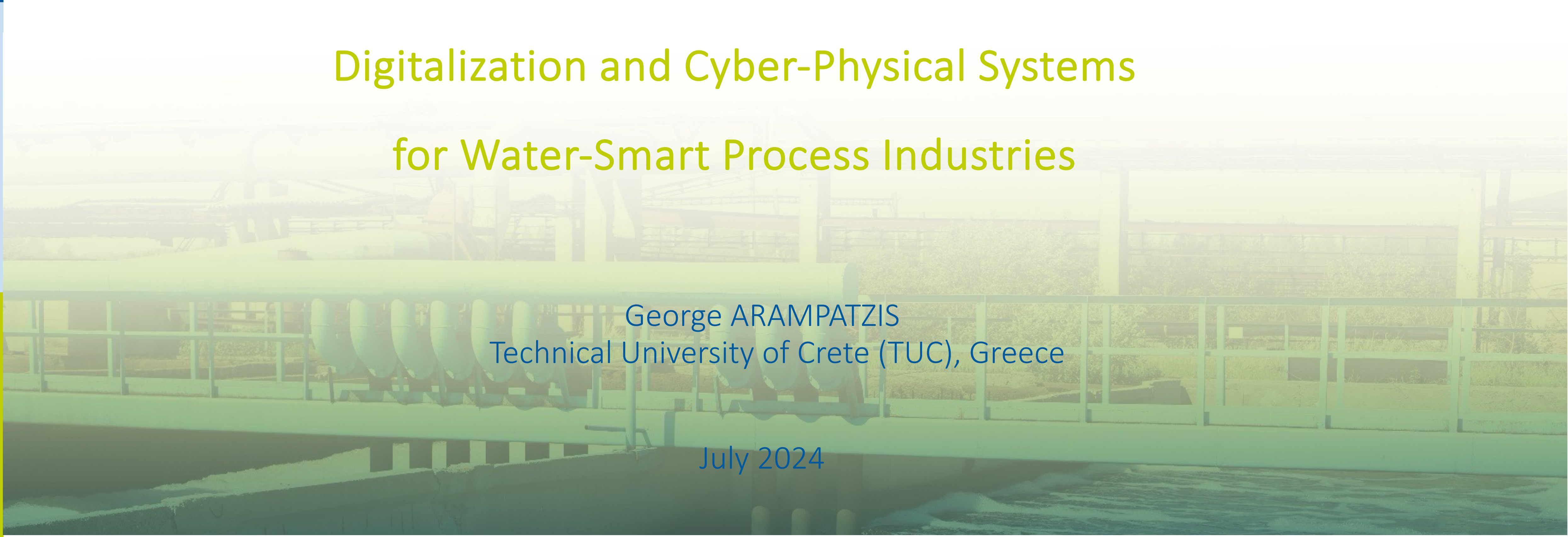
Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovation

Achieving Water-Smart Management in the Process Industry
An Educational Perspective



Digitalization and Cyber-Physical Systems for Water-Smart Process Industries

George ARAMPATZIS
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TECHNICAL UNIVERSITY OF CRETE

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Industrial and digital innovations research group

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Lecture Outline

01 INTRODUCTION

02 CURRENT TRENDS AND CHALLENGES

03 INDUSTRY 4.0/5.0 AND TWIN TRANSITION

04 ENABLING TECHNOLOGIES

05 CYBER-PHYSICAL SYSTEMS AND DIGITAL TWINS

06 DIGITAL COGNITION

07 AQUASPICE WATERCPS

01 – Introduction

Aims

- Provide an overview and explore the emerging field of **digital and green transition** of industry and other sectors
- Present the **challenges and opportunities** regarding the digitalisation of industry
- Present the **enabling technologies** underpinning the digitalisation of industry
- Present European **research** initiatives and relevant research projects
- Present and assess **use cases** of digital transition of industry

Some Terms

- Industry 4.0
- Industry 5.0
- Twin transition
- Circular Economy
- Resilience
- Sustainability
- Adaptation

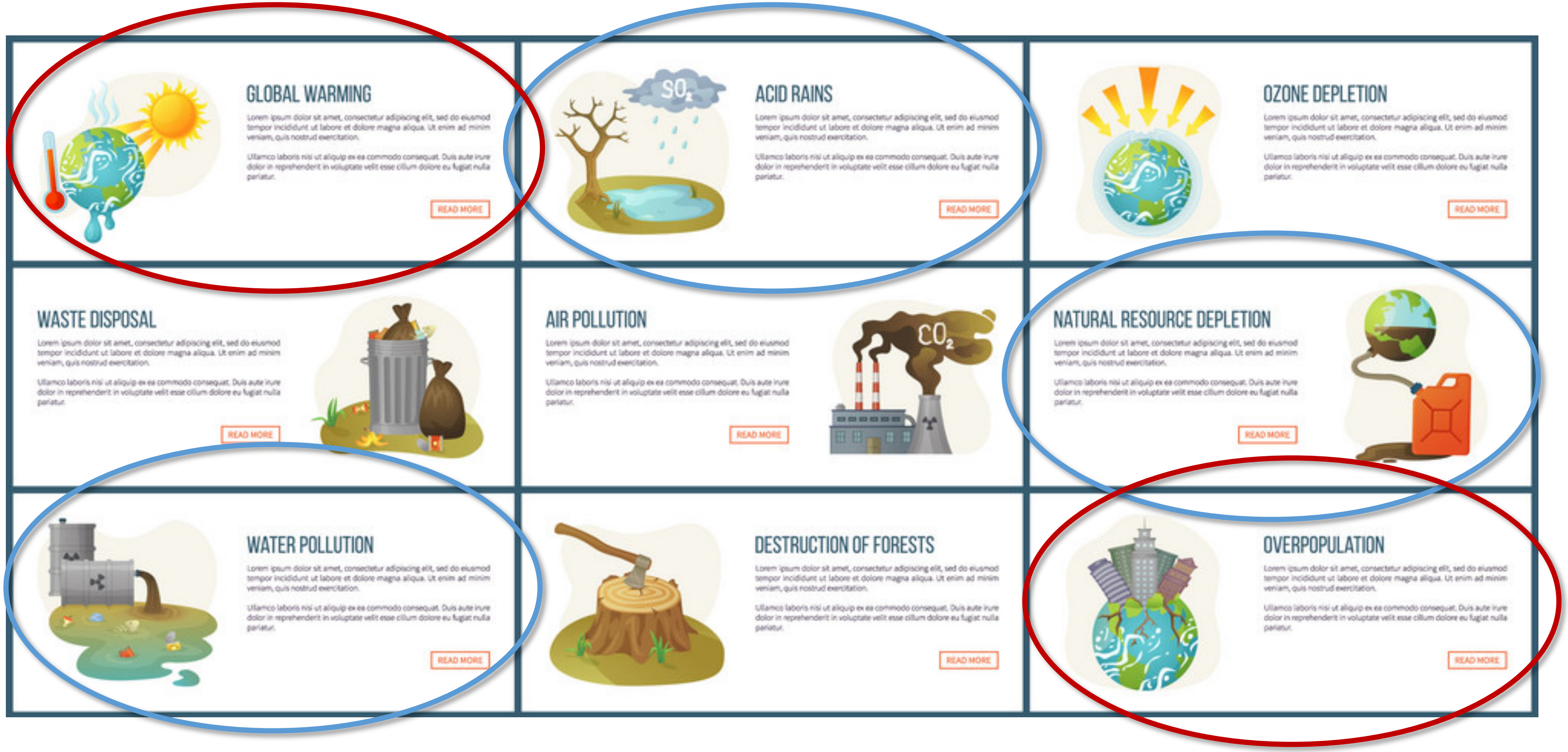
- Sustainable Development Goals
- Cyber-Physical Systems
- Digital Twins
- Internet of Things
- Big Data
- Digital Cognition
- Data Analytics

Learning Outcomes

- Have an overall view on **twin transition of industry**
- Identify and distinguish **technologies for digital transition**
- Know **applications** of each technology
- Understand the **opportunities, challenges** brought about by digitalisation
- Understand how organisations and individuals should **prepare to reap the benefits**

02 – Current Trends and Challenges

Main Problems of our Planet



UN Sustainable Development Goals

The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity.

Motivation and Challenges

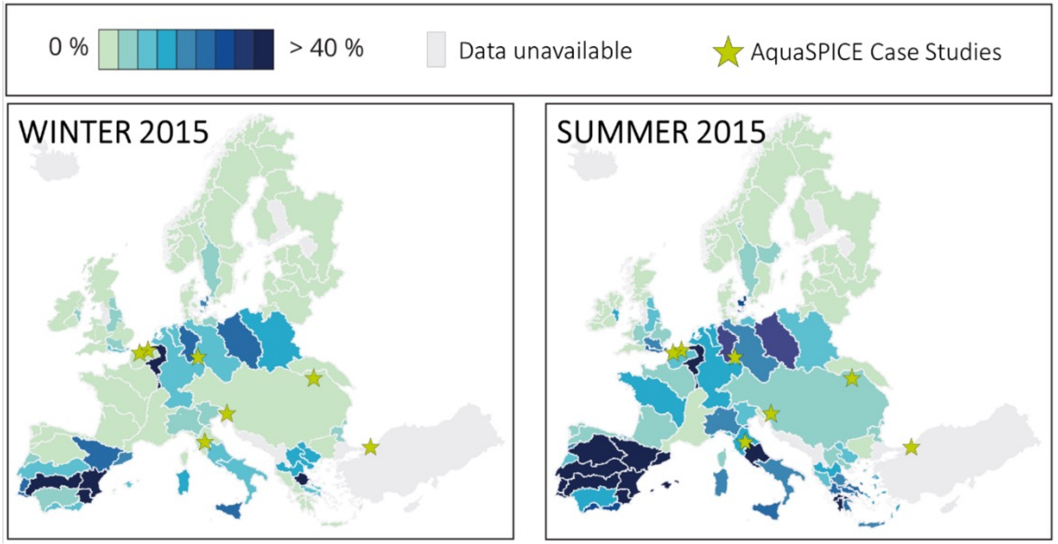
Climate change leads to increasing water scarcity problems

Increasing global water use, at more than twice the population growth rate during the last century

SDG 6: Ensure the availability and sustainable management of water for everyone

Industry relies on a sufficient water supply as water is an essential component in almost all production processes

It is estimated that 20% of all freshwater consumption globally is used by industry and this share is increased to 50% in industrialised countries



Water Exploitation Index by River Basin in 2015, adapted from:

“European Environment Agency, The European environment: State and outlook 2020: knowledge for transition to a sustainable Europe,” Luxembourg, 2019.”

Business As Usual IS NOT an option!

Pressure Factors that Create Challenges

Pushing Key Community Systems Towards Increased Digitalisation

1. Pressure for environmental **sustainability** and minimisation of the consumption of natural resources (e.g. water)
    - Drives a trend for accountability, assessment and prognosis of the use of resources and any factor &contingency related to the maximisation of resource efficiency

2. Pressure for quick and economically sustainable **adaptation** to changing technologies, market conditions and trends (**resilience**, **agility**)
    - Drives value chain connectivity, interoperability, supply & demand balancing, cost minimisation, production/product optimisation, social acceptance of production and supply chains

03 – Industry 4.0/5.0 and Twin Transition

First Definition of Industry 4.0

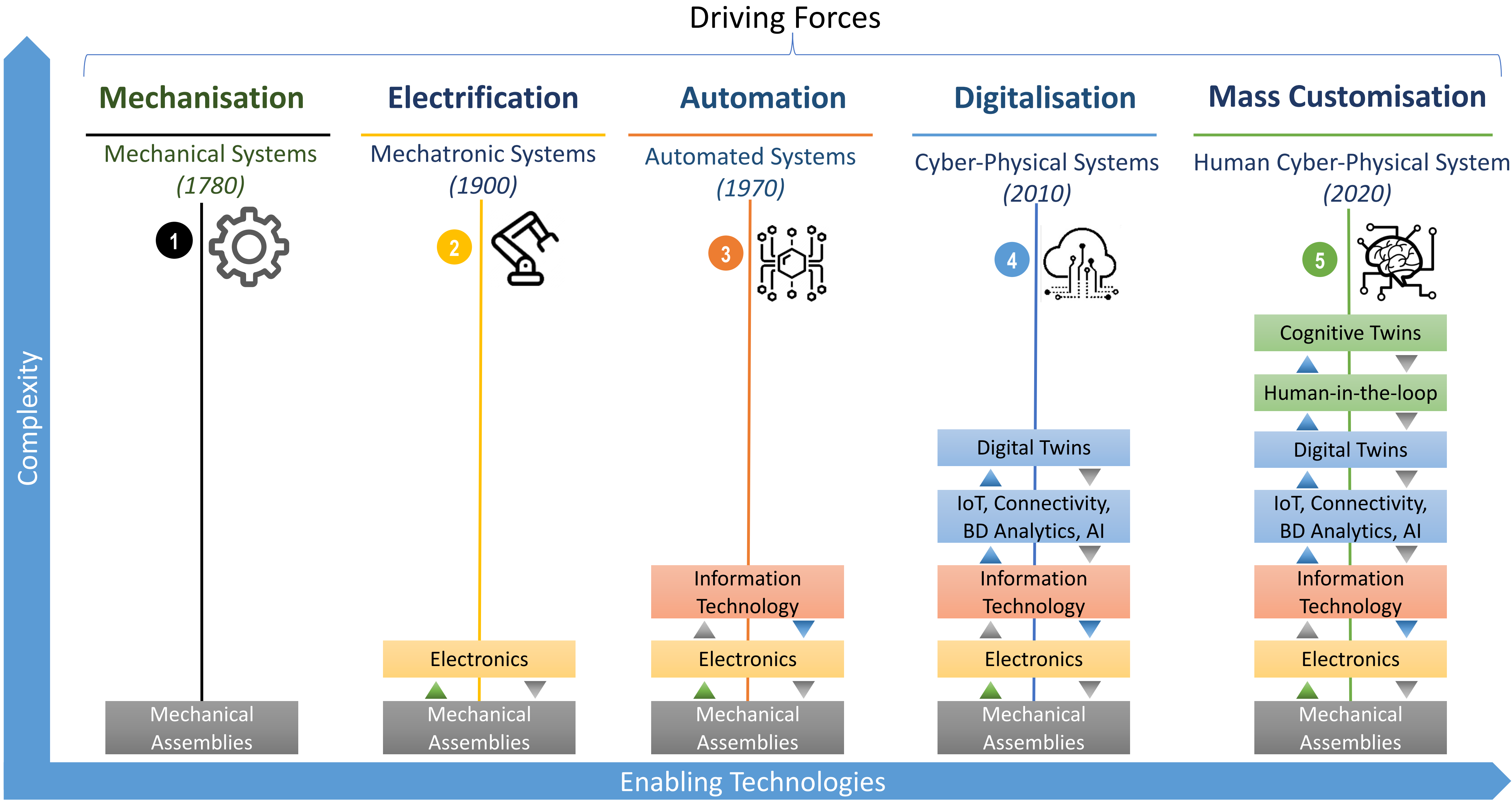
The German term ‘Industrie 4.0’ was first used at the 2011 Hannover Messe trade fair

This concept marks the fourth industrial revolution and emphasizes the use of cyber-physical systems, the Internet of Things (IoT), and cloud computing to create smart factories with interconnected machines and systems that can autonomously exchange information, trigger actions, and control each other independently.

Not all Definitions of Industry 4.0 are the same

- Industry 4.0 has a different meaning for each company.
- Even within the same company there isn't one definition of Industry 4.0. It is dependent on the strategy for each factory.
- Industry 4.0 is better defined not by its underlying technologies, but by the paradigm shift that is moving us away from centralized control to a world of decentralized, intelligent process units.

Stages in the Development of Industry



Driving Forces

Complexity

Mechanisation

Mechanical Systems *(1780)*

1

- Mechanical Assemblies

Electrification

Mechatronic Systems *(1900)*

2

- Electronics
- Mechanical Assemblies

Automation

Automated Systems *(1970)*

3

- Information Technology
- Electronics
- Mechanical Assemblies

Digitalisation

Cyber-Physical Systems *(2010)*

4

- Digital Twins
- IoT, Connectivity, BD Analytics, AI
- Information Technology
- Electronics
- Mechanical Assemblies

Mass Customisation

Human Cyber-Physical Systems *(2020)*

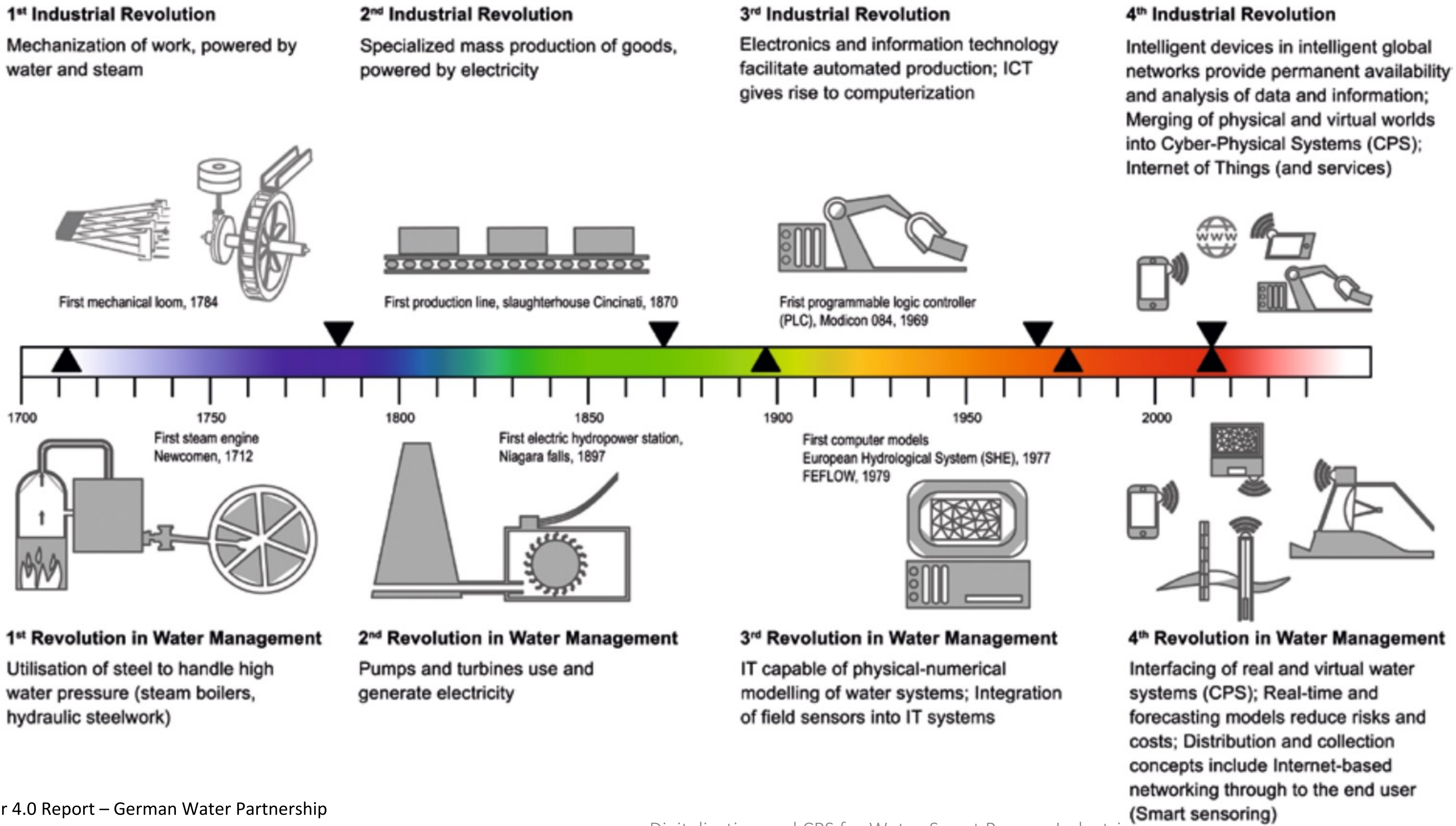
5

- Cognitive Twins
- Human-in-the-loop
- Digital Twins
- IoT, Connectivity, BD Analytics, AI
- Information Technology
- Electronics
- Mechanical Assemblies

Enabling Technologies

Industry 4.0 is not just about Factories

Water Management Evolution



1st Industrial Revolution

Mechanization of work, powered by water and steam

2nd Industrial Revolution

Specialized mass production of goods, powered by electricity

3rd Industrial Revolution

Electronics and information technology facilitate automated production; ICT gives rise to computerization

4th Industrial Revolution

Intelligent devices in intelligent global networks provide permanent availability and analysis of data and information; Merging of physical and virtual worlds into Cyber-Physical Systems (CPS); Internet of Things (and services)

1st Revolution in Water Management

Utilisation of steel to handle high water pressure (steam boilers, hydraulic steelwork)

2nd Revolution in Water Management

Pumps and turbines use and generate electricity

3rd Revolution in Water Management

IT capable of physical-numerical modelling of water systems; Integration of field sensors into IT systems

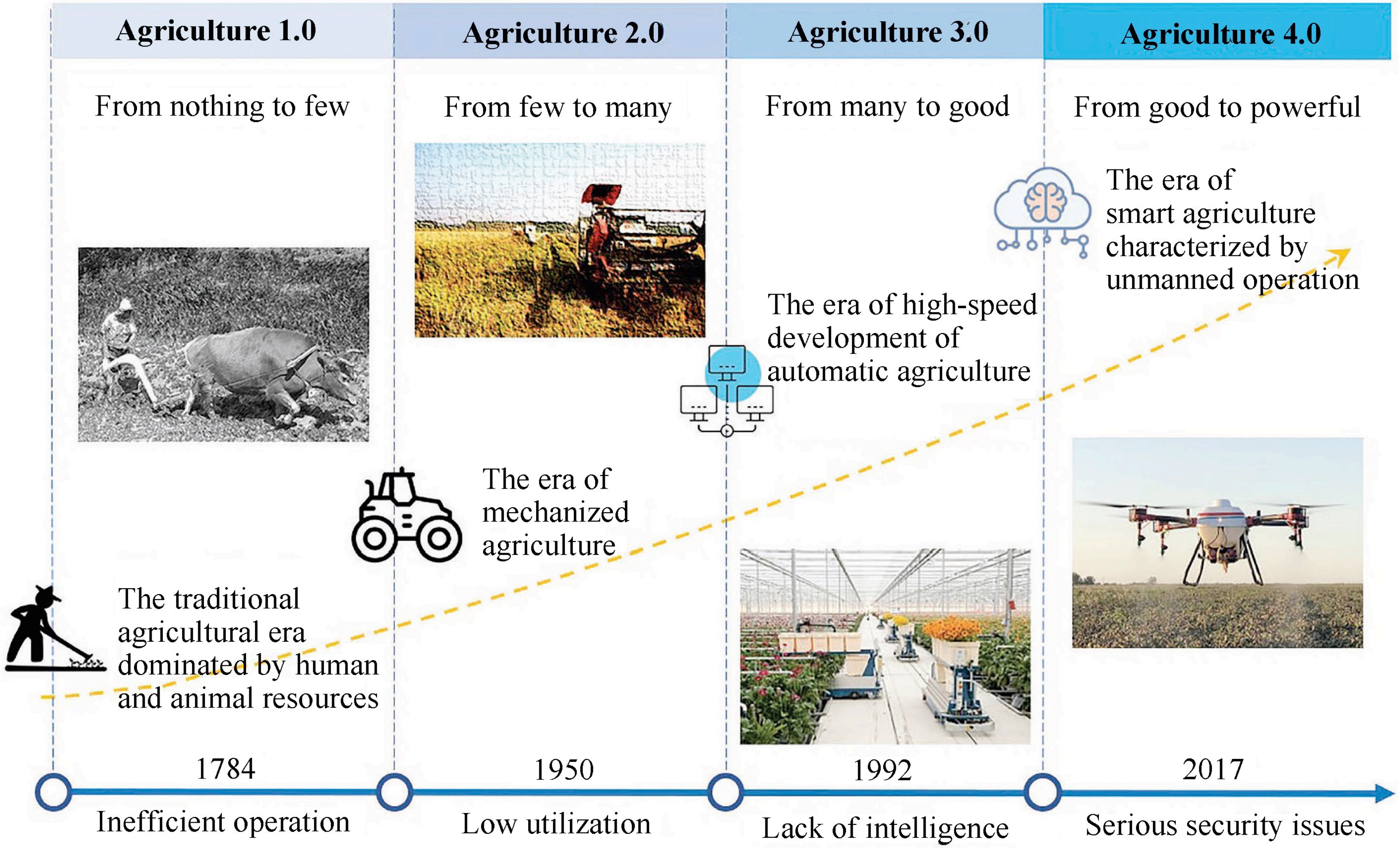
4th Revolution in Water Management

Interfacing of real and virtual water systems (CPS); Real-time and forecasting models reduce risks and costs; Distribution and collection concepts include Internet-based networking through to the end user (Smart sensoring)

SOURCE: Water 4.0 Report – German Water Partnership

Industry 4.0 is not just about Factories

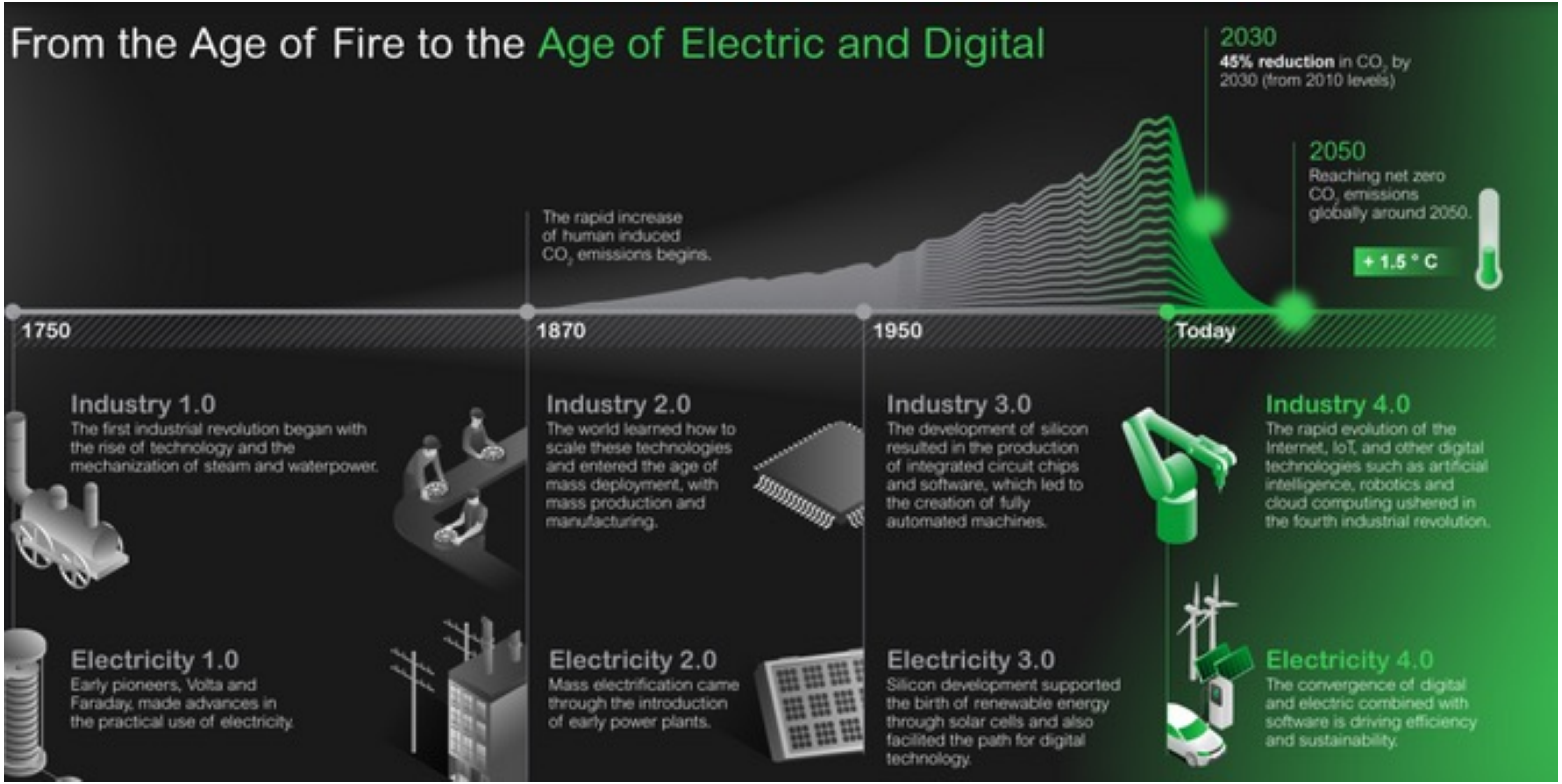
Agricultural Evolution



SOURCE: Xing Yang, Lei Shu, Jianing Chen, Mohamed Amine Ferrag, Jun Wu, Edmond Nurellari and Kai Huang, A Survey on Smart Agriculture: Development Modes, Technologies, and Security and Privacy Challenges, IEEE/CAA JOURNAL OF AUTOMATICA SINICA, VOL. 8, NO. 2, FEBRUARY 2021

Industry 4.0 is not just about Factories

Electricity Evolution



From the Age of Fire to the Age of Electric and Digital

1750

1870

1950

Today

The rapid increase of human induced CO_2 emissions begins.

2030

45% reduction in CO_2 by 2030 (from 2010 levels)

2050

Reaching net zero CO_2 emissions globally around 2050.

+ 1.5 ° C

Industry 1.0
The first industrial revolution began with the rise of technology and the mechanization of steam and waterpower.

Industry 2.0
The world learned how to scale these technologies and entered the age of mass deployment, with mass production and manufacturing.

Industry 3.0
The development of silicon resulted in the production of integrated circuit chips and software, which led to the creation of fully automated machines.

Industry 4.0
The rapid evolution of the Internet, IoT, and other digital technologies such as artificial intelligence, robotics and cloud computing ushered in the fourth industrial revolution.

Electricity 1.0
Early pioneers, Volta and Faraday, made advances in the practical use of electricity.

Electricity 2.0
Mass electrification came through the introduction of early power plants.

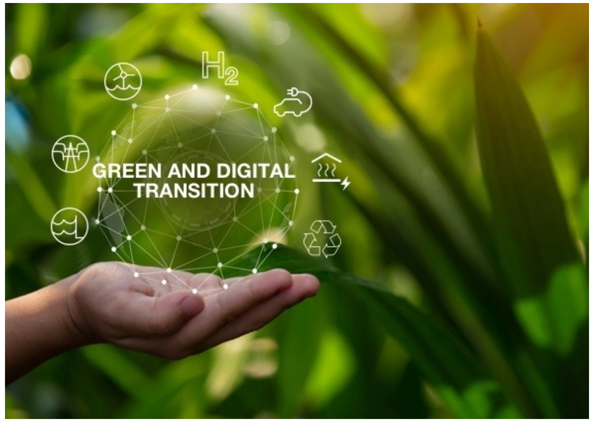
Electricity 3.0
Silicon development supported the birth of renewable energy through solar cells and also facilited the path for digital technology.

Electricity 4.0
The convergence of digital and electric combined with software is driving efficiency and sustainability.

SOURCE: Powering the future: Schneider Electric's Electricity 4.0, https://energydigital.com/articles/Powering-the-future-Schneider-electrics-Electricity-4.0

Twin Ecological and Digital Transition

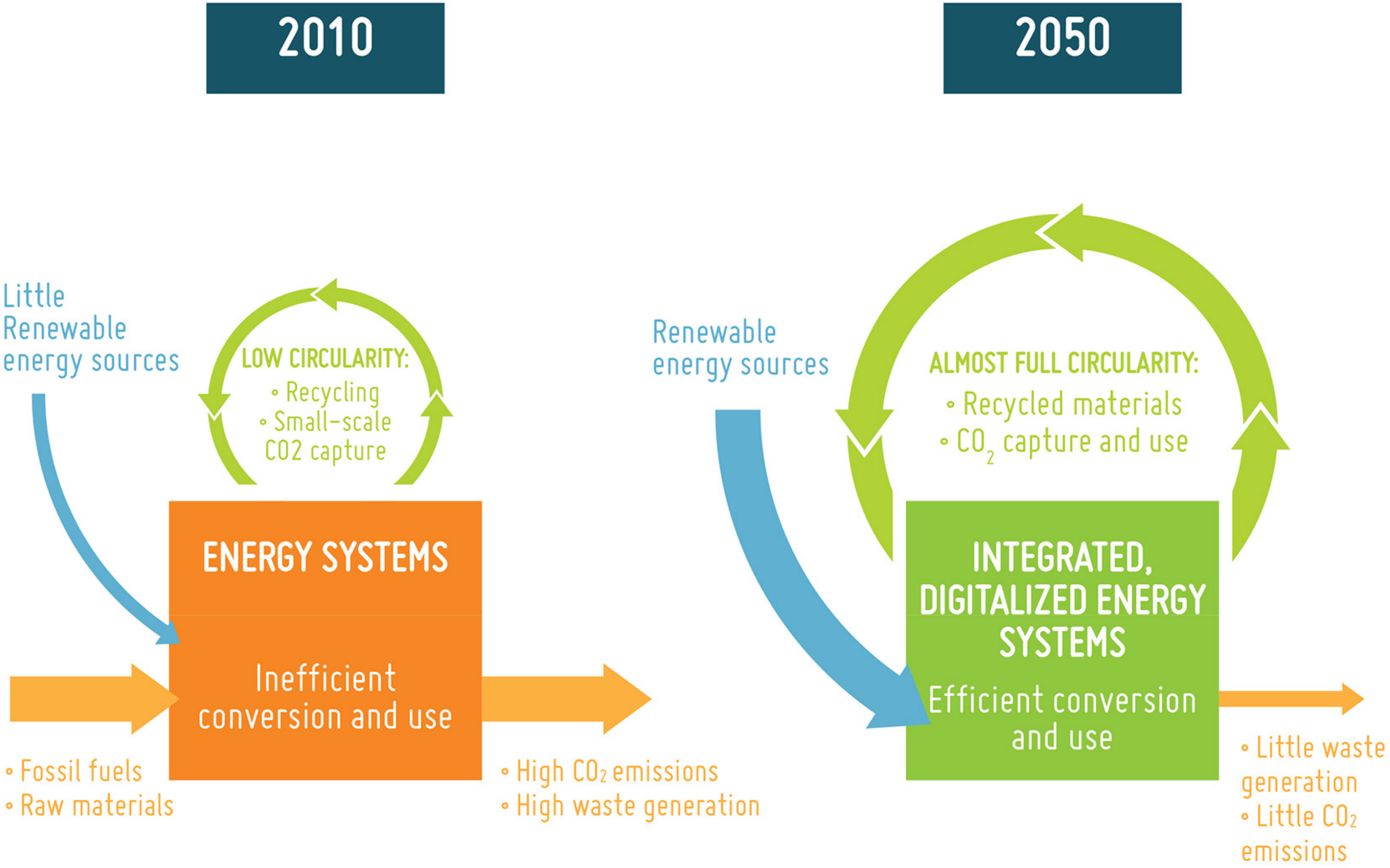
EU Strategy



European policy, through the **European Green Deal**, has set as goals:

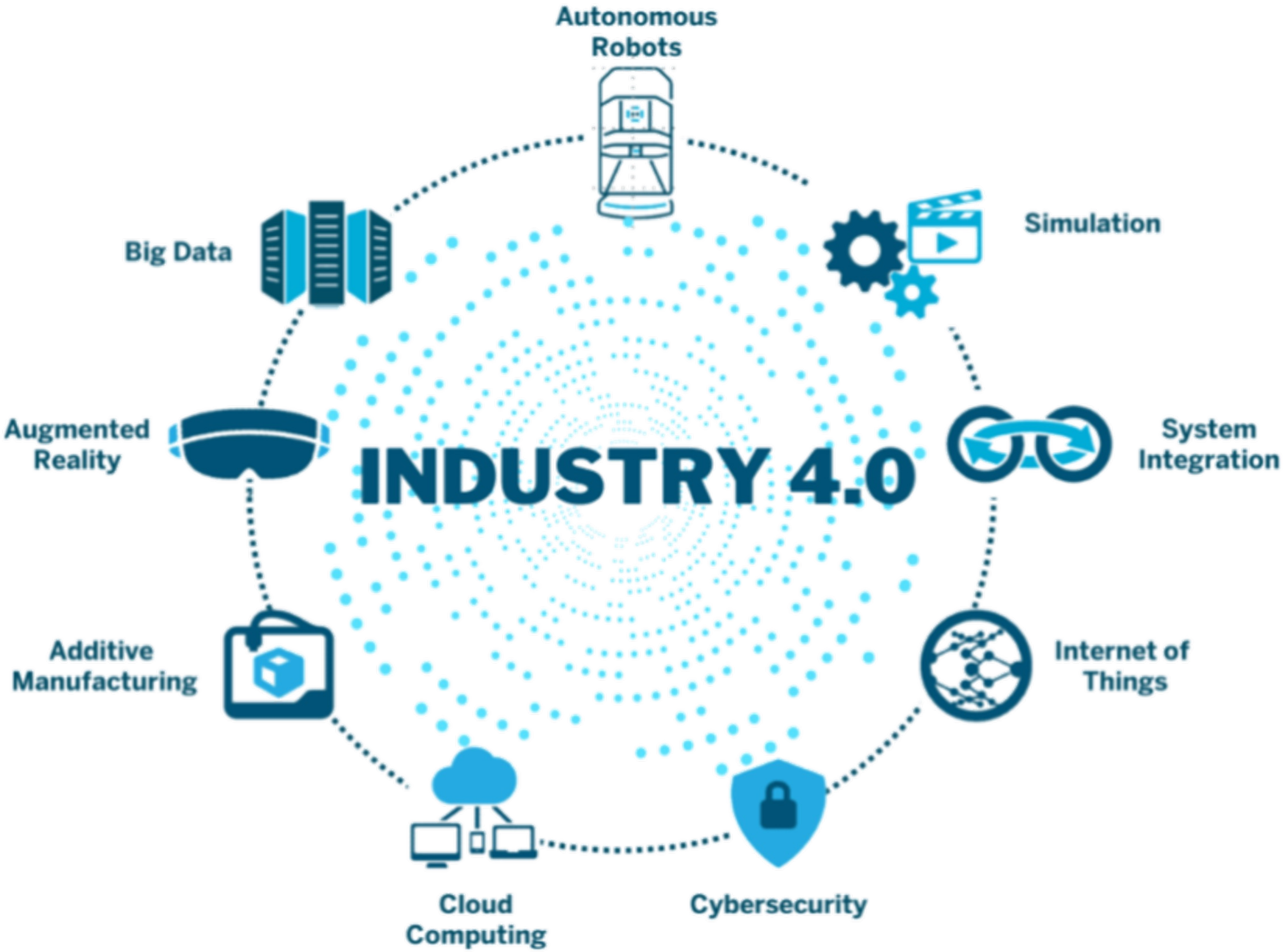
- **Green** Transition (Circular Economy Action Plan) a prerequisite for achieving climate neutrality
    - Transition from the current linear economic model towards a **Circular Model**, which tries to maximize products and materials value as much as possible, closing both their technical and biological cycles.
- **Digital Transition (**Industry 4.0, Industry 5.0) (EU Digital Strategy)
    - Industry is involved in the so-called 4th industrial revolution or **Industry 4.0 and Industry 5.0**, characterised by the implementation of digital technologies in the different industrial processes.

Energy Transition in EU



04 – Enabling Technologies

Building blocks of Industry 4.0



Internet of Things (IoT)

- Refers to scenarios where network connectivity and computing capability extends to **objects**, **sensors** and **everyday items** not normally considered computers
- Allows these devices to **generate, exchange and consume data** with minimal human intervention
- **Connectivity Models**: Device-to-Device, Device-to-Cloud, Device-to-Gateway, and Back-End Data-Sharing

Internet of Things - What is - How it Works

YouTube video: https://www.youtube.com/watch?v=LlhmzVL5bm8

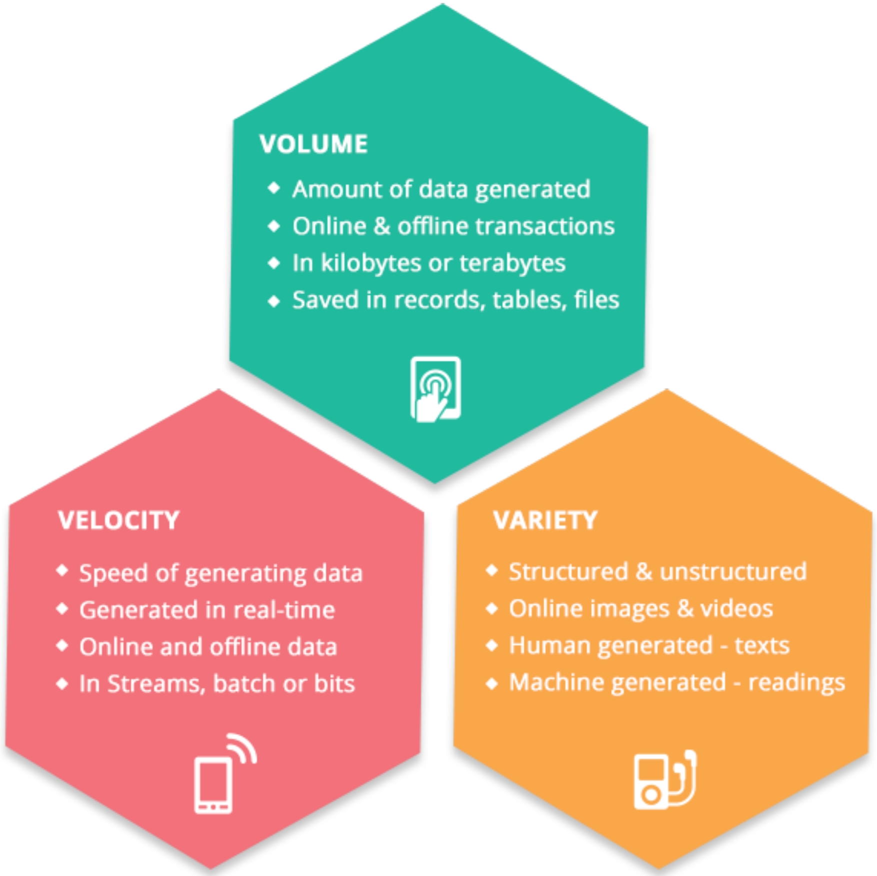
Big Data Management

Big data in general is defined as high volume, velocity and variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight and decision making

- ‘Big Data’ is similar to ‘small data’, but bigger in size
- Big Data generates value from the storage and processing of **very large quantities** of digital information that cannot be analysed with traditional computing techniques
- Aim to solve new problems or old problems in a **better way**
- Having data bigger it requires **different approaches**: Techniques, tools and architecture

Characteristics of Big Data

The 3Vs of Big Data



VOLUME

- Amount of data generated
- Online & offline transactions
- In kilobytes or terabytes
- Saved in records, tables, files

VELOCITY

- Speed of generating data
- Generated in real-time
- Online and offline data
- In Streams, batch or bits

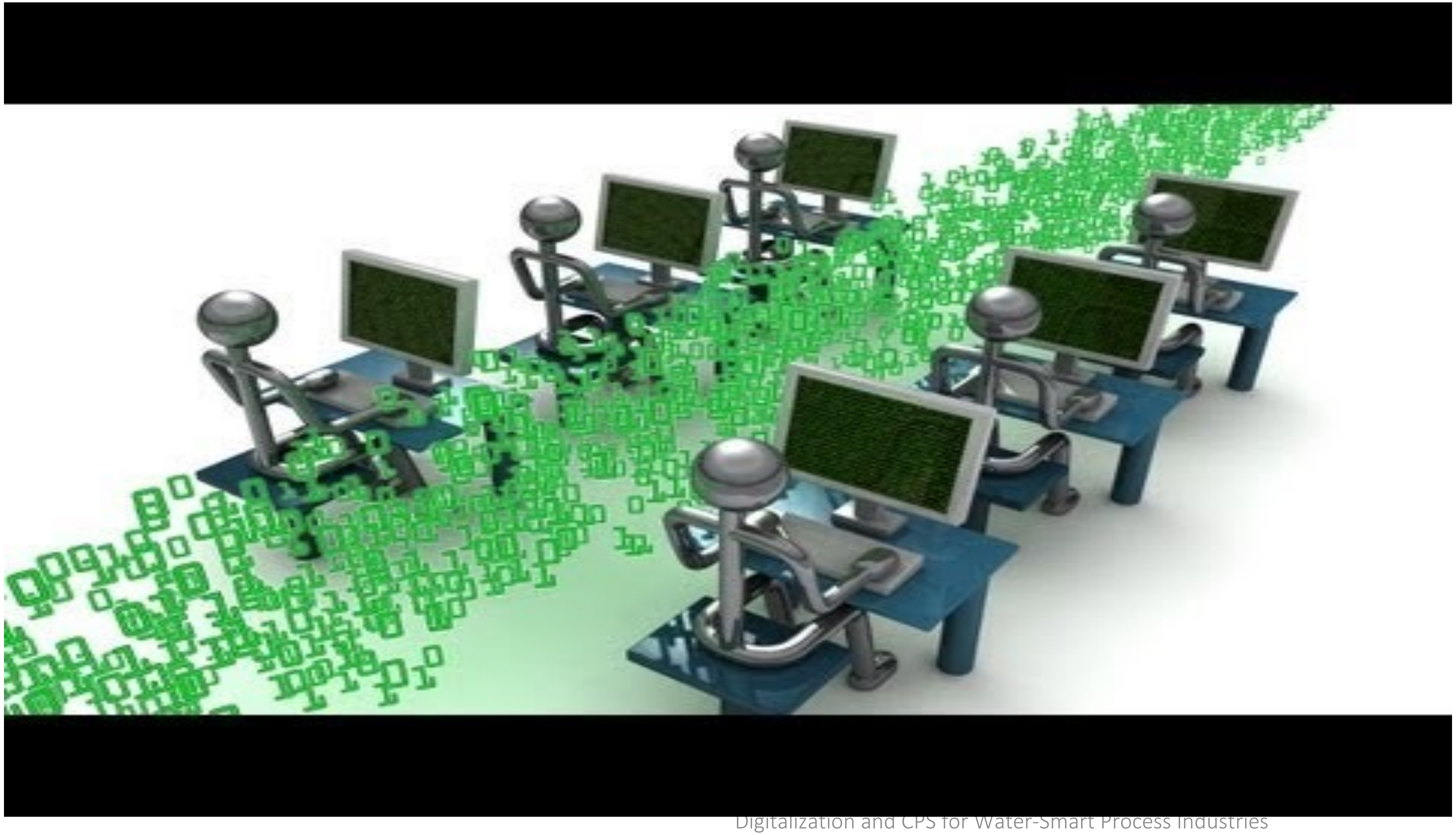
VARIETY

- Structured & unstructured
- Online images & videos
- Human generated - texts
- Machine generated - readings

www.whishworks.com

Explaining Big Data

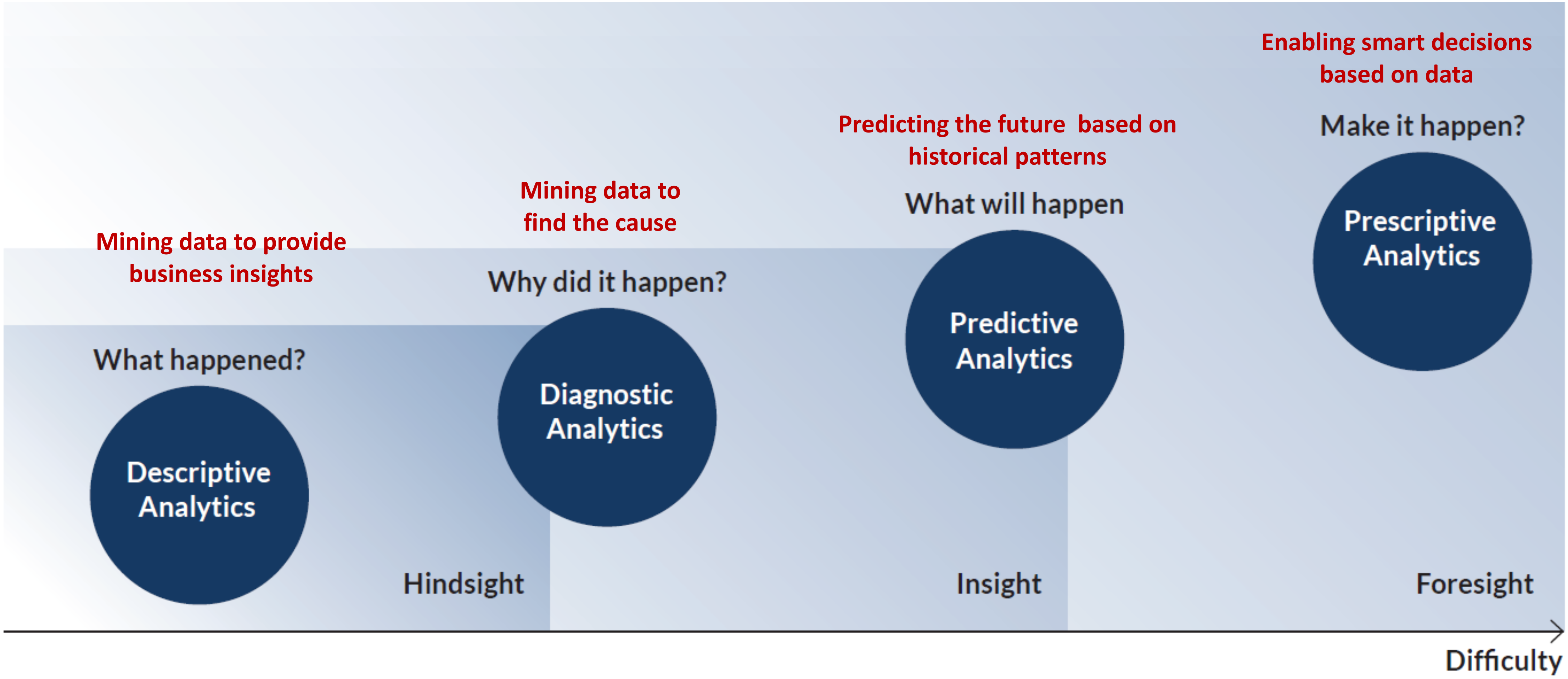
YouTube video:
https://www.youtube.com/watch?v=7D1CQ_LOizA



Data Analytics

- Data Analytics is:
  - Discovery, interpretation, and communication of meaningful patterns and knowledge in data
  - Applying those patterns towards effective decision making
- Data Analytics uses:
  - Mathematics
  - Statistics
  - Predictive modeling
  - Machine learning techniques

Data Analytics Types

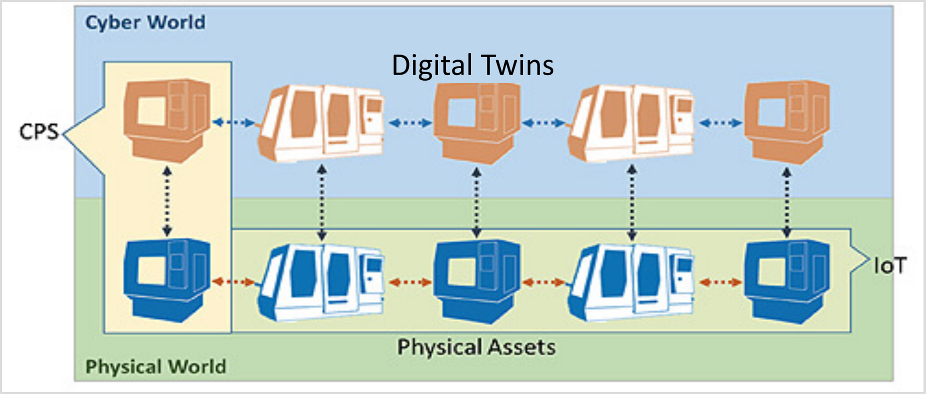


https://worldmanufacturing.org/wp-content/uploads/WorldManufacturingForum2020_Report.pdf

05 – Cyber-Physical Systems and Digital Twins

Core Digitalisation Concepts

Paradigms Characterising Digitalisation

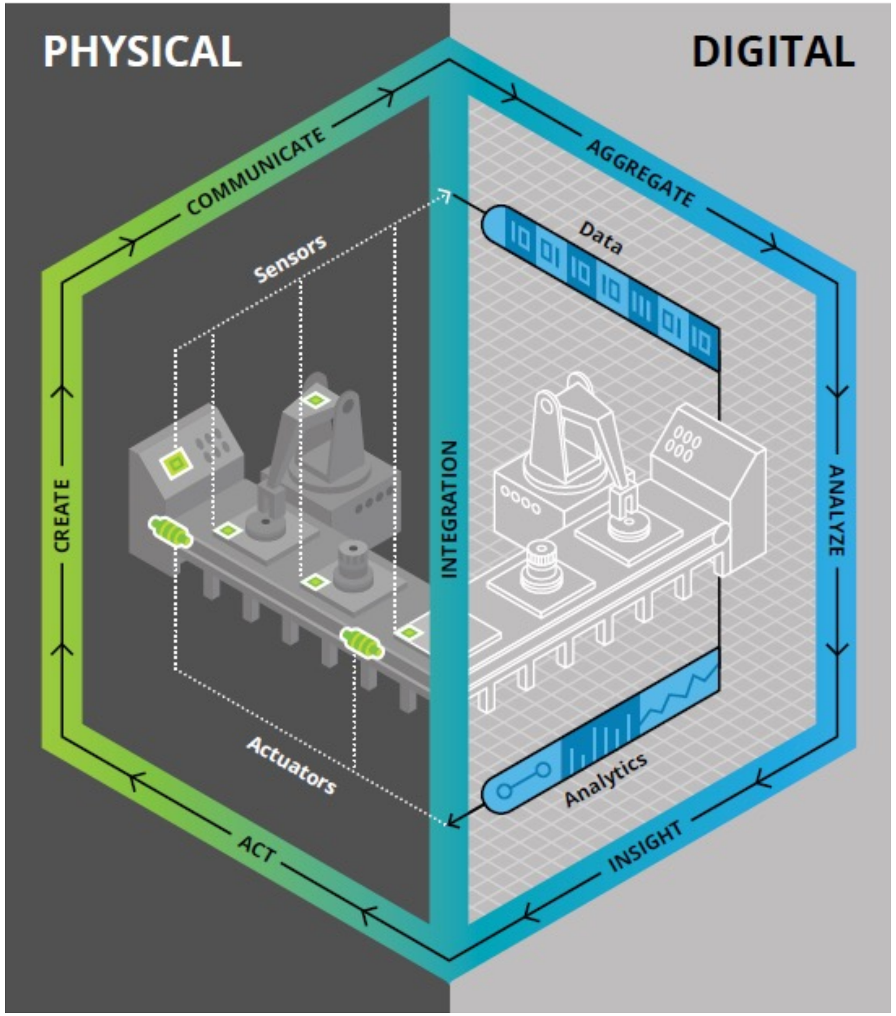


- **Cyber-Physical Systems (CPS)**: Networked systems with embedded sensors, processors, and actuators that can sense and interact with the industrial environment (including human) and provide real-time services
  - General Directive: The tighter the coupling of the digital part of the CPS to its physical system (production, supply chain), the better
  - Necessities: (i) Accurate and holistic modelling and representation of the physical system in CPS' digital part; (ii) Dynamic representation, i.e. follow in time closely the physical system's evolution, state and behavior

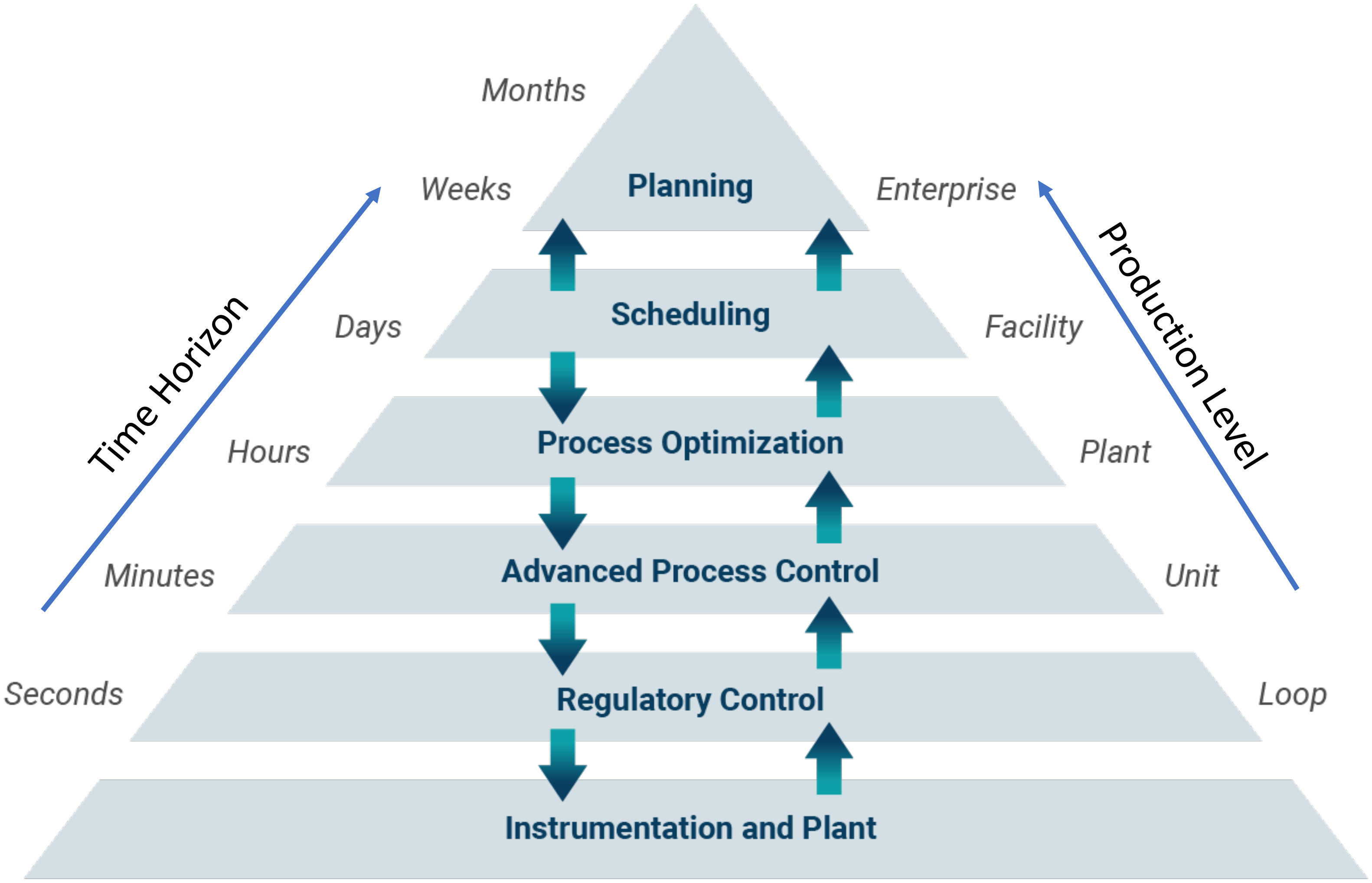
- **Digital Twins (DT)**: Replicates digitally a production process, production line, factory and/or supply chain, accurately modeling it and its entities and simulating uniquely its state and behavior at any instance by being connected to it and updating itself in response to system changes

Digital Twins Fundamental Elements

- **Sensors** distributed throughout the physical system create signals enabling the twin to capture data pertaining to the physical process in the real world
- **Data** Real-world operational and environmental data
- **Integration** Sensors communicate the data to the digital world through integration technology
- **Analytics** techniques used to analyze data through algorithmic simulations and visualisation routines
- **Actuators** Should an action be warranted in the real world, the digital twin produces the action by way of actuators, subject to human intervention, which trigger the physical process



Automation/Optimisation Pyramid in Modern Production Systems



Time Horizon

Months

Weeks

Days

Hours

Minutes

Seconds

Planning

Scheduling

Process Optimization

Advanced Process Control

Regulatory Control

Instrumentation and Plant

Production Level

Enterprise

Facility

Plant

Unit

Loop

Digital Support

Enterprise Resource Planning (ERP)

Manufacturing Execution System (MES)

Cyber Physical System (CPS)

Model Predictive Controller (MPC)

Programmable Logic Controller (PLC)

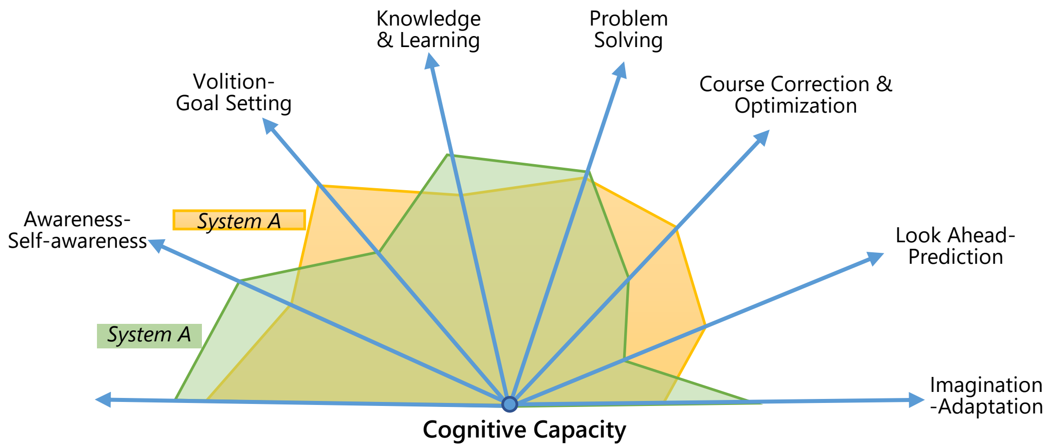
Sensors and Actuators (IoT)

06 – Digital Cognition

Semantics of Cognition

Cognitive Behavioural Vector (Attributes)

Cognitive technologies are ones that
mimic human brain functions



1. Dynamic sensing provides comprehensive, concurrent and continuous views of environment and self, distinguishing between the two, with immediate recognition of changes
2. Awareness of self and others, as well as internal & external situations and events relevant to them
3. Volition motivated by setting/pursuing goals and evaluating/ assessing status against them
4. Memory of past experiences and learning, i.e. converting experiences into active new knowledge
5. Identification of problems, dangers, opportunities, unexpected events and finding responses/solutions
6. Improvement/optimisation of course towards a position or goal while minimizing risks and/or effort
7. Looking ahead to anticipate the future, even plan for resources, sustainability or contingencies
8. Adapting to changes in environment or own capacities/needs, using knowledge & imagination

Mapping Biological to Digital Cognition

Digital Cognition follows the Paradigm Human Cognition

	Cognition Attributes	Map	Digital Cognition	Challenges
1	**Senses/Views** *Self vs Environment*	➡	Real-time monitoring enabling Dynamic behavior, Security, Edge analytics, Process calibration	**Environmental Sustainability** ⬇ **Resource Efficiency**
2	**Awareness** *Situation vs Self*	➡	Systemic & Value chain view, System dynamics, Big data analytics, Statistics & Visualization	
3	**Volition – Goal Setting** *Understanding (set) vs Assess (pursue)*	➡	Dynamic assessment & Self-assessment, Benchmarking, Business rules & Decision support	
4	**Knowledge (past)** *Remember vs Learning*	➡	Semantics, Knowledge engineering/representation, Databases, Machine learning	
5	**Problem Solving (now)** Identifying vs Responding	➡	Anomaly detection, AI inference & Root-cause analysis, Proactive & Reactive responses	**Economic Sustainability** ⬇ **Agility**
6	**Course Correction/Optimization (now)** *Minimize Risk vs Effort*	➡	Optimization algorithms and tools, Self-calibration, Expert rules	
7	**Looking Ahead (future)** *Sufficiency vs Contingencies*	➡	Prediction of inputs/outputs/key factors, Capacity planning, Production rescheduling	
8	**Adaptability (to change)** *Environment vs Needs*	➡	What-if evaluations, Scenario building & Simulation, Self-adaptation	

Typical Digital Cognition Process in a Production System

1 DETECT VARIATIONS

- **Goal**
  - Find variations by observing data
- **Role in Cognition**
  - Trigger the Cognition process
- **Methods**
  - Validate data against a model
  - Data-driven models (data analytics learns models from data)
  - Statistical Process Control (variation detection methods)

2 UNDERSTAND VARIATIONS

- **Goal**
  - Provide additional context/knowledge for problem (variation) analysis and support root cause analysis
- **Role in Cognition**
  - Contextualization of the problem
- **Methods**
  - Root-cause analysis
  - Hypothesis testing using process models

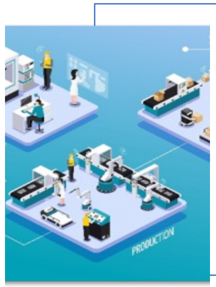
3 UNDERSTAND THE IMPACT

- **Goal**
  - Support understanding what is the impact of the problem
- **Role in Cognition**
  - Understanding when (if) to react on detected problem
- **Methods**
  - Data analytics
  - Simulation

4 OPTIMISE BEHAVIOUR

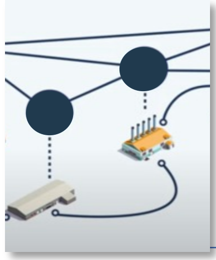
- **Goal**
  - Support the analysis for which changes are required
- **Role in Cognition**
  - Understanding how to react
- **Methods**
  - Data analytics
  - Optimisation

Application Areas



Smart Industries (Local Intelligence)

- Interconnected software manages the local operating parts of the company
- Cyber-Physical Systems manage process and monitor each other

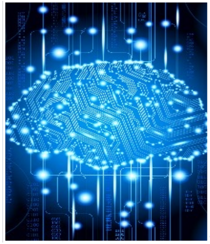


Virtual Factories (Dynamic Supply Chains)

- Network of businesses from multiple regions that resolve issues of processes, dependencies and interrelations, data and material flows between companies and between customers and suppliers

Asset Performance Management

- Improving reliability and performance of equipment and assets through better visibility, predictability and operations



Process and Quality Improvement

- Optimizing yield and productivity of manufacturing operations, from design through warranty support

Resource Efficiency Optimisation

- Optimising energy efficiency, facility productivity, product reliability, quality, safety and yield while reducing costs

Supply Chain Optimisation

- Improving visibility and insights to build a dynamic supply chain that accelerates innovation, efficiency and performance.

Predictive Maintenance

- Determines the condition of in-service equipment in order to estimate when maintenance should be performed with the intention to minimize the consequences from equipment disorders

Anomaly Detection

- The identification of patterns, events or observations which raise suspicions by differing significantly from the normality of the observed data

07 – AquaSPICE WaterCPS

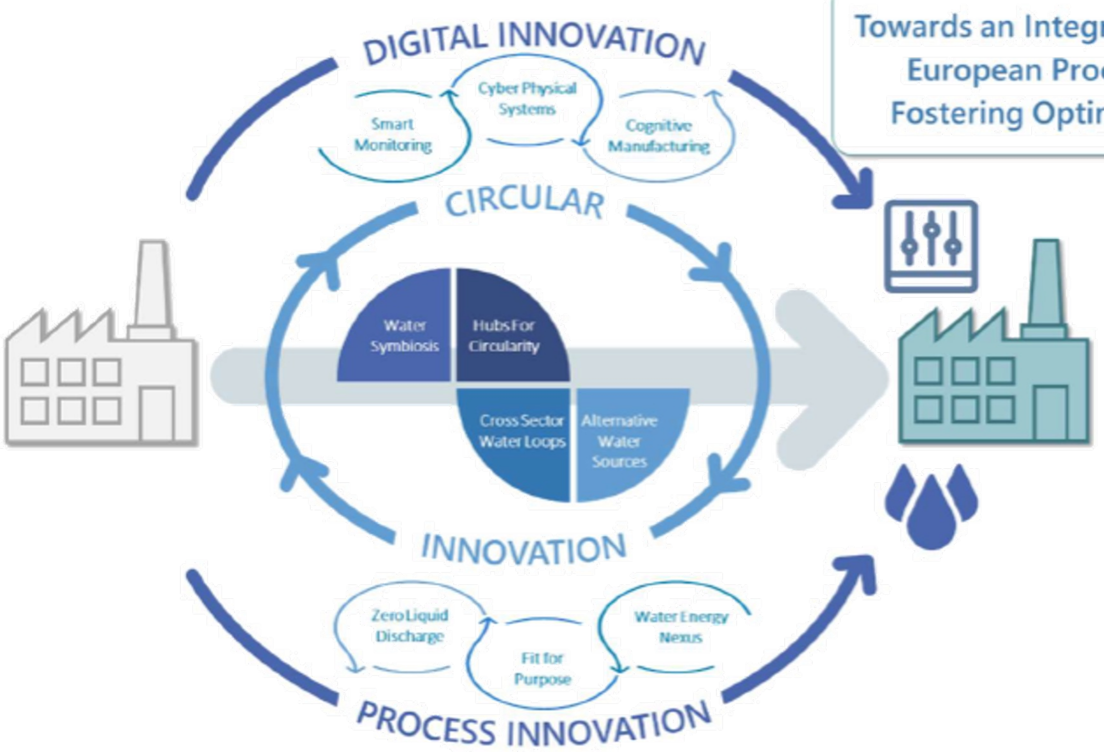
AquaSPICE Innovation Pillars

CIRCULAR INNOVATION

- Water re-use options at different levels
- Closed loops practices for water, energy and substances

PROCESS INNOVATION

- Installation,
- Operation, and
- Assessment of advanced water treatment technologies and practices with energy and substances recovery



Towards an Integrated and Digital European Process Industry Fostering Optimal Water Use

DIGITAL INNOVATION

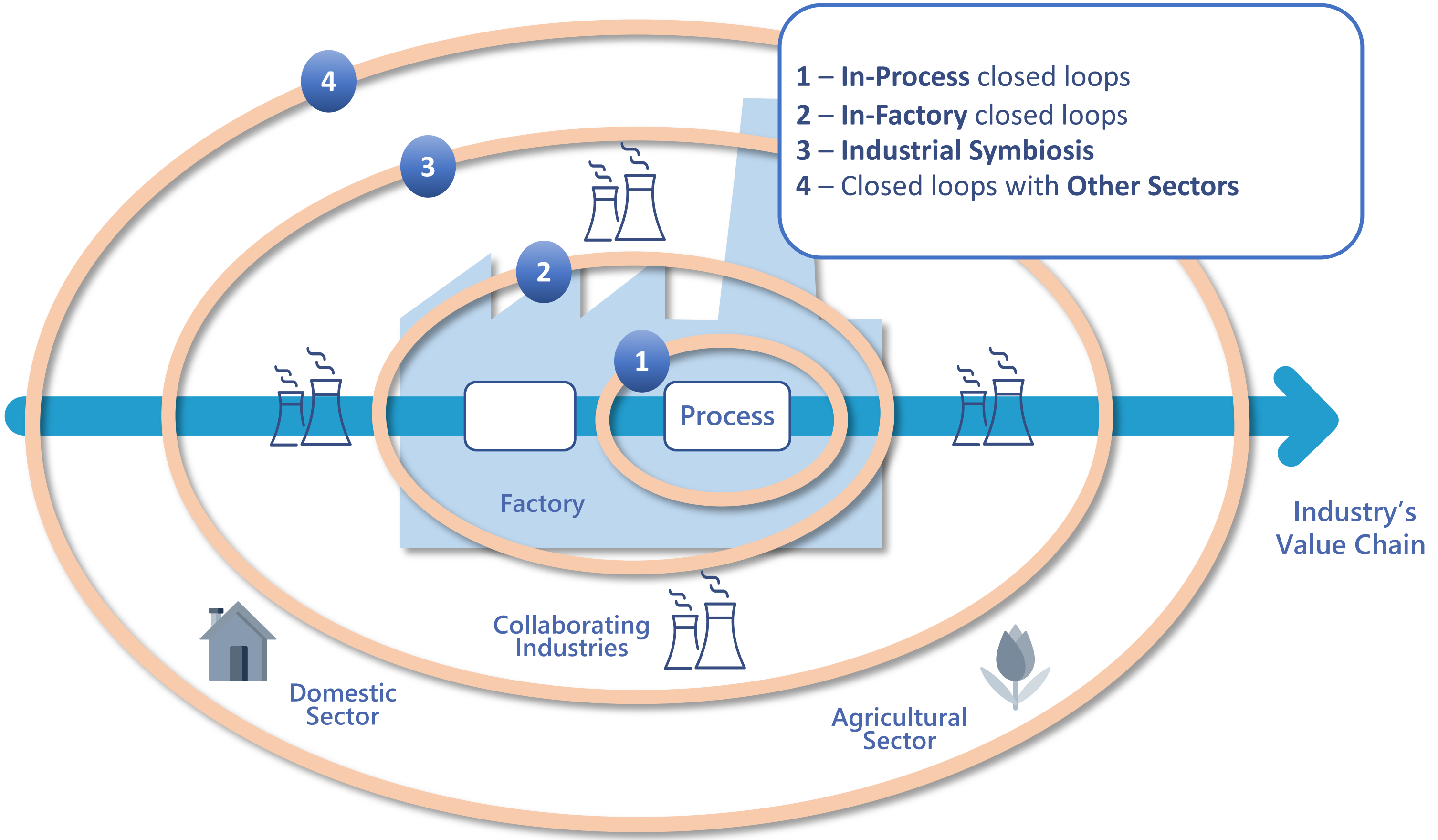
- **Real-time monitoring and distributed data management system** connects the physical and digital worlds through smart sensor networks, IIoT and cloud/edge technologies
- **Water-specific Cyber-Physical-System (WaterCPS)** synthesises **digital twins** of industrial and value chain entities to provide advanced water-saving awareness and optimised water efficiency at different industrial levels

AquaSPICE Circular Innovations

Industrial Water Circular Practices

Water Policy Relevance of AquaSPICE in the Circular Economy Action Plan

- 1 – **In-Process** closed loops
  - DOW Boehlen, Terneuzen
  - TUPRAS, Turkey
- 2 – **In-Factory** closed loops
  - BASF, Port of Antwerp
- 3 – **Industrial Symbiosis**
  - AGRICOLA, Romania
- 4 – Closed loops with **Other Sectors**
  - SOLVAY, ARETUSA, Italy



AquaSPICE Digital Innovations

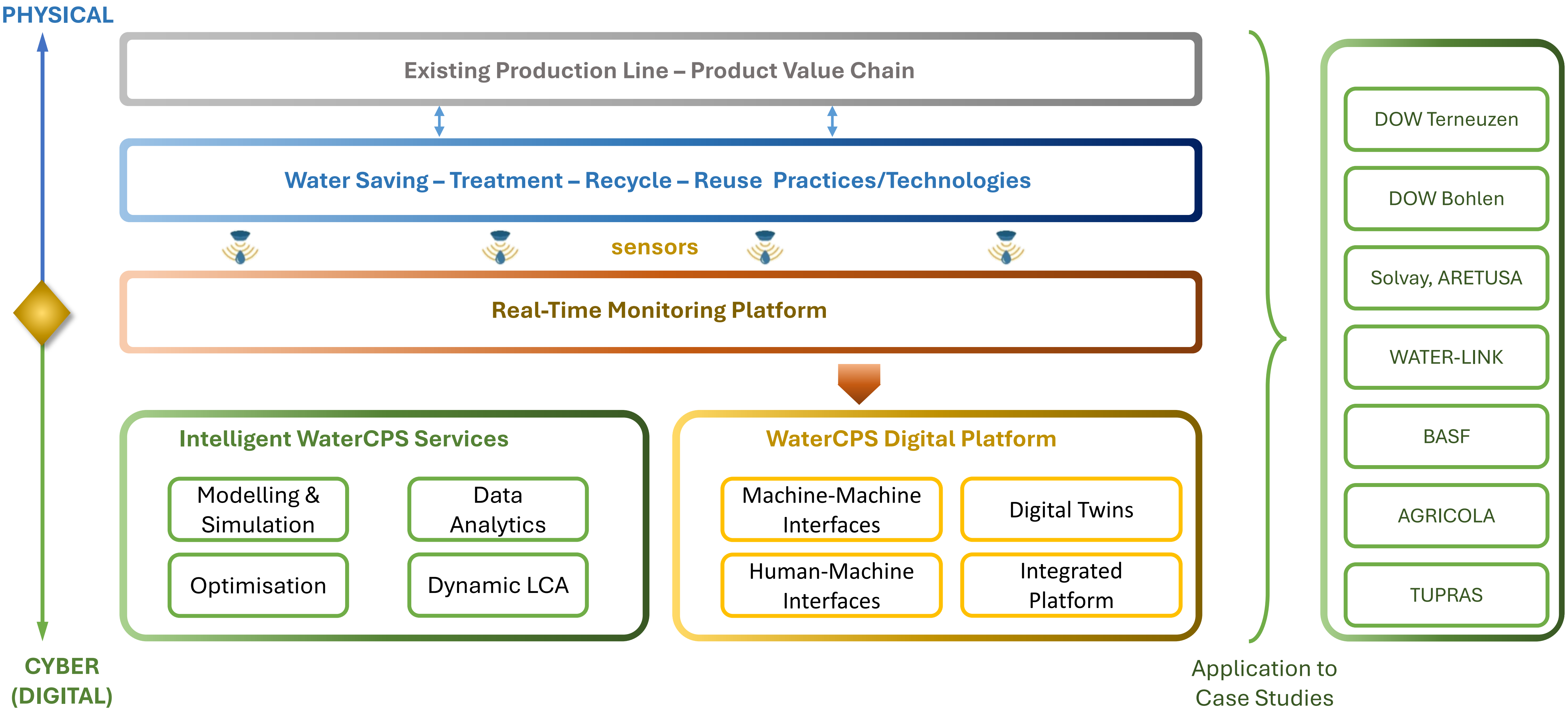
WaterCPS – Key Innovation of AquaSPICE

- A Cyber-Physical System (CPS) specialized to **enhance water efficiency** in the **Process Industry**

- Water efficiency enhancement is approached from three directions:
  - **Production chain enhancement** (design and application of SotA water treatment & recovery technologies & practices)
  - **Diagnostic** (monitoring water efficiency, diagnosing problems, estimating improvement margins)
  - **Optimisation** (of water use/recovery/reuse processes & practices)

AquaSPICE WaterCPS Architecture

Key Digital Innovation



PHYSICAL

Existing Production Line – Product Value Chain

Water Saving – Treatment – Recycle – Reuse Practices/Technologies

sensors

Real-Time Monitoring Platform

Intelligent WaterCPS Services

- Modelling & Simulation
- Data Analytics
- Optimisation
- Dynamic LCA

WaterCPS Digital Platform

- Machine-Machine Interfaces
- Digital Twins
- Human-Machine Interfaces
- Integrated Platform

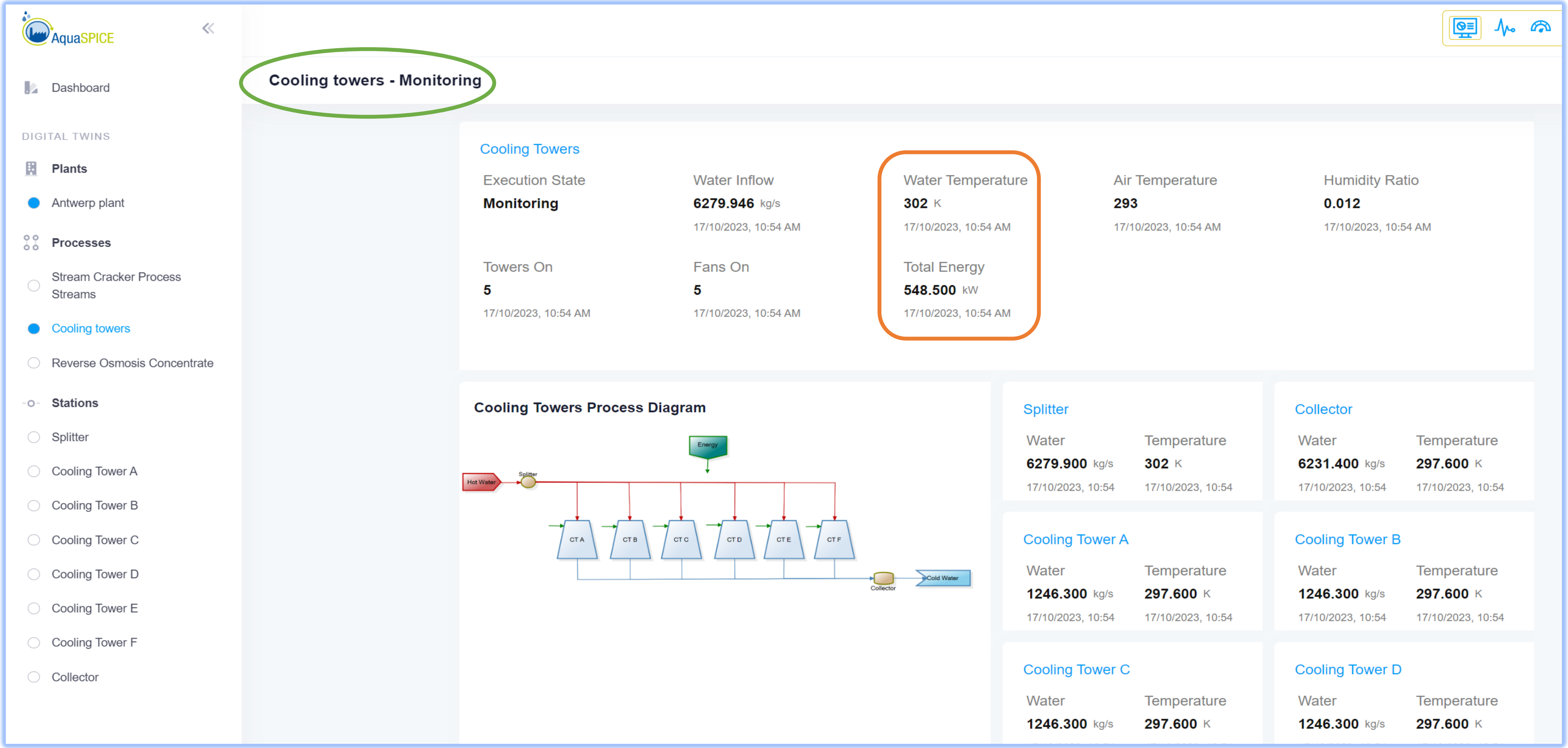
CYBER (DIGITAL)

- DOW Terneuzen
- DOW Bohlen
- Solvay, ARETUSA
- WATER-LINK
- BASF
- AGRICOLA
- TUPRAS

Application to Case Studies

WaterCPS Digital Platform

Cooling Towers Monitoring



AquaSPICE

Dashboard

DIGITAL TWINS

Plants

- Antwerp plant

Processes

- Stream Cracker Process Streams
- Cooling towers
- Reverse Osmosis Concentrate

Stations

- Splitter
- Cooling Tower A
- Cooling Tower B
- Cooling Tower C
- Cooling Tower D
- Cooling Tower E
- Cooling Tower F
- Collector

Cooling towers - Monitoring

Cooling Towers

Execution State	Water Inflow	Water Temperature	Air Temperature	Humidity Ratio
Monitoring	**6279.946** kg/s	**302** K	**293**	**0.012**
	17/10/2023, 10:54 AM	17/10/2023, 10:54 AM	17/10/2023, 10:54 AM	17/10/2023, 10:54 AM

Towers On	Fans On	Total Energy
5	**5**	**548.500** kW
17/10/2023, 10:54 AM	17/10/2023, 10:54 AM	17/10/2023, 10:54 AM

Cooling Towers Process Diagram

Splitter

Water	Temperature
6279.900 kg/s	**302** K
17/10/2023, 10:54	17/10/2023, 10:54

Collector

Water	Temperature
6231.400 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower A

Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower B

Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower C

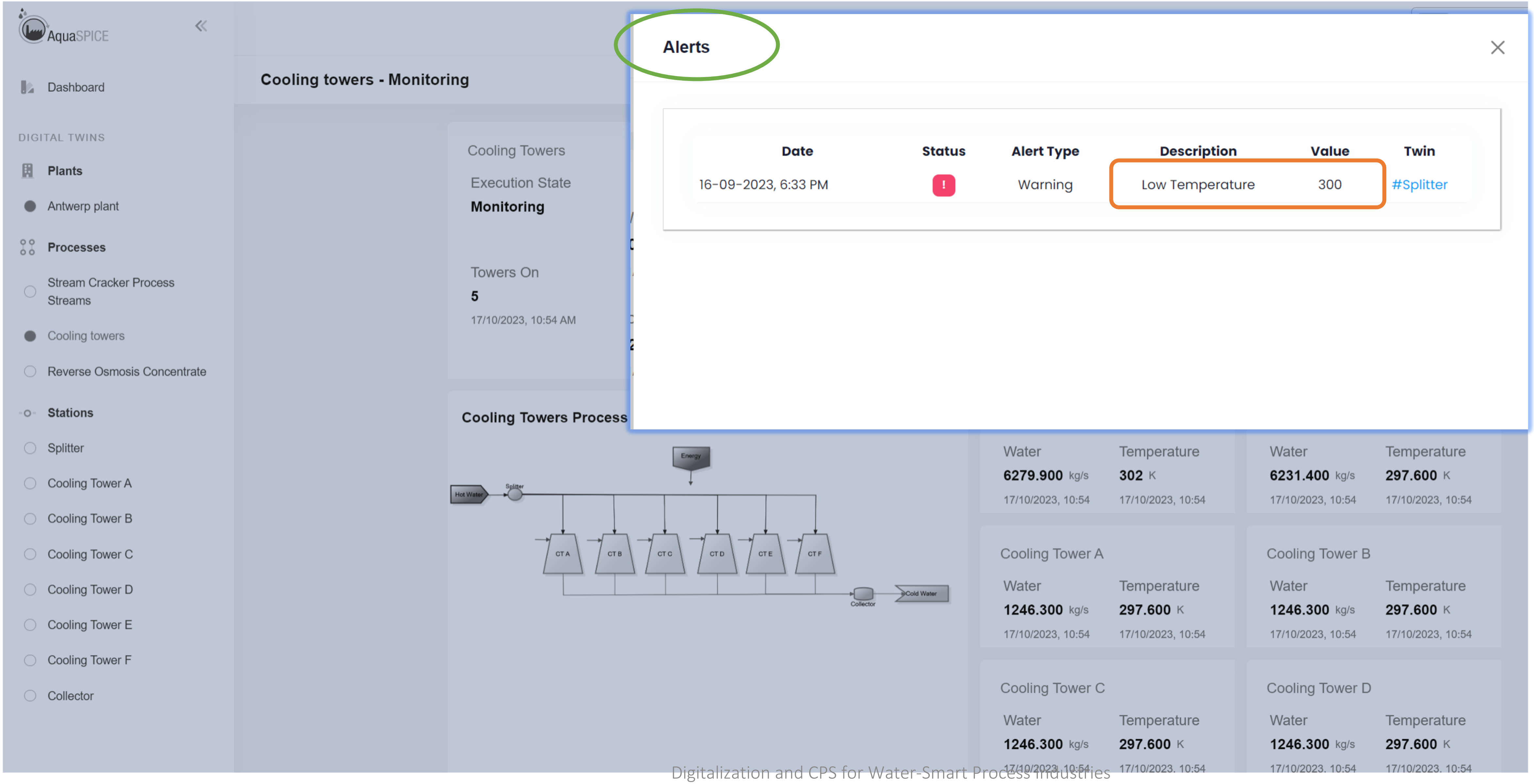
Water	Temperature
1246.300 kg/s	**297.600** K

Cooling Tower D

Water	Temperature
1246.300 kg/s	**297.600** K

WaterCPS Digital Platform

Cooling Towers Anomaly Detection



Cooling towers - Monitoring

Cooling Towers

Execution State
Monitoring

Towers On
5
17/10/2023, 10:54 AM

Cooling Towers Process

Alerts

Date	Status	Alert Type	Description	Value	Twin
16-09-2023, 6:33 PM	!	Warning	Low Temperature	300	#Splitter

Water	Temperature
6279.900 kg/s	**302** K
17/10/2023, 10:54	17/10/2023, 10:54

Water	Temperature
6231.400 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower A

Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower B

Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower C

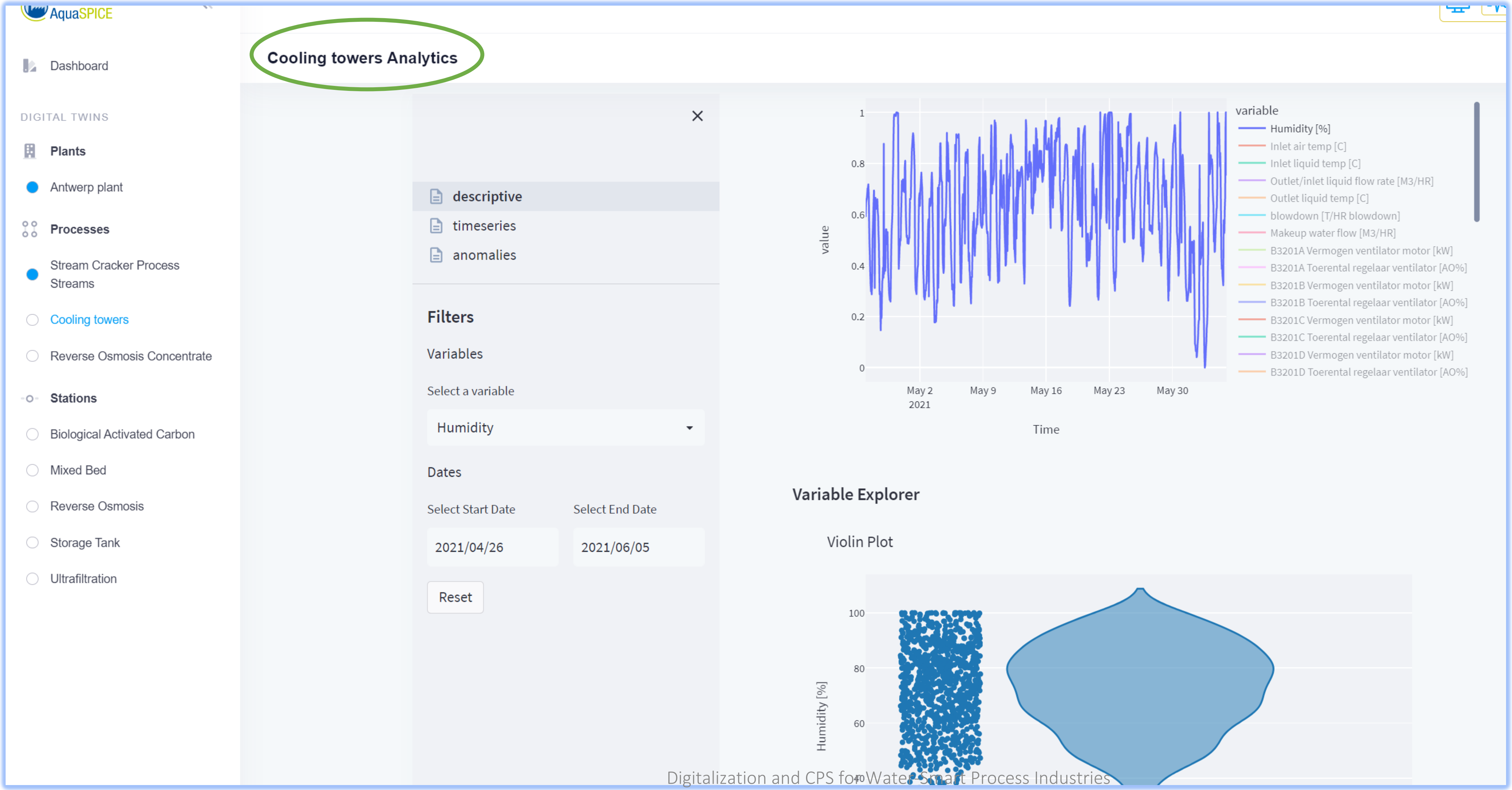
Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

Cooling Tower D

Water	Temperature
1246.300 kg/s	**297.600** K
17/10/2023, 10:54	17/10/2023, 10:54

WaterCPS Digital Platform

Cooling Towers Route Cause Analysis



Cooling towers Analytics

Filters

Variables

Select a variable: Humidity

Dates

Select Start Date: 2021/04/26

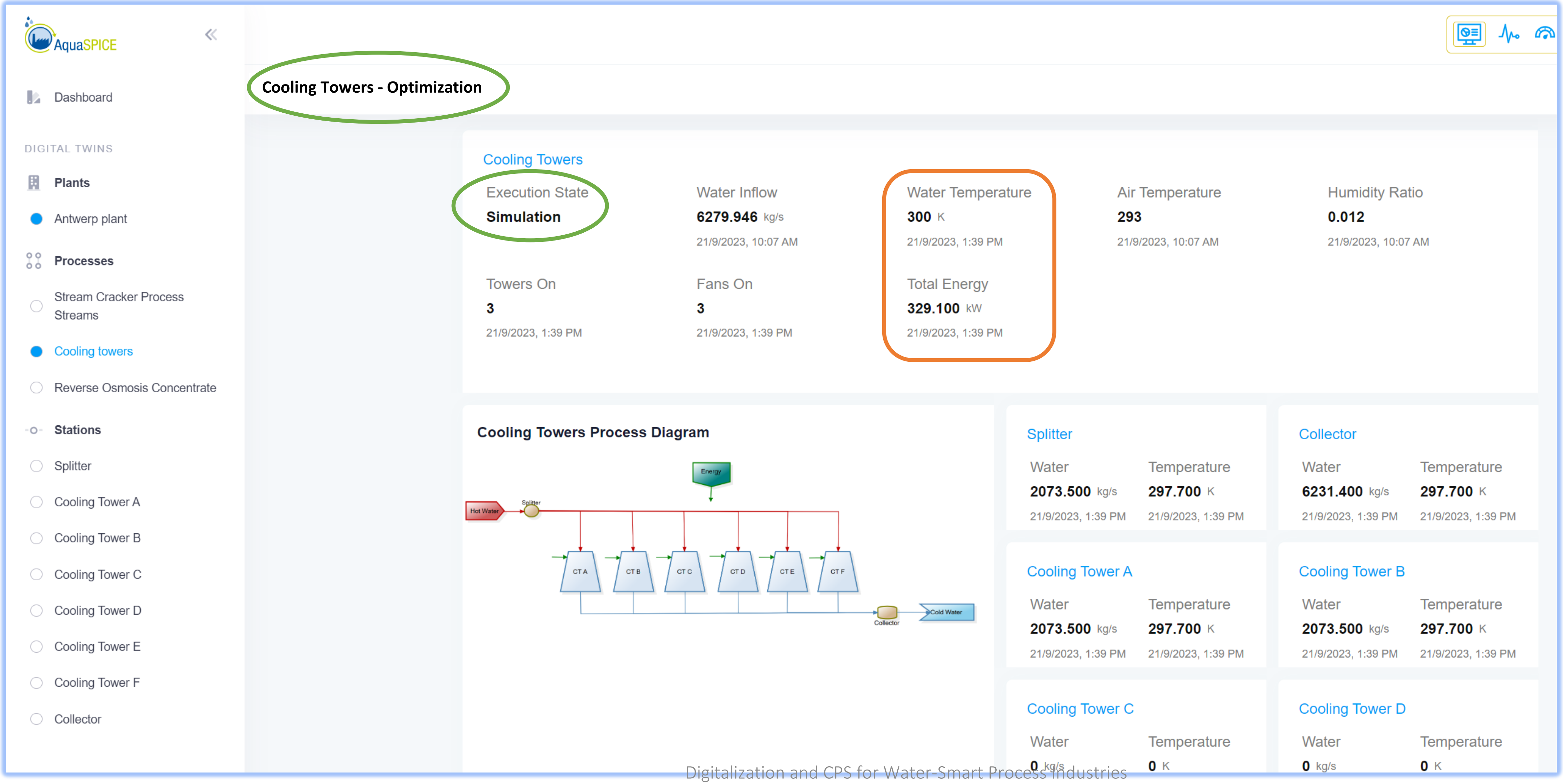
Select End Date: 2021/06/05

Variable Explorer

Violin Plot

WaterCPS Digital Platform

Cooling Towers Optimisation and Simulation



AquaSPICE

Dashboard

DIGITAL TWINS

Plants

● Antwerp plant

Processes

○ Stream Cracker Process Streams

● Cooling towers

○ Reverse Osmosis Concentrate

Stations

○ Splitter

○ Cooling Tower A

○ Cooling Tower B

○ Cooling Tower C

○ Cooling Tower D

○ Cooling Tower E

○ Cooling Tower F

○ Collector

Cooling Towers - Optimization

Cooling Towers

Execution State **Simulation**	Water Inflow **6279.946** kg/s 21/9/2023, 10:07 AM	Water Temperature **300** K 21/9/2023, 1:39 PM	Air Temperature **293** 21/9/2023, 10:07 AM	Humidity Ratio **0.012** 21/9/2023, 10:07 AM
Towers On **3** 21/9/2023, 1:39 PM	Fans On **3** 21/9/2023, 1:39 PM	Total Energy **329.100** kW 21/9/2023, 1:39 PM		

Cooling Towers Process Diagram

Splitter

Water	Temperature
2073.500 kg/s	**297.700** K
21/9/2023, 1:39 PM	21/9/2023, 1:39 PM

Collector

Water	Temperature
6231.400 kg/s	**297.700** K
21/9/2023, 1:39 PM	21/9/2023, 1:39 PM

Cooling Tower A

Water	Temperature
2073.500 kg/s	**297.700** K
21/9/2023, 1:39 PM	21/9/2023, 1:39 PM

Cooling Tower B

Water	Temperature
2073.500 kg/s	**297.700** K
21/9/2023, 1:39 PM	21/9/2023, 1:39 PM

Cooling Tower C

Water	Temperature
0 kg/s	**0** K

Cooling Tower D

Water	Temperature
0 kg/s	**0** K

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