CS4800: Designing Sustainable ICT Systems

Lecture 1: Introduction

September 4, 2025

Lecturer: Przemysław Pawełczak
Authors: Alex Nedelcu, Przemysław Pawełczak

CS4800-EWI@tudelft.nl

Course team

- Przemysław Pawełczak (course admin and main lecturer)
  - Associate Professor at TU Delft leading http://github.com/tudssl
- TA team: Cristian Cuțitei, Alex Despan, Radosław Majer, Alex Nedelcu, Liwia Padowska, Alexandru Postu
- Contact: CS4800-EWI@tudelft.nl (you can try your luck with my personal email, but the odds are against you)

Course made possible by SIDN Fund support through grant "Educational ecosystem aimed at sustainable ICT system design"

Learning objectives

1. **List** the methods for assessing ICT industry climate impacts
2. **Comprehend** the implications of different ICT system design decisions on the climate
3. **Apply** ICT system design techniques that minimize climate impact
4. **Analyze** how each ICT system design technique affects climate impact
5. **Create** new methods of ICT system design with sustainability as a core performance metric

Course organization

Lectures

- Thursdays, 15:45-17:30, on campus (check MyTimetable!)
- Each cover one component of sustainable ICT
- Course material: lecture slides + lecture notes (posted after each lecture)

Labs

- Fridays, 15:45-17:30 (check MyTimetable!)
- Project work: presentation and feedback
- Online guest lectures: practitioners in the field

Detailed information in official course repository; announcements on Brightspace

Course organization

Week 1.1: Introduction

Week 1.2: Defining Sustainability

Week 1.3: Sustainable Software

Week 1.4: Sustainable Cloud Computing

Week 1.6: Sustainable AI

Week 1.7: Sustainable Electronics Design

Grading and assessment

70% practical assignment

- Two possible assignments (sustainable software/AI), described later today
- Work in groups of two/three
- Meant to develop deeper understanding of specific topic
- 60% report grade, 10% presentation grade

30% exam

- Multiple choice questions, practice questions available at end of each lecture
- Based on lecture slides + lecture notes
- Meant to test course knowledge
- Thursday, November 6, 13:30-16:30 / Wednesday, January 21, 13:30, 16:30 (resit)

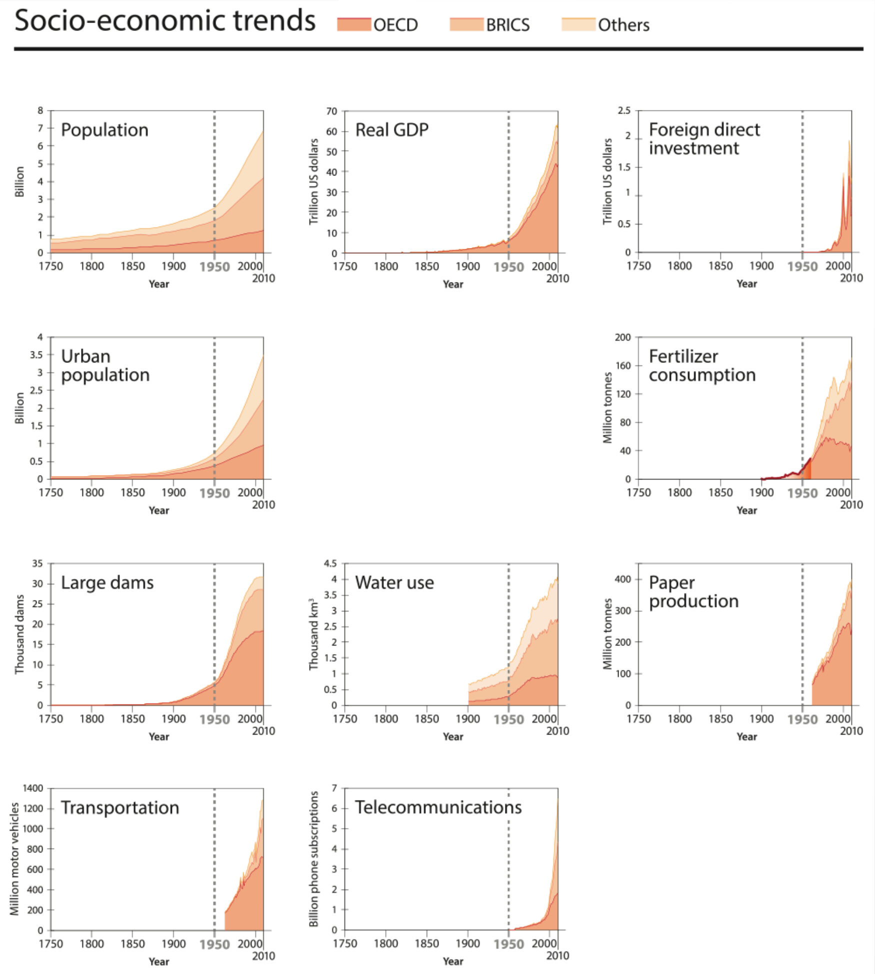
What will you learn in this lecture?

Week 1.1: Introduction

- Basics of climate change
- ICT impacts on the environment
- Prospective solutions
- Economic aspects

"The Great Acceleration"

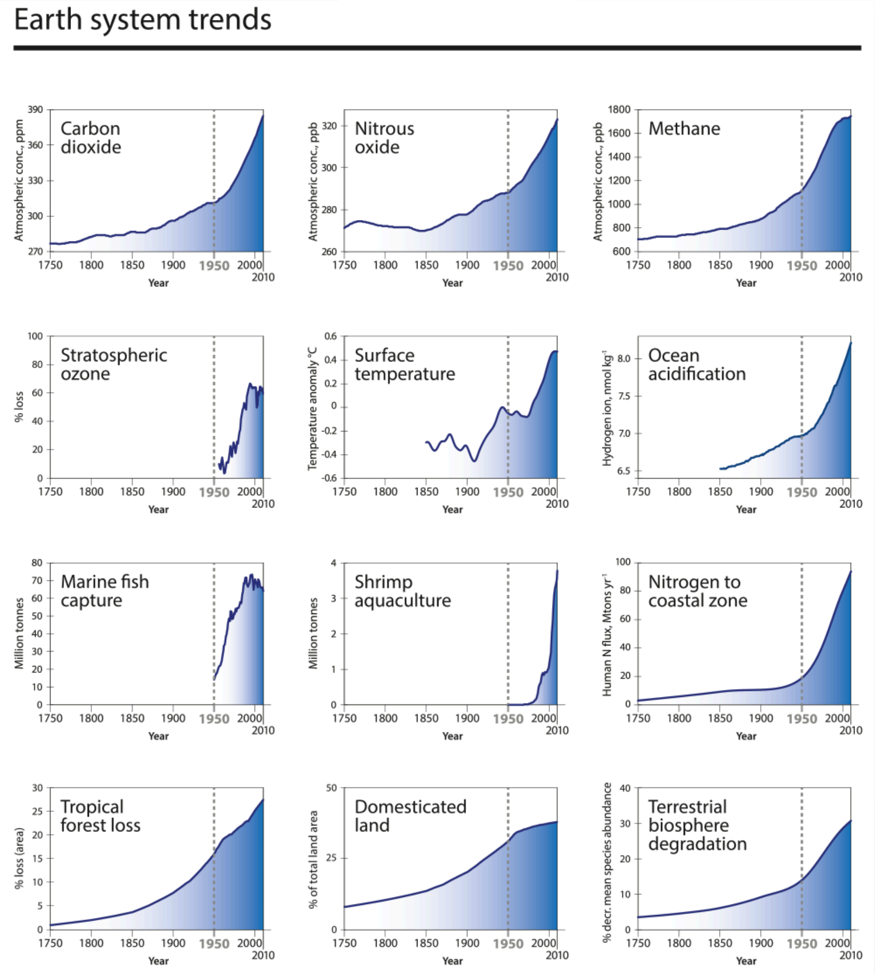
- Human society has been expanding continuously and exponentially
- Human population, economic development, and technological innovation have grown



Historic socio-economic trends

"The Great Acceleration"

- … but so have environmental impacts of human society on Earth system!

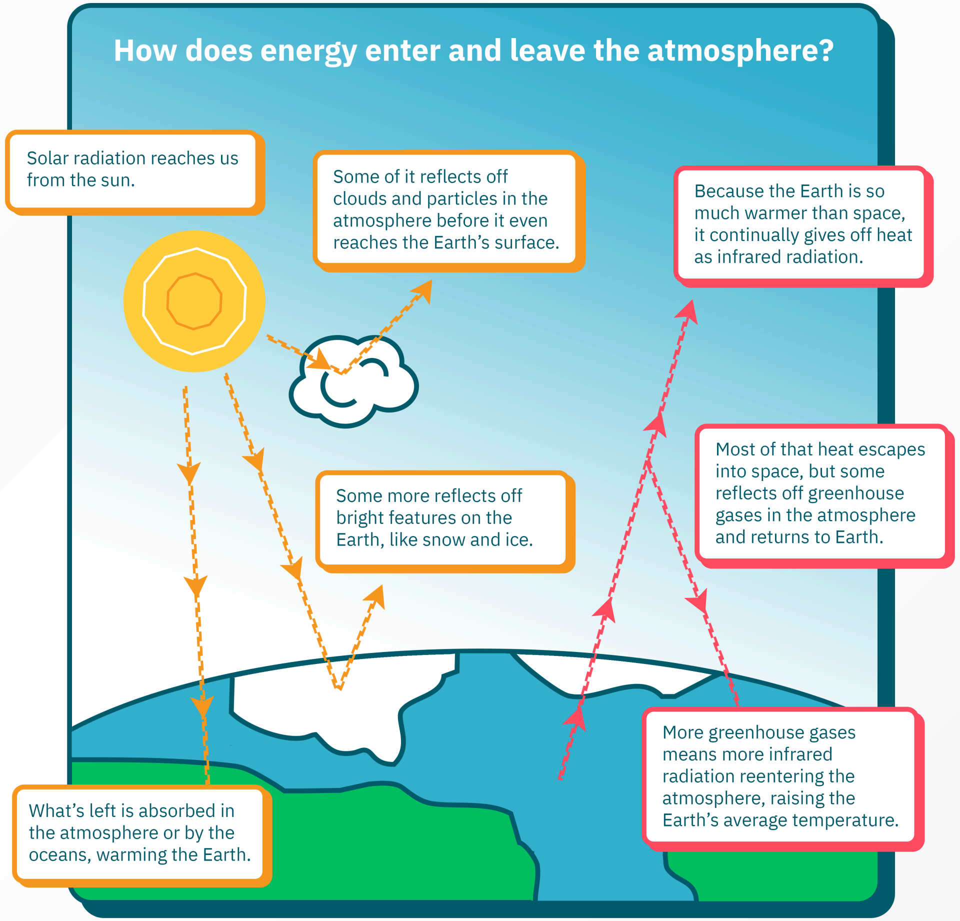


[Historic Earth system trends]

Climate change

- Earth is in energy equilibrium: incoming solar radiation is equal to infrared energy emitted
- Radiated energy is correlated with Earth's temperature:

$$\text{infrared radiation} \propto T^4$$

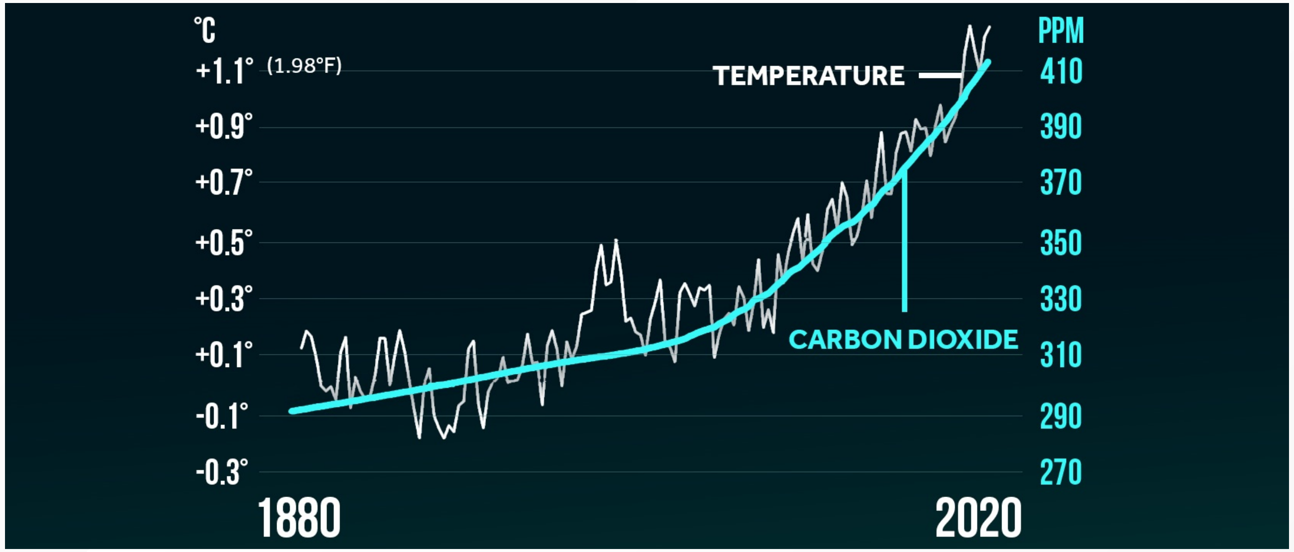


The energy balance within Earth's atmosphere

TU Delft

Climate change: greenhouse gases

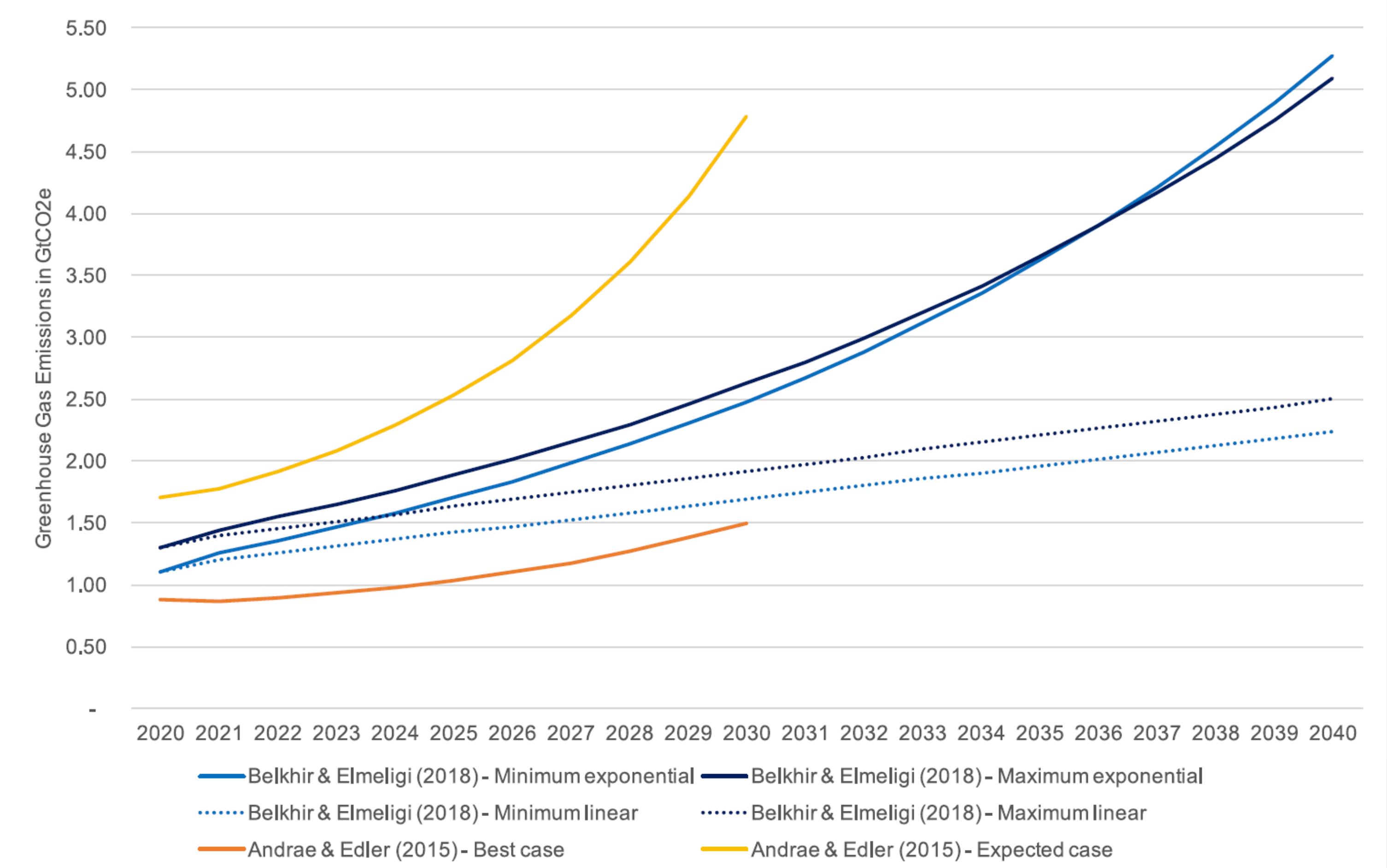
- World economy relies on combustion of fossil fuels
- Greenhouse gases (GHG's) like CO_2, methane are introduced into atmosphere
- GHG's absorb infrared energy emitted by Earth
- Atmosphere heats up to maintain equilibrium → global warming!
- Warmer atmosphere also stores more water → extreme weather patterns!



Correlation between CO_2 concentrations and global temperature

ICT emissions

- Software requires hardware to run it
- Hardware requires energy to run
- Energy production emits GHG's
- Therefore, ICT growth means GHG emissions increase!
- 2020: up to 4% of global emissions, greater than aviation, maritime sector



Various estimates for ICT emissions growth

TU Delft

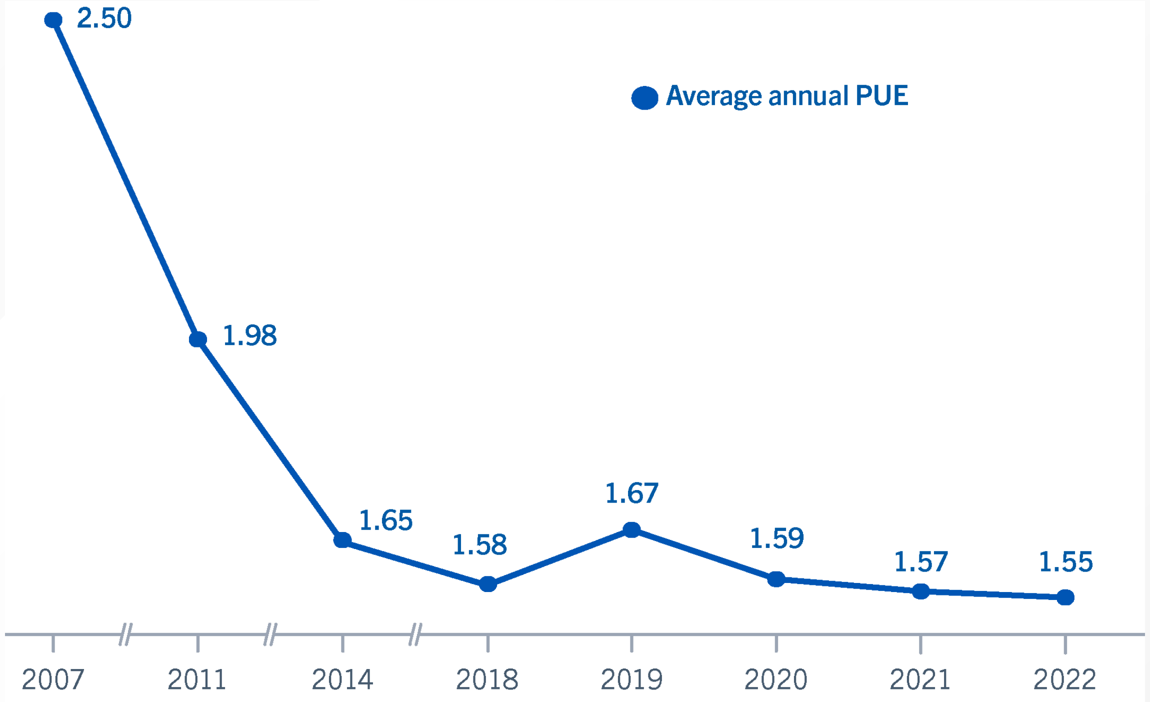
What solutions have been proposed to this problem so far?

TU Delft

Prospective solutions: improving efficiency

- More efficient ICT systems consume less energy per unit of compute

- Historically: data center workloads increased by 550%, emissions kept stable
- Moore's Law stalling, thermodynamic limits ('quantum entanglement') near
- Efficiency gains slowing



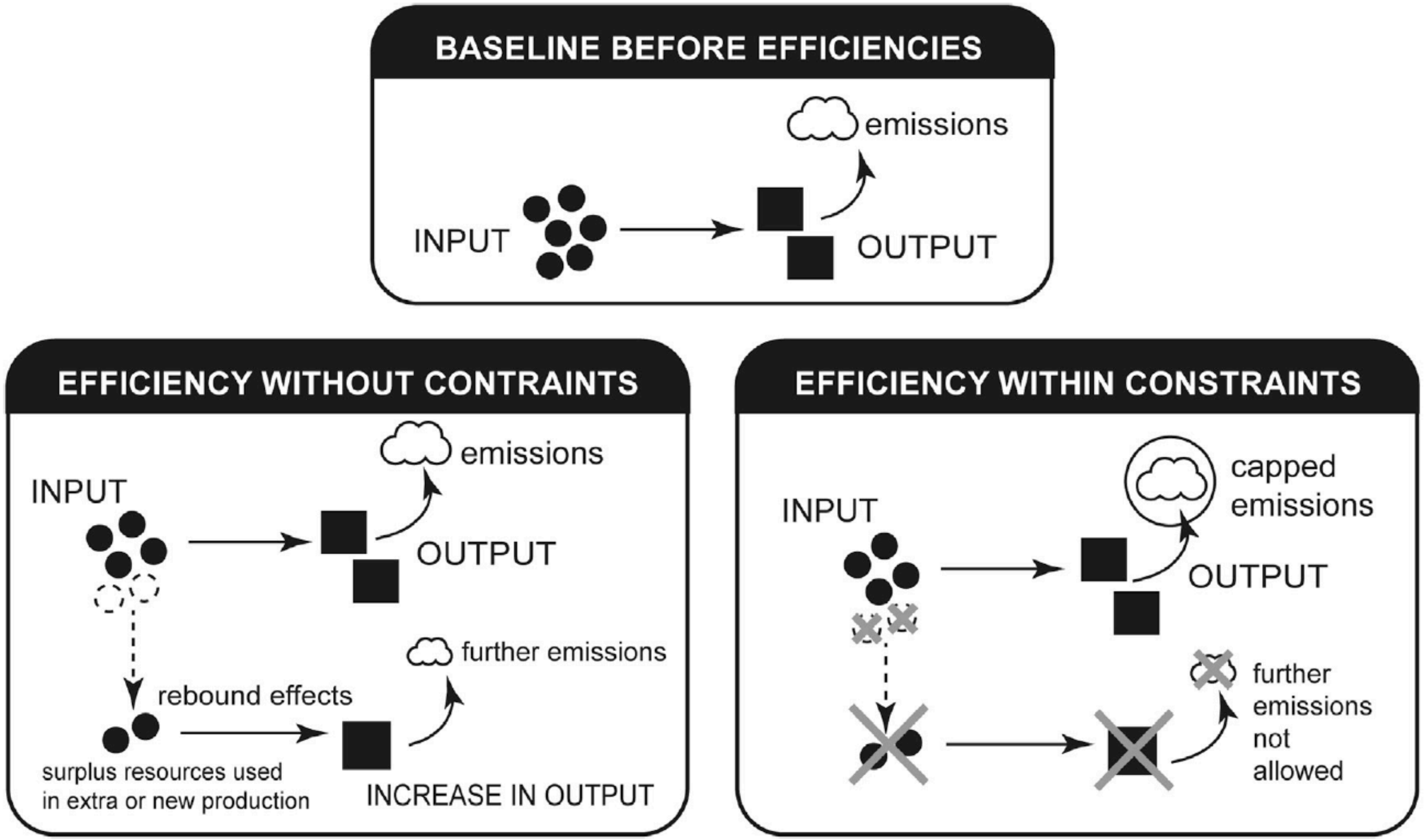
Data center power usage effectiveness trend

TU Delft

Prospective solutions: rebound effects

1. More efficient process requires less input per output…
2. Cost per output becomes lower…
3. … so more people use it!

→ Efficiency improvements eaten up by rebound effects, unless specifically constrained by regulation



Limiting emissions only possible by constraining further consumption from rebound effects

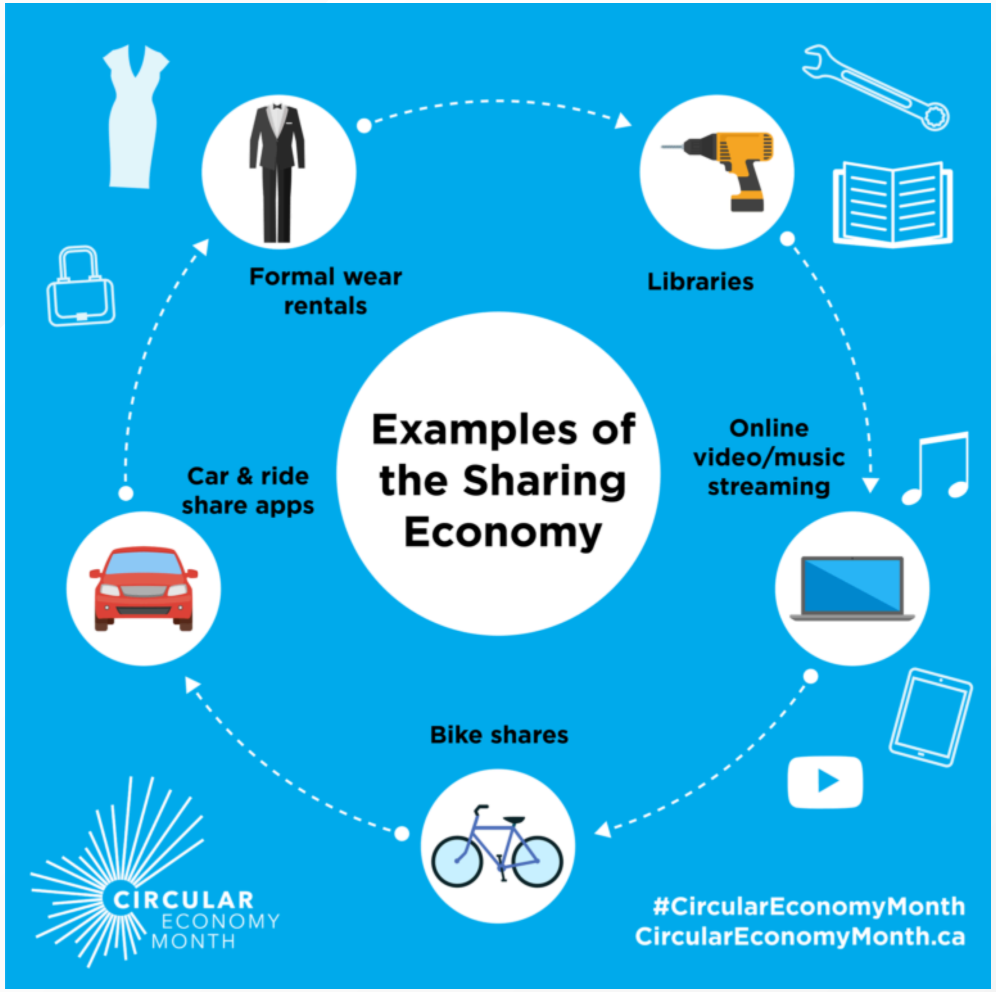
Prospective solutions: saturation

- Once every person on Earth has a smartphone, we should reach a theoretical cap for emissions
- However, companies keep releasing new products and services
- Saturation is incompatible with how the economy works!

Planned obsolescence makes saturation unlikely

Prospective solutions: digital sharing

- Industry claims that ICT can help decarbonize other sectors
- Such effects have not yet materialized
- The digital sharing economy might partially help: people use products only when they need them, reducing the amount of products required



Examples of digital sharing

Prospective solutions: carbon removal

- Some form of carbon removal (wetland restoration, ocean capture, enhanced rock weathering) will probably be necessary for 'hard-to-abate' sectors
- Tree planting and other natural methods are insufficient!
- (Still nice to do it)

Planting a few trees can't hurt

Example: carbon capture and storage

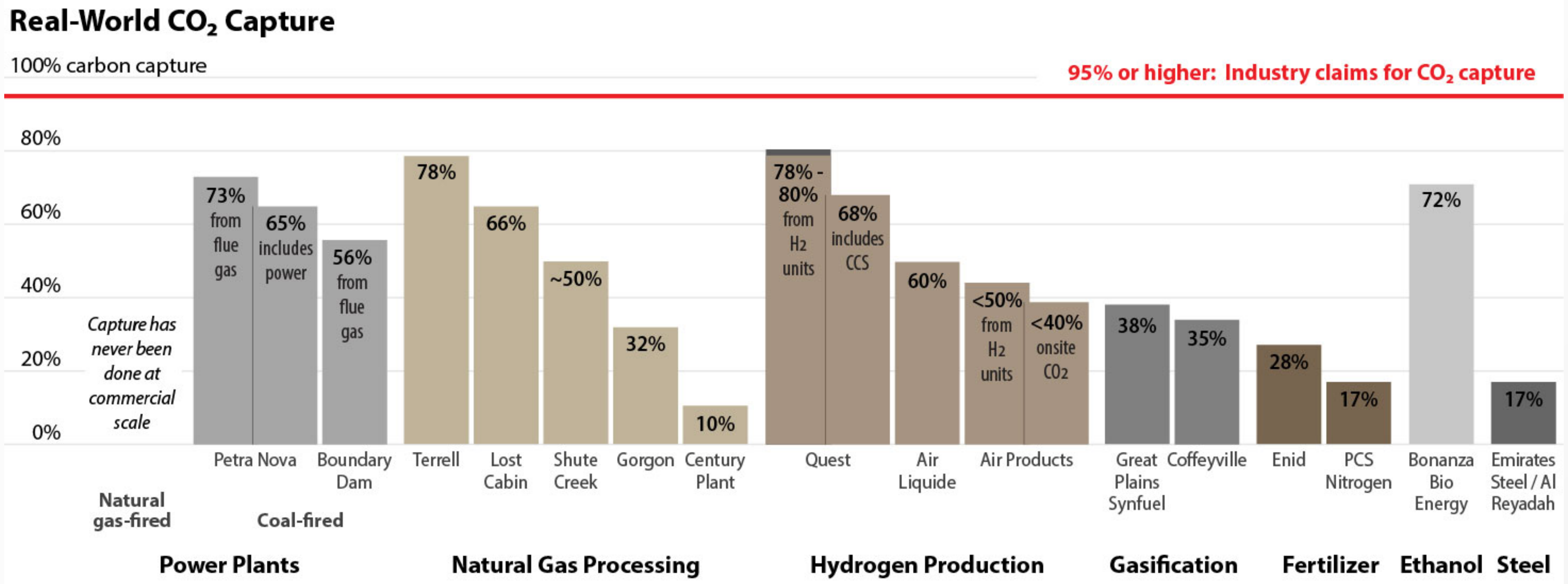
- Industrial carbon capture and storage (CCS) or utilization (CCU): scrubbing of industrial exhaust gas
- Exhaust gas is chemically treated at high temperatures → high energy consumption, needs special chemical solvents
- Resulting CO2 stream stored or used as feedstock

Industrial CCS facility in Japan

TU Delft

Example: carbon capture and storage

- CCS technology [does not work]() in real life as well as proponents claim
- Requires additional energy, which [could be used to directly decarbonize]()
- We would need [enormous amounts]() of chemicals and energy to capture all global emissions



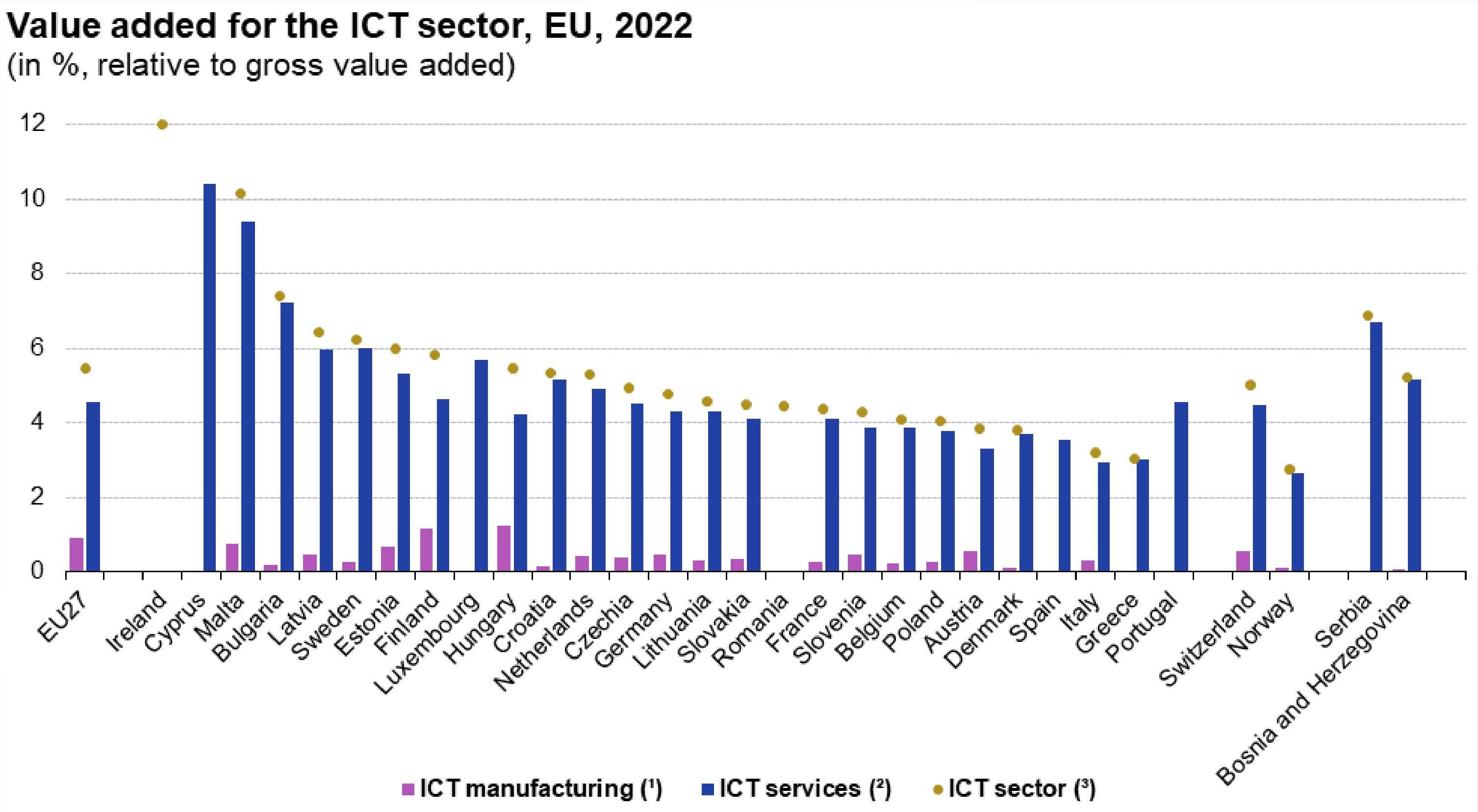
[Carbon capture rates in real-world projects vs industry claims]()

How do we engage with the planet?

Economics: GDP

- Planet seen as natural capital, extraction produces economic value
- Economic activity measured through Gross Domestic Product (GDP)

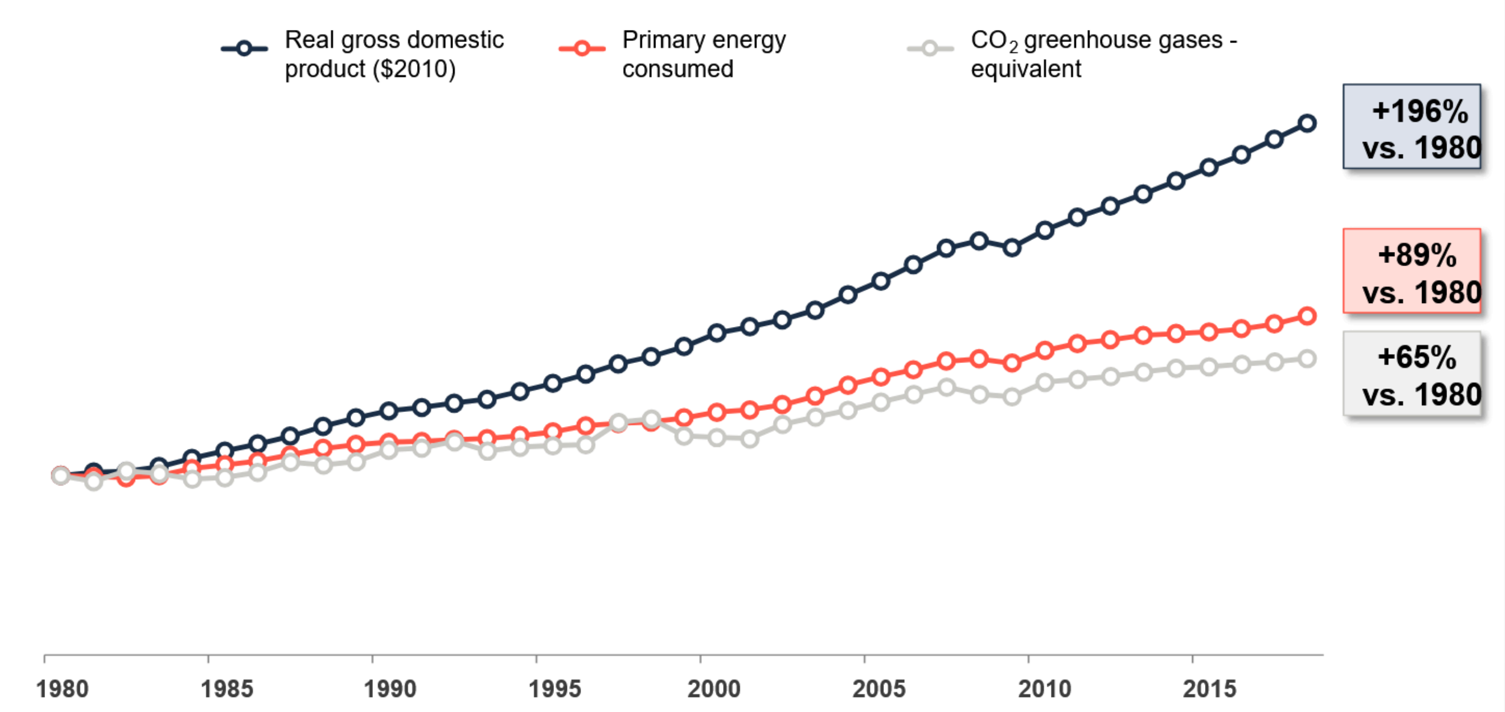
- Example: software contribution measured with standard System of National Accounts
- Economic growth traditionally seen as necessary



Share of value added (not GDP) produced by EU ICT sector

Economics: energy and emissions coupling

- All economic activity requires energy: energy-GDP coupling
- Energy currently comes from fossil fuels, so GDP and emissions are also coupled
- No sustained absolute decoupling has been observed anywhere!



Relative decoupling between GDP growth, energy consumption, and emissions

Economics: growth or degrowth?

- Is it even possible to decouple growth, energy consumption, and emissions?
- Complex economic, political, and philosophical question -> lots of opinions, (respectful) debate invited
- In this course: focus on reducing environmental impacts of ICT systems!
  - Improve software efficiency
  - Study data center design
  - Trade-off costs and benefits of AI
  - Redesign electronics

Recap

- Climate change is caused by combustion of greenhouse gases
- The ICT sector causes a significant part of global emissions
- Proposed solutions are important, but not sufficient to decrease impacts
- Significant future questions about GDP growth and coupling

Exam(ple) questions

1. **Why is carbon capture insufficient to compensate for global emissions? Choose the false answer.**
   a. Practical applications have capture rates below what we would desire
   b. There isn't enough space underground to store all the carbon dioxide we capture
   c. It would take up a huge amount of materials to capture and transport all emissions
   d. It would be more efficient to use the energy to directly decarbonize

2. **Why are critics questioning the possibility of GDP-emissions decoupling?**
   a. It is impossible to fully eliminate the use of fossil fuels
   b. It is impossible to support human well-being without economic growth
   c. No sustained absolute decoupling has been observed anywhere in the world
   d. It is impossible to convince people to stop consuming carbon-intensive products

Feedback

- This is the first edition of the course - we need your feedback!
- Feedback on Lecture 1 slides/notes:

Project Organization

- Two possible assignments: sustainable software or sustainable AI
- Assignment specification posted on Brightspace
- Deliverables: project report (60% of course grade), final presentation (10% of course grade)
- Make your own groups of 2/3, choose preferred assignment
- Diversity of perspectives preferred (don't just pick your friends!)
- Sign up on Brightspace by **Thursday, September 11, 15:45** - mandatory to participate in course!

Assignment: Sustainable Software

- Simulating typical server workloads to assess energy consumption
- Implementing just-in-time (JIT) compilation to improve energy efficiency
- Assessing environmental impact: carbon emissions
- Includes coding tasks: Linux, Java Spring Boot, Python

Assignment: Sustainable AI

- Designing AI system for conservation case study: data, training strategy, deployment strategy
- No model training required: focus on system design
- Assessing environmental impact: carbon emissions, water consumption, material use

Thank you for your attention!

Next lecture: Defining Sustainability

Thursday, September 11, 15:45-17:30, EEMCS Hall F

- Conceptualizing sustainability
- Defining sustainable ICT systems
- Frameworks for sustainability: planetary boundaries, circular economy, digital sufficiency
- Sustainability indicators: global warming potential, emissions reporting, carbon/energy/ material/water intensity

Questions?