CODEN:LUTEDX/(TEIE-7292)/1-9/(2022)

Industrial Electrical Engineering and Automation

The impacts of digitalization in the water-energy nexus

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2022-11-30

Introduction

Let us start with two definitions – digitalization and digitization. Digitalization is defined as "the adoption or increase in use of digital or computer technology by an organization, industry, country, etc." (OED, 2022a), whereas digitization is defined as "the action or process of digitizing; the conversion of analogue data (esp. in later use images, video, and text) into digital form" (OED, 2022b). Both digitalization and digitization have been given a lot of attention in the last decades. Digitalization is one of the world's megatrends and the development and use of digital tools can be seen in all parts of society. It is regarded as a key enabling factor for achieving the United Nations' (UNs) sustainable development goals (SDGs; Mondejar et al., 2021). Good examples have been shown in:

- **Food production and agriculture**
  Digitalization in agriculture include smart sensing and monitoring, analyses and planning of lands and crops to maximize yields, track livestock, and much more (Wolfert et al., 2017). Sensors can be used to detect diseases in crops, or to plan irrigation and fertilization (Yang, 2020; Johnson et al. 2020). Precision irrigation can reduce the water footprint and optimize the water use (Abioye et al., 2022).
- **Energy and electricity production**
  Digitalization can increase sustainability in energy production. Distributed electricity production and the use of scalable renewable energy sources like wind and solar can be improved (Mondejar et al., 2021). It is expected to provide smart technologies to control and optimize electricity production as well as distribution (Kangas et al., 2021). However, while the energy efficiency tends to increase from digitalization, the energy consumption tends to also increase which counteracts the effects from improved efficiency (Lange et al., 2020).
- **Industries**
  Digital tools have been used extensively in the past and is still a key feature in many process and manufacturing industries. Common applications are production planning, control, predictive maintenance, and layout planning for a smarter and more efficient production (Kritzinger et al., 2018). Monitoring, forecasting, decision support, and control and automation are traditional applications but are expected accelerate using digital twins (Pantelides & Renfro, 2013; Martinez et al. 2018).
- **Education and health**
  Remote working and education have become viable options that increase accessibility which is important from a social sustainability perspective but also poses a threat to mental health. Digitalization, particularly the use of artificial intelligence (AI), in medicine is expected to facilitate disease detection and diagnostics (Apostolopoulos & Mpesiana, 2020; Bradshaw et al., 2022; Corridon et al., 2022).
- **Water and Wastewater**
  The water and wastewater sector has for a long time been dependent on communication technologies and digital tools for control (Creutzig et al., 2022). Process modelling for

optimization has also been an important tool historically (see e.g. Jeppsson, 1999; Gernaey et al., 2004). The current digital transformation in the water and wastewater sector is from offline process simulation to real-time digital twins for control and operational support (Torfs et al., 2022; Zekri et al., 2022). Applications include advanced control strategies such as model predictive control, fault diagnostics, predictive maintenance, and much more (Avialiotis et al., 2019; Newhart et al., 2019; Stentoft et al., 2019; Mamandipoor et al., 2020).

Digitalization brings promises of solutions that might revolutionize all sectors in society. On the other hand, the increased demand on digital products will have negative impact on water, energy, greenhouse gas (GHG) emissions, and pollution (Bordage, 2019). Mining of rare minerals and metals needed for digital products affect water quality and energy consumption locally. Production and transportation of the digital products as well. Data centres and servers require massive amounts of electricity and water for cooling. Looking solely at the internet, it accounts for up to 7% of the global electricity consumption and 3.8% of the GHG emissions (Andrae, 2020; Bordage, 2019).

In 2020, 60% of the world's population had access to internet (Ritchie and Roser, 2017a). The UN Environment Programme (UNEP) recently published a Foresight Brief with the title *The growing footprint of digitalisation*, where the UNEP raises their concerns regarding the environmental footprint of the internet. Digitalization has shown to increase the environmental impact and can have negative impact on social sustainability by increasing inequality (Creutzig et al., 2022). Concerned voices are raised in all sectors (see e.g., Lange et al., 2020; UNEP, 2021; Sacco et al., 2021; Creutzig et al., 2022).

The objective of this study is to shine light on how much the collection, transfer, and storage of data is worth in terms of Wh of power, litres of water (water footprint), and the overall carbon footprint, mainly in a water and wastewater context (Figure 1). The issue will be discussed based on existing literature and examples from a Swedish water resource recovery facility (WRRF).

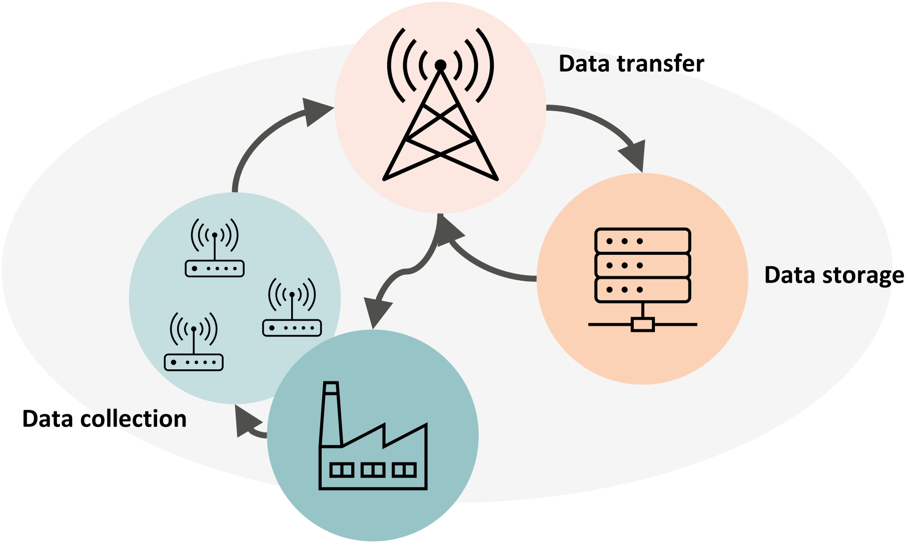

Figure 1. Schematic overview of the data flows in a wastewater treatment context.

Data collection

Data is collected on-line from a multitude of sensors, actuators, and mechanical equipment in WRRFs. PLCs, Industrial PCs, local servers, and other electronic devices are also needed in treatment plants (Figure 2). Bordage et al. (2019) reports that most of the primary energy consumption, GHG emissions, water use, and electricity use for information and communication technology (ICT) is related to the manufacturing and use of devices. One should note that this is explained by the vast number of devices in the world. In Sweden, the number of Internet of Things (IoT) devices online is 21.9 per 100 inhabitants (OECD, 2017). Estimates indicates that the number of internet users, connected devices, and M2M (Machine-To-Machine) connections all increase and will continue to do so (Cisco, 2020). The M2M connections will make up half of the connected devices and connections by 2023, out of which 48% will be applications for smart homes (lighting, appliances, home automation etc.; Cisco, 2020). A direct translation from the society in general to a water and wastewater context may be an over-simplification. It is, however, fair to assume that (1) the demand for more technically advanced sensors and equipment in WRRFs will increase in line with the digital transformation, and (2) the environmental impact of the electronic devices and mechanical equipment is non-negligible. ICT devices has an environmental footprint across their whole lifecycle: from mining of minerals and materials, to processing, production, transportation, and usage. This chapter will provide a qualitative review on the topic.

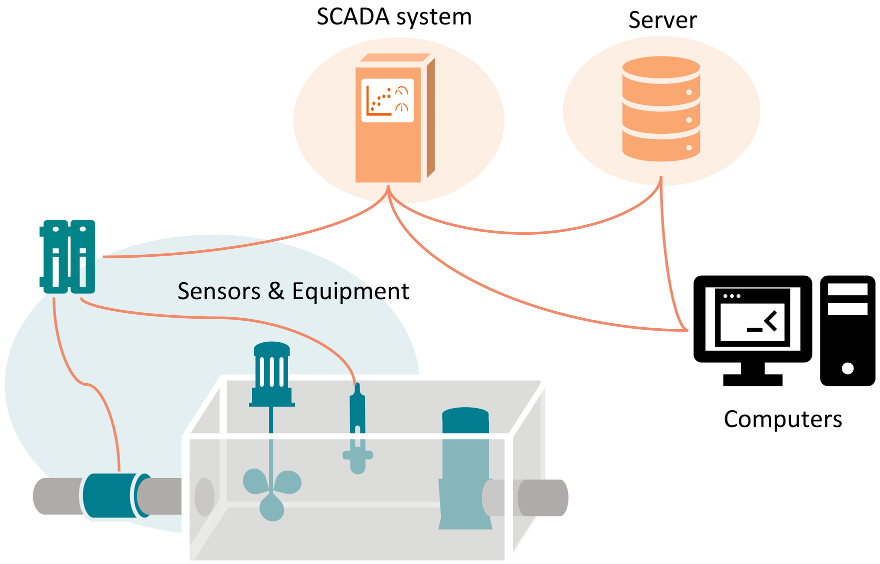

Figure 2. Schematic overview of the types of electronical and mechanical devices in a WRRF.

Sensors in WRRFs include, but is not limited to, electromagnetic flow meters, ultrasound level sensors, and optical suspended solids and dissolved oxygen sensors. They all contain plastics, metals, and sensor specific technology. Many sensors support Bluetooth and have built-in processors. Common metals are aluminium, titanium, tantalum, and platinum. Stainless steel is also a common material (e.g. ABB, 2022; Cerlic, 2022; Siemens, 2022). Mining and refining are, in general, energy intensive, and thus, depending on the energy mix, a large contributor to the GHG emission (Nunez & Jones, 2015). Mining can lead to the depletion of water bodies due to acidification and eutrophication, tailings, and a high water consumption. Human health effects, ecotoxicity effects on land and in water are other serious issues (Kossoff et al., 2014; Farjana et al., 2018). Mines leads to the loss of vegetation cover, loss of biodiversity, and land-use changes, as well as social and health impacts such as conflicts, food insecurity, and air pollution (Hilson, 2002; Worlanyo & Jiangfeng, 2021).

The plastics in sensors are commonly used for coating. They are made durable to withstand chemical exposure, and therefore fossil-based plastic like polypropylene (PP) and polytetrafluoroethylene (PFTE, also known as Teflon), and synthetic rubber (e.g. ethylene propylene diene (EDPM)) are common (e.g. ABB, 2022; Cerlic, 2022; Siemens, 2022). The environmental impact in a lifecycle perspective from fossil-based plastics is similar to the ones from mining: high energy consumption with GHG emissions as an additional effect, depletion of water bodies through eutrophication and acidification, terrestrial acidification, and ecotoxicological effects, as well as release of microplastics. Plastics, both fossil and bio plastics, are carbon-based which of course lead to carbon emissions (Walker & Rothman, 2020).

Data transmission and storage

It is estimated that 97ZB (zettabyte, zetta = 1000^7) of data will be created, captured, copied, and consumed globally in 2022. This number is expected to grow to 181ZB by 2025 (Statista, 2022). This is data that must be transmitted and stored, locally or remotely, in servers and data centres. This chapter gives an overview and, where applicable, a quantitative estimate of the environmental impact of data transmission and storage.

Data generation

Henriksdal WWTP in Stockholm, Sweden, is the largest WWTP in Sweden treating water from more than 1.5 million people. In their supervisory system, they currently have more than 8 000 signals in form of sensor signals, control signals, and equipment data, all measured online at resolution of down to 1s. This adds up to approx. 47 kB each second, or 4 GB per day and 1,460GB per year.

ICT accounts for approximately 4.2% of the primary energy consumption, 5.5% of the global electricity use, and 3.8% of the global GHG emissions (Bordage, 2019). The user equipment, such as PCs and monitors, is the biggest contributor to these high numbers. Servers and data centres account for about 15-23% of the estimated carbon dioxide (CO_2) emissions and 17% of the primary energy demand in ICT (Bordage, 2019; Rong et al., 2016). The electricity use for data centres (crypto mining excluded) was 220-320TWh in 2021, and data transmission networks used 250-340TWh the same year. Studies have indicated that the energy and carbon footprints of the ICT sector are decreasing due to more energy efficient devices (Malmodin & Lundén, 2016), while other studies expect the footprints to increase globally as the access to internet increase (Creutzig et al., 2022). Efforts to increase the efficiency in data centres has resulted in a lower energy demand *per computation*, but the *total* energy demand is still increasing (Masanet et al., 2020).

Primary energy

The internet traffic was 3.4ZB in 2021 (IEA, 2022). On an average, that means that the transmission and data centre energy use is approximately 817Wh/GB. The electricity need is 140-220Wh/GB. On a yearly basis, that sums up to a primary energy demand of almost 1200kWh and an electricity demand of 201-283kWh at Henriksdal WRRF.

The environmental impact from primary energy and electricity use is strongly correlated to the type of energy and electricity. GHG emissions originates from the manufacturing of the ICT devices, and the energy and electricity needed to operate them (Bordage, 2019). The CO_2 emissions from primary energy production can range from 0.03kgCO_2/kWh to 0.6kg CO_2/kWh (Ritchie et al., 2020). The carbon footprint from ICT is thus strongly dependent on the energy mix used (Malmodin & Lundén, 2016). The world average energy mix emits 0.22kgCO_2/kWh, while a Swedish energy mix emits 0.06kgCO_2/kWh since most of the electric power in Sweden is generate from hydro, nuclear, and wind power. For the total energy demand of ICT, that makes a difference of approximately 1 billion tonnes CO_2 (Ritchie et al., 2020).

GHG emissions

The GHG emissions from 1GB of data is 0.21kg. Applied on the annual data generation at Henriksdal WRRF (1,460GB), the emissions sum up to 300kg GHG which is equivalent to emissions of approximately 1kg of nitrous oxide.

A change in energy mix can reduce the GHG emissions but may have other negative impacts on the total environmental or water footprints. Renewable energy like solar power often requires metals and rare earth minerals (UNEP, 2021). Hydropower can affect the land-use and of course the water use. Nuclear power requires uranium (which require mining) and has a high water demand. In conclusion – there are many aspects to consider, as highlighted in Olsson (2022).

Just like the GHG emissions, the water footprint of the ICT sector is highly dependent on the primary energy and electricity production. The most water intense energy source, from a water withdrawal perspective, is hydropower. Looking at non-renewable energy sources, coal power and nuclear power (that both require water for mainly cooling) has the highest water withdrawal. From a water consumption perspective, fossil fuels and biofuels are the most intense (Mekonnen et al., 2015; Olsson, 2022). The water footprints varies from 720m^3/TWh for wind power to 3 billion m^3/TWh for hydropower (Mekonnen et al., 2015). Lowering the carbon footprint may cause an increase in the water footprint (Mekonnen et al., 2016).

The water consumption for users, networks, and data centres accounts for 0.2% of the global water consumption, which may sound low but is approximately the same as the total water consumption of the United Kingdom in 2017 (Ritchie and Roser, 2017b). Most of the water footprint, 73%, originates from manufacturing of the user equipment. 12% is needed for operation of data centres and data transmission networks (Bordage, 2019). These figures do not include the water needed for electricity production, which is also a substantial part that should be accounted for (Mytton, 2021). 40% of the energy consumption in data centres is needed to run the servers and 40% is needed for cooling (Rong et al., 2016). In data centres, the water is needed for cooling and to power the servers. The energy demand is strongly connected to cooling. Relocating servers to colder areas can reduce the water footprint locally (Mytton, 2021).

Water footprint (energy production excluded)

The freshwater footprint for ICT is 8,000,000,000m^3 annually (Bordage, 2019; Ritchie and Roser, 2017b). 16% of that is needed for data centres and data transmission, which, averaged over the annual data traffic of 3.4ZB, means that 1GB of data require 0.38 litres of freshwater. Including the manufacturing and usage of user equipment, the freshwater demand is 2.4 litres/GB (excluding the water demand for primary energy production).

Outlook and conclusion

Digital tools can help improve operations in manufacturing and process industries. It can be used to optimize food production and agriculture. Digitalization is regarded as a key enabling factor for sustainable development and to reduce negative environmental impact. While this may be true in many cases, it is not a universal truth. 1GB of data traffic demands 0.21kg GHG emissions, 0.38liters for freshwater, 817Wh primary energy, and 140-200Wh of electricity (Figure 3). This may seem small from a single business' perspective. There is no obvious incentive to reduce the environmental impact from digitalization, especially since the positive effects often may exceed the negative on small scale. On a global level, however, the impact is quite big. The annual data creation, usage, and consumption is 97ZB and is expected to grow, which is why these things need to be addressed.

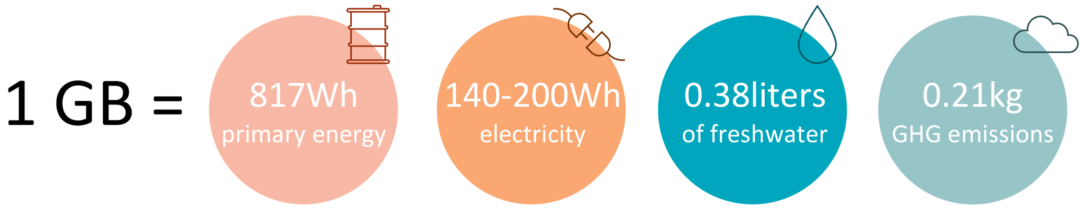

Figure 3. Infographic on the estimated footprints of creation, transmission, and storage of 1GB data.

Make use of the generated data

The first question one must ask is – is all data we create needed? Only a small portion (ca. 6%) of the data created globally is used (Ingham, 2020). This goes for the thousands of signals in WRRFs too. The sensors, actuators, pumps, and mechanical equipment are essential for operation of the treatment plant, but they generate data that just goes to waste. Going forward, it should be considered to reduce the number of signals by choosing what data to create and store, what sensors to install, and how to make the best use of the data we have. With the use of AI or other data-driven modelling tools, one can find relations in data that could be used to monitor or optimize the operation of WRRFs. Creating soft sensors to monitor parameters can reduce the need for new sensors (Newhart et al., 2019). Algorithms for predictive maintenance can extend the lifetime of equipment (Barthelmey et al., 2019). The European Union's waste hierarchy (Directive 2008/98/EC) of prevention, reuse, and recycling should function as a standard approach also in the ICT sector.

Improve energy efficiency in ICT services

Major data centre and ICT providers have already taken steps towards a more sustainable future. The tech giants like Google and Microsoft are of course contributing to the global environmental impact but have reduced their footprints by relocating data centres to colder areas, using cloud services, increase efficiency (more computations per Wh), and procuring renewable energy (Masanet et al., 2020; Mytton et al., 2021). Using cloud services instead of physical infrastructure can reduce the environmental impact (Mytton et al., 2021). Reusing the generated heat at data centres could be considered. Creating energy efficient software is something that can be done on a business scale.

Be aware and make demands

When putting numbers on the environmental impact (albeit a simplified analysis in this study) of creation, transmission, and storage of 1GB of data, it may not look alarming. But the total effect on a global level is. There are aspects that must be considered both on a global scale and for individual businesses and organizations. To be aware of the negative environmental impacts in terms of resources, production, transportation, and usage is a first step. To set requirements on environmental and social sustainability on products and systems in public procurement can reduce the negative impacts (UNEP, 2021).

A final note

Digitalization should be regarded as a tool in a toolbox, not a universal solution. Ask first what the problem is, then evaluate if digitalization is the right tool or if other solutions exist. It is not certain that the digitalization efforts will lead to sustainability on all levels.

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