors to trust in the scheme's persistence (Burdack et al. 2014).

Thus, this approach is mainly suitable for rural regions not relying on a central water supplier for most water consumption, with monitoring necessary at every well and policing to ensure no wells outside the scheme are in use. Moreover, in order to allow the benefit of this market solution to have an effect, a sufficient number of market actors, none of which with a disproportionate market share, are paramount. As a result, this scheme could be suitable to water systems in rural regions in most European countries. In contrast, given the overwhelming market share of the local water supplier, this is less applicable to urban areas.

Figure 3: Cap-and-Trade – Summary and Impact

Legal Instruments: Cap-and-Trade

Transferability of Concepts from Electricity to Water Sector

🟩 Water allowances allocated to Actor A and B

☐ Allowances surplus or deficit to be traded

Transferability to water sector

- Overall system simpler than for emissions
  - ⇨ Sustainably retrievable water quantity as total allowance cap
  - ⇨ No auctions required, all allowances can be allocated freely (no damage cost to cover if sustainable cap is complied with)
- Fees for transfers between different drainage basins advisable

Examples

Australia's Murray-Datling Basin for agricultural use

Potential benefits

Incentivizes cost-effective water savings

Challenges

- Implementation costs
- Monitoring costs and technical difficulties
- Limitation in scale: requires all actors to be located in same catchment area

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6.2.2 Water saving obligation schemes

Based on the existing concept of energy saving obligation schemes (EEOS), which are widely implemented across the globe and most notably in the European Union, a water saving obligation scheme as legal instrument to fund the curbing of freshwater consumption is assessed in this chapter. The idea is to harness market efficiencies in order to generate cost-effective freshwater savings, analogously to EEOSs in the energy sector.

6.2.2.1 General functioning in energy sector

In order to fulfil the requirements of the European Union, Member States must achieve a clearly defined volume of energy savings each year that go beyond autonomous energy efficiency developments (European Parliament; Council of the European Union 2023). While some Member States implement these requirements via a myriad of subsidy programmes, several other states rely on so-called energy savings obligation systems (Fawcett et al. 2019).

As part of EEOS in the energy sector, states pass on all or part of the national savings obligations to the relevant companies so that they must incur and ensure savings to avoid penalties. These are usually energy suppliers, whereby the savings to be achieved are typically allocated in proportion to energy sales. The advantage lies in the companies' expertise in savings potentials and their proximity to the customers, where savings can be achieved (Fawcett et al. 2019). However, these savings explicitly do not need to be achieved among the customer base, so obligated and third parties can scout for the most cost-effective savings instead (thereby, not jeopardising their own energy sales). In addition, suppliers must recoup the costs through their energy prices without jeopardising their competitiveness, so that the most economical savings potential is addressed. This, in turn, generally leads to more cost-effective savings than those achieved through subsidy programmes (Rosenow and Bayer 2017).

In the energy sector, the exact design of these systems differs significantly between Member States. This can include the specification of suitable measures, whether the system is based on primary or final energy savings (whereby the underlying EU regulation is based on final energy), whether third parties are allowed to generate and sell the savings, or how savings certificates are traded. For instance, in some places, savings certificates are traded on centralised trading platforms similar to an exchange, while in other countries they can only be traded directly bilaterally (Berger et al. 2023). However, an important detail is that the calculation methodology is not concerned with the change in total energy consumption, but merely with the expected savings from implemented measures. This means that the savings do not depend on effects such as economic growth (and the associated increase in energy demand) or weather.

6.2.2.2 Transferability to water sector

The concept of an EEOS could theoretically be applied to the water sector by requiring water suppliers to achieve a certain volume of water savings. This would make sense insofar as they know the critical points of their network and therefore know where and how water can be saved most effectively. This would also give water suppliers a reason to actively help reduce water demand and tackle the problem of water scarcity. In order to apply such a system to the water sector, it would have to be designed in such a way that the differences to the energy sector are considered.

Water suppliers could act as obligated parties, as they are closest to end customers and have the most in-depth expertise in related infrastructure. The obligation could be allocated to water suppliers in proportion to water sales (Bertoldi et al. 2015). Suitable measures could include all measures to reduce the extraction of freshwater resources, such as greywater use. However, measures to improve the regeneration of groundwater reservoirs, to prevent excessive evaporation or to avoid surface run-off could also be included. To determine the expected water savings, calculations would have to be submitted by the water suppliers, with random checks of the projects by the supervisory authority. In the long term, the calculation methods could then be standardised, as is the case for certain measures in several EEOSs.

In order to create an incentive to generate more water savings in one's own area than the allocated obligation, the trading of obligation certificates could be made possible. However, a central exchange-like trading platform should be avoided in order to increase obligated water suppliers' due diligence, as buyers on such a trading platform have no information about the seller and thus about the reliability of the water savings achieved, lowering their possibility to scrutinise the acquired savings' reliability (Berger et al. 2023). In addition, third parties should be allowed to generate and sell savings to obligated companies.

This could also direct investments to regions with the most severe water problems, as the expected revenue of a measure is highest where water is the most expensive. As a result, people implementing the necessary measures would need less co-financing to be nudged to carry those out. Moreover, with the necessary investments in mind in case water consumption is not reduced, water utilities with scarce water resources might overperform on their obligation and sell their saving certificates for prices lower than the costs of implementing the same measure in an area without resource shortages.

Finally, to incentivise the implementation of larger projects beyond the annual savings obligation, it should be possible to bank or borrow the obligation to a certain extent (i.e. to credit savings in the prior or following year). This would also prevent erratic market prices for savings and ensure a more stable market (Bertoldi et al. 2010).

Given the monopoly position that water suppliers generally have in their area, it cannot be expected that market and competition prevent excessive costs from being passed on to end customers. On the other hand, similar problems exist in the energy sector in Member States that are still at the beginning of their market liberalisation and therefore still have quasi-monopolistic structures. As a solution, in some countries, authorised surcharges for the generation of energy savings are set by the responsible supervisory authority (Bertoldi et al. 2010). This approach could be adopted in the water sector, where general water prices are already being scrutinised, for instance in Germany by the Federal Network Agency as the responsible supervisory authority, due to the absence of competition. Nevertheless, this entails additional bureaucracy and monitoring.

Sustainability of implementation in the water sector:

If implemented and successful, the scheme could lead to a reliable reduction of freshwater abstractions, similar to reported savings in the electricity sector in implementing countries. In the long term, this could eliminate the need for more extensive infrastructure projects to tap new water sources, which in turn would conserve resources, reduce conflicts over water use and protect environment and biodiversity, given water developments' related negative impacts (Gorenflo and Warner 2016; Verones et al. 2017; Verones et al. 2013).

The scheme would initially lead to an increase in water prices, due to the apportionment of implemented water-saving projects' costs. However, additional costs might be partially offset by achieved water savings, although this might not be the case for all customers. Especially given water networks' high share of fixed costs, monetary savings should be expected to be significantly lower than in the energy context. Still, this would also result in a more significant financial incentive to save water. From a distributional perspective, this would in absolute terms predominantly affect affluent households, given their typically higher per capita water consumption. However, due to precarious households' generally higher water cost to disposable income ratio, they would be disproportionally affected in relative terms by the resulting price hike. In the long term, the costs of more expensive additional water supply (aforementioned tapping of new water sources or in extreme cases even supply of fresh water with trucks) would also make a positive economic contribution to the system, curbing future price hikes, whereas the current approach merely shifts the problems onto future generations (Sultana 2018; Chakkaravarthy 2019). In contrast, such a framework to reduce the need for fresh water supply could contribute towards security of water supply for generations to come.

Due to the implementation by water suppliers, the expected high costs of broad subsidy programmes targeting customers to generate water savings could be prevented (Rosenow and Bayer 2017). In addition, suppliers’ proximity to end customers means that they can partially avoid transaction costs. The trading component could also ensure the targeted addressing of the most economic potential (Bertoldi et al. 2010). Although additional costs are of course incurred as a result of implemented projects, it can be assumed that projects that would have been necessary sooner or later will also be implemented under the scheme.

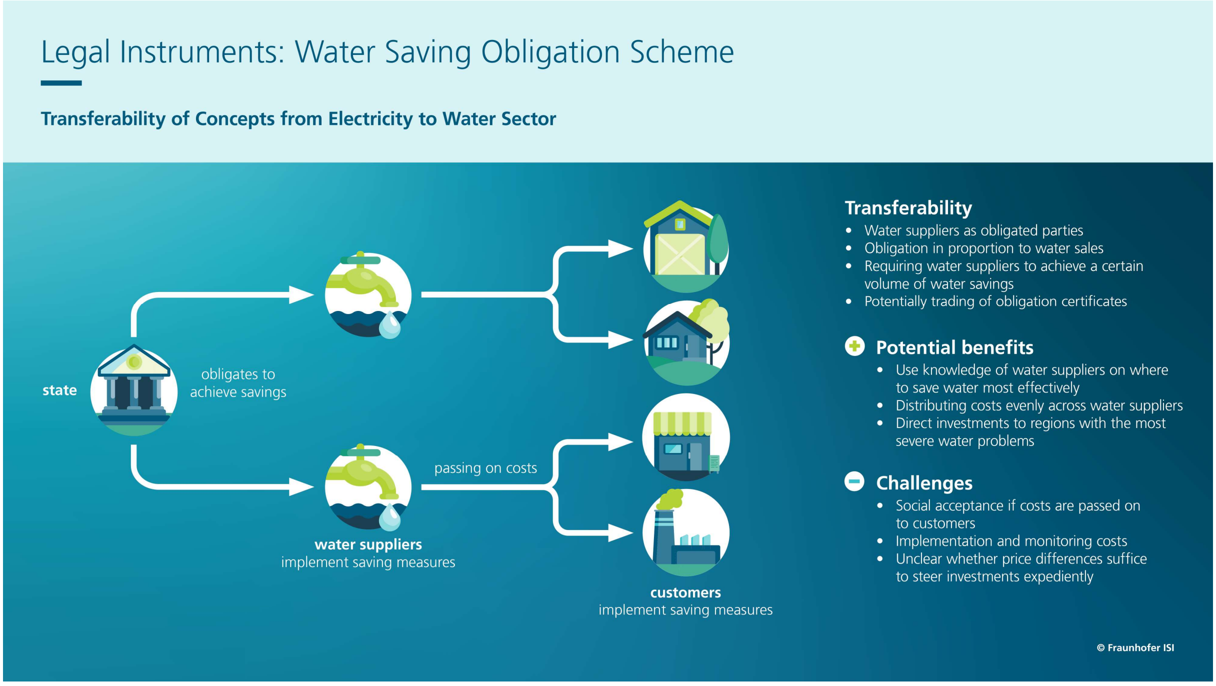
In order to implement this water saving obligation system, a corresponding law defining the legal framework, the allocation of the obligation, suitable measures, the responsible supervisory authority, etc. would need to be passed (Bertoldi et al. 2015). Although there would be some additional administrative burden, including for the competent supervisory authority, a greater administrative burden can be expected to achieve the same benefits by other means, if the experience with energy savings obligation schemes is reflected upon (Rosenow and Bayer 2017).

Moreover, the question of effectiveness remains, particularly when obligating a myriad of water suppliers without the underlying problem of water resource scarcity. This instrument would constitute a more even approach to looming necessary investments in water infrastructure compared to an alternative, where merely affected water suppliers must account for required investments. With an obligation scheme, merely a smaller share of the costs would fall to affected regions, while the majority would be rather evenly distributed across the scheme's obligated parties. If the lessons from the energy sector are transferrable, the approach could be more cost-effective than an approach of financing necessary future investments through federal grants. However, these benefits might get eaten up by additional bureaucracy.

Generally, this instrument should be seen as a funding instrument to distribute costs of necessary measures more evenly across water suppliers. As such, freshwater savings merely constitute a significant monetary value to water suppliers in regions with depleting water reservoirs expecting to require expensive additional infrastructure to maintain their service. Hence, measures funded under this instrument would be expected to be carried out predominantly in such areas, as merely these water suppliers would reap benefits from minimising their necessary infrastructure investments. However, given low water prices, effective monetary savings might turn out significantly lower than the cost of measures, resulting in water suppliers shying away from transaction costs associated with certificate trading. Thus, water suppliers would only implement convenient measures in their area of responsibility despite low expected revenue, impeding the allocation of water-saving measures to regions with most severe water scarcity, leading the whole scheme ad absurdum.

This concept could have synergies with other funding programmes aiming at sustainable water use. However, further development of this concept is required to ensure the underlying allocation effect materialises and the benefits outperform potential additional bureaucracy costs, as well as to address the issues concerning multilevel governance, as it involves different institutions and stakeholders at different levels.

Figure 4: Water Saving Obligation Scheme – Summary and Impact



Legal Instruments: Water Saving Obligation Scheme

Transferability of Concepts from Electricity to Water Sector

Transferability

- Water suppliers as obligated parties
- Obligation in proportion to water sales
- Requiring water suppliers to achieve a certain volume of water savings
- Potentially trading of obligation certificates

Potential benefits

- Use knowledge of water suppliers on where to save water most effectively
- Distributing costs evenly across water suppliers
- Direct investments to regions with the most severe water problems

Challenges

- Social acceptance if costs are passed on to customers
- Implementation and monitoring costs
- Unclear whether price differences suffice to steer investments expediently

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6.3 Extended sector coupling

Sector coupling within the energy sector

Sector coupling is the integration of various energy sectors, such as electricity, heating, cooling, and transportation, to create a more efficient and sustainable energy system. By connecting these sectors, energy produced in one sector can be used across others, optimizing overall energy use.

For example, surplus renewable electricity from solar or wind power can be used to charge EVs or operate heat pumps for building heating. This approach enhances energy flexibility, supports the use of renewable energy, and accelerates the transition to a low-carbon, sustainable energy future.

6.3.1 General functioning in electricity sector

Sector coupling refers to the integration and interconnection of different energy sectors, such as electricity, heating, cooling, and transportation, to create a flexible, efficient, and sustainable energy system. In the context of the energy transition, sector coupling is a key technology to maximize the use of renewable energy while simultaneously reducing CO_2 emissions. The primary function of sector coupling is to deliver energy where it can be used most efficiently and sustainably, transferring excess energy from one sector to others. By connecting the sectors, energy produced in one can be utilized across others, enabling better energy management (IRENA Coalition for Action 2022). By using renewable energy across various sectors, the dependency on fossil fuels is decreased. This is particularly important in areas like transportation and industry, which have traditionally relied heavily on oil and gas. Also heating still relies mostly on fossil technologies. Sector coupling can significantly contribute to achieving climate goals through the adoption of EVs and the use of green hydrogen in industry, both of which help decarbonize these sectors. At the same time reduced energy losses can lead to cost savings and sector coupling can create new businesses opportunities by utilizing unused potentials of services and flexibility within smart grid infrastructure and new technologies.

Sector coupling enables better integration of renewable energy into the existing energy infrastructure. While the electricity sector plays a central role in providing clean energy, other sectors such as heating and transport can also benefit from renewable energy use. For instance, electricity generated from wind or solar energy can be used to power heat pumps for heating or cooling buildings. This not only improves the carbon footprint of the heating market but also reduces the demand for fossil fuels. This approach allows renewable energy to be used more effectively instead of being wasted. Another important feature of sector coupling is the increased flexibility it provides to the energy system. As already mentioned, renewable energy production is often volatile, as it depends on weather conditions and time of day. Through sector coupling, flexible loads can be utilized to balance fluctuating production. For example, EVs can act as flexible storage: they can be charged when electricity production is high (e.g., during sunny or windy periods) and discharged during times of higher demand. This helps reduce the strain on the electricity grid and improve the stability of the entire system.

In conclusion, sector coupling is a vital approach for transforming the energy system into one that is more efficient, flexible and sustainable. It not only enhances the use of renewable energy but also contributes to reducing CO_2 emissions by replacing fossil fuels across various sectors. As technologies like EVs, heat pumps, and hydrogen solutions continue to develop, the role of sector coupling will become even more significant, playing a crucial part in the global energy transition.

6.3.2 Transferability to water sector

Besides to the coupling of different sectors of energy demand, the integration of the water sector can offer a transformative expansion of energy systems, combining energy, water, and resource management to maximize efficiency and sustainability. Water plays a critical role in this extended sector coupling due to its local availability and its multifunctional uses across energy and resource systems. In addition to its main purpose of water supply for classical use, it can be utilized in various ways to be part of a broadened energy infrastructure. By incorporating water systems into energy planning and the other way around, more innovative approaches can be developed. This interconnected system enhances both energy and water flows, optimizing overall performance while supporting climate resilience.

Green Roofs

A lightweight and indirect integration of water can be achieved by implementing greening measures, such as green roofs and walls. Besides benefits like improved rainwater retention and biodiversity, enhancement of water and air quality the integration of vegetation into building infrastructure also leads to lower temperatures and reduces the need for additional cooling (Shafique et al. 2018). Especially in urban areas the heat island effect can be reduced and help to enhance urban cooling and resilience to climate change. The use of grey water as resource for irrigation maximizes its utilization and helps manage water supply, particularly during periods of low rainfall (Schmitz et al. 2018; Hochschule Weihenstephan-Triesdorf 2016).

PV Cooling and Cleaning

Photovoltaic systems, central to renewable energy strategies, lose efficiency at higher temperatures, reducing their power output by approximately 0.4–0.5% per degree Celsius above 25°C. (Prudhvi and Chaitanya Sai 2012) To mitigate this, cooling strategies are employed, including both passive and active methods. In extend to the cooling effects on buildings temperatures, the installation of PV can benefit from greening measures as well. This passive cooling takes advantage of the evaporative cooling effects of vegetation and thereby improving module efficiency (Shafique et al. 2020).

Active measures, such as water circulation systems beneath PV arrays or sprinkler systems provide direct cooling, further boosting performance. By using greywater or stored rainwater can be utilized also here to provide the necessary resources. In addition to the temperature effect water can serve as cleaning medium as well, to prevent extensive pollution of the modules and thereby increase the power output significantly (Qi et al. 2025).

Besides the cooling effect of an applied water film, the provided radiation can be used in the process of the solar water disinfection method (SODIS)[2], which also benefits from higher temperatures. It can be demonstrated that water treated in this manner can meet the standards set by Regulation (EU) 2020/741 on minimum requirements for water reuse (Torres et al. 2024).

Thermal energy source

Heat pumps using groundwater or other natural water bodies (e.g. lakes and rivers) as heat source is a well-known concept and widely used. New possibilities of extended sector coupling include the use of using the water sewerage system as a heat source or heat distribution network within district heating networks. The first option utilizes the withdrawal of its thermal energy to operate heat pumps while the second option uses the network to transfer water of a certain temperature to a destination more efficiently where other options are not available. For example, the use of warm or hot water from industrial processes or municipal wastewater treatment plants can be fed into dis-

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[2] UN Climate Technology Centre and Network (CTCN), https://www.ctc-n.org/technologies/solar-water-disinfection

trict heating networks, providing low-carbon heating solutions to residential and commercial buildings. This reduces the need for additional energy inputs, while also improving the overall efficiency of district energy systems (Bundesamt für Energie 2004; Umweltbundesamt 2021; Bieker et al. 2021).

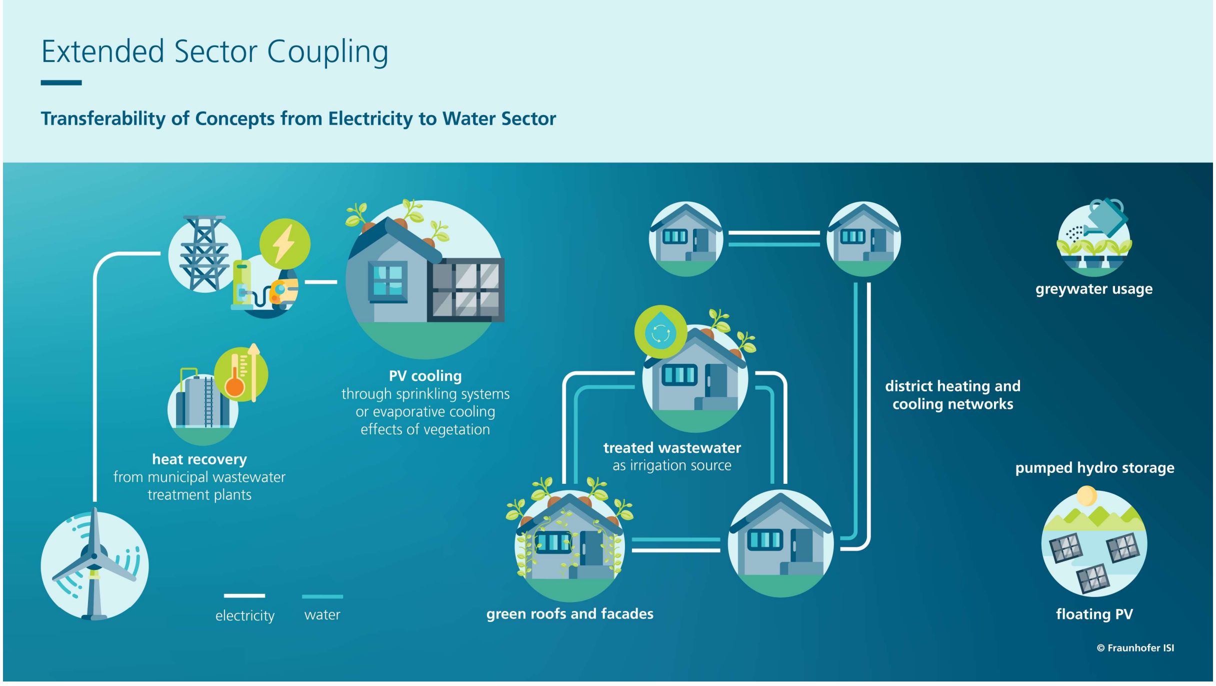
Floating PV

On a larger scale floating photovoltaic systems represent another innovative application of sector coupling. By installing solar panels on water bodies like lakes, reservoirs, or wastewater treatment ponds, these systems benefit from natural cooling due to the surrounding water. This increases the performance of the PV, while also offering environmental advantages such as reducing water evaporation and slowing algae growth (Rosa-Clot et al. 2017; Ilgen et al. 2024; Dörenkämper et al. 2021; Haas et al. 2020). In urban areas where space is limited, using water surfaces for renewable energy generation offers a valuable solution to the growing demand for green energy.

In conclusion, expanding sector coupling to include the water sector transforms the traditional energy-focused approach into a more holistic and sustainable system. By integrating renewable energy, recovering waste heat, and recycling water, communities can lower CO_2 emissions, enhance energy efficiency, and establish resilient local resource cycles. This approach not only tackles current environmental challenges but also paves the way for sustainable urban development.

The synergy between energy and water systems in extended sector coupling offers significant benefits, yet its successful implementation requires overcoming several challenges. Advancements in technology – such as efficient wastewater treatment, heat exchangers, and water circulation infrastructure – are crucial for enabling this integration. Urban planning must incorporate the convergence of energy and water management, embedding these principles into building design and public infrastructure. This transition demands both upfront investment and long-term maintenance. Additionally, supportive regulatory frameworks, including policies for wastewater reuse, renewable energy integration, and green infrastructure standards, will be essential to drive widespread adoption.

Figure 5: Extended Sector Coupling – Summary and Impact



7 Discussion and conclusion

Both the water and the electricity sector face common challenges like climate and urban development changes. Despite obvious differences, the water and the electricity sector share some analogies and the transfer of knowledge from one sector to another can unlock opportunities for innovation and growth in both. Such transfer aligns with the broader trend towards cross-sectoral integration in addressing environmental challenges.

We examined three concepts – smart meters and dynamic pricing schemes, legal instruments such as cap-and-trade schemes and water saving obligation schemes, and extended sector coupling using the example of decentralised districts – for their potential applicability in or adaptability to the water sector. These concepts have proven successful in the electricity (or a related) sector and could be adapted to address key water sector challenges related to resource management, demand response, regulatory compliance, and system integration.

Smart metering and dynamic pricing models from the electricity sector offer promising approaches for more efficient water use. While smart meters enable precise consumption monitoring and early leak detection, dynamic pricing models create incentives for better demand management. By using smart meters, households and utility providers gain real-time data on water consumption, allowing for more accurate billing and targeted demand management. More precise tracking of usage patterns enhances efficiency and awareness, reducing unnecessary losses with economic and environmental benefits. A key advantage is the early detection of irregularities in the supply system, improving maintenance processes and infrastructure control. Combined with pricing models such as block tariffs or seasonal adjustments; consumers can reduce costs and use water more sustainably. Implementing daily dynamic pricing is unlikely in the water sector, as demand is relatively price inelastic and supply remains stable throughout the day – in contrast to the electricity sector, where intraday fluctuations are significant. Seasonal price adjustments, however – such as higher tariffs during summer months – may offer a more practical mechanism for promoting water conservation. Additionally, ensuring a stable base price for essential use while charging more for excessive consumption could send a strong signal to consumers about responsible usage. Successful implementation requires investments in digital infrastructure and socially balanced tariff structures. Although initial costs exist, automated processes and improved resource planning can lead to long-term savings. Experiences from the electricity sector demonstrate that these measures can contribute to sustainability.

Cap-and-trade schemes are a key instrument to cost-effectively regulate carbon emissions in the energy sector (as well as in industry). In the water sector, first schemes have been developed as well, mainly regulating water consumption in arid rural regions. There main use is in giving the valuable and scarce resource of water a significant monetary value and being able to set an upper consumption limit. It internalises external costs linked to water scarcity into actors' (often mainly farmers) considerations and calculations. In combination with an allocation of water rights, it can for instance prevent the cultivation of crops that are not cost-effective when taking external costs of water into account, while still compensating farmers through allowance trading revenues. With increasing strain on groundwater aquifers in historically less arid climate zones, the writing is on the wall with the need for stiffer caps on water consumption (and in particular large consumers) being only a matter of time. Cap-and-trade schemes can play a central role in this push, despite substantial administrative and monitoring efforts necessary to insure their sound implementation.

Water saving obligation schemes could work in the water sector insofar more studies on saving potentials are carried out. It is commonly believed that water use for residential and industrial purposes is already efficient enough. In some places of Germany, a considerable decline in drinking water per capita has been achieved since the 90’s due to the use of efficient water appliances. Yet, agriculture could still participate in the saving schemes, since there is still efficiency potential. Despite overall water withdrawals for irrigation purposes being quite small in Germany, it can still play a role in regions where irrigated agriculture dominates. Additionally, the use of alternative water sources can also be included (e.g. water reuse from treated wastewater, rainwater use, desalination etc.) in the scheme. Despite that it doesn´t change the consumption quantity, it can still relieve the pressure on conventional water resources like surface or groundwater. This could be, under certain circumstances, as desired outcome.

Extended sector coupling offers significant opportunities by integrating energy and water systems, maximizing efficiency and sustainability. By connecting these sectors, excess renewable energy, such as from wind or solar, can be used more effectively across energy and water infrastructure. This not only reduces waste and reliance on fossil fuels but also enhances the overall use of renewable energy, helping to minimize CO_2 emissions. Water systems can contribute to flexibility by balancing fluctuations in renewable energy production, such as through heat exchange or using wastewater for energy generation. This integration increases system resilience and stability, reducing vulnerabilities in both sectors. Additionally, recovering waste heat and reusing wastewater improves resource efficiency and supports a circular approach to resource management. The coupling also opens new business models and technologies, driving economic growth while fostering innovation in energy storage, flexible demand, and resource recovery. Lastly, by enhancing climate resilience, sector coupling helps communities better manage challenges like temperature fluctuations and water scarcity, supporting sustainable urban development. Overall, the integration of water and energy systems through extended sector coupling can lead to a more efficient, low-carbon, and resilient future.

With exemption of the saving obligation schemes, all concepts have, to different degrees, been implemented in the global water sector, even though their prevalence is still negligible. This could be due to the sector’s structure, comparably low dynamism, and temporally limited political spotlight.

The water sector is more fragmented compared to the electricity sector. For instance, the national water market is comprised of numerous small, local entities with high demands on the security of supply and detailed legal framework conditions, leading to slower diffusion of new technologies. This could limit the uptake of concepts like smart meters and dynamic pricing schemes, which benefit from widespread adoption and associated standardisation of processes.

With some exemptions, the water sector is a rather undynamic environment, since water suppliers have a de facto monopoly in their area of responsibility, whereas most parts of the electricity system are subject to competition. Therefore, the water sector leaves little room for innovative actors and the pressure to adapt to more innovative approaches is rather low. Furthermore, water quality is of high concern, whereas any electricity coming out of the socket is of equal quality to its user, requiring stricter guardrails on any innovative approaches concerning water supply. In the case of fundamental changes to the framework conditions, it should be noted that water networks are typical natural monopolies, so that liberalisation, for example, is accompanied by the risk of overall system costs increasing and water quality deteriorating (Brackemann et al. 2000). Further examples on failed liberalisation of water companies are written in the book “Whose water is it, anyway?” (Barlow 2020)

Water-related problems are mainly addressed regionally, and its severity is typically seasonal. In contrast, ever since the oil crisis in the seventies, energy policy, and with it the electricity sector, has been a central political topic, with a smorgasbord of different controversially discussed approaches to achieve security of supply and low prices. This is illustrated not least by the fact that about a dozen EU Member States’ ministries carry the term “energy” in their name, with only Belgium and

Bulgaria having ministry names including the term “water”. In the electricity sector, this political spotlight and the link to climate change have resulted in several upheavals, inter alia markets’ liberalisation or the seminal EU Emission Trading Scheme. In contrast, there is hardly any political momentum to impose major alterations to the water sector’s status quo.

In conclusion, the analysis suggests opportunities for cross-sector learning and innovation between the water and electricity sectors. While direct concept transfer may not always be feasible due to the specific conditions and constraints of the water sector, these concepts offer a starting point for innovative solutions. Further research and pilot projects are necessary to explore the feasibility and impact of these concepts in the water sector. By leveraging the lessons learned from the electricity sector, we can enhance the resilience, efficiency, and sustainability of water systems, contributing to a more sustainable future.

8 List of figures

9 List of tables

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