Sustainability challenges for energy harvesting and Digital Twins

Adrian M. Ionescu, Nanolab, EPFL

Outline

- Introduction:
  - ✓energy efficient technologies for wearables and IoT
- Energy scavenging
  - ✓from light
  - ✓from vibrations
  - ✓thermoelectrical generators
- Digital Twins for sustainability
- Conclusions

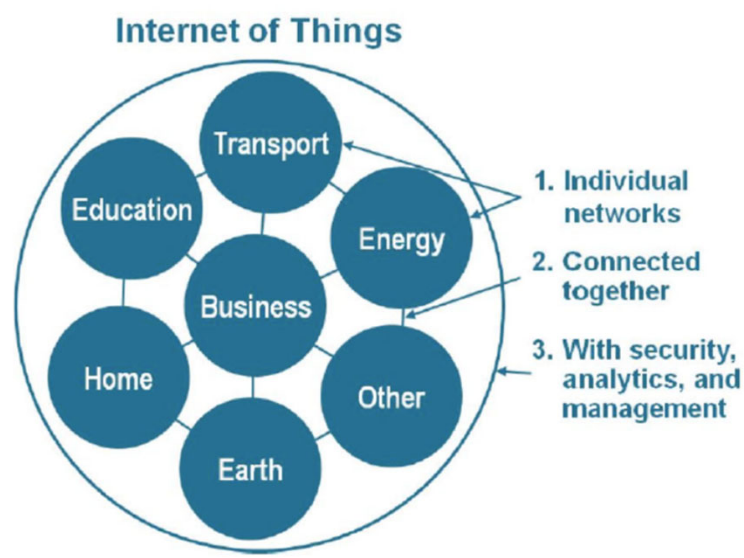
What is Internet of Things?

1) Wikipedia:

- The Internet of Things (IoT) is a **system of interrelated computing devices**, mechanical and digital machines, objects, animals or people that are provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.

2) Cisco/Gartner:

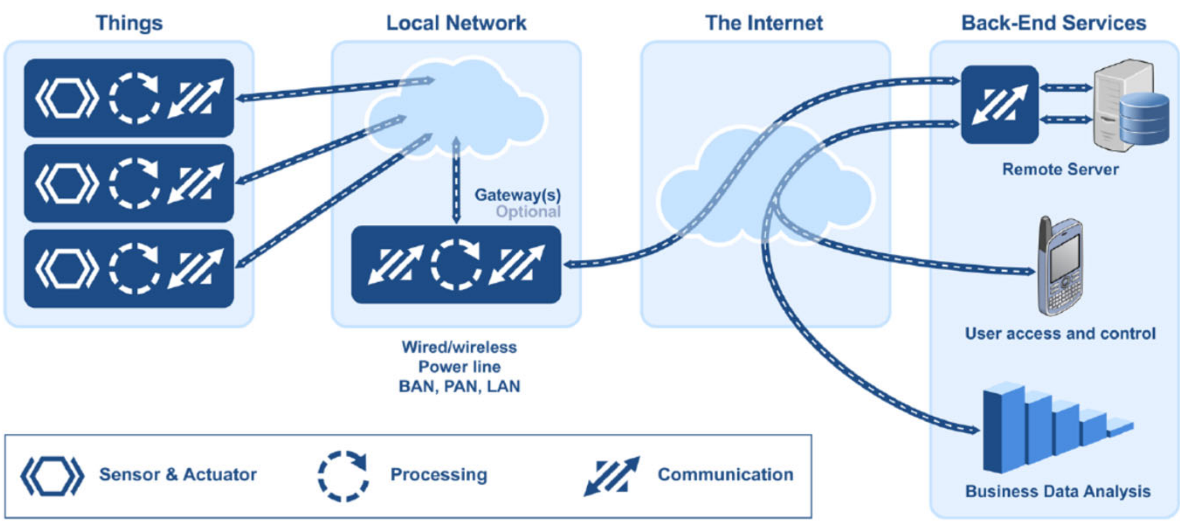
- The **Internet of Things (IoT) is the network of physical objects that contain embedded technology to communicate and sense or interact** with their internal states or the external environment.



Structure of the IoT

Four (4) main components of an IoT system:

- The **thing itself** (that is, the device)
- The **local network** (this can include a gateway, which translates proprietary communication protocols to Internet Protocol)
- The **Internet**
- **Back-end services** (enterprise data systems, PCs and mobile devices)

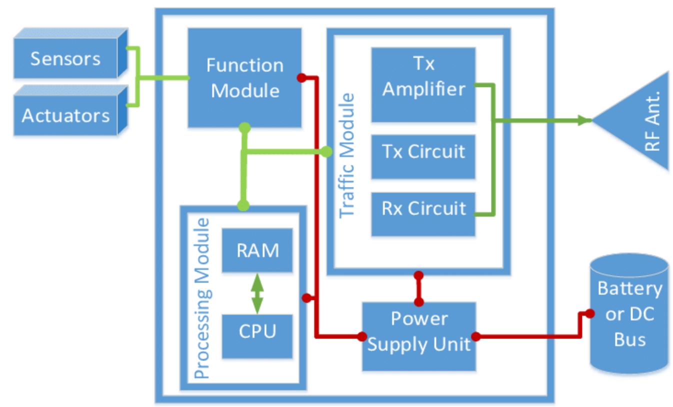


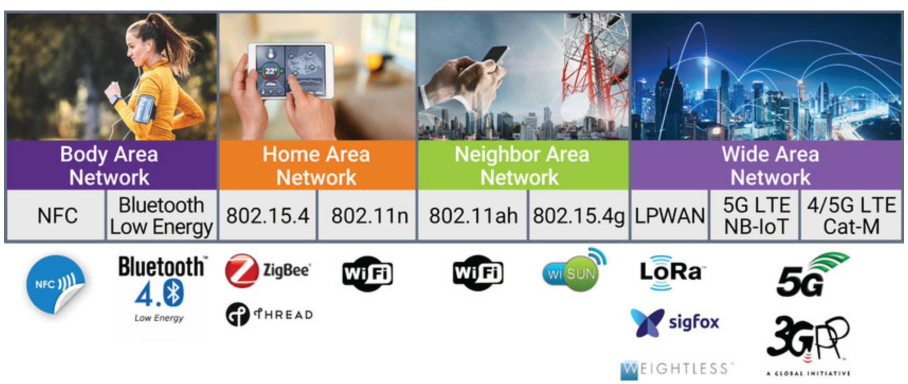
Challenge:
billions to trillion of things
consuming energy and producing data!

Industrial IoT nodes

- size and power consumption: mm^3 to cm^3 with 100's uW to 10's mW.

- Sensing
- Processing
- Communications

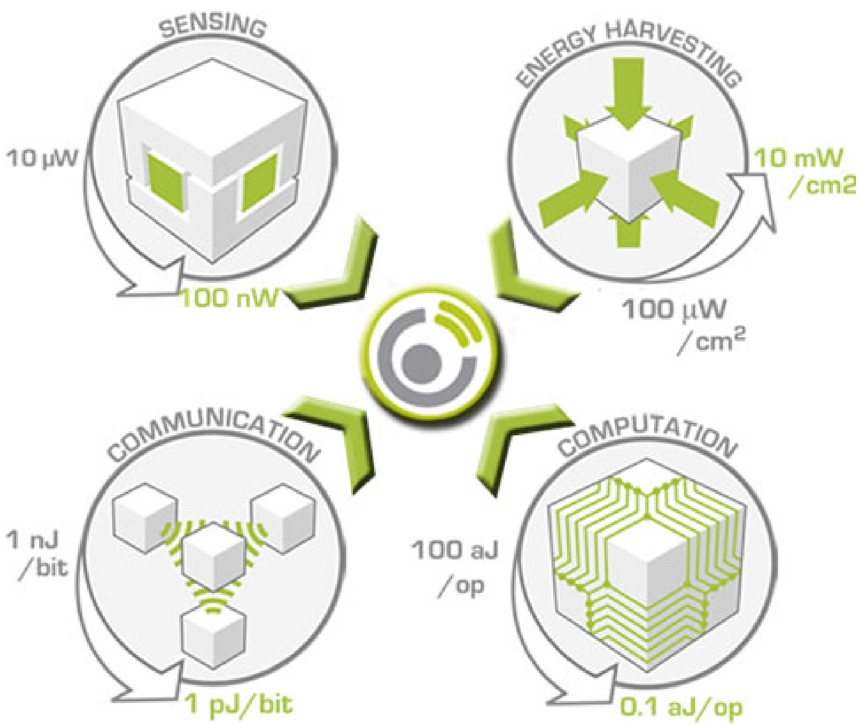




Energy problems @ node level:
- **No digital data reduction**
- **Expensive ADC and digital processing**
- **Expensive data communication**

Zero-Power Internet of Things

- Zero-Power technology = Autonomous Smart Systems

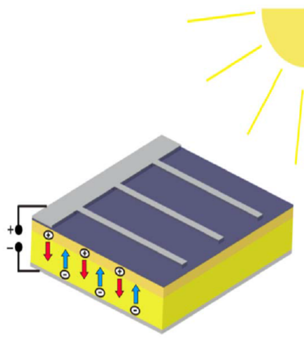


Energy Challenges for IoT

- x 1000 more energy efficient bit computation
- x 1000 more energy efficient bit transmission
- x 100 more efficient energy harvesting

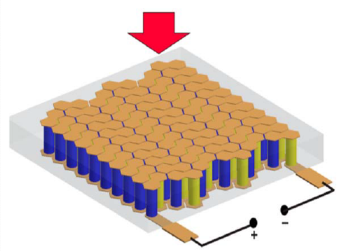
Types of energy harvesting

Solar Energy



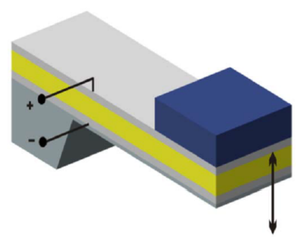
Photovoltaic Cells

Thermal Energy



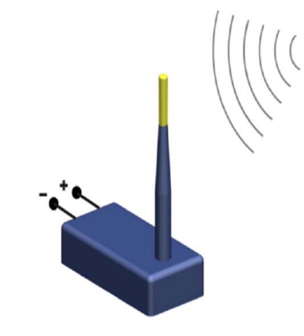
Thermoelectric Generators

Vibration Energy



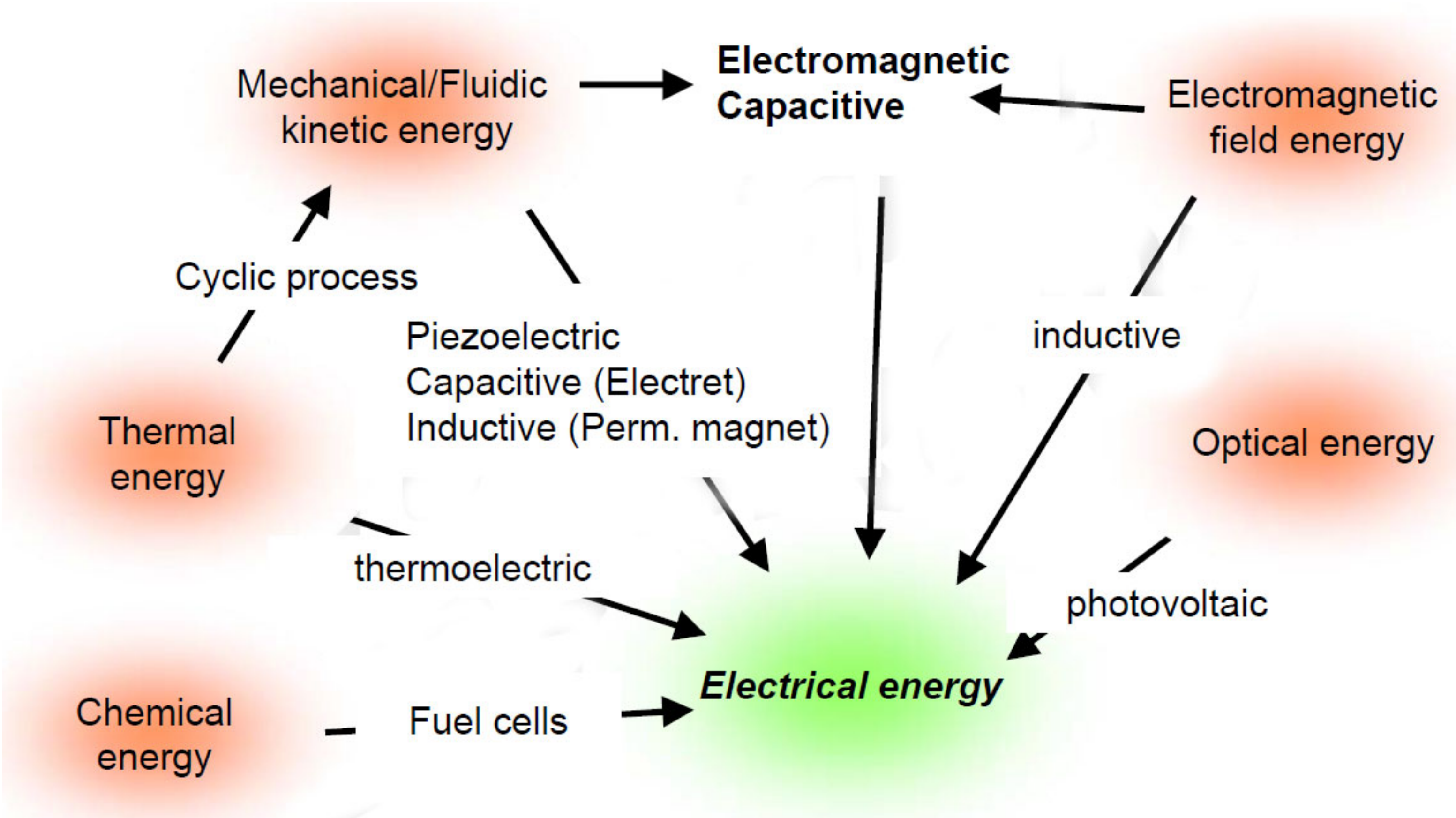
Piezoelectric
Electromagnetic
Electrostatic
Generators

RF Energy



Electromagnetic Generators

Mechanisms of coversion to electrical energy



Short Overview

Micropower energy harvesting

R.J.M. Vullers [a,*], R. van Schaijk [a], I. Doms [b], C. Van Hoof [a,b], R. Mertens [b]

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Solid-State Electronics 53 (2009) 684–693

Table 2
Characteristics of various energy sources available in the ambient and harvested power.

Source	Source power	Harvested power
Ambient light		
Indoor	0.1 mW/cm^2	10 µW/cm^2
Outdoor	100 mW/cm^2	10 mW/cm^2
Vibration/motion		
Human	0.5 m @ 1 Hz 1 m/s^2 @ 50 Hz	4 µW/cm^2
Industrial	1 m @ 5 Hz 10 m/s^2 @ 1 kHz	100 µW/cm^2
Thermal energy		
Human	20 mW/cm^2	30 µW/cm^2
Industrial	100 mW/cm^2	1–10 mW/cm^2
RF		
Cell phone	0.3 µW/cm^2	0.1 µW/cm^2

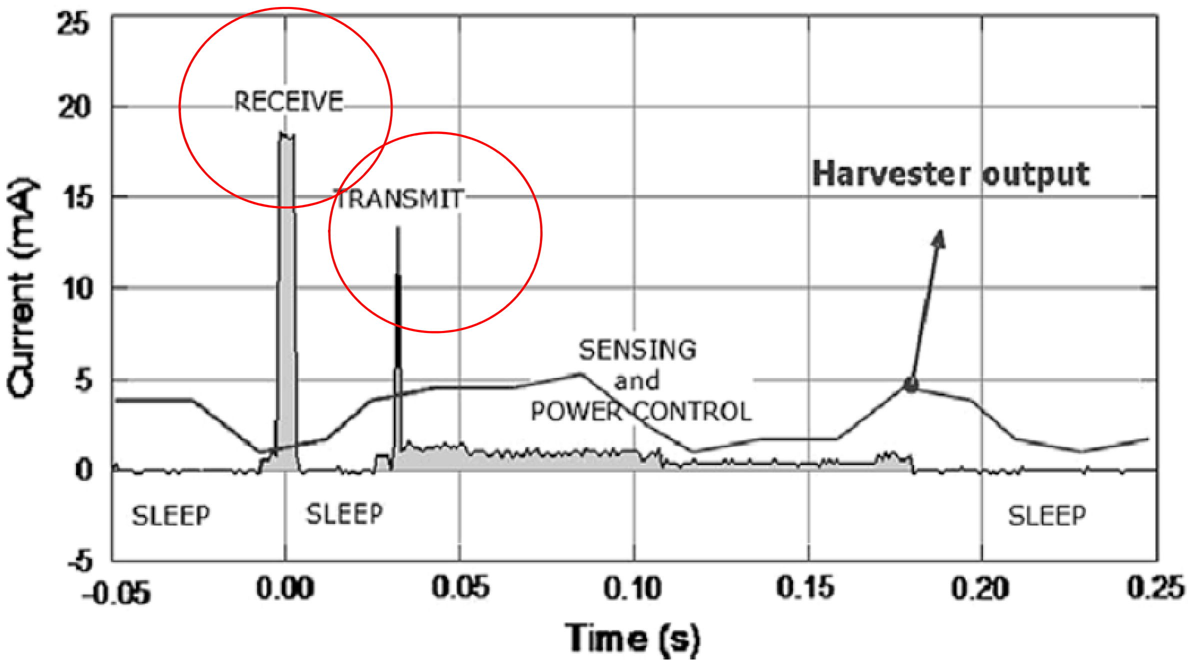
Table 3
Characteristics of batteries and supercapacitors.

	Battery		Supercapacitor
	Li-ion	Thin film[a]	
Operating voltage (V)	3–3.70	3.70	1.25
Energy density (W h/l)	435	<50	6
Specific energy (W h/kg)	211	<1	1.5
Self-discharge rate (%/month) at 20 °C	0.1–1	0.1–1	100
Cycle life (cycles)	2000	>1000	>10,000
Temperature range (°C)	−20/50	−20/+70	−40/+65

[a] Data calculated including the packaging.

Energy harvesting vs tramsmit energy

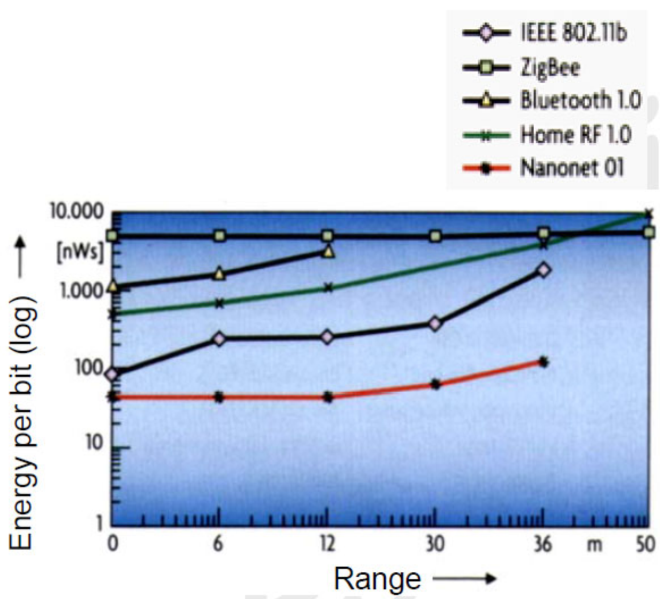
Peaks of ‘receive’ and ‘transmit’ cannot be supplied just by the harvester, even if the average energy consumption is very low. Need: **a hybrid energy management strategy**.

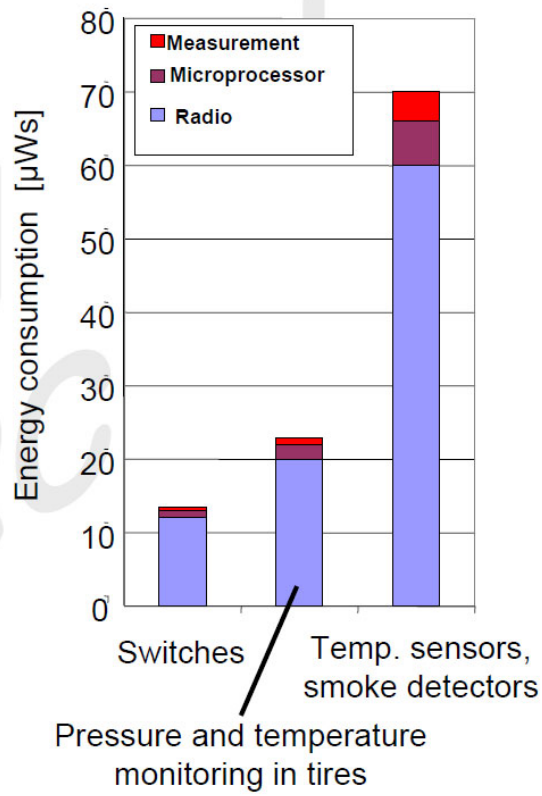


Where the energy goes?

Who is consumming so much? The communication links!

Energy consumption per bit for various radio transmission standards (W. Haecker, Elektronik 22/2002, p. 48)

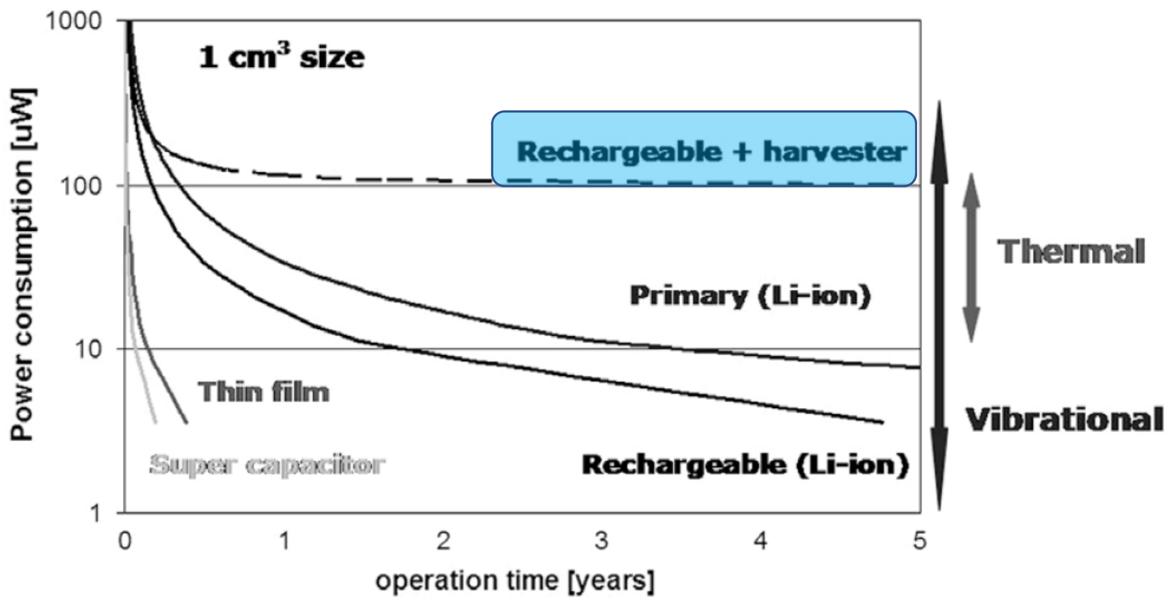




Fraction of the various functionalities from the energy consumption of a microsystem (F. Schmid, EnOcean, 2003)

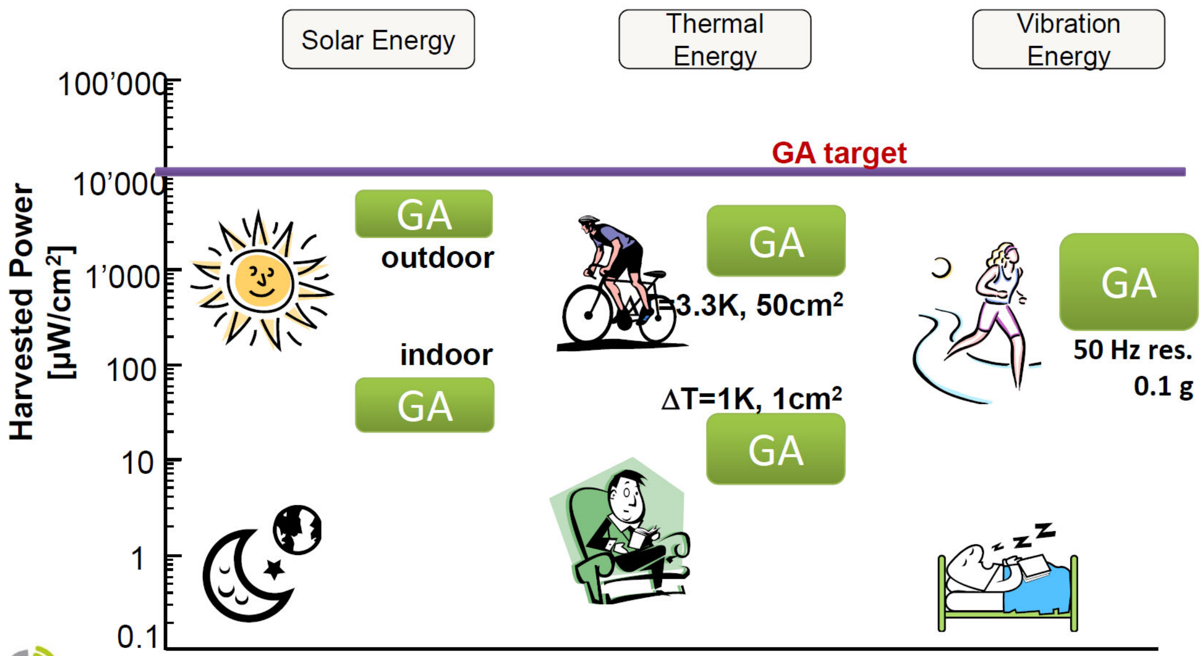
Scenario: energy harvesting + rechargeable batteries

- A more reallistic solution: rechargeable battery + harvester.
- Battery lifetime and operation extended to months or years for 100microWatts sensor nodes.



Energy harvesting

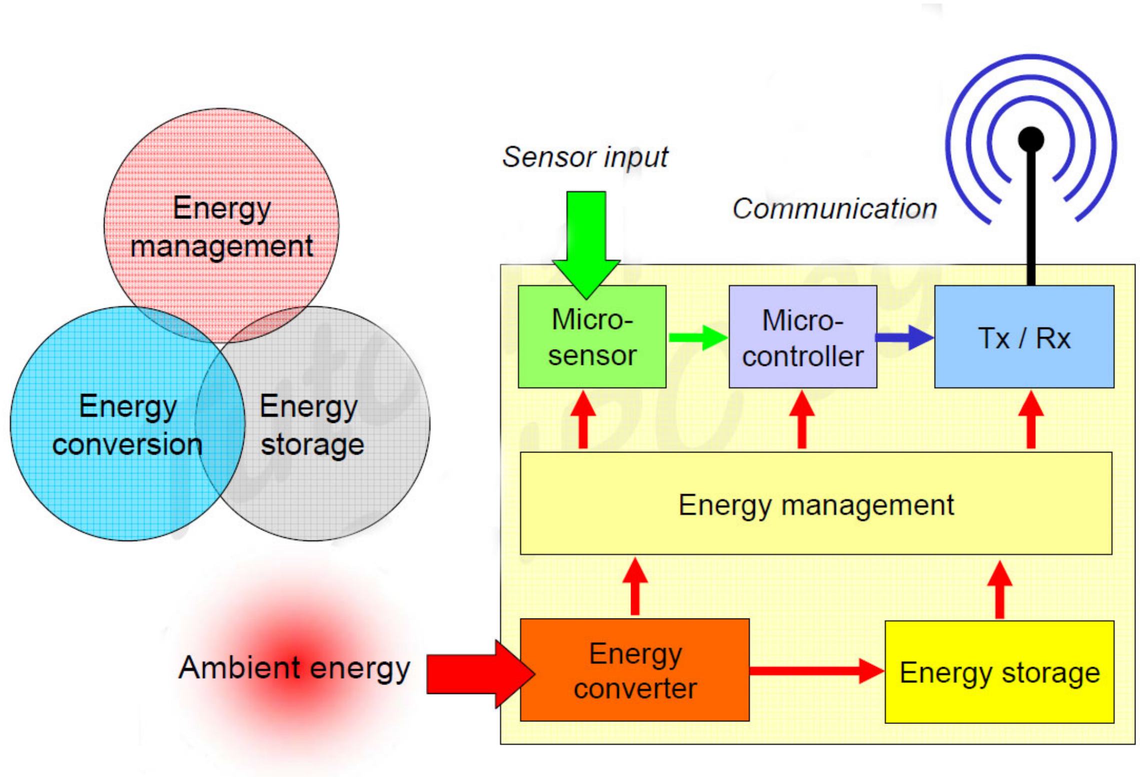
- Challenge: continuous operation under dynamic conditions.
- Choose multi-harvesting interfaces, storage and form factors according to applications – **NO SINGLE UNIVERSAL SOLUTION AVAILABLE!**



Guardian Angels

Energy scavenging is a <u>system level</u> problem!

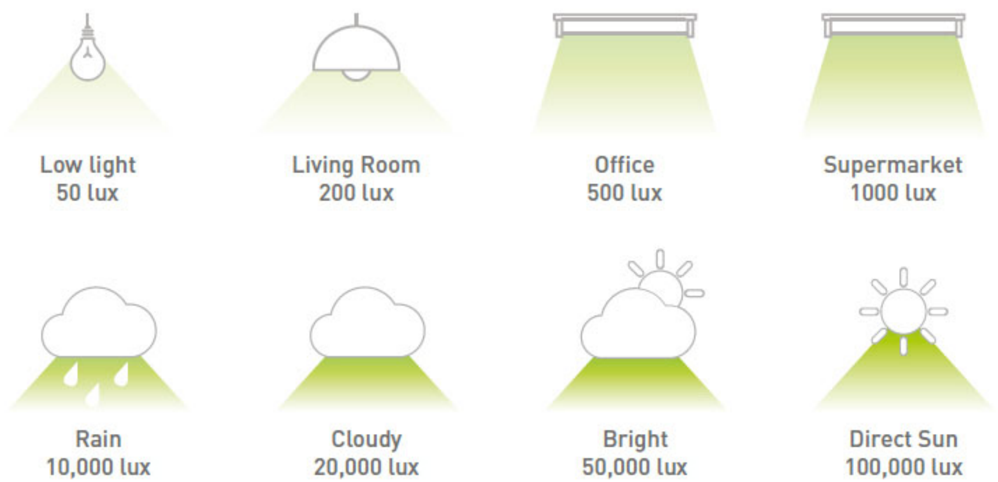
- **Complete approach:**
  - ➢ **Energy conversion**
  - ➢ **Energy storage**
  - ➢ **Energy management**



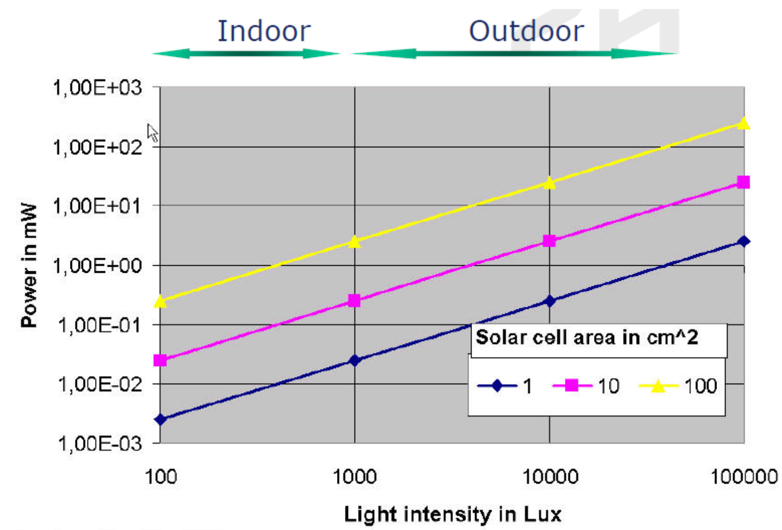
Source: prof. Manoli, IMTEK, Tutorial ESSCIRC 2009.

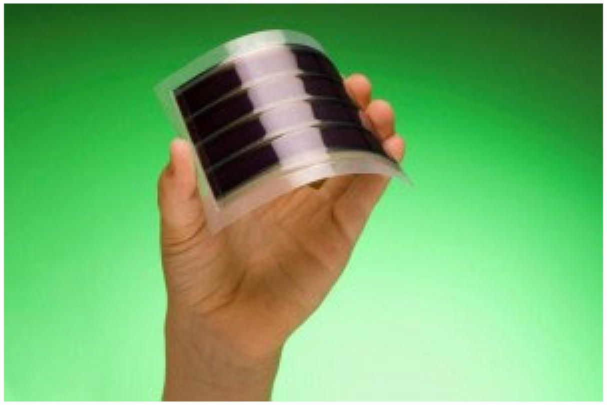
Energy scavenging from light

Challenge:
Indoor versus Outdoor!
Flexible solar cells:
indoor Dye Sensitized Solar Cells (DSSC) that are flexible and boast superior low light performance (Gcell).



Classical thin film cell





Solar cell energy efficiency

TABLE 2 Characteristics of different solar cell types

Generation	Solar cell type	Efficiency	Power density (W/m^2)	References
First	Mono-crystalline	17% – 18%	111 – 142	18
First	Poly-crystalline	12% – 14%	111 – 125	19
Second	Amorphous Silicon	4% – 8%	50 – 77	20
Second	Copper Indium di-Selenide	16% – 23%	91 – 111	21
Second	Cadmium Telluride	9% – 11%	77 – 91	20
Third	Nano-crystal/Quantum Dot	7% – 9%	—	22
Third	Polymer	3% – 10%	—	23
Third	Dye Sensitized	9% – 12%	—	24
Third	Concentrated	≈ 33% – 46%	—	25
Third	Perovskite	≈ 28%	—	26,27

DOI: 10.1002/er.7626

REVIEW PAPER

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

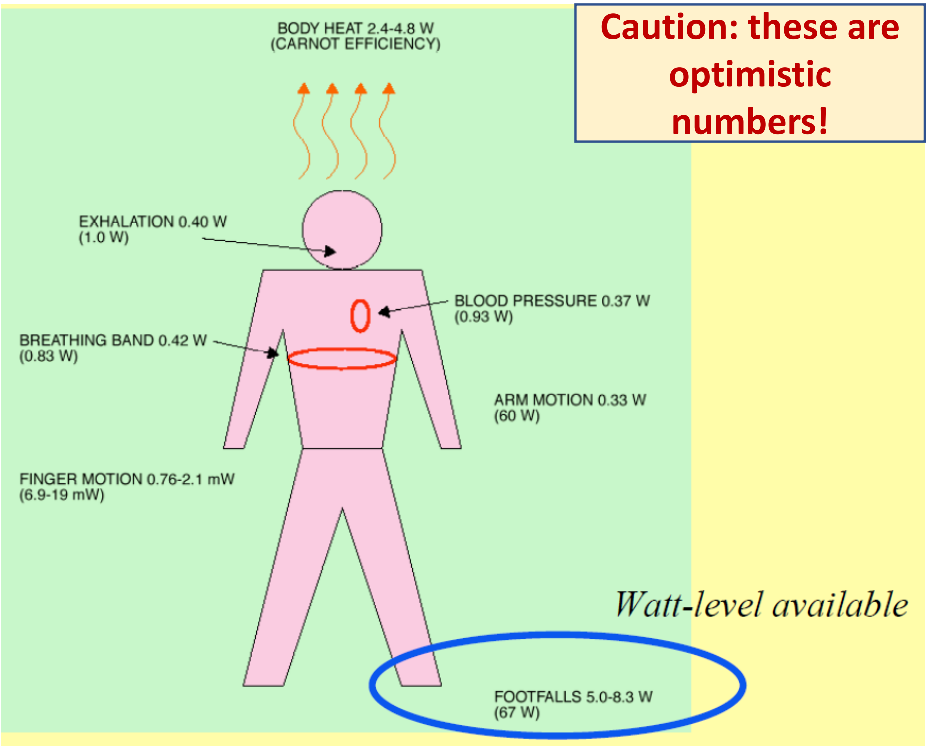
Review of contemporary energy harvesting techniques and their feasibility in wireless geophones

A. Naveed Iqbal[1,2] | Mudassir Masood[1,3] | Ali Arshad Nasir[1,3] | Khurram Karim Qureshi[1,3]

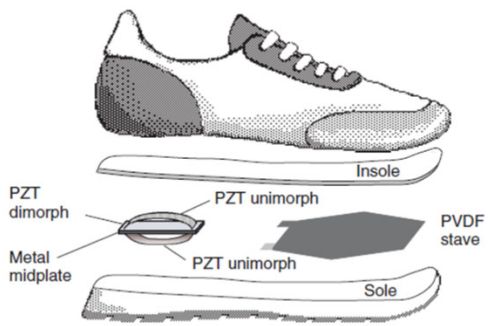
Motion harvesting: human energy >100's W

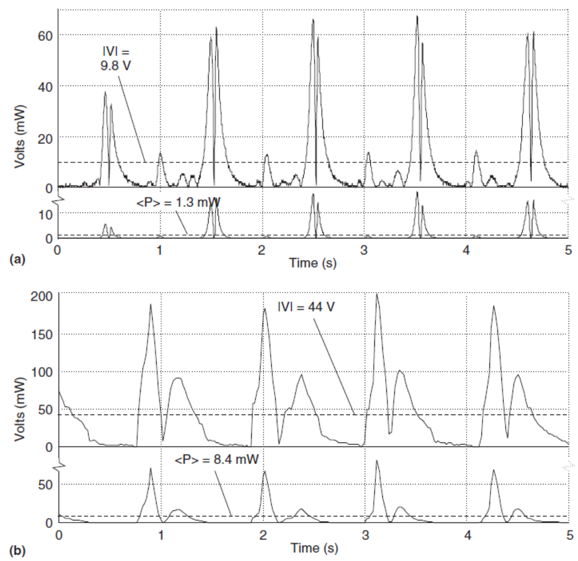
Activity	*Kilocal/hr*	*Watts*
sleeping	70	81
lying quietly	80	93
sitting	100	116
standing at ease	110	128
conversation	110	128
eating meal	110	128
strolling	140	163
driving car	140	163
playing violin or piano	140	163
housekeeping	150	175
carpentry	230	268
hiking, 4 mph	350	407
swimming	500	582
mountain climbing	600	698
long distance run	900	1,048
sprinting	1,400	1,630

Where to tap the power?



MIT's piezoelectric shoes (1998)





Rich Meier et al.,
A piezoelectric energy-harvesting shoe system for podiatric sensing, 2014 Conference of the IEEE Engineering in Medicine and Biology Society.

10-20 µJ of energy per step

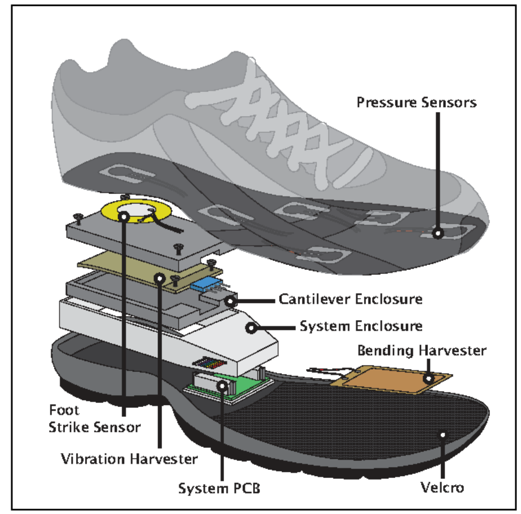


Fig. 1. Expanded view of the shoe system and all integrated components.

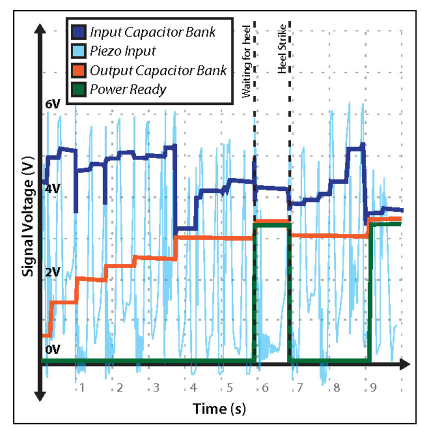
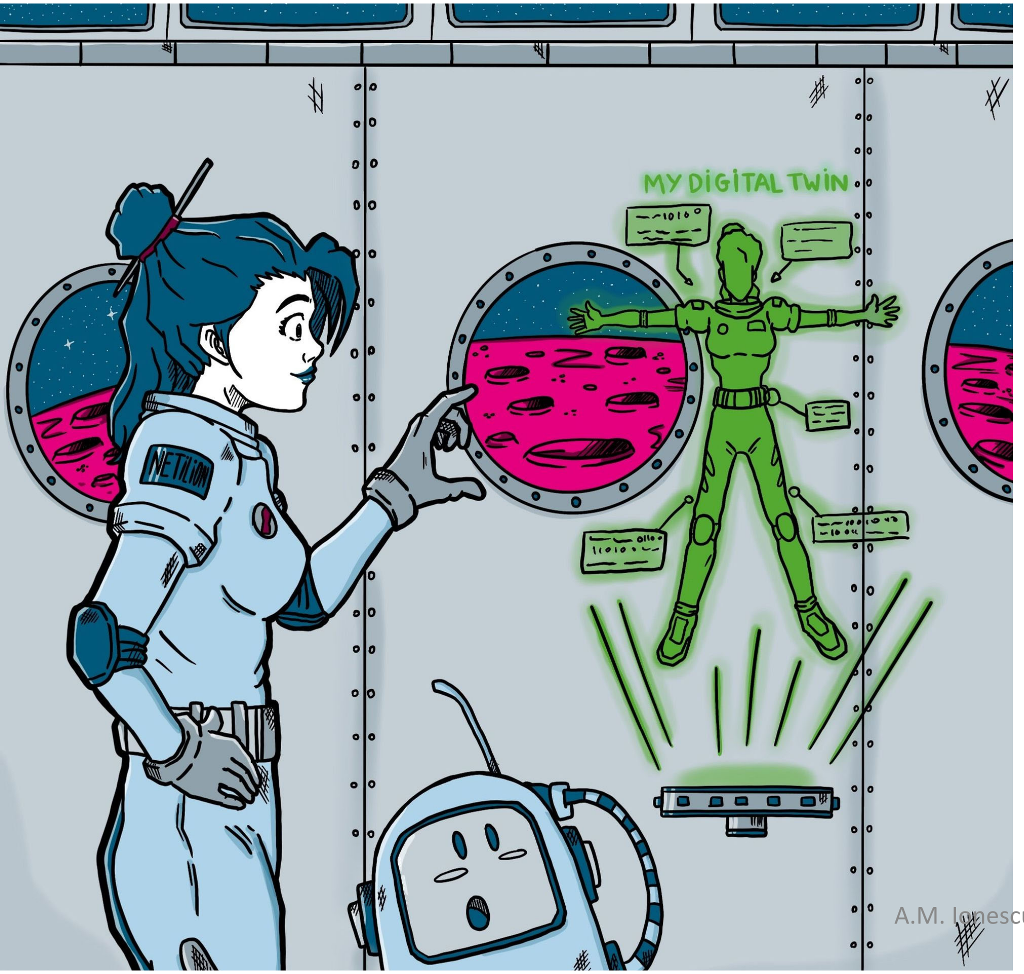


Fig. 3. A time-domain graph of energy capture in lab walking test. Note

Digital Twins as mainstream technology for digitalisation

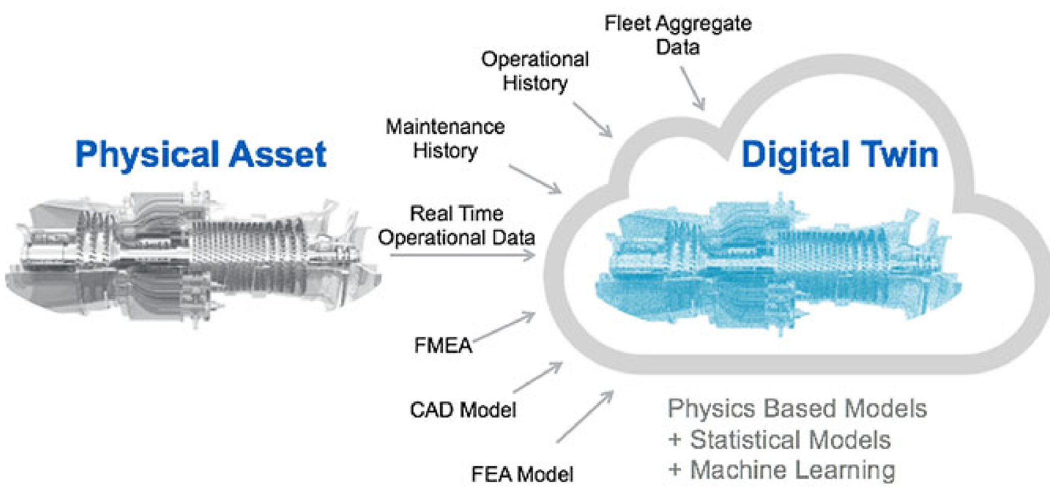


- **digital replica** of an object or a process in the physical world…

One source of truth…

Three main purposes to implement a DT:

- A **PRODUCT Digital Twin** – to guarantee reliable design in product development and improvements.
- A **PRODUCTION Digital Twin** – to improve production planning and manufacturing.
- A **PERFORMANCE Digital Twin** – to capture, analyse and act on data while an asset is in operation.



Key components:

- **MODEL**
- **TIME SERIES DATA**
- **UNIQUE IDENTIFIER**
- **MONITORING CAPABILITY**

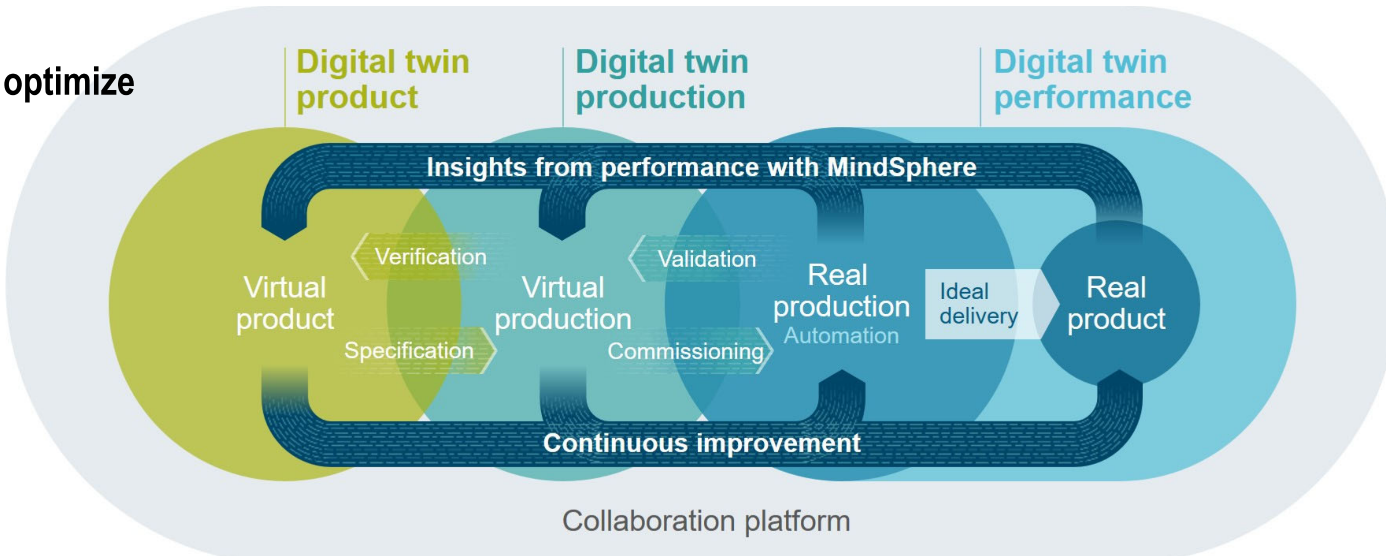
Expected benefits

- Enhances **efficiency and productivity**:
  - ❑ Using digital twins, businesses no longer need to fully experiment with physical objects to improve processes.
  - ❑ Don't need to halt ongoing processes and can simply run simulations in the lab to understand the risks and benefits
- Reduces product **quality** issues:
  - ❑ Digital twins simulate different "what-if" real-world scenarios
- Lowers **maintenance** costs:
  - ❑ Digital twins predict maintenance failures via simulation models that capture information about various risk factors
  - ❑ They save costs, improve equipment reliability, reduce downtime, and extend the equipment life span.
- Improves employee **training**:
  - ❑ Employees can be also trained to handle equipment that isn't physically close or is too costly to be given hands-on training.
  - ❑ Digital twins can recreate real-life hazardous situations to train employees.

Digital twins of performance

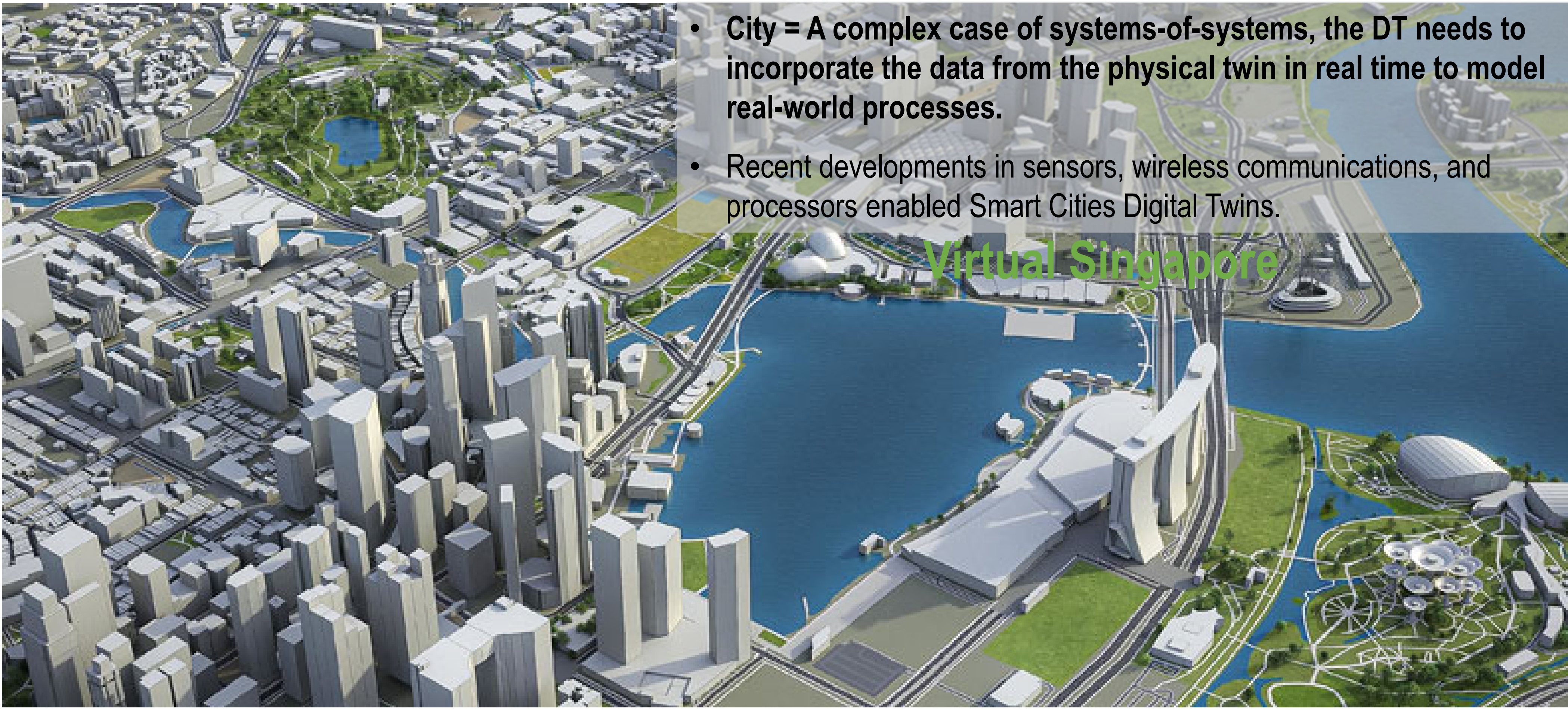
- Siemens manufacturers implement the **in conjunction with IIoT** to eliminate the unknowns and make near real-time production optimization decisions.
- The **performance twin** involves capturing and sending back live performance data of the production line and of product itself, at a customer location. This **near real-time data** allows engineers to determine if the production line and product behave as they were intended. If not, this information will quickly drive **actionable insights** and informed decision making back into the product and production line design.

Closing the loop to optimize decision making



Can Digital Twins Transform Cities Environment in a more Sustainable way?

- **City = A complex case of systems-of-systems, the DT needs to incorporate the data from the physical twin in real time to model real-world processes.**
- Recent developments in sensors, wireless communications, and processors enabled Smart Cities Digital Twins.



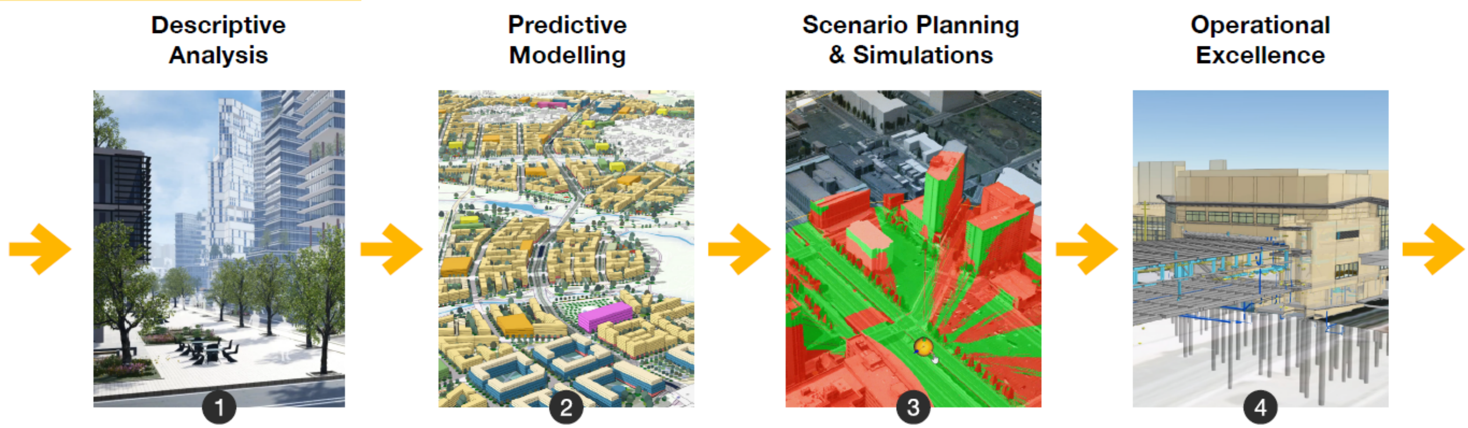
How digital twins can make smart cities better

Monitoring of multiple physical assets

- The smart city a digital twin continuously collects information from the built environment: sensors, drones and mobile devices for **up-to-the-second picture.**
- An urban digital twin will be receiving data from sources including vehicles, buildings, infrastructure and individuals. Key: data captured by smart city **Internet of Things (IoT) and additionally augmented by the use of artificial intelligence (AI).**

Strategy accelerator

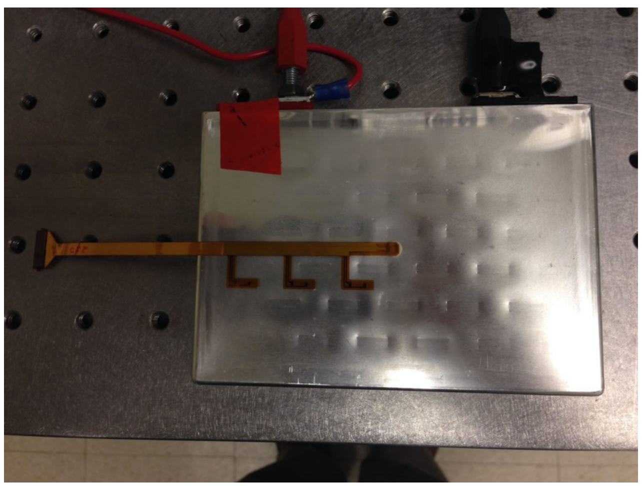
- The digital twin is **a "strategy accelerator" that** enables public sector organisations to identify insights and connections more effectively, and **drives better solutions with more confidence**.
- **Examples**: Cities including Singapore, Sydney and Amaravati, are already using digital twins to enable smart development.

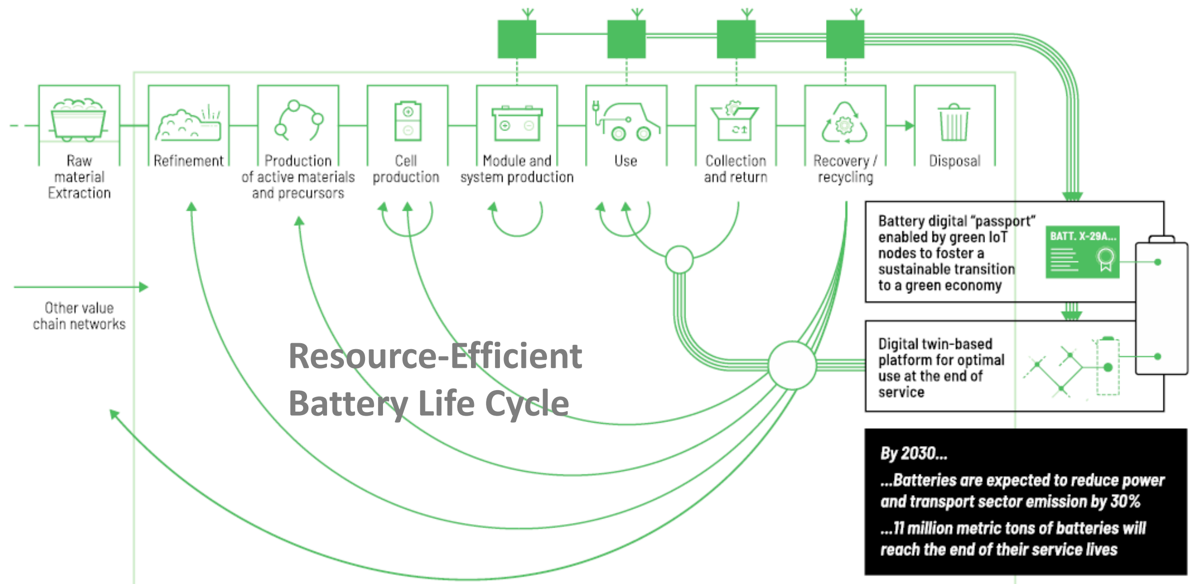


Source: PWC.

Digital twins of smart batteries

- https://www.ge.com/news/reports/scientists-built-a-digital-twin-of-a-car-battery-to-make-it-last-longer
- shrink the battery size, shave production expenses by 15%, all while maintaining long-term reliability and life.





Digital Twins of All Humans

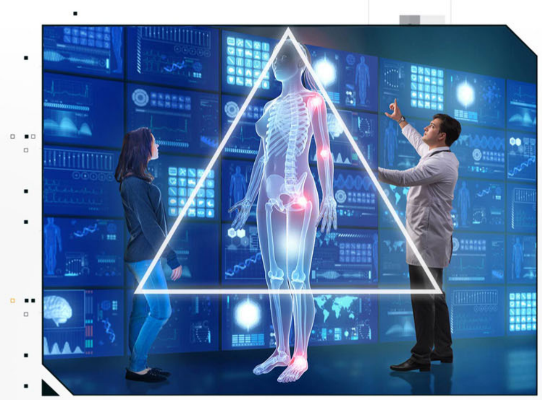
- **Reactive healthcare is unsustainable**
- **Digital twins will apply to people too**
- **Towards a more sustainable Personalized, Preventive and Participatory (P3) Healthcare**

The missing link…

… for breaking barriers between Medical Knowledge Creation and Medical Knowledge Application

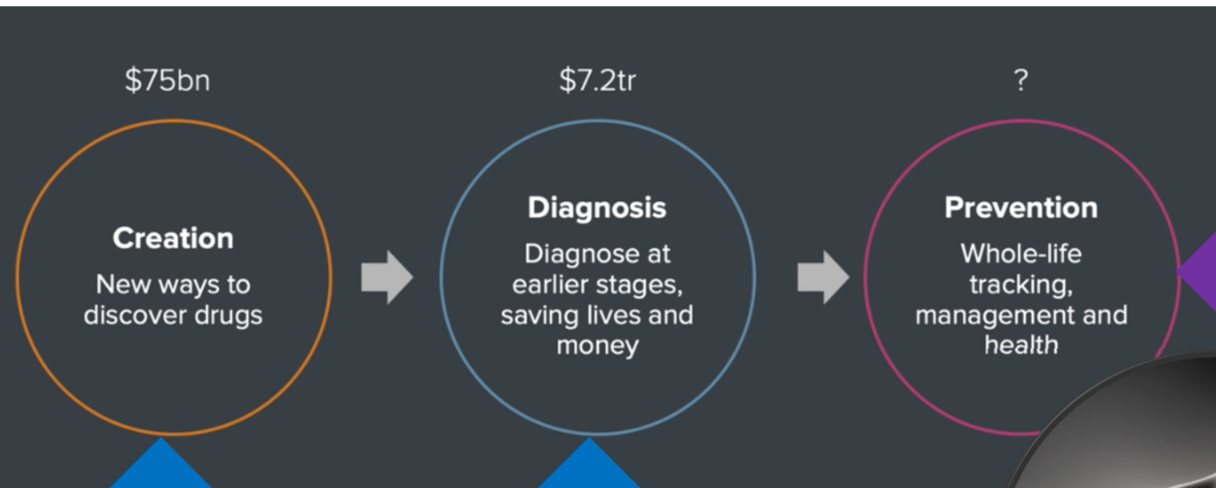
… for creating the triangle Citizen – Human Avatar – Clinical Professional

… for a sustainable healthcare in 21st Century



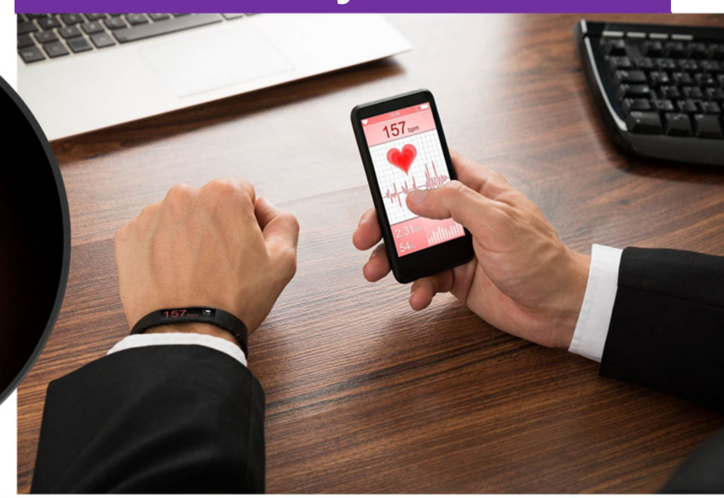
Re-thinking the future of P3 healthcare with DT

- What's the real opportunity for future Digital Twins in P3 healthcare?



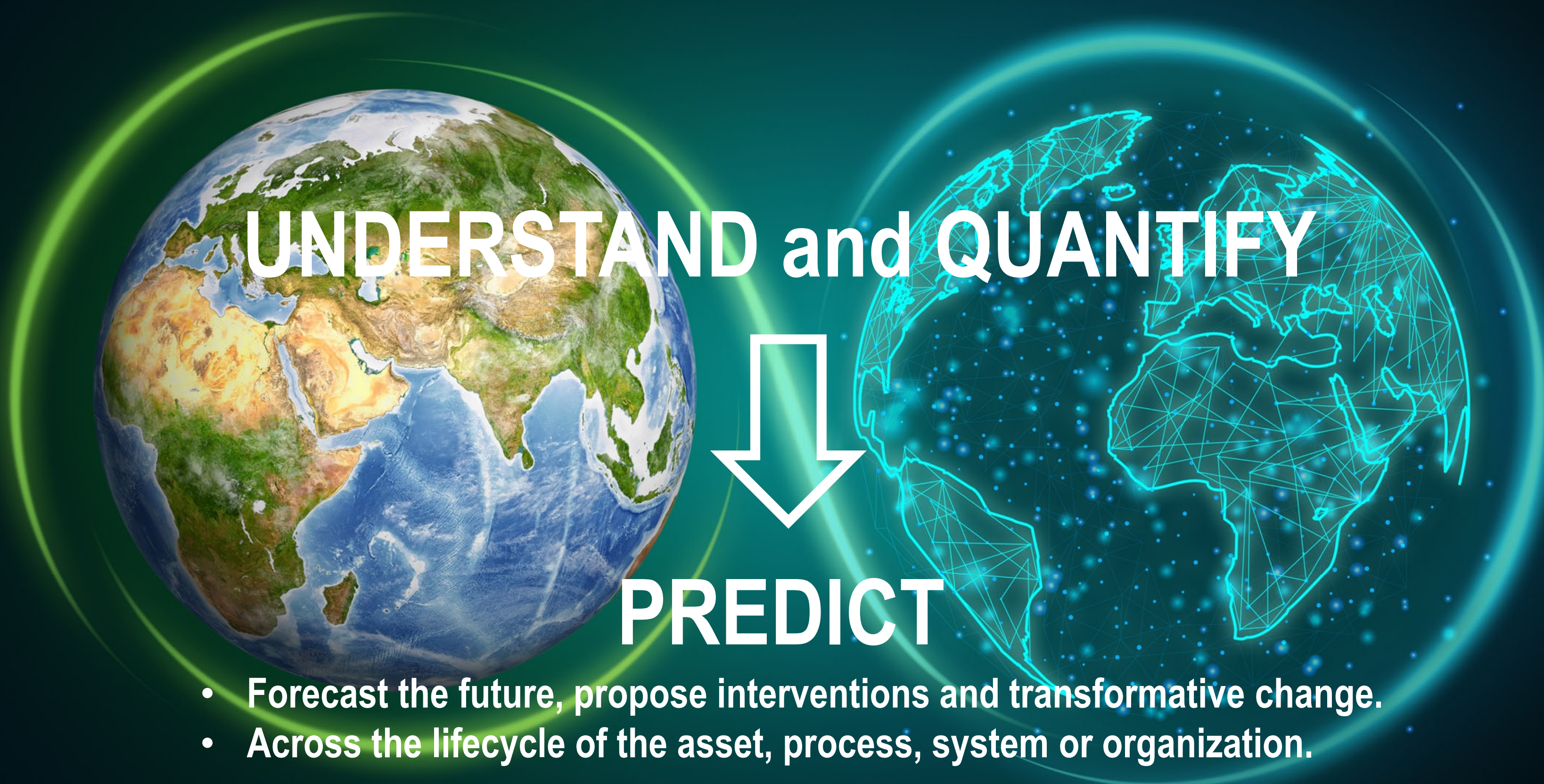
The value of NOT being sick = healthy?

The value of being sick



Overcoming sustainability challenges with digital twins

https://global.royalhaskoningdhv.com



UNDERSTAND and QUANTIFY

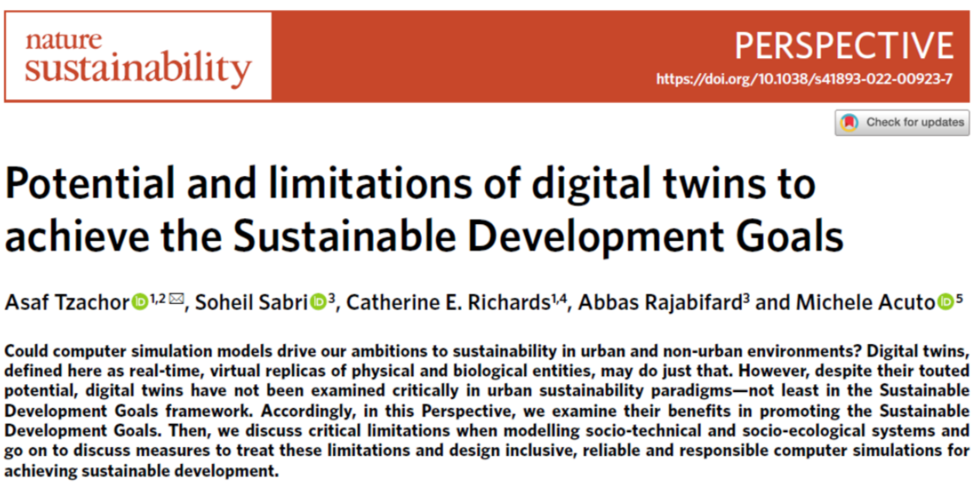
⇩

PREDICT

- Forecast the future, propose interventions and transformative change.
- Across the lifecycle of the asset, process, system or organization.

Perspective: Sustainable Development Goals

- Possible **only with** two key digitalization components: **IoT/Edge AI and Digital Twins!**
- Sustainable chips & software



nature sustainability

PERSPECTIVE

https://doi.org/10.1038/s41893-022-00923-7

Check for updates

Potential and limitations of digital twins to achieve the Sustainable Development Goals

Asaf Tzachor[1,2], Soheil Sabri[3], Catherine E. Richards[1,4], Abbas Rajabifard[3] and Michele Acuto[5]

Could computer simulation models drive our ambitions to sustainability in urban and non-urban environments? Digital twins, defined here as real-time, virtual replicas of physical and biological entities, may do just that. However, despite their touted potential, digital twins have not been examined critically in urban sustainability paradigms—not least in the Sustainable Development Goals framework. Accordingly, in this Perspective, we examine their benefits in promoting the Sustainable Development Goals. Then, we discuss critical limitations when modelling socio-technical and socio-ecological systems and go on to discuss measures to treat these limitations and design inclusive, reliable and responsible computer simulations for achieving sustainable development.

Key Takeaways

- Sustainability can be addressed by some emerging technologies:
  - ✓ **Energy harvesting in Internet of Things** -> replacement of batteries
  - ✓ **Digital twins** as predictive supporting tools:
    - Industry 4.0
    - Smart cities
    - Personalized and predictive healthcare
    - Climate change

Class Projects

Potential topics for your projects:

- Enhancing Sustainability in AI and Quantum Computing: A Critical Review of Data Center Energy Consumption and Mitigation Strategies
- Edge AI in Autonomous Systems: Evaluating Its Potential and Challenges for Sustainable Deployment
- Energy Harvesting Technologies in the Internet of Things: Enabling Sustainable and Self-Powered Smart Devices
- Digital Twin Technologies for Sustainability: From System Modeling to Predictive Optimization for Resource Efficiency