D7.9 CRITICAL RAW MATERIALS AND THE INDUSTRIAL INTERNET OF THINGS (IIOT)

INSIGHTS INTO THE ANTICIPATED GROWTH IN THE IIOT VALUE CHAIN AND HOW IT MAY IMPACT CRM DEMAND

Hanski, J (VTT); Kivikytö-Reponen, P (VTT); Roman Ross, G (Amphos 21); Bruno, A (Amphos 21); Vercelli, M (Amphos 21); Hill, D (IUK KTN); Binding, S (IUK KTN).

This working paper identifies, summarises and considers the technology and devices essential to the expansion of the Industrial Internet of Things (IIoT) and highlights a range of critical raw materials (CRMs) that are (or will be) required to deliver the benefits of the IIoT.

CONTEXT, DEFINITIONS AND FOCUS

The list of CRMs was updated in 2023, with further insights and detailed formation to be found on the SCRREEN website: https://scrreen.eu/crms-2023/.

In general terms, the broad Internet of Things (IoT) is a familiar domestic concept, encapsulating things using networked devices such as smart doorbells, smart fridges, smart speakers, exercise trackers and heating controls. The term IIoT can often be used interchangeably and / or as a subset of IoT and alongside industrial concepts such as Smart Factories and Industry 4.0.

There is a wide range of differing definitions for the IIoT. For the purposes of this report, we consider the IIoT as a system that displays:

- *A network of intelligent and highly connected components*
- *Components are used in an industrial context to generate benefits including increased efficiency, improved safety and reduced costs.*
- *A system that includes real-time monitoring and effective control and management of equipment, processes, and time.*

Within this report we have therefore concentrated on a few (what we think to be) key areas to consider, which both 'set the scene' as to the importance, make up and size of the IIoT value chain and focus it on areas that join the dots to the requirement and demands for CRMs.

1. **Scene-setting**: what are the common devices, technologies and systems utilised within the IIoT value chain – showing the breadth and importance of their application.
2. **Joining the dots**: The utilisation of CRMs in the IIoT value chain and a summary of the anticipated future demand for CRMs by IIoT.
3. **A focussed look** into two of interest; water management (showing the breadth of devices and technologies used and the use of CRMs) and the digital mine (offering a different slant, showing how IIoT can support material management in the mining environment).

SCENE SETTING: DEVICES, TECHNOLOGIES AND SYSTEMS USED WITHIN THE IIOT – THE BREADTH AND IMPORTANCE OF THEIR APPLICATION.

IIoT inherently refers to the automation and optimisation of industrial processes in which different devices collect, organise, and visualise data and where that is subsequently analysed in real-time with novel technologies such as cloud computing, machine learning, big data, artificial intelligence, and real-time analytics (Khan, 2020).

IIoT devices are the **physical** objects that gather, sort, process and visualise information about industrial systems, while IIoT technologies are a set of **methods and algorithms** that allow the elaboration of such pieces of information.

IIoT devices – application summary

IIoT devices are physical objects that can remotely sense and actuate in industrial environments (Sathyabama, 2023).

They integrate production machines with electronic devices for networking and computation, constituting the foundation of IIoT and generating massive amounts of raw data streams (Nandhini, 2022).

Table 1 below summarises the common types of IIoT devices and how they are used.

Table 1: Common types of IIoT devices and their most common applications

IIOT Devices – common types and applications
Sensors *What they do / what they are* - Process, exchange, and store information, integrating sensor chips, communication chips, microprocessors, drivers, and software algorithms (Rika Sensors, accessed 2023). *Common applications* - Predictive maintenance-enabling real-time monitoring of machinery, operations, processes, and warehouses (Michele Mackenzie, 2023).
Smart Meters *What they do / what they are* - Measure and monitor utility consumption (electricity, water, and gas). *Common applications* - Wide range of both domestic and industrial scenarios.
Surveillance cameras *What they do / what they are* - Loaded with sensors and connectivity capabilities, integrate into the IIoT network for industrial facilities' video surveillance, remote monitoring, and security purposes. *Common applications* - Marine, aerospace, aviation, and manufacturing sectors (Scoutcam).
Actuators *What they do / what they are* - Convert digital commands or signals from a control system or a network into physical actions, movements, or changes in the physical world. *Common applications* - Guiding robotic arms and machinery in automated processes (Rupareliya, 2022).
Robots *What they do / what they are* - Loaded with sensors and cameras. *Common applications* - Material handling, transportation, and inventory management in warehouses (Copper Digital, Inc.).
Wearables *What they do / what they are* - Body-worn devices that enable real-time monitoring, remote collaboration, personalised perspectives, and enhanced ability in industrial settings. *Common applications* - Head-mounted displays, body-worn sensors, exoskeletons, retinal devices, and adjustable clothing (Opher, 2017).
Batteries and energy storage systems *What they do / what they are* - Batteries are energy storage systems that allow powering of devices not connected to the energy grid in open-air environments. *Common applications* - Mining, agriculture, water, and energy distribution.
Industrial routers and gateways *What they do / what they are* - In the IIoT, devices are arranged as a mesh of objects, connected to each other and to the outer networks using routers and gateways. *Common applications* - Manufacturing and logistic plants, water management, renewable and fossil-fuel energy stations, distribution networks.
Programmable Logic Controllers (PLCs) *What they do / what they are* - Industrial computers that monitor sensor inputs, make decisions based on programmed logic, and control the outputs sent to actuators. - In IIoT, PLCs collect and manage the information received from sensors, as well as programme the maintenance of machinery, and optimize the industrial operations (Mellado, 2022) *Common applications* - Highly automated manufacturing plants. (Lemay).
Asset tracking devices *What they do / what they are* - Track and identify products, components, or assets in industrial environments and connect to the IIoT network to provide real-time data on inventory levels, production progress, or logistics. - Common types included radio frequency identification (RFID) and global positioning system (GPS). *Common applications* - Manufacturing, healthcare, oil and gas, mining, steel, information and communication technology (ICT), and pharmaceutical sectors (SmartHUB).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

IIoT technologies – applications summary

IIoT technologies are a set of methods and algorithms that enable the analysis of data in industrial environments. They are employed to produce novel information for the optimization, prediction, and organisation of the manufacturing plant, by using the information collected and organised by IIoT devices.

Table 2 below summarise the common types of IIoT technologies and how they are used.

Table 2: Common types of IIoT technologies and their most common applications

IIOT Technologies – common types and applications
Big Data Analytics *What it is / what it does* - Computational analysis of information to reveal patterns, trends, and associations between data pieces. *Common applications* - In manufacturing (Klaess, s.f.), big data can contribute to predictive maintenance, predictive quality, anomaly detection, tool life-cycle optimization, production forecasting and yield improving.
Digital twins *What it is / what it does* - Virtual copies of a physical system (e.g., a process, a plant, a product, a natural environment, or a person), created using real-time data collected by sensors - they enhance predictive machinery maintenance and real-time diagnostics. *Common applications* - Energy production, water management, automotive, aviation, manufacturing and healthcare (Capgemini, 2022) (Karaarslan, 2023).
5G *What it is / what it does* - The fifth generation of mobile network *Common applications* - Potential in sectors delivering 24/7 and mobile services, such as production lines, warehouses, logistics and healthcare.
Cloud computing *What it is / what it does* - The cloud is composed of thousands of data centres which are facilities that host servers, networks, and hardware devices. *Common applications* - Across many domestic and industrial sectors.
Artificial intelligence (AI) *What it is / what it does* - The simulation of human intelligence by machines trained to learn and mimic human actions. AI is the foundation of IIoT, enabling the processing of an enormous quantity of information previously collected by several devices. *Common applications* - Many industrial sectors (food tech, manufacturing, healthcare, transportation and logistics.
Augmented reality (AR) *What it is / what it does* - Overlapping of live images of the physical environment with computer-generated sensory elements such as sound, video, graphics, and GPS data. Widely used in smart glasses, tablets, projectors, and smartphones (Vule Reljic, 2021) (Starch, 2020). *Common applications* - Numerous, ranging from worker remote assistance and increased employee safety to pre-sale and after-sale customer experience improvement.

Data centres and data transmission network

IIoT systems can incorporate either wireless or wired transmission networks. This section focuses on fixed broadband (BB) access network, which has a market value of 15-20 billion €, the mobile/wireless/cellular access network valued at 45-50 billion €, and enterprise networks, valued at 30-40 billion € (Carrara et al., 2023). Within wireless systems, transmitters and receivers can be embedded into portable devices.

Data transmission networks consumed between 260-340 TWh in 2021, which is equivalent to 1.1-1.4% of global electricity use. The energy efficiency of data transmission has seen significant advancements in both fixed-line and mobile networks in recent years (IEA, 2022a). Although global internet traffic has been steadily growing, rising 23 % in 2021 and between 40-50 % in 2020, the electricity consumption by operators only increased by 5 % in 2021 and a mere 1 % between 2015 and 2018.

In 2020, data centres and data transmission networks were responsible for 300 Mt CO_2 equivalent emissions,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

which is 0.6 % of total global GHG emissions. Emissions have only grown modestly, despite growing demand for digital services since 2010. This is attributable to energy efficiency improvements, renewable energy purchases by ICT companies, and the widespread decarbonisation of electricity grids in many regions. (IEA, 2022a)

IIoT consumes a considerable share of total ICT energy use. ICT related energy use between 2015 and 2021 is presented in table 3. These figures do not factor in the recent developments in energy consumption related to the machine learning training and foundation model processes. Notably, these figures do not cover the vast need of energy in raw materials extraction, processing and manufacturing needed to produce the necessary ICT equipment and infrastructure.

Table 3. ICT related energy use between 2015 and 2021.(IEA, 2022a)

	2015	2021	CHANGE
INTERNET USERS	3 billion	4.9 billion	+60 %
INTERNET TRAFFIC	0.6 ZB	3.4 ZB	+440 %
DATA CENTRE WORKLOADS	180 million	650 million	+260 %
ENERGY USE IN DATACENTRES (EXCL. CRYPTO)	200 TWh	220-320 TWh	+10-60 %
CRYPTO MINING ENERGY USE	4 TWh	100-140 TWh	+2300-3300 %
DATA TRANSMISSION NETWORK ENERGY USE	220 TWh	260-340 TWh	20-60 %

JOINING THE DOTS: SUMMARISING THE LINKS BETWEEN IIOT AND THE USE OF CRMs

CRMs are indispensable to the EU economy and are essential for a wide range of vital technologies to strategic sectors, including digital technologies.

Two recent EU policies connect IIoT and CRMs: the European Chips Act and the European Critical Raw Materials Act (CRMA).

The Chips Act addresses Europe's competitiveness and resilience in semiconductor technologies and applications. A concrete goal of this act is to increase European semiconductor production capacity from 10 % to 20 % of the global market by 2030. Achieving this requires considerable public and private investments, as well as the availability of components containing many critical raw materials for setting up the production.

The CRMA aims to ensure that EU has access to a secure and sustainable supply of critical raw materials, thus allowing Europe to achieve its 2030 climate and digital objectives. Specific aims of CRMA include:

- Setting benchmarks by 2030 for EU's domestic capacities in
    - extraction (10 %)
    - processing (40 %)
    - recycling (15 %)
    - reducing dependence on any single third country for CRMs to a maximum 65 % per single country
- Creating secure and resilient supply chains
- Enhancing supply risk preparedness and mitigation
- Improving sustainability and circularity of raw materials within the EU
- Diversifying imports

IIoT energy and raw materials consumption and the environmental impacts

Digital technologies have both direct and indirect effects on energy consumption and greenhouse gas emissions (IEA, 2022a). According to ICT industry sources, the most significant influence of digital technologies lies in their potential to facilitate more efficient energy and raw material usage, and environmental performance in other economic sectors (ITU 2012, Ojala et al. 2020). Nonetheless, estimating the overall net effect of ICT is challenging, primarily because of the intricacies of direct and indirect impacts (Horner et al. 2016).

Factors such as the rising number of connections, data creation and storage, and the number of devices (as seen in previous sections) necessitate increased manufacturing of sensors, end-user equipment and supporting infrastructure, such as data centres and data transmission networks (Eerola *et al.*, 2021).

These dynamics have led to modestly rising electricity consumption and GHG emissions and rising raw materials

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

consumption in the ICT sector. Additionally, IIoT consumes a portion of both renewable and fossil-based energy production – energy otherwise allocated to energy-intensive sectors such as steel or cement manufacturing (Eerola *et al.*, 2021).

Energy production, transmission and storage demand a significant amount of critical and strategic raw materials including aluminium, nickel, copper, lithium, cobalt, natural graphite and many others (Hanski and Kivikytö-Reponen, 2023).

IIoT devices and CRMs

The IEA estimated that there were approximately 9 billion digitally enabled automated devices in use in 2021. Breaking this down: 6.4 billion were sensors or other IoT devices, 1.1 billion were smart meters, and the remaining 1.5 billion were lighting and audio devices, appliances, or other devices. The number of digitally enabled automated devices has been steadily increasing from 1.9 billion devices in 2015. (IEA, 2022b)

As the installed base of IIoT systems and devices grows, then IIoT raw materials consumption is increasing.

When compared to energy use and emissions, the total raw materials consumed by ICT is modest. Malmodin et al. (2018) estimated that the combined ICT, entertainment, and media sectors consumed about 0.5 % of all raw materials between 2010 and 2015.

However, for specific raw materials, like indium, gallium and germanium, the ICT accounts for 80–90% of global use (Malmodin, Bergmark and Matinfar, 2018). Table 4 presents the key raw materials for high-tech products, batteries and other IIoT commodities.

Table 4. Key raw materials for high tech products, batteries and other IIoT commodities. Based on (Bobba et al., 2020; Eerola et al., 2021; Carrara et al., 2023).

High tech raw materials	Battery raw materials	Other commodities for IIoT
Boron (B)	Cobalt	Aluminium (Al)
Chromium (Cr)	Graphite	Chromium (Cr)
Cobalt (Co)	Lithium (Li)	Copper (Cu)
Gallium (Ga)	Manganese (Mn)	Gold (Au)
Germanium (Ge)	Nickel	Iridium (Ir)
Graphite (C)	Vanadium (V)	Nickel
Indium (In)		Palladium (Pd)
Magnesium (Mg)		Platinum (Pt)
Nickel (Ni)		Ruthenium (Ru)
Niobium (Nb)		Silicon metal (Si)
Rare earth Elements (REE)		Silver (Ag)
Tantalum (Ta)		Tin (Sn)
Thallium (Th)		
Tungsten (W)		

IIoT raw material needs for end devices and displays, data storage and servers, robotics and data transmission networks are presented in Figure 1 based on (Carrara *et al.*, 2023).

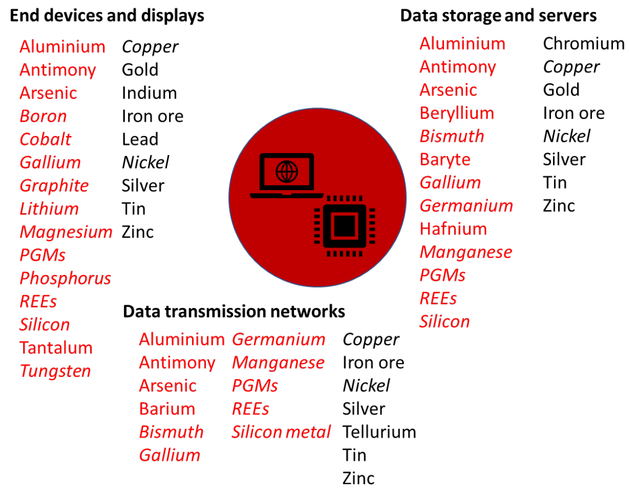


Figure 1 Raw material needs of IIoT. Red colour = critical raw materials. Italics = strategic raw materials.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

CRMs in data centres and data transmission networks

Data centres and data transmission networks rely on several critical and strategic raw materials as highlighted in Figure 1. The chassis and housing elements in these infrastructures include critical and strategic materials such as aluminium, manganese and nickel as well as non-critical iron. Manganese and nickel are important alloying elements in steel production. Cables and antennas contain elements such as copper, manganese and zinc. Other key components include optical fibres, permanent magnets, connectors, power amplifiers, printed circuit boards (PCBs) and solders. These components consume many critical and strategic raw materials, including copper, silicon metal, gallium and neodymium.

CRMs in data storage and servers

Data storage devices and servers are integral for IIoT systems in applications like data collection, processing and analysis and edge computing. Data storage and servers consist of computer systems and associated components, mostly operated interconnectedly and typically housed in data centres. Similarly, data centres and networks, chassis and housing contain aluminium, manganese, nickel and iron.

Key data storage technologies include hard disk drives (HDD) and solid-state drives (SSD). HDDs may contain strategic and critical raw materials such as aluminium and ruthenium in platters and casing, gallium and germanium in controllers, and cobalt and neodymium in magnetic alloys and permanent magnets. SSDs contains aluminium, copper, gallium and germanium, neodymium and silicon metal (Carrara *et al.*, 2023)

Servers contain components such as PCBs, CPUs, RAMs, power supplies, casings and various data storage technologies. They contain critical raw materials like copper, silicon metal, platinum group metals (PGMs), aluminium, bismuth and tantalum. Additionally, servers contain the raw materials found in HDDs and SDDs. (Carrara *et al.*, 2023)

CRMs and end devices

Devices like smartphones, tablets, and laptops consist of numerous components made from a wide variety of critical and strategic raw materials. Their casing is often made of aluminium, occasionally blended with magnesium for lightweight properties. Standard li-ion batteries within end devices contain lithium, cobalt, nickel, manganese and graphite. Displays contain indium, silicon metal and rare earth elements (REEs). Semiconductors and circuitry are composed of, for instance, silicon metal, copper, gallium and tantalum. Moreover, these devices also contain data storage, cameras and sensors, vibration and sound devices, and other components (Eerola *et al.*, 2021; Carrara *et al.*, 2023).

CRMs in robotics

Robots are integral for many IIoT systems in various parts of industrial value chains including manufacturing, transportation, agriculture and defence. Robots may contain a variety of CRMs including beryllium in electro-optical systems, gallium in communication and power systems**,** aluminium**,** manganese**,** niobium and titanium in steel alloys, and boron**,** dysprosium**,** neodymium and praseodymium in permanent magnets (Carrara et al., 2023).

FOCUSSED LOOK 1: FUTURE TRENDS IN KEY TECHNOLOGIES.

Key IIoT technologies including data transmission, servers and storage are expected to grow significantly due to the global digital transformation megatrend. The predicted widespread adoption of cloud computing, internet of things including IIoT, AI and big data applications will increase the need of cable systems, ICT processing and storage resources. End device demand is expected to be constant and saturate by 2030 (Carrara et al. 2023).

Current and future global IIoT market

IIoT is a subset of broader IoT market, focusing on industrial applications, which in turn is a subset of global ICT market. Because the data on current and predicted raw materials consumption is at ICT sector level or total Internet of Things (IoT) level, it is necessary to estimate the share of IIoT of the total IoT sector. One way of doing this is to compare the market sizes of global IIoT, global IoT market and global ICT markets. This can be used to provide a rough estimate of the current and future raw materials needs of the IIoT.

The Global IoT market is currently in 2023 valued at about €630 billion and is expected to grow to about €3200 billion by 2030 (Fortune Business Insights, 2023).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

In comparison, the global IIoT market is valued at about €300 billion and is expected to reach about €1100 billion by 2032 (Precedence Research, 2023). Global ICT market is estimated at value of €4200 billion in 2022 and €5200 billion in 2030 (Tadviser, 2023; Brookings, 2019).

Based on these figures, it can be estimated that currently IIoT covers about 50 % of IoT sector but the share is expected to drop to one third (33 %) by 2030, whereas IIoT is about 7 % of the current value of ICT sector and grow to about 20 % of the estimated value in 2030.

The total global consumption of selected CRMs in ICT sector, demand in 2020 and forecast in are presented in Table 5.

Table 5. Demand for CRMs in ICT sector 2020 and forecast 2030 (Carrara et al. 2023; SCRREEN, 2023).

Raw materials	Total global use	Global		EU	
	2020	2020	2030	2020	2030
Pd	213 t	18 t	19 – 28 t	3 t	3 – 4 t
Ga	301 t	21 t	18 – 26 t	2 t	2 – 3 t
Nd	26845 t	1093 t	1162 – 1740 t	153 t	156 – 232 t
Dy	708 t	59 t	62 – 93 t	8 t	8 – 12 t

Table 6 presents the IIoT raw materials consumption in selected CRMs and using 7 % for 2020 and 20 % for 2030 share of IIoT.

Table 6. IIoT raw materials consumption in selected CRMs based on Table 1 and using 7 % for 2020 and 20 % for 2030 share of IIoT.

Raw materials	Global		EU	
	2020	2030	2020	2030
Pd	1.3 t	4 – 6 t	0.2 t	0.6 – 0.8 t
Ga	1.5 t	4 – 5 t	0.1 t	0.4 – 0.6 t
Nd	77 t	232 – 348 t	11 t	31 – 46 t
Dy	4 t	12 – 19 t	0.5 t	1.5 – 2.5 t

Focused Look 2: Smart Water Management

N.B. This paper defines 'water management' as the systematic planning, development, distribution, and sustainable utilisation of water resources, encompassing assessment, regulation, conservation and optimization to meet diverse societal, economic, and environmental needs. This discipline entails effective coordination of infrastructure, policies, practices, and educational efforts aimed at ensuring adequate, safe, and equitable access to water while considering environmental conservation and long-term sustainability.

This section focuses on the application of the Industrial Internet of Things (IIoT) to water management and identification of CRMs needed for, and contained within, necessary devices.

Context

The topic is extremely broad, so to provide a snapshot the focus of this section is limited to three elements of water management:

- *water supply*, the delivery of potable water to final users,
- *wastewater treatment*, the treatment of wastewater before reintroducing it into natural and artificial water cycles,
- and *stormwater management*, the infrastructure used to collect, convey, treat, and manage rainfall runoff.

Gradual technification and digitalisation has led to significant changes in the very structure and functioning of water management systems. In literature, these progressive advances are defined as "water revolutions" (Adedeji, 2022).

During the so-called Water 1.0 era, drinking water was piped in- and sewaged out urban settings through *ad-hoc* systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

With the second water revolution, water was chemically and physically treated to neutralise potentially dangerous microorganisms and reduce the transmission of diseases, while the third water revolution introduced the use of computers into wastewater treatment plants for process optimization (Adedeji, 2022).

A new revolution, usually referred to as **Water 4.0 or Smart Water management**, has arisen in the last decade. Smart Water is built on the fast deployment of IoT technologies and devices, cloud computing, AI, and automated systems, leading to the emergence of more efficient infrastructures for drinking- and rainwater management, as well as of wastewater treatment facilities (Onyeneho) (Mahmoud, 2023).

To demonstrate the significance of this sector, the Global Smart Water Management Market 2023 reports (Skyquest, 2023) the market size of the Smart Water sector at 13.73 billion $ in 2021 and predicted to grow from 15.15 billion $ in 2022 to 31.73 billion $ by 2030, (with a CAGR growth of 10.3%).

Smart water management technology benefits numerous organisations by aiding in the identification of network problems, promoting water conservation among consumers, and, most significantly, mitigating non-revenue water losses resulting from deteriorating piping infrastructure (Alabi, 2019).

Uses and applications.

There are several applications of IIoT in water management including:

- monitoring water quality,
- water consumption forecasting,
- leak detection,
- smart irrigation,
- aquifers management,
- flood prediction and management,
- drought monitoring and mitigation and decision support system.

Coupled with data collected by sensors, as well as artificial intelligence and statistical methods, Smart Water management can help detect water leakage in real-time and predict pipe bursts in distribution networks. Several studies have analysed the potential of big data and artificial intelligence in the sustainable management of surface and underground water resources, for example with early warning systems, in order to inform about chronic lowering of groundwater levels, seawater intrusion or degradation of water quality (Gaffoor, 2020) (Ghernaout, 2018) (Xiaoyan W., 2019).

Data collected by sensors is wirelessly transferred to cloud-based analytics platforms to predict performance, detect faults, and provide troubleshooting insights. Moreover, the information constantly collected by several types of sensors can be merged to make-up digital twins, which will assist in the optimization of water/wastewater facility design, operations, and maintenance. Digital twins can be coupled with 3D spatial mapping of the facility, to obtain a real-time visual monitoring of assets, or for training, remote maintenance, and customer assistance.

In stormwater management, the use of sensors and actuators, and the integration of weather and model-based forecasts allows city managers to work with a preventive and adaptative approach towards storms and heavy rainfalls (Sweetapple, 2023) (Webber, 2022).

Together with geographic information systems (GIS), database management, data analytics, communication, and a knowledge-based expert system, Smart Water management can provide support in the decision-making process by helping in comparing the impacts of new measures and processes in future scenarios and making choices to optimize the preservation of the environment and water resources, and reduce costs (Adedeji, 2022).

At larger scale and in longer temporal periods, forecasts show that the implementation of IIoT in water management will provide access to vast data sets, which is key both at company and governmental level. A wide availability of historic data allows for goal-oriented data analysis, which is in turn useful for determining national losses and waste reduction targets, and for optimizing companies' operations for cost reduction (Alabi, 2019).

In summary, Smart Water has the potential to improve water management through the following (Adedeji, 2022) (Alliance for Internet of Things Innovation (AIOTI), 2018):

- Detect water leakages in the distribution networks.
- Control pipeline health.
- Manage efficiently water supplies.
- Monitor water quality in water reserves.
- Provide information for predictive maintenance.
- Forecast future water demand.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

- Predict impacts of changes in operations.
- Optimize operations in water management.
- Keep track of water consumption; and
- Improve safety in treatment plants.

Devices for smart water management & use of CRMs

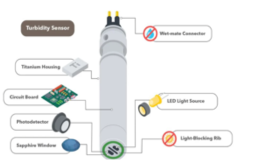
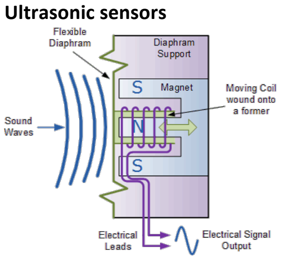
Real-time measurements require several IoT devices, in particulars sensors and actuators. The main parameters to assess water quality through sensors are water pH, dissolved oxygen concentration, flow rate, and turbidity (Pujar, 2020).

To detect abrupt water level reduction in off-grid areas, water levels in tanks can be measured with ultrasonic sensors. As an example, control strategies against Legionella, which are fundamental measures to provide safe drinking water to consumers, comprise maintaining water temperatures below 25 ºC, and this task carried out by temperature sensors (Manmeet, 2021).

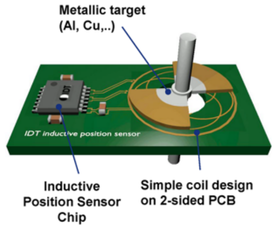
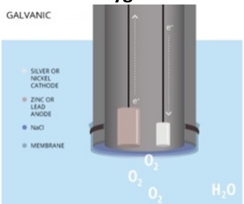
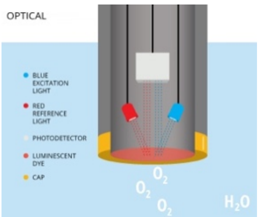
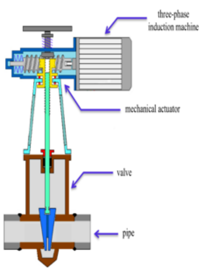
The most used actuators are valve actuators, for flow and pressure control in water supply, wastewater management and stormwater management systems.

A short description of the functionality and CRM usage of the main IIoT devices for the water management is provided in Table 7.

Table 7: *Functionality and CRM usage of the main IIoT devices for the water management*

Device	Application	CRM usage
Turbidity sensors  *Figure 1. General structure of a turbidity sensor. Source: (AtlasScientific, 2022).*	• Measures the cloudiness or haziness of water, a proxy indicator for potential sources of water pollution and hazardous organisms for human health. • Used in water supply and wastewater treatment. • They measure the light transmittance and scattering rate of the solution, which change according to the turbidity of the water (AlMetwally, 2020).	• A turbidity detector is constituted of several components, both digital and electronic. • These devices are formed by a titanium housing, containing a circuit board, a photodetector, a sapphire window, a LED light source, and a light-blocking rib. • Titanium metal is listed as an EU critical raw material, together with gallium (Ga) used in photodetectors, copper in circuit boards, and bauxite, starting material for artificial sapphire production. • LEDs contain critical elements such as indium (In) and several rare earth elements (REEs: Y, Eu, Ce).
Ultrasonic sensors  *Figure 2. General structure of a transducer, the main constituent of an ultrasonic sensor. Source: (The Instrument Guru, s.f.).*	• Widely used to detect water levels in tanks. • Fundamental to evaluate reservoirs' water availability in areas located outside the water grid. • Transducers, the main components of ultrasonic sensors, radiate pulses of sound waves to the water surface of the tank and measure the quantity of water into the deposit by measuring the time necessary for the sound signal to return to the emitter (AlMetwally, 2020).	• Transducers contain permanent magnets, which are composed of **iron** and several critical raw materials *(neodymium, praseodymium, dysprosium, and terbium)* (Gauß, 2021) (MaxBotix, 2023). • The moving coil is made of *copper*.
Water flow sensors	• Used to evaluate the volume of water flowing pipes at any given period (usually is measured in m^3/s). • Used in water supply networks, wastewater	• *Copper and bauxite*, necessary for obtaining aluminium, are the main critical raw materials for producing these devices.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Device	Application	CRM usage
 *Figure 3. General structure of an inductive position sensor, a principal component of water flow sensors. Source: (Datlinger, 2020).*	treatment plants and stormwater management services. • Each rotation of the internal pinwheel sends an electrical pulse to an inductive position sensor chip, translating to a water volume measurement (AlMetwally, 2020).	
Dissolved oxygen sensors  *Figure 4. Graphic scheme of an electrochemical dissolved oxygen sensor. Source: (Fondriest, s.f.).*	• Monitor the concentration of oxygen in wastewater treatment plant - needed for the correct removal of pollutants and microorganisms. • Dissolved oxygen diffuses from wastewater across an oxygen permeable membrane and into the sensor. Once inside, O_2 undergoes a chemical reduction reaction, which produces an electrical signal, that can be read to determine the concentration of oxygen in wastewater (Sensorex, s.f.).	• Might contain *nickel*, a critical raw material, in the cathode. • Membranes can be made of polytetrafluoroethylene (PTFE), a polymer containing fluor, which is often extracted from *fluorspar mineral*, listed as critical raw material.
Optical dissolved oxygen sensors  *Figure 5. Graphic scheme of an optical dissolved oxygen sensor. Source: (Fondriest, s.f.).*	• Assess the oxygen concentration taking advantage of light-based measurement techniques. They contain a luminescent dye which glows in presence of blue light. Oxygen optically interferes with this luminescent phenomenon and a photodiode take advantage of this effect to assess O_2 concentration in wastewater (ABB Limited , 2023).	• LEDs contain critical elements such as *indium (In)* and several rare earth elements (*REEs: Y, Eu, Ce*). • The photodetector contains *gallium (Ga).*
Valve actuators  *Figure 6. Graphic scheme of a motor-operated valve for fluid flow control. Source: (Dey, s.f.)*	• These devices convert energy into valve motion, and they are fundamental components both of water supply networks and wastewater treatment plants. Valves actuators control water flow and ensure it is distributed efficiently, according to water demand in supply networks. Moreover, they play a critical role in regulating valves' position and water pressure in supply networks (ProActuator, 2023).	• Actuators for flow control are generally mechanical, meaning that they are mainly composed of metal pieces. • Therefore, the only critical raw materials potentially included are those necessary to form corrosion-resistant metal alloys, such as *nickel (Ni), manganese (Mn), cobalt (Co), copper (Cu), vanadium (V), tungsten (W).*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Future look

- Current and future development of artificial intelligence in water management is closely tied to the availability of some specific critical materials (REE, Ti, Ga, In, Cu, bauxite, fluorspar, Ni, Mn, Co, V and W).
- Managing availability will require strategic planning, sustainable sourcing, recycling, and responsible consumption.
- The strategies require the diversification of material sources, the prioritisation of sustainable sourcing, the implementation of recycling and circular economy and research and innovation.
- By integrating sustainability principles and responsible practices into the development and deployment of IIoT, the water management sector can effectively contribute to manage the availability of critical raw materials while advancing the use of IIoT for improved water resource management.

Focussed Look 3: Digital Mine.

Mineral production covers the processing of minerals from the earth's crust, using open pits or underground mines. It also covers activities such as breaking ground, excavation, loading, hauling and transportation, as well as mineral processing (inc. crushing, grinding and separation).

In recent years, digital mine concepts have been developed by many stakeholders and companies, especially for underground mining, where digital and remote solutions can help with safety concerns.

The phrase 'digital mine' refers to digital technologies that support mineral processing.

There are some key benefits of the digital mine (McKinsey), including the monitoring of real time performance of mines, an increased mechanisation via automation (automated drills, mobile fleet and plant) resulting in deeper understanding of the resource base, an optimisation of materials and resource flows, and improved safety.

These activities can lead to cyber-physical systems such as self-driving machines, services for predictive maintenance or prescriptive maintenance, and digital twinning of mine resource base and the mine process.

Digital technologies are supporting technologies for the raw materials sector through enhanced mineral exploration, raw material processing optimisation and raw material traceability, which is an enabler to identify the origin and location of the elements and critical raw materials.

The digital solutions around material passports for tracking selected raw materials, possible 'conflict minerals' and various solutions targeting critical material efficiency are under active discussion (Eerola et al., 2021)

The Internet of Things (IoT), the digital infrastructure and data security are identified as the main contributors to the digital transformation of the raw materials sector and to the optimisation of processes, resource efficiency and productivity.

EIT Raw Materials, 2020 outline the IoT and digital infrastructure relevant for raw materials sector:
(i) 5G
(ii) Reliable server infrastructure and software solutions
(iii) Cloud-based solutions and edge computing
(iv) Unlocking of B2B and customer relations
(v) Blockchain
(vi) Certification - Trustworthy, secure and seamless tracking of raw materials from source to product.

Benefits of digital solutions include the support to reduce, reprocess, downcycle and upcycle strategies in mines (Kinnunen et al. 2022). One key challenge related to mining is the high amount of waste generated compared to produced ore and concentrates. Mining waste prevention pathways can be supported by digital technologies.

Generally, IIoT and digital technologies can monitor waste and water streams, providing accurate data and information about the availability, location, quantity and quality of materials, and can control the process more efficiently (Antikainen et al., 2018).

The need for critical raw materials can be divided based on the IIoT process flows and devices needed in them: data acquisition (including sensors), edge computing, data transfer, data storing/management and data analysis.

Data acquisition and edge computing devices in particular are exposed to the mine environmental conditions - dust, vibrations, elevated temperatures, moisture, radiation etc. This implies that the components and materials have certain durability and long-term performance requirements in demanding conditions. Furthermore, the

IIoT devices are required to be embedded in mining machines, e.g., near drill pits.

IIoT devices for data collection, data transfer, data storage, edge computing, cloud computing cover wide range of digital hardware from sensors to edge computers and displays in remote operations, many of these including wide range of CRMs only in a single device. Taking here an example of one of the most studied and common devices, a smartphone, and useful device for IIoT, especially connecting humans in the loop and making control of IIoT user friendly and easily available. Smartphones consist of a wide range of elements (53 metals according to a recent study, Bookhagen et al, 2020) - CRMs in red bold.

More than 1 g on average per single device:

- Fe, **Si, Mg, Al, Cu, Ni**, Cr.

More than 0.1 g (0.1 g < x < 1 g) on average per single device:

- Sn, Zn, **Sr, Ba, W, Nd, Mn, Ti.**

between 0.1 g and 0.01 g on average per single device:

- **Pr, Co, Ta**, Mo, Zr, Au, **V, Dy**, Ag.

below 0.01 g on average per single device:

- Pb, **Gd, Ga, Nb, As,** In, **Y, Pd, Li, Er, Sc, Hf, Ho, Tb, Bi, Sb, Pt, Ge, Ce, La,** Rb, **Yb**, Hg, **Sm, Be**, Lu, **Eu**, Cd, Te.

Many of these metals are in CRM list, found especially in small amounts.

Referring to the current fact of criticality of elements and low recycling rates of these CRMs used for IIoT, the maintenance and repair for taking care of IIoT devices is important, as is taking care of any industrial assets.

Concluding remarks

This Working Paper considered the range and breadths of devices and technologies used in the ever expanding IIoT and highlighted CRM applications, requirements and demand.

The IIoT is a vast subject matter, so this paper focussed in on a few application areas to illustrate the use of and demand for CRMS.

The paper report is necessarily light touch, given the vast expanse of the subject matter, the sheer range of the devices and technologies involved and the (apparent) lack of wide availability of studies / data making direct linkages to IIoT and CRM demand – highlighting the need for further study in this area.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730227

Annex 1: IIoT – key device and technologies (expanded from Table 1)

IIOT Devices – common types and applications	
Device	**Application**
Sensors	- Function is to acquire, process, exchange, and storage information, integrating sensor chips, communication chips, microprocessors, drivers, and software algorithms (Rika Sensors, accessed 2023). - Sensors measure physical parameters such as temperature, pressure, humidity, vibration, proximity, and flow rate, and transfer them to data servers for their analysis. - Role in IIoT is crucial as they enable real-time monitoring of machinery, operations, processes, and warehouses (Michele Mackenzie, accessed 2023). Act as the first step in predictive maintenance, to anticipate and prevent serious damage to machinery (Yokogawa, s.f.). - The implementation of smart sensors has a great potential to increase profit margins for several sectors, primarily ICT (information and communication technologies), automotive, industrial and production engineering and logistics (Zaugg, 2020).
Smart meters	- A specific type of sensor used for measuring and monitoring utility consumption, such as electricity, water, and gas, that transmits consumption data in real-time for analysis and optimization. For example, smart meters in the water management industry are being widely deployed for the fast detection of leaks, a key issue to prevent water losses (Sisinni, 2018). - Can be used to monitor power consumption of machineries and detect overuse, helping companies to optimise energy consumption and reduce costs.
Surveillance cameras	- Cameras can be equipped with sensors and connectivity capabilities, being integrated into the IIoT network for video surveillance, remote monitoring, and security purposes in industrial facilities. When coupled with image analysis, machine learning and artificial intelligence, surveillance cameras have the potential to increase the production efficiency and safety of industrial plants (Vukićević, 2021). Some of the applications of these devices are the marine, aerospace, aviation, and manufacturing sectors (Scoutcam).
Actuators	- Actuators are devices responsible for converting digital commands or signals from a control system or a network into physical actions, movements, or changes in the physical world. - When data about machinery is collected and analysed, actuators can perform corrective actions and operate upon machinery, both mechanically and electromechanically. For example, they can open and close valves, adjust motor speeds and activate alarms. The widest use of actuators in manufacturing is for guiding robotic arms and automated machinery in automated processes (Rupareliya, 2022).
Robots	- Robots are widely employed in industrial applications, and provide an increase in product quality, productivity, and cost reductions. One type of robot - *mobile robots* - are equipped with sensors and cameras and are ideal for material handling, transportation, and inventory management in warehouses (Copper Digital, Inc.). The most innovative robots and their driving technologies are expected to consolidate *transformable production*, a manufacturing system adaptable to high product variation, short life cycles, and smaller batch sizes, which fits modern requirements for mass customization of goods (Pedersen, 2016).
Wearables	- Wearables are body-worn devices that enable real-time monitoring, remote collaboration, personalised perspectives, and enhanced ability in industrial settings.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

IIOT Devices – common types and applications	
	- The main advantages of using wearables in industry are the increase in efficiency, productivity, safety, quality, and cost reduction. Some examples of wearables applied in the processing industry are head-mounted displays, body-worn sensors, exoskeletons, retinal devices, and adjustable clothing (Opher, 2017).
Batteries and energy storage systems	- Batteries are energy storage systems that allow powering devices not connected to the energy grid in open-air environments. - Some industrial sectors such as mining, agriculture, water, and energy distribution require an extensive deployment of energy storage systems, given the technical obstacles and prohibitively expensive costs of hard-wiring hundreds or thousands of devices over vast areas. - The variety of batteries employed depends on the type of devices to power and their energy demand. For example, in some cases, a non-rechargeable battery is the best option, while in others high voltage and power consumption necessitate rechargeable lithium-ion batteries (Teschler, 2018).
Industrial routers and gateways	- In the IIoT, devices are arranged as a mesh of objects, connected to each other and to the outer networks using routers and gateways. - Industrial routers allow for the connection of objects within a local network, while gateways act as intermediaries between local networks and the cloud or other external networks (Marietta, 2020). Gateways are fundamental components in an IIoT system, as they collect real-time data from field-level devices and perform data cleaning, formatting, processing, and subsequently transfers the data to the cloud. - The importance of gateways in IIoT is their ability to collect and translate to a common communication protocol several information pieces originating from different kinds of on-site devices and transfer them to data centres for data analysis (Chao Liu, 2022). - Some of the sectors where industrial routers and gateways are used are manufacturing and logistic plants, water management, renewable and fossil-fuel energy stations, and distribution networks.
Programmable Logic Controllers	- Programmable Logic Controllers (PLCs) are industrial computers that monitor inputs from sensors, that make decisions based on programmed logic, and control the outputs that will be subsequently sent to actuators. PLCs consist of multiple elements, including central processing units, which are responsible for executing the PLC program and retaining associated data. In IIoT, PLCs collect and manage the information received from sensors, as well as programme the maintenance of machinery, and optimize the industrial operations (Mellado, 2022). PLCs are used mainly in highly automated manufacturing plants, making for a more integrated production process control (Lemay).
Asset tracking devices	- Asset tracking devices are used for tracking and identifying products, components, or assets in industrial environments. They can be connected to the IIoT network to provide real-time data on inventory levels, production progress, or logistics. The fundamental contribution of asset tracking devices to IIoT is the possibility to connect non- or low-powered devices at a low cost, for example for the identification of their location for improved traceability. Some examples of asset-tracking devices are: - Radio frequency identification (RFID), which are wireless systems comprised of two components: an RFID tag located on the product to be tracked, and an RFID reader. The reader emits radio waves to detect signals from nearby RFID, communicating their identity and other information. RFID tags can store a wide range of information, such as their serial number, codes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

IIOT Devices – common types and applications	
	for traceability or technical specifications (Soori, 2023). - Global Positioning System (GPS), which is a tracking device attached to an asset that sends satellite signals processed by a receiver. This system is used when real-time tracking of products or vehicles is needed. - The widest implementation of asset tracking solutions is expected in the manufacturing, healthcare, oil and gas, mining, steel, information and communication technology (ICT), and pharmaceutical sectors (SmartHUB).

References

5G Alliance for Connected Industries and Automation. (2021). 5G for Industrial Internet of Things (IIoT): Capabilities, Features, and Potential. Frankfurt am Main. Retrieved from https://5g-acia.org/whitepapers/5g-for-industrial-internet-of-things/

ABB Limited . (2023). How the latest advances in dissolved oxygen sensor technology are delivering enhanced levels of accuracy and reliability. White paper. Retrieved 09 07, 2023, from https://library.e.abb.com/public/ff8ddbe3dcc444b794d3c0c8146cbd93/WP_ANAINST_001-EN_A.pdf

Aceto, G. e. (2020). Industry 4.0 and Health: Internet of Things, Big Data, and Cloud Computing for Healthcare 4.0. Journal of Industrial Information Integration, 18(100129). doi:https://doi.org/10.1016/j.jii.2020.100129.

Adedeji, K. e. (2022). Towards Digitalization of Water Supply Systems for Sustainable Smart City Development - Water 4.0. Applied Sciences, 12, p. 9174. doi:https://doi.org/10.3390/app12189174.

Alabi, M. O. (2019). Industry 4.0: innovative solutions for the water industry. Proceedings of the American Society for Engineering Management 2019 International Annual Conference. Retrieved from https://www.researchgate.net/publication/339055922_INDUSTRY_40_INNOVATIVE_SOLUTIONS_FOR_THE_WATER_INDUSTRY

Alexy, T. (2023, 01 11). Water 4.0: digital journey of water. Retrieved 09 05, 2023, from https://www.ey.com/en_in/technology/water-4-0-digital-journey-of-water

Alliance for Internet of Things Innovation (AIOTI). (2018). Research and Innovation Priorities for IoT: Industrial, Business and Consumer Solutions. Retrieved 09 04, 2023, from https://aioti.eu/wp-content/uploads/2018/09/AIOTI_IoT-Research_Innovation_Priorities_2018_for_publishing.pdf

AlMetwally, S. A. (2020). Real-Time Internet of Things (IoT) Based Water Quality Management System. 30th CIRP Design 2020, 91, pp. 478-485. doi:https://doi.org/10.1016/j.procir.2020.03.107.

Åmand, L. e. (2013). Aeration control – a review. Water Science & Technology, 67(11), pp. 2374-2398. doi:https://doi.org/10.2166/wst.2013.139.

Antikainen et al., 2018 https://doi.org/10.1016/j.procir.2018.04.027

AtlasScientific. (2022). What Is A Turbidity Sensor? Retrieved 09 07, 2023, from https://atlas-scientific.com/blog/what-is-a-turbidity-sensor/

Bobba, S. et al. (2020) Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Brookings (2019). Trends in the Information Technology sector. Available at: https://www.brookings.edu/articles/trends-in-the-information-technology-sector/.

Capgemini. (2022). Digital twins: adding intelligence to the real world. Retrieved from https://prod.ucwe.capgemini.com/wp-content/uploads/2022/05/Capgemini-Research-Institute_DigitalTwins_Web.pdf

Carrara, S. et al. (2023) 'Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study', Publications Office of the European Union [Preprint]. Available at: https://single-market-economy.ec.europa.eu/system/files/2023-03/Raw%20Materials%20Foresight%20Study%202023.pdf.

Chao Liu, e. a. (2022). Service-oriented industrial internet of things gateway for cloud computing. Robotics and Computer-Integrated Manufacturing, 73(102217). doi:https://doi.org/10.1016/j.rcim.2021.102217.

Chui, M. e. (2021). The Internet of Things: Catching up to an accelerating opportunity. Retrieved 08 30, 2023, from https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/iot-value-set-to-accelerate-through-2030-where-and-how-to-capture-it#/

Copper Digital, Inc. (n.d.). The Future is Here: How Robotics is Driving Industry 4.0 Objectives. Retrieved 09 21, 2023, from https://copperdigital.com/blog/role-of-robotics-in-achieving-industry-4-0-objectives/

Datlinger, C. e. (2020). Benchmark of Rotor Position Sensor Technologies for Application in Automotive Electric Drive Trains. Electronics, 9(7), p. 1063. doi:https://doi.org/10.3390/electronics9071063.

Deliotte (2017). The digital mine What does it mean for you? https://www.deloitte.com/content/dam/assets-zone1/au/en/docs/industries/energy-resources-industrials/2023/er-digital-mine-030817.pdf

Dey, A. K. (n.d.). What is a Motor Operated Valve or MOV? Types, Working, Applications, and Datasheet for MOV. Retrieved 09 08, 2023, from https://whatispiping.com/motor-operated-valve-mov/?expand_article=1

Doyle, S. (2021). 5G for Industry 4.0 operational technology networks. London. Retrieved 09 21, 2023, from https://www.gsma.com/iot/wp-content/uploads/2021/03/2021-03-GSMA-5G-Industry-4.0-Op-Tech-Networks.pdf

Eerola, T. et al. (2021) 'Digitalization and natural resources'. Available at: https://tupa.gtk.fi/raportti/arkisto/50_2021.pdf (Accessed: 24 April 2023).

EITRaw Materials, 2020, https://eitrawmaterials.eu/wp-content/uploads/2020/03/2020-03-12_EIT-RawMaterials_Digitalisation-RM-Sector.pdf

ESA (2020), DIGITAL MINE. https://business.esa.int/projects/digital-mine

European Commission: Accessed October 2023. Chip Act. Online version. https://digital-strategy.ec.europa.eu/en/policies/european-chips-act. .

European Commission. March,2023. Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future. Press release.. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661.

Fondriest. (n.d.). Measuring Dissolved Oxygen. Retrieved 09 08, 2023, from https://www.fondriest.com/environmental-measurements/measurements/measuring-water-quality/dissolved-oxygen-sensors-and-methods/

Fortune Business Insights (2023). Internet of things market. Available at: https://www.fortunebusinessinsights.com/industry-reports/internet-of-things-iot-market-100307

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Gaffoor, Z. e. (2020). Big Data Analytics and Its Role to Support Groundwater Management in the Southern African Development Community. Water, 12, p. 2796. doi: https://doi.org/10.3390/w12102796

Gauß, R. e. (2021). European Raw Materials Alliance. A report by the Rare Earth Magnets and Motors Cluster of the Raw Materials Alliance. Report, Berlin. Retrieved from https://eitrawmaterials.eu/wp-content/uploads/2021/09/ERMA-Action-Plan-2021-A-European-Call-for-Action.pdf

Ghernaout, D. e. (2018). Applying big data in water treatment industry: A new era of advance. International Journal of Advanced and Applied Sciences, 5(3), pp. 89-97. doi: https://doi.org/10.21833/ijaas.2018.03.013

Guide to PBCs and the IoT. (n.d.). Retrieved 08 30, 2023, from https://www.mclpcb.com/blog/guide-pcbs-iot/

Hanski and Kivikytö-Reponen, 2023 Towards carbon neutral industry - a critical raw materials perspective https://scrreen.eu/wp-content/uploads/2023/08/Attachment_0-14.pdf

Horner, N. C., Shehabi, A. & Azevedo, I. L. 2016. Known unknowns: Indirect energy effects of information and communication technology. Environ. Res. Lett. Available at: https://doi.org/10.1088/1748-9326/11/10/103001

IEA (2022a) Data Centres and Data Transmission Networks. Available at: https://www.iea.org/reports/data-centres-and-data-transmission-networks (Accessed: 19 June 2023).

IEA (2022b) Digitalisation. Available at: https://www.iea.org/reports/digitalisation (Accessed: 19 June 2023).

ITU 2012. Toolkit on environmental sustainability for the ICT sector 314. Available at: https://www.itu.int/dms_pub/itu-t/oth/4B/01/T4B010000060001PDFE.pdf.

Karaarslan, E. e. (2023). Digital Twin Driven Intelligent Systems and Emerging Metaverse. Singapore: Springer. doi: https://doi.org/10.1007/978-981-99-0252-1

Khan, W. e. (2020). Industrial internet of things: Recent advances, enabling technologies and open challenges. Computers and Electrical Engineering, 81. doi: https://doi.org/10.1016/j.compeleceng.2019.106522.

Kinnunen et al. 2022 https://doi.org/10.1016/j.clet.2022.100499

Klaess, J. (n.d.). Big Data For Manufacturing: An Intro To Concepts & Applications. Retrieved 09 15, 2023, from https://tulip.co/blog/big-data-for-manufacturing/

Lemay, P. (n.d.). Programmable Logic Controller: What Is a PLC and How Does It Work? Retrieved 09 21, 2023, from https://tulip.co/blog/programmable-logic-controller-what-is-a-plc/

Mahmoud, A. e. (2023). Artificial Intelligence and Modeling for Water Sustainability (1st Edition ed.). Boca Raton, Florida, USA: CRC Press. doi: https://doi.org/10.1201/9781003260455

Malmodin, J., Bergmark, P. and Matinfar, S. (2018) 'A high-level estimate of the material footprints of the ICT and the E&M sector', in. ICT4S2018. 5th International Conference on Information and Communication Technology for Sustainability, pp. 168–148. Available at: https://doi.org/10.29007/q5fw.

Manmeet, S. e. (2021). IoT based smart water management systems: A systematic review. Materials Today: Proceedings, 46, pp. 5211–5218. doi: https://doi.org/10.1007/s13201-019-1111-9

Marietta, J. e. (2020). A Review on Routing in Internet of Things. Wireless Personal Communications, 111, pp. 209-233. doi:https://doi.org/10.1007/s11277-019-06853-6

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

MaxBotix. (2023). How Ultrasonic Sensors Work. Retrieved 09 07, 2023, from https://maxbotix.com/blogs/blog/how-ultrasonic-sensors-work

McKinsey & Company. (2022). What are Industry 4.0, the Fourth Industrial Revolution, and 4IR? Retrieved 08 31, 2023, from https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-are-industry-4-0-the-fourth-industrial-revolution-and-4ir

Mellado, J. e. (2022). Design of an IoT-PLC: A containerized programmable logical controller for the industry 4.0. Journal of Industrial Information Integration, 25. doi: https://doi.org/10.1016/j.jii.2021.100250

Michele Mackenzie, e. a. (n.d.). What is the IoT value chain and why is it important? Retrieved 08 30, 2023, from https://www.analysysmason.com/research/content/articles/iot-value-chain-rdme0/

Minerals Council of Australia (2022). The Digital Mine: A review of Australia's mining innovation ecosystem. https://minerals.org.au/wp-content/uploads/2022/12/The-Digital-Mine_2022.pdf

Nandhini, R. S. (2022). A Review of the Integration of Cyber-Physical Systems and Internet of Things. International Journal of Advanced Computer Science and Applications, 13(4). doi: https://dx.doi.org/10.14569/IJACSA.2022.0130453.

Ojala, T., Mettälä, M., Heinonen, M. & Oksanen, P. 2020. The ICT sector, climate and the environment–interim report of the working group preparing a climate and environmental strategy for the ICT sector in Finland. Ministry of Transport and Communications. Available at: https://julkaisut.valtioneuvosto.fi/handle/10024/162473

Onyeneho, I. A. (n.d.). Machine learning for water main pipe condition assessment. White paper, Fracta, Inc., Floor Redwood City. Retrieved 09 07, 2023

Opher, A. e. (2017). Leveraging wearables and the IoT to disrupt, transform and unlock value - Predictions on the future of wearables and the IoT in the enterprise. Retrieved 08 29, 2023, from https://www.ibm.com/downloads/cas/O50QV9NK

Pedersen, M. R. (2016). Robot skills for manufacturing: From concept to industrial deployment. Robotics and Computer-Integrated Manufacturing, 37, pp. 282-291. doi: https://doi.org/10.1016/j.rcim.2015.04.002

Precedence Research (2023). Industrial IoT market. Available at: https://www.precedenceresearch.com/industrial-iot-marke t

ProActuator. (2023). The Power of Actuators in Water Management: A Comprehensive Guide. Retrieved 09 07, 2023, from https://www.proactuator.com/the-power-of-actuators-in-water-management-a-comprehensive-guide/

Pujar, P. e. (2020). Real-time water quality monitoring through Internet of Things and ANOVA-based analysis: a case study on river Krishna. Applied Water Science, 10(22). doi: https://doi.org/10.1007/s13201-019-1111-9

Rika Sensors. (n.d.). Talking about the application of sensors in industry 4.0. Retrieved 09 21, 2023, from https://www.rikasensor.com/talking-about-the-application-of-sensors-in-industry-4-0.html

Rupareliya, K. (2022). A Guide To Actuators In IoT: Types, Anatomy & Examples. Retrieved 08 29, 2023, from https://www.intuz.com/blog/actuators-in-iot-guide

Sathyabama. (n.d.). Industrial Internet of Things. School of Electrical and Electronics. Department of Electronics and Communication Engineering. Retrieved 08 29, 2023, from https://sist.sathyabama.ac.in/sist_coursematerial/uploads/SECA4005.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Scoutcam. (n.d.). ScoutCam Revolutionizing the Industry 4.0 Revolution. Retrieved 09 21, 2023, from https://www.odysight.ai/wp-content/uploads/2022/04/ScoutCam-I4.0-company-presentation-Jan2022.pdf

SCRREEN, 2023

Sensorex. (n.d.). Selecting Among Dissolved Oxygen Measurement Methods. Retrieved 09 08, 2023, from https://sensorex.com/dissolved-oxygen-measurement-methods/

Sisinni, E. e. (2018). Industrial Internet of Things: Challenges, Opportunities, and Directions. IEEE Transactions on Industrial Informatics, 14(11), pp. 4724-7934. doi: https://doi.org/10.1109/TII.2018.2852491

Skyquest. (2023). Global Smart Water Management Market. Retrieved 09 07, 2023, from https://www.skyquestt.com/report/smart-water-management-market

SmartHUB. (n.d.). What industries benefit from fixed asset tracking solutions? Retrieved 09 21, 2023, from https://smartxhub.com/what-industries-benefit-from-asset-tracking-solutions/

Soori, M. e. (2023). Internet of things for smart factories in industry 4.0, a review. Internet of Things and Cyber-Physical System, 3, pp. 192-204. doi: https://doi.org/10.1016/j.iotcps.2023.04.006

Starch, E. e. (2020). Using Augmented Reality and Internet of Things for Control and Monitoring of Mechatronic Devices. Electronics, 9(8). doi: https://doi.org/10.3390/electronics9081272

Statista. (n.d.). Sensors & Actuators - Worldwide. Retrieved 08 29, 23, from https://es.statista.com/outlook/tmo/semiconductors/sensors-actuators/worldwide

Sweetapple, C. e. (2023). Realising smarter stormwater management: A review of the barriers and a roadmap for real world application. Water Research, 244. doi: https://doi.org/10.1016/j.watres.2023.120505

Tadviser (2023). ICT (Global Market). Available at: https://tadviser.com/index.php/Article:ICT_(Global_Market)

Takyar, A. (n.d.). AI use cases & Applications across major industries. Retrieved 09 21, 2023, from https://www.leewayhertz.com/ai-use-cases-and-applications/

Teschler, L. (2018). Why the industrial IoT needs industrial lithium batteries. Retrieved 08 30, 2023, from https://www.powerelectronictips.com/why-the-industrial-iot-needs-industrial-lithium-batteries/

The Instrument Guru. (n.d.). Transducer. Retrieved 09 07, 2023, from https://theinstrumentguru.com/transducer/

US Natural Resources Conservation Service. (n.d.). Water Management. (US Department of Agriculture) Retrieved 09 06, 2023, from https://www.nrcs.usda.gov/water-management

Vukićević, A. e. (2021). A smart Warehouse 4.0 approach for the pallet management using machine vision and Internet of Things (IoT): A real industrial case study. Advances in Production Engineering & Management, 19(3), pp. 297-306. doi: https://doi.org/10.14743/apem2021.3.401

Vule Reljic, e. a. (2021). Augmented Reality Applications in Industry 4.0 Environment. Applied Sciences, 11(12). doi: https://doi.org/10.3390/app11125592

Webber, J. L. (2022). Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives. Water Research, 218. doi: https://doi.org/10.1016/j.watres.2022.118409

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Wiśniowska, E. (2023). Integrated Water Management—Directions of Activities and Policies. In Water in Circular Economy (1st ed.). Switzerland: Springer Cham. doi: https://doi.org/10.1007/978-3-031-18165-8_2

Xiaoyan W., e. a. (2019). Water quality monitoring and evaluation using remote sensing techniques in China: a systematic review. Ecosystem Health and Sustainability, 5(1), pp. 47-56. doi: https://doi.org/10.1080/20964129.2019.1571443

Yokogawa. (n.d.). IIoT sensors – The foundation of digital industry. Retrieved 08 30, 2023, from https://www.yokogawa.com/at/solutions/featured-topics/digital-infrastructure-wiki/dx-components/iiot-sensors-the-foundation-of-digital-industry/#top

Zaugg, D. (2020). How smart meters are driving Industry 4.0 forward. Retrieved 09 21, 2023, from https://www.ey.com/en_ch/industrial-products/how-smart-sensors-are-driving-industry-4-0-forward

Zohaib, J. e. (2023). Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities. Expert Systems With Applications, 216. doi: https://doi.org/10.1016/j.eswa.2022.119456

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227