Prospective scenarios for the carbon footprint of mobile networks – case study of France

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Report

Results presented here are published in a technical report [Buquicchio et al., 2024b]:

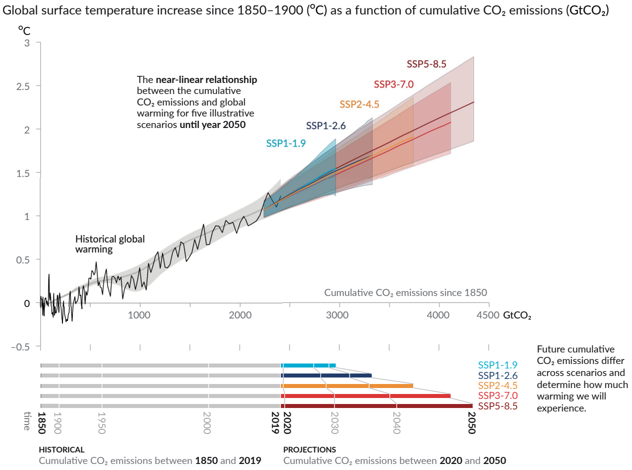
Ingrid Buquicchio, Marceau Coupechoux, Marlène De Bank, Maxime Efoui-Hess, Hugues Ferreboeuf, Gaël Guennebaud, Julia Meyer, Florian Millet and François Richard (working group on Networks)

"Lean Networks for Resilient Connected Uses"
The Shift Project, 2024

Outlines

Outline

Context : Global warming



- We have a finite carbon budget if we want to meet Paris agreement's objectives [IPCC, 2023]

Context : Other environmental footprints

Examples of other footprints [ITU-T, 2019]:

- Ozone depletion
- Human toxicity
- Respiratory inorganics/particulate matter
- Ionising radiation
- Eutrophication
- Acidification
- Land use
- **Water use**
- **Depletion of abiotic resources**

Declining biodiversity: “More species of plants and animals are threatened with extinction now than at any other time in human history” [IPBES, 2020]

Context: ICT footprint

ICT = Information and Communication Technologies

- Main components:
  - Devices: smartphones, screens, PCs, tablets, IoT, etc.
  - Networks: routers, base stations, switches, access points, etc.
  - Data centers: servers
- ICT represents 1.8-3.9% of GHG emissions in 2020 (around 1.2-2.2 GtCO2eq out of which 200-300 MtCO2eq for mobile networks).
  [Freitag et al., 2021, Malmodin and Lundén, 2018, Andrae and Edler, 2015, SG Andrae, 2020, Belkhir and Elmeligi, 2018, Bordage, 2019]
- Latest ref: 1.4% of GHG emissions (764 MtCO2eq) for ICT, 118 MtCO2eq for mobile networks in 2020 with an increasing trend since 2015 (+5%) [Malmodin et al., 2024]
- In France: ICT represents 2.5% of the carbon footprint with a trend of +2 to +4%/y [ADEME/ARCEP, 2022].

Context: ICT footprint

Breakdown of the ICT footprint

%	Energy	GHG	Water	Elec.	ADP
User equipment	60%	63%	83%	44%	75%
Network	23%	22%	9%	32%	16%
Data centres	17%	15%	7%	24%	8%

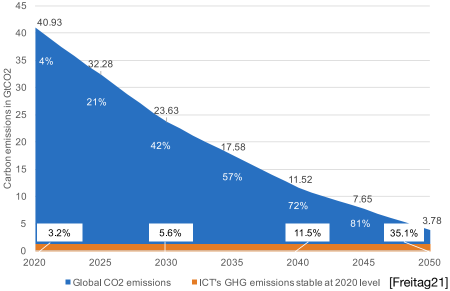
Breakdown of impact of the digital world in 2019 [GreenIT.fr]

GHG balance	Manufacturing	Use	Total
User equipment	40%	26%	66%
Networks	3%	17%	19%
Data centres	1%	14%	15%
	44%	56%	

Greenhouse gas emissions balance 2019 [GreenIT.fr]

- Shares vary according to the sources.
- Most impactful sources: 1) manufacturing of user devices, 2) power consumption of user devices, 3) power consumption of networks, 4) power consumption of data centers, 5) manufacturing of network elements, 6) manufacturing of data centers

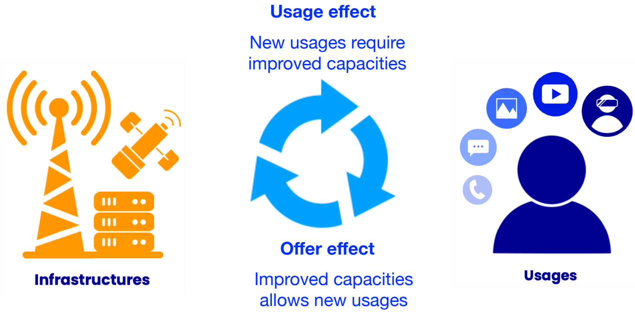
Context: ICT footprint



- ICT emissions assuming the 2020 level remains stable and global CO_2 emissions reduced in line with 1.5°C under scenario SSP2-19 (shares are wrt 2010).
- To be in line with other parts of the economy: ICT should reduce emissions by 42% in 2030, 72% in 2040 and net zero in 2050 [Freitag et al., 2021].
- ITU has proposed a target of -45% in 2030 wrt 2020 [SBTI, 2020].

Context: Digital infrastructures

Usages and infrastructures reinforce each other. ICT is a catalyst that allows to optimize, accelerate, streamline activities.



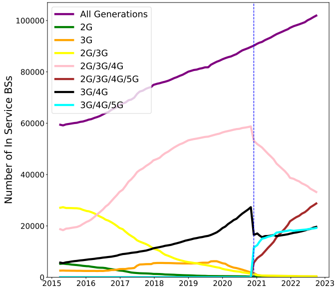
$\Rightarrow$ The decisions we take today will have an impact for years.

Context: Mobile networks

Mobile networks in France:

- Huge energy efficiency gains have at least been compensated by the increase in data traffic (see also [Lange et al., 2020, Bol et al., 2021]).
- Huge growth of mobile data: +62% every year since 2012.
- +6%/y of electricity consumption bw 2017 and 2021 (4 operators)
- A steady increase of the number of base stations [Ahmed and Coupechoux, 2023]

⇒ An unsustainable trajectory that needs to be reversed



Outline

Overall Approach: Trend-based vs Consequential

Trend-based approach:

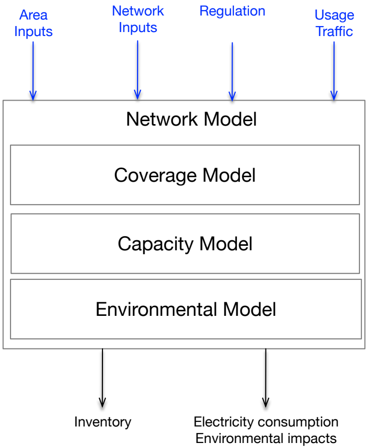
- Starts with global figures of traffic (GB) and electricity consumption (kWh)
- Builds ratios using an *attributional* methodology, e.g. kWh/GB
- Uses forecast traffic to extrapolate
- Adopted e.g. in [Ferreboeuf et al., 2021]

Consequential approach:

- Studies the impact of decisions on deployments
- Similar to consequential LCA [Schaubroeck et al., 2021]: What is the impact of one additional consumed or produced unit? What is the consequence of a decision?
- Adopted in [Stobbe et al., 2023] for Germany

⇒ We consider a generic operator and simulate its deployment strategy over time using a consequential approach

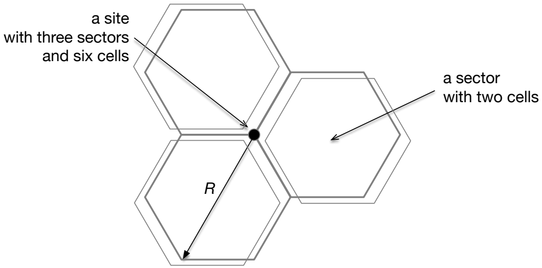
Overall Approach



Network Model: Operators, Tech, Spectrum

- 4 identical mobile operators
- 3 technologies: 4G, 5G, 6G
  Note: 2G, 3G will be decommissioned in the coming years and 4G is present on almost all sites since 2023
- 4 frequency bands:
  - LOW: 700-800-900 MHz
  - LOWER_MID: 1800-2100-2600 MHz
  - UPPER_MID: 3.5-6 GHz
  - HIGH: mmW
- Bandwidths are averaged over operators allocations in 2024
- Refarming possible in LOW and LOWER_MID

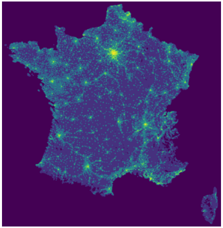
Network Model: Sites and Cells



- A site = a geographical location (can be shared by several operators)
- A base station = transmission/reception equipment for a single operator, characterized by an avg number of sectors
- A cell = a couple (techno,band) deployed over a sector, characterized by a cell range in the LOW band and a cell capacity
- Specific cells: small mmW cells, cells deployed along the main roads

Coverage Model

Territory characteristics:

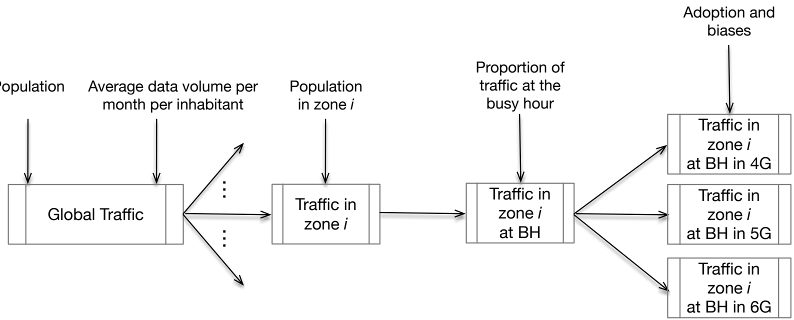


- Metropolitan France is divided into 8 geographical zones: EMPTY, RURAL_1, RURAL_2, RURAL_3, PERI_URBAN_1, PERI_URBAN_2, URBAN_1, URBAN_2
- Zones are supposed to be homogeneous
- Metropolitan french population increases linearly

Coverage constraints:

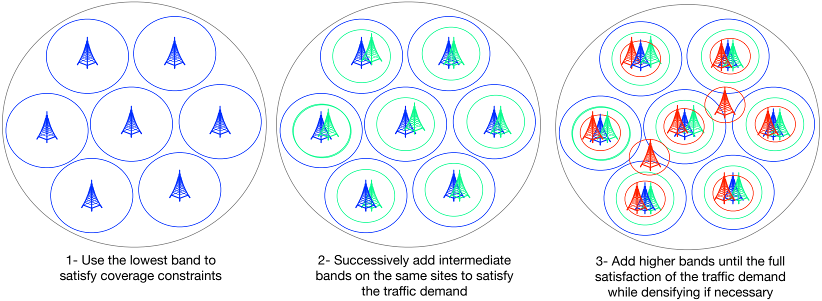
- percentage of covered area and population ⇒ use LOW band
- regulation: number of 5G UPPER_MID sites
- regulation: balanced deployment of 5G UPPER_MID sites bw urban and rural
- regulation: proportion of sites with LOWER_MID
- regulation: coverage of main roads and highways

Capacity Model: Traffic



- Adoption is estimated thanks to the number of unique SIM having access a technology (publicly available)
- We assume a bias in traffic volume for 5G and 6G users [Rizzato, 2020].

Capacity Model: Deployment Strategy



In every geographical zone, in increasing order of the technologies:

1) Remove traffic served by already deployed cells
2) Add cells of increasing band and technology in existing sites
3) Densify with the highest band

Refarming = optimize the bandwidth allocation to technologies

Capacity Model: mmW Small Cells

- mmW small cells are supposed to provide very high data rate in specific hot spots [Global5G.org, 2019] ⇒ focus on user experience
- It is not a coverage nor a capacity solution

⇒ We consider a ratio of 5G UPPER_MID macro cells in URBAN_1 and URBAN_2

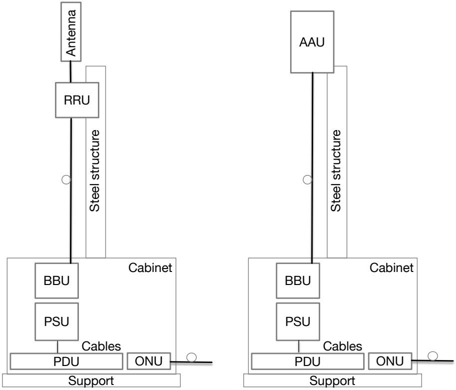
- The same approach has been adopted in [Haut Conseil pour le Climat, 2020], while [Stobbe et al., 2023] has a coverage target

Environmental Model

Main steps of the algorithm:

1) Make an inventory based on BS configurations
2) Compute the stock and flow of every equipment
3) Compute the energy consumption during the operational phase using models
4) Compute the embodied carbon footprint using the life duration of equipment

Environmental Model: Inventory



(a) LOW, LOWER_MID

(b) UPPER_MID, HIGH

- From these BS architectures and the number of deployed base stations, we are able to make an inventory of all equipment.

Environmental Model: Energy Consumption

- We adopt an affine model similar to the EARTH model [Auer et al., 2011] :

$$P_r^{(e)}(t) \quad = \quad P_{base}^{(e)}\eta^{(e)}(t) + N_{tx}^{(e)} P_{tx}^{(e)} \eta^{(e)}(t) + \ell_{e(b)}^{(i)}(t) \frac{P_{out}^{(e)}}{\eta_{PA}(t)(1-\sigma_{feed})}$$

- Cell load is derived from the capacity model
- Energy efficiency is accounted with a factor $\eta^{(e)}(t)$ per equipment

Environmental Model: Stock and Flows

There are two main approaches to account for the lifetime of equipment:

- Stock approach: embodied emissions of an equipment are amortized along its life duration $\Rightarrow$ shows a trend by smoothing the impact over the years
- Flow approach: the embodied emissions of new equipment (renewing of old equipment or newly deployed equipment) are fully imputed to the year of deployment $\Rightarrow$ shows dynamics of the investments

Dynamic stock-flow model:

$$I_e(t) = \Delta I_e(t) \cup \left(\cup_{t'=t_w}^{t} I_e(t')\theta_e(t-t') \right) \tag{1}$$

where $I_e(t)$ is the inventory at t, $\Delta I_e(t)$ is the new equipment and θ_e is the lifetime distribution (probability that the lifetime is more than $t - t'$)

Data

Where does the data come from?

- ARCEP, the french regulator for traffic data (history) and some cell characteristics.
- ANFR plans, manages and monitors the use of public radio frequencies in France. Provides a public data set of all equipment above 5W in France.
- "Grey" literature for traffic forecasts.
- Models, equipment data sheets, available open/published data for environmental data. In particular, [Stobbe et al., 2023, Madon, 2021] for carbon footprints.
- Electric mix: 60 gCO2e/kWh in 2020 to 34 gCO2e/kWh in 2035 [Comité d'experts techniques sur les réseaux mobiles, 2022].
- Energy efficiency: +3 % every 3 years [Stobbe et al., 2023].
- Still missing values: set based on experience.

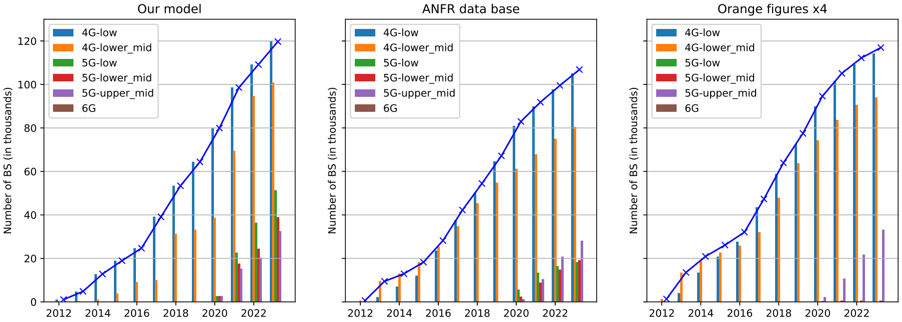
⇒ We need open data!

Outline

Reference Scenario

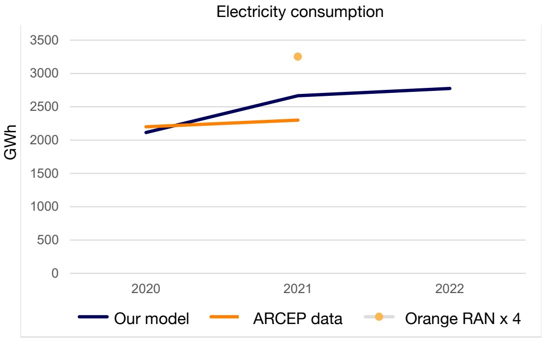
- Low band coverage targets
- Regulatory constraints:
  - Number of UPPER_MID 5G sites
  - Homogeneous deployment of UPPER_MID 5G
  - Main roads and highways coverage
  - Theoretical maximum download data rate of 240 Mbit/s for 100% of sites in 2030
- 6G deployment in 2030
- Stable network sharing as in 2024
- Traffic assumption: historical data (ARCEP) up to 2023 [ARCEP, 2024b], Arthur D Little (ADL) projections until 2030 [Jakopin et al., 2023], linear extrapolation until 2035.

Validation



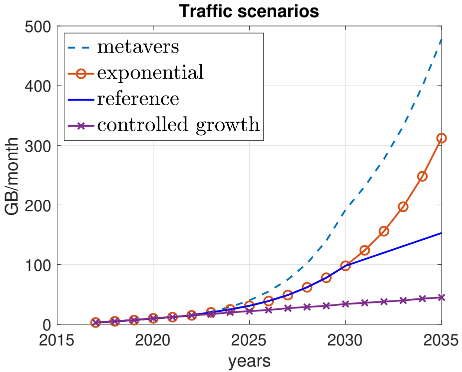
- Same order of magnitude, similar to Orange (slightly above at the end of the period).
- 2012-2017: our model deploys less 4G LOWER_MID because we favor LOW and introduce LM only for capacity reasons.
- The exact distribution of BSs depends on the operator strategy

Validation



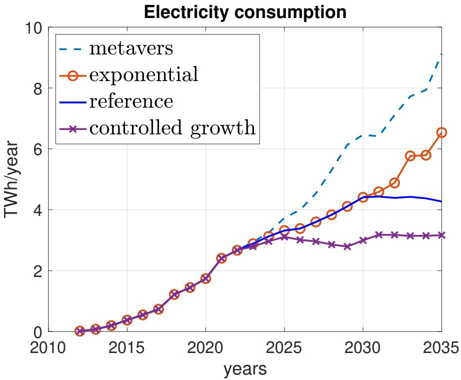
- We compare to ARCEP aggregate data [ARCEP, 2024a] and to Orange RAN [Rouphael et al., 2023].
- Same order of magnitude: between average and Orange.
- Differences due to various approximations and discretizations.

Traffic Assumptions



- `reference`: ARCEP (hist) + ADL (2024-2030) + linear (2031-2035)
- `metavers`: The Shift Project, Gartner, Ericsson [Buquicchio et al., 2024a]
- `exponential`: ARCEP + ADL + exp
- `controlled growth`: ARCEP + linear

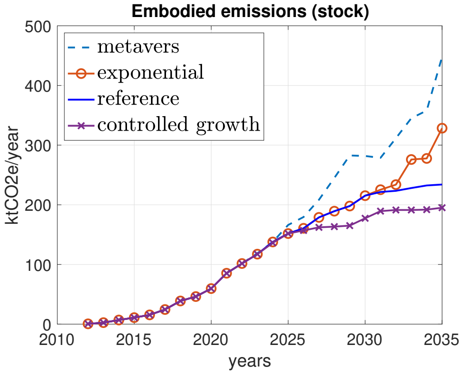
Electricity Consumption



- `reference`: $\times 1.5$, i.e. $+2.5$ TWh in 2030 wrt 2020, benefits from energy efficiency gains after 2030.
- `controlled growth`: benefits from low traffic increase and energy efficiency gains.
- `exponential`: $+2$ TWh wrt `reference`.

$\Rightarrow$ The traffic evolution plays a crucial role

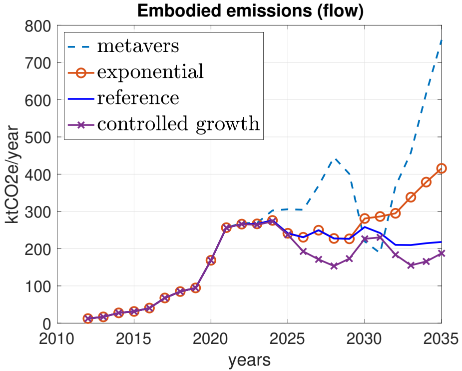
Embodied Emissions (stock)



- `reference`: $\times 2.5$ annual carbon footprint wrt 2020.
- `controlled growth`: suffers from regulatory constraints and 6G deployment.
- The traffic increase requires the deployment of new sites. Old sites should also be renewed.

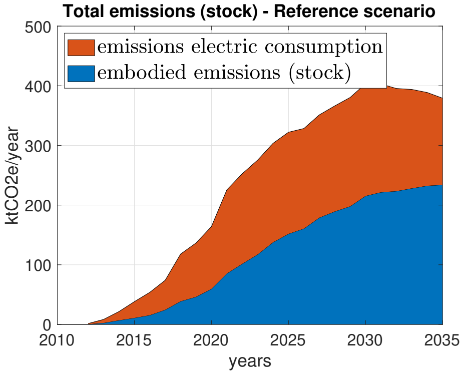
$\Rightarrow$ The decisions taken today have an impact during ten years.

Embodied Emissions (flow)



- The flow approach is less smooth and reflects year by year investments.
- There have been a massive deployment since 2020 for 5G.
- It is expected to have a peak for 6G around 2030.
- The flow of emissions is maintained due to post-2025 regulatory constraints.

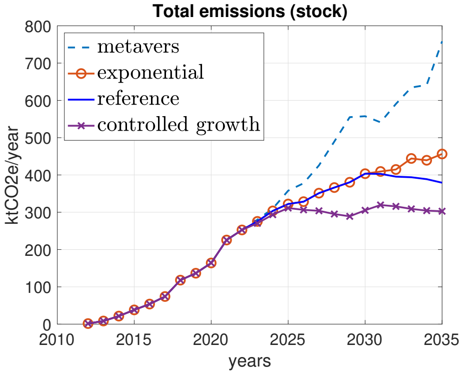
Total Emissions (stock)



- The proportion due to usage is higher except in the last period where manufacturing is dominant (due to energy efficiency gains).

⇒ We are above literature in terms of share of the embodied emissions [Malmodin et al., 2024]

Total Emissions (stock)



- Generalizing the metavers is not sustainable at all.
- Total emissions can be stabilize only if the traffic growth is controlled.
- `reference`: the slow down after 2030 due to energy efficiency is not compatible with the targets.

⇒ It will be probably required to control the traffic growth.

Eco-design and Frugality Scenarios

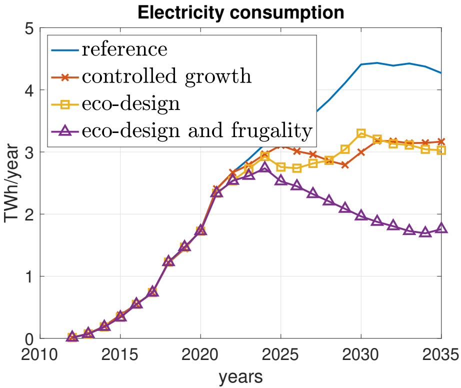
`eco-design`:

- Coverage ensured only with LOW bands
- Freeze 5G regulatory constraints in 2024
- Suspend the roll out of 6G
- Extend lifetimes of equipment (+2y)
- Improve energy efficiency of network equipment
- Reduction of traffic volumes thanks to e.g. most efficient codecs (`ref` – 20%)

`eco-design and frugality`:

- Eco-design +
- Average data consumption per person continues to increase but according to a linear dynamic to reach 45 GB/month/person in 2035 (vs 20 GB in 2024).
- Combines eco-design levers, controlled traffic growth and suspension of regulatory constraints and 6G.

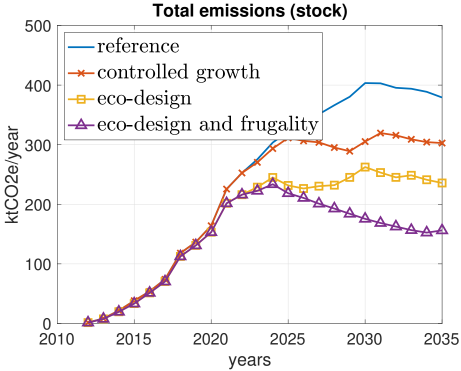
Eco-design and Frugality - Electricity



- `eco-design`: eco-design levers cannot on their own mitigate the effects of traffic growth, problems are probably only postponed.

$\Rightarrow$ `Only eco-design and frugality` allows to get back to 2020 level.

Eco-design and Frugality - Emissions



- By suspending the roll out of 6G, freezing regulatory constraints and extending lifetimes, `eco-design` makes better than `controlled growth`.
- `Again, only eco-design and frugality` allows to get back to 2020 levels.

Outline

Conclusion and Recommendations

An observation:

- ICT is not only about virtual, it's very concrete: antennas, routers, e-waste, etc.
- ITU recommends -45% carbon footprint in 2030 wrt 2020.
- Metavers/6G promises are taken seriously at french and european level but lead to an exploding impact.

$\Rightarrow$ Obviously we are not on the right track.

Possible recommendations:

- Eco-design: increase equipment lifetime, focus new technologies on energy efficiency, use carbon criteria, open data, use lower quality codecs by defaults, etc.
- Sharing: support infrastructure sharing among operators.
- Frugality: Make any increase in traffic or network infrastructure performance conditional on compliance with the trajectory for reducing the network's carbon-energy impact, focused deployment of 5G, make the reduction of the absolute environmental impact of networks a key criterion in the specifications for 6G, etc.

Thank you for your attention!

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