"Assessing the ICT and Internet Carbon Footprint"

I3S Lab, G. Urvoy-Keller, L. Deneire

Is it an important problem ?

We can break the initial question into two parts :

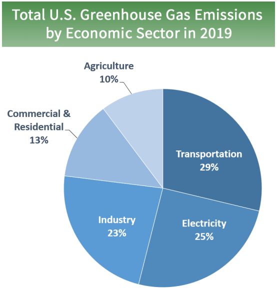
- Which fraction of the international/national carbon footprint does ICT/Internet represent ?
- How is it going to evolve given our addiction to ICT technology ?

US global footprint

Dominating factors [1] :

1. Transportation
2. Electricity : "Approximately 62 percent of our electricity comes from burning fossil fuels, mostly coal and natural gas"
3. Industry

Do you see ICT/Internet ? Be careful as a lot of sectors has been digitalized



1. Source EPA (Environmental Protection Agency) - https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

US global footprint

In absolute terms

Total Emissions in 2019 = 6,558 Million Metric Tons of CO2 equivalent.

- "CO2 equivalent" : remember that it is not always CO2 that is produced
- E.g. cows produce methane during their digestive process or air conditioning can release (leakage) gas

Properties of Methane

Chemical Formula: CH_4

Lifetime in Atmosphere: 12 years

Global Warming Potential (100-year): 25[1]

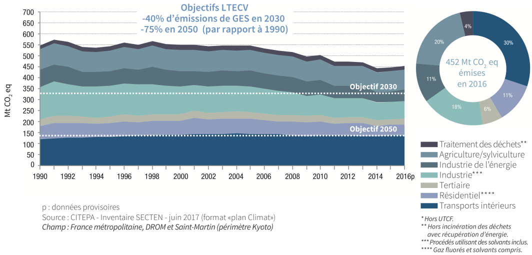
What about France ?

1. Transportation (30%)
2. Agriculture (20%)
3. Industry (18%)

There is a trick for Energy ! ☺ 

https://www.edf.fr/groupe-edf/espaces-dedies/l-energie-de-a-a-z/tout-sur-l-energie/produire-de-l-electricite/qu-est-ce-que-l-energie-nucleaire

A5. Émissions totales de GES par secteur *

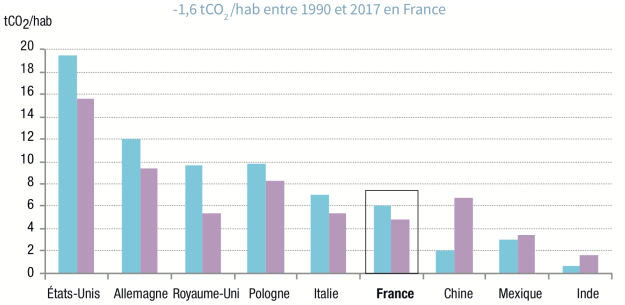


https://librairie.ademe.fr/changement-climatique-et-energie/1725-climat-air-et-energie-9791029712005.html

If you want to compare countries

Dividing by the number of inhabitants sounds fair :

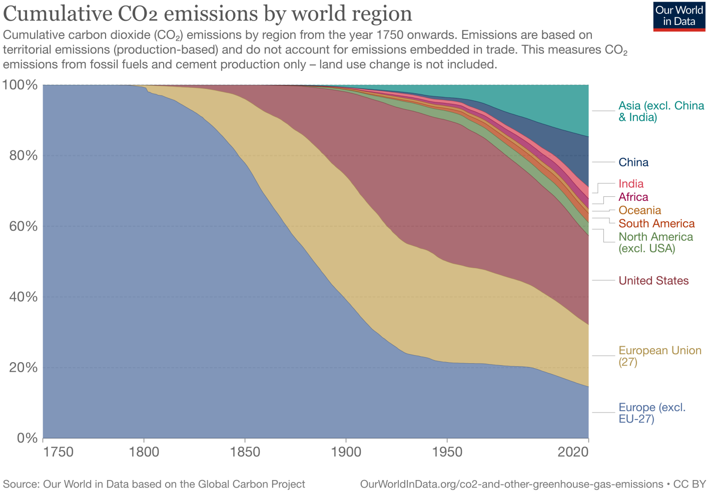
A2. Émissions directes de CO_2* par habitant dans le monde



** Émissions de CO_2 liées à la combustion de l'énergie.*

Source : Enerdata - août 2018
Champ France : métropole

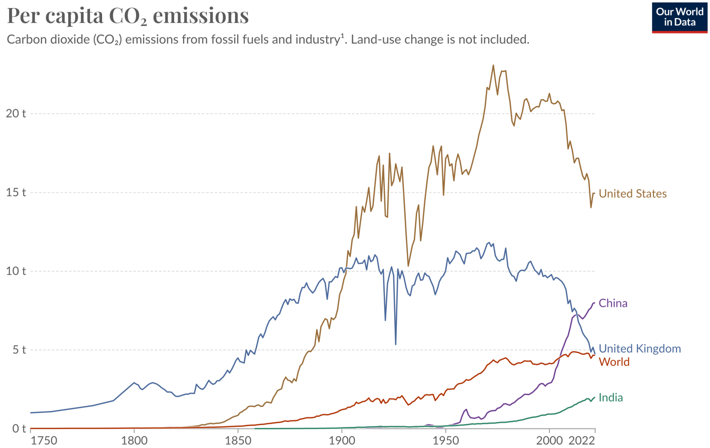
Annual GHG emissions vs. historical emissions



Per capita emissions

Per capita CO_2 emissions

Carbon dioxide (CO_2) emissions from fossil fuels and industry[1]. Land-use change is not included.



Data source: Global Carbon Budget (2023); Population based on various sources (2023)
OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

1. **Fossil emissions**: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Part 1 : Assessing the ICT Carbon Footprint

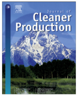
Reference 1

Journal of Cleaner Production 177 (2018) 448–463

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Assessing ICT global emissions footprint: Trends to 2040 & recommendations

Lotfi Belkhir*, Ahmed Elmeligi

W Booth School of Engineering Practice & Technology, McMaster University, Canada

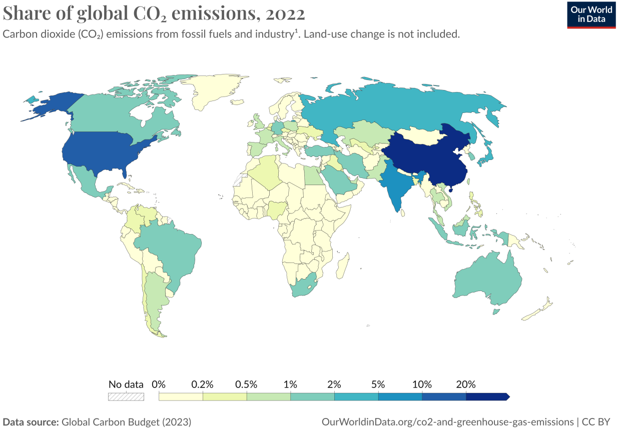
The paper in a nutshell

Key message

"ICT GHGE relative contribution could grow from roughly 1-1.6% in 2007 to exceed 14% of the 2016-level worldwide GHGE by 2040, accounting for more than half of the current relative contribution of the whole transportation sector [a]"

a. US centric style study – see previous slides

If ICT were a country ?



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https://ourworldindata.org/co2-emissions-metrics

Scope of study

Scope of Our Study

Computing Devices
- Desktops
- Notebooks
- LCD Displays
- CRT Displays
- Smart Phones
- Tablets

Data Centers
- Servers
- Communication
- Storage
- Cooling and power

Communication Networks
- Customer premises access equipment (CPAE)
- Office networks
- Telecom operator
- Cooling and power

All other ICT equipment is out of scope, including TV's, set-top boxes, and printers.

Quantities to estimate

- Production Energy (PE). Includes material extraction and manufacturing energy
- Useful Life (UL) of component, including any secondary use.
- Use Phase Energy (UPE) : average annual energy consumption

PE and UPE converted to their corresponding carbon footprint in kg of CO2-e using EPA tool :
`https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator`

Estimating the Useful Life(UL)

- They estimate UL from stocks and sales in 2007-2016
- Algo :
  - Denoting the Installed Base and Annual Shipments in year N as IB(N) and AS(N), and Useful Life as UL
  - We have a series of actual IB(N) and AS(N) for N ranging from 2007 to 2016.
  - Assume a seed value of UL to start with,
  - Calculate $IB_c(N+1) = IB_c(N)*(1-1/UL) + AS(N+1)$, where the "c" subscript of IB(N) denotes the calculated rather than the actual value.
  - Calculate the variance between the actual and the calculated IB(N+1) for each year in the known range
  - Solve for the UL that minimizes the total variance over the whole set of known values.
- Following (Williams, 2004a [2]), we use Lifecycle Annual Footprint (LAF) defined as :
  $LAF = UPE + PE/UL \rightarrow$ distribute production cost over lifetime
  ...except for DC as they consider long lifetime (?)

2. Ref in the paper

Desktop : PE, UPE, LAF

Table 2
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for desktops (not including display).

	Useful Life (years) (Williams, 2004a; Statista, 1975; Van Heddeghem et al., 2014; Curran et al., 2005; EPA, 2017)		Production Energy (kg CO_2-e) (Statista, 1975; Urban et al., 2014)		Use Phase Energy (kg CO_2-e/yr) (Williams, 2004b; Urban et al., 2014)		Lifecycle Annual Footprint (kg CO_2-e/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Home	5	7	218	628	93	116	124	241
Office	5	7	218	628	69	75	100	200

How do we obtain kg CO2-e ?

Use Phase Energy :

- Given in KWh
- Need to have initial energy used to produce 1kWh
- and then transform into e-CO2.

Use EPA Calculator and Conversions :

- https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
- https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

They used :

- 7MJ of initial energy to produce one KWh
- 0.5 kg CO2-e/KWh

Summary for all ICT devices

Table 9
Summary of key GHGE emissions data for all the devices constituting the scope of our data.

	Useful Life (years)		Production Energy (kg CO_2-e)		Use Phase Energy (kg CO_2-e/ yr)		Lifecycle Annual Footprint (kg CO_2-e/ yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Desktops Home	5	7	218	628	93	116	124	241
Desktop Office	5	7	218	628	69	75	100	200
Notebooks Home	5	7	281	468	27	35	67	129
Notebooks Office	5	7	281	468	20	23	60	117
CRT Displays	5	7	200	200	51	95	79	135
LCD Displays	5	7	95	95	23	43	37	62
Tablets	3	8	80	116	4.50	5.25	14.5	43.9
Smart Phones	2	2	40	80	4.50	5.25	24.5	45.3

Data centers and communication networks

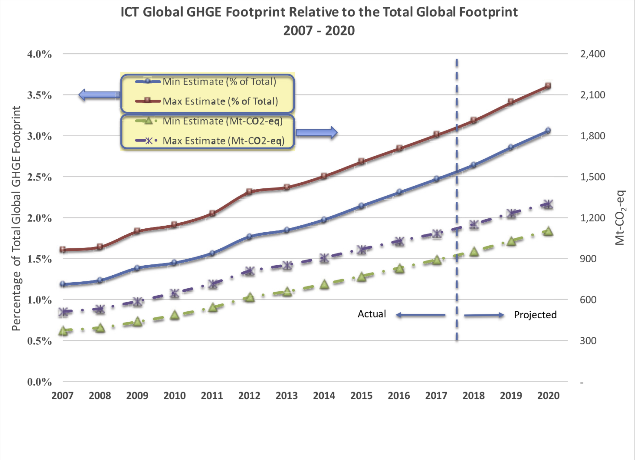
DC :

- Assume long lifetime and thus neglect PE
- Not unreasonable if we assume 24/7 basis for 3 to 10 years $\rightarrow$ PE $\approx$ 2 to 8% of total energy

Table 11
Annual energy consumption of data centers and communication networks in units of Mt−CO_2-e from 2007 to 2020. The dotted line marks the border between the estimated data from cited references from the projected data.

	Annual Energy Consumption (Mt−CO_2e/yr)	
	Data Centers (Vereecken et al., 2009; Chang et al., 2010; Technavio, 2014; Technavio, 2015)	Communication Networks (Van Heddeghem et al., 2014; Lambert et al., 2012; Pickavet et al., 2008b)
2007	113.4	101.5
2008	127.0	114.0
2009	142.3	127.0
2010	159.3	138.0
2011	178.5	152.0
2012	199.9	167.0
2013	223.9	178.6
2014	250.7	191.5
2015	280.8	204.4
2016	314.5	217.4
2017	352.2	230.3
2018	394.5	243.2
2019	441.8	256.1
2020	494.9	269.1

Results 2007-2020



3 to 4% of total worldwide emission by 2020→ Non negligible

Results 2007-2020

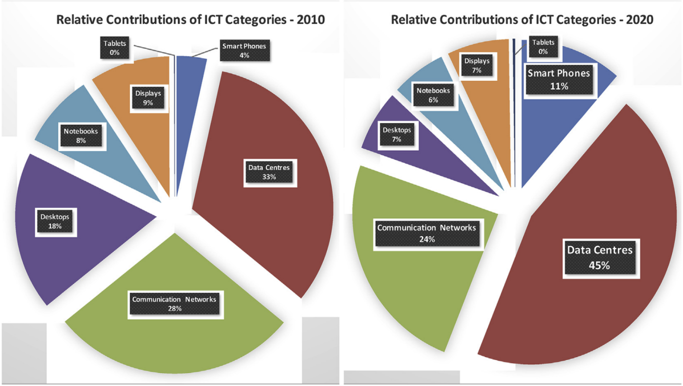


Fig. 6. (a)Relative contribution of each ICT category in 2010. (b): Relative contribution of each ICT category in 2020.

Lion share for DC. Different from ADEME (!)

Results 2040

Linear or Exponential

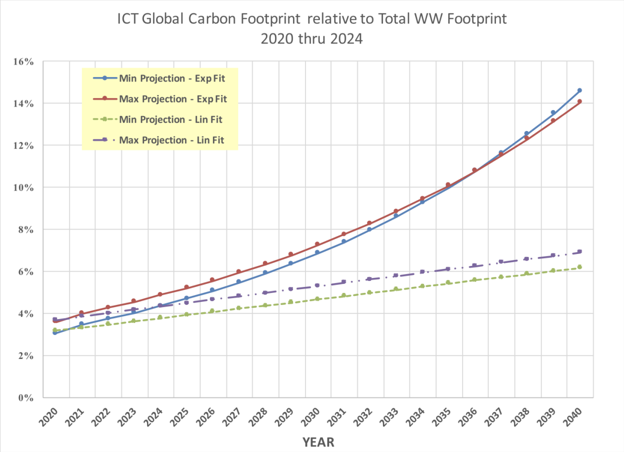


Fig. 7. ICT footprint as a percentage of total footprint projected through 2040 using both an exponential and linear fits.

- Why Linear or Exponential fit ?
  - Exponential seems more realistic from a sociological viewpoint...
  - ... but both seem to work (statistically speaking) given the 2007-2017 trends.
- Why does the min crosses the max curve for exponential fit ?
  $\rightarrow$ The two curves are fitted independently !
- Even the optimistic linear projection indicates a fraction of 6%
  $\rightarrow$ this is bad as all economic sectors should see their carbon footprint decrease !

Discussion

- Smartphone footprint increases at a high rate : 4% in 2010, 11% in 2020 or 17 MT-CO_2-e to 125 Mt-CO_2-e
- Smartphone key problem is lifetime : 80-95% of the impact is due to production
- *“[...]extending the use life of smart phones to 4 or more years. The latter however could face strong resistance from the phone manufacturers for whom the accelerated obsolescence of their cell phones is central to their business model.”* ☹

Reference 2 : Freitag et al.

Patterns

CellPress
OPEN ACCESS

Review

The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations

Charlotte Freitag,[1] Mike Berners-Lee,[1] Kelly Widdicks,[2,*] Bran Knowles,[2] Gordon S. Blair,[2] and Adrian Friday[2]
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https://doi.org/10.1016/j.patter.2021.100340

Meta-study : comparison of other works

Breakdown per tier

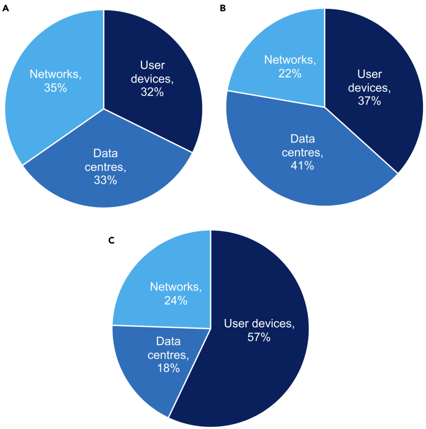


Figure 3. Proportional breakdown of ICT's carbon footprint, excluding TV
(A) Andrae and Edler (2015): 2020 best case (total of 623 $MtCO_2e$).
(B) Belkhir and Elmeligi (2018): 2020 average (total of 1,207 $MtCO_2e$).
(C). Malmodin (2020): 2020 estimate (total of 690 $MtCO_2e$).
Andrae and Edler's[3] best case is displayed because more recent analysis by the lead author suggest that this scenario is most realistic for 2020. Note that Malmodin's estimate of the share of user devices is highest; this is mostly because Malmodin's network and data center estimates are lower than those of the other studies.

Quite different from ADEME+ARCEP ? ? ?

Forecasts : a clear increase ! !

Reminder : global economy should decrease at -7% per year ! ! !

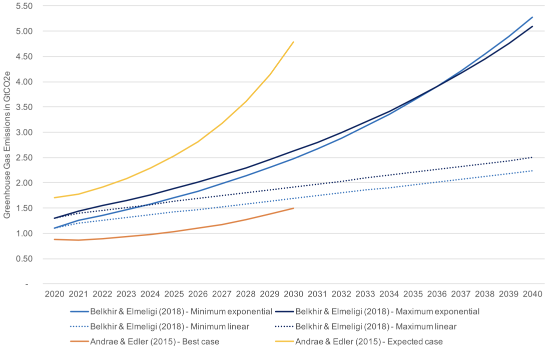


Figure 4. Projections of ICT's GHG emissions from 2020

(A) Andrae, (B) Belkhir, (C) Malmodin, personal communication. Belkhir and Elmeligi[7] judge their exponential scenario as most realistic, while the linear growth scenario is more conservative and reflects the impact of mitigating actions between now and 2040. Malmodin and Lundén[8,9] did not make concrete estimates beyond 2020, but Malmodin suggests that ICT's carbon footprint in 2020 could halve by 2030—offering a 2030 estimate of 365 $MtCO_2e$ in a recent techUK talk.[14]

Part 2 : Assessing the Internet Carbon Footprint

The mission ! ! !

- Objective : Assessing the carbon footprint of the Internet
- Open Questions :
  - Which boundary : from the cloud to the end user equipment ?
  - Usage ? Production ?
  - Carbon footprint of an infrastructure ? Of a service (e.g. a video conference) ?

References

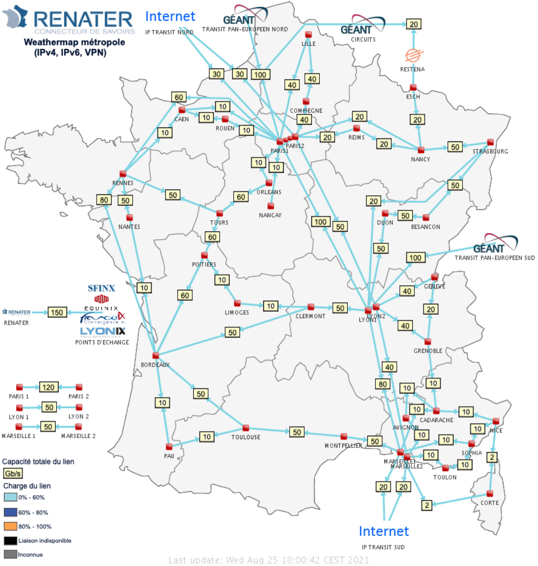
- Marion Ficher, Françoise Berthoud, Anne-Laure Ligozat, Patrick Sigonneau, Maxime Wisslé, Badis Tebbani : Assessing the carbon footprint of the data transmission on a backbone network. ICIN 2021 : 105-109
  - Recent study of French Internet research backbone provider
  - "Full" LCA : production+usage
  - eCO2 (equivalent CO2 emission rather than electricity consumption)
- Aslan, J., Mayers, K., Koomey, J. G., France, C. Electricity intensity of Internet data transmission : Untangling the estimates. Journal of Industrial Ecology 22.4 (2018) : 785-798.
  - Surveys a number of previous studies
  - Tries to unify them
  - Usage

Marion Ficher, Françoise Berthoud, Anne-Laure Ligozat, Patrick Sigonneau, Maxime Wisslé, Badis Tebbani :
Assessing the carbon footprint of the data transmission on a backbone network.
ICIN 2021 : 105-109

Objective

- " What are the greenhouse gas (GHG) emissions of transmitting 1 GB from A to B on the Renater French Research Backbone Network ?"
- Scenarios :
  - Peak day and off-peak day defined as week day and week-end day
  - One segment in a dense area (in Paris region)
  - One segment crossing France (Orsay - Montpellier)
- Methodology (with respect to Belkhir et al. paper) is direct measurement
- Focus on Production and Usage

Renater Network



Detailed Network Equipment List

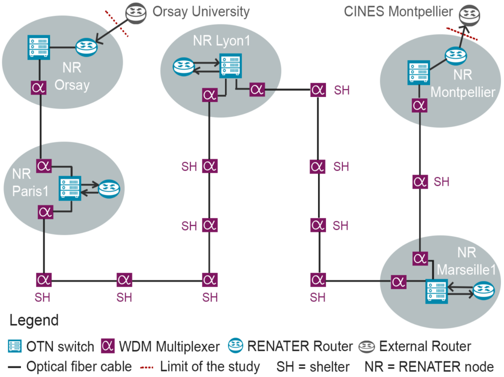


Fig. 1. Network model between Orsay and Montpellier

Equipments - Orsay-Paris

TABLE I
ORSAY-JUSSIEU SEGMENT DEVICES

Orsay-Jussieu segment (3 hops)		
Site	**Equipment**	**OS / Model**
Orsay	Router Cisco ASR 9910	IOS-XR 6.6.3
	WDM Multiplexer Infinera	mTera
	OTN Switch Infinera	Hit 7300
Paris1	Router Juniper MX2010	JunOS 18.4R1.8
	WDM Multiplexer Infinera	mTera
	OTN Switch Infinera	Hit 7300
Jussieu	Router Cisco ASR 9910	IOS-XR 6.6.3
	WDM Multiplexer Infinera	mTera
	OTN Switch Infinera	Hit 7300

Equipments - Orsay-Montpellier

TABLE II
ORSAY-MONTPELLIER SEGMENT DEVICES

Orsay-Montpellier segment (5 hops)		
Site	**Equipment**	**OS / Model**
Orsay	Router Cisco ASR 9910	IOS-XR 6.6.3
	WDM Multiplexer Infinera	mTera
	OTN Switch Infinera	Hit 7300
Paris1	Router Juniper MX2010	JunOS 18.4R1.8
	WDM Multiplexer Infinera	mTera
	WDM Multiplexer Infinera	Hit 7300
	OTN Switch Infinera	Hit 7300
Lyon1	Router Juniper MX2010	JunOS 18.4R1.8
	WDM Multiplexer Infinera	mTera
	WDM Multiplexer Infinera	Hit 7300
	OTN Switch Infinera	Hit 7300
Marseille1	Router Juniper MX2010	JunOS 18.4R1.8
	WDM Multiplexer Infinera	mTera
	WDM Multiplexer Infinera	Hit 7300
	OTN Switch Infinera	Hit 7300
Montpellier	Router Cisco ASR 9910	IOS-XR 6.6.3
	WDM Multiplexer Infinera	mTera
	OTN Switch Infinera	Hit 7300

Directly measured from devices on June 2020

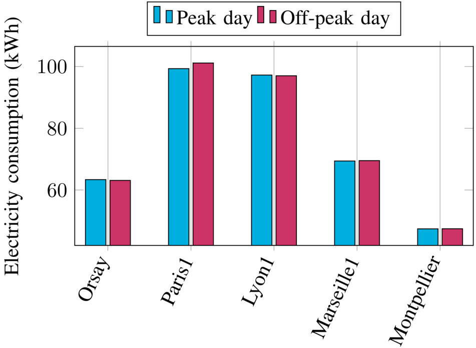


Fig. 3. Electricity consumption measured on Orsay-Montpellier segment during one day

IP traffic

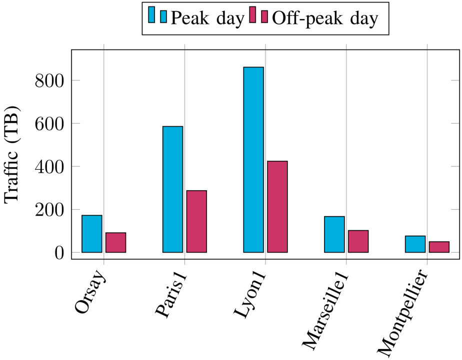


Fig. 2. Routers traffic measured on Orsay-Montpellier segment during one day

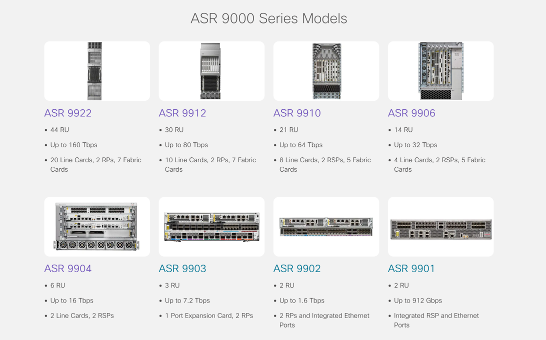
Overall :

- 0.007 kWh/GB for off-peak days
- 0.002 kWh/GB for peak days
- in line with previous paper (Aslan eta.) for 2020 estimate !

Let's scratch a bit our head

- Why peak day is “better” than off-peak day ?
  - Because energy consumption is **independent** from traffic for those devices
- but then why {Lyon1,Paris1,Marseille1} and {Orsay,Montpellier} do not feature the same electricity consumption as these are the same equipment in the two groups
  - Because of a different configuration : a different number of line cards

CISCO ASR Series (Renater = 9910)



Source : `https://www.cisco.com/c/en/us/products/routers/asr-9000-series-aggregation-services-routers/index.html#~models`

"Energy consumption independent from traffic?"

Is it good or bad ?

- Good : hardware so much optimized that it is independent from traffic.
- Bad : If base consumption is too high and traffic intensity often small, lack of efficiency.

Need to maximize traffic !

GHG impact assessment

NOC is the Network Operation Center

$$impact_{1GB} = \sum_{e \in E} (I_{production}(e) + I_{use}(e)) + I_{NOC} + I_{fiber}$$

GHG impact assessment

Assumptions :

- Power Usage Effectiveness (PUE) of the network sites is considered to be 1.8 (refer to Belkhir et al. paper)
- Routers lifetime : 10 years
- Optical devices : 12 years.
- Production impact : divide production cost by total number of estimated bytes over lifetime

$$I_{production} = \sum_{e \in E} \frac{I_{production}(e)}{T(e, 1\ year) \times L(e)}$$

- Production cost : from manufacturer or using ecodiag for the NOC that consists of servers mostly. `https://ecoinfo.cnrs.fr/ecodiag-calcul/`

Use Phase Energy - Devices

$$I_{use} = \sum_{e \in E} \frac{C(e,d) \times PUE(e)}{T(e,d)} \times EF \qquad (3)$$

with:

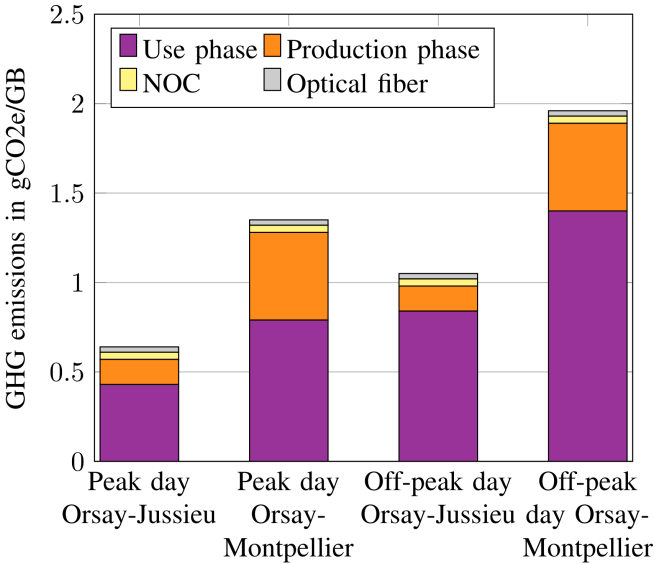
- d the duration considered (1 day or 1 year)
- $C(e,d)$ the energy consumption of equipment e for duration d, in kWh.
- $T(e,d)$ the traffic on equipment e during duration d, or supervised by equipment e in the case of NOC devices.
- PUE the PUE of the equipment datacenter when relevant, which was here actually considered a constant, as specified in III, and 1 otherwise.
- EF the emission factor of electricity for France, in kg CO_2e/kWh. We use EF = 0.108 kgCO2e/kWh from ELDC database.

$$I_{fiber} = \frac{EF_{fiber} \times \#km}{L_{fiber} \times T(total\ network,\ 1\ year)} \qquad (4)$$

with :

- EF_{fiber} the emission factor of the optical fiber in kgCO2e/km. We use EF_{fiber} = 1.27 kgCO2e/m from ACOME manufacturer for a cable with 96 fibers.
- L_{fiber} the lifetime of the optical fiber in years.
- $\#km$ the length of optical fiber on the network.
- $T(total\ network,\ 1\ year)$ the total traffic of the network during one year.

GHG impact assessment



GHG impact assessment

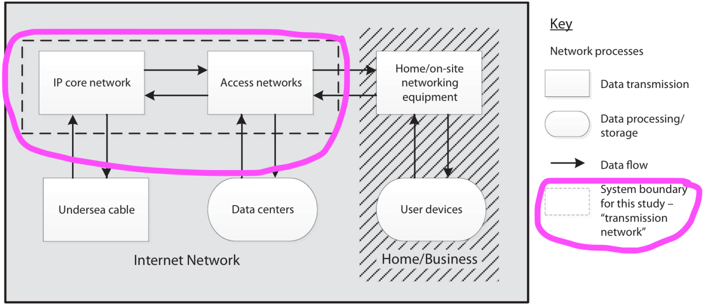
- Use phase dominates $\approx$ in line with Belkhir et al. who neglected production cost
  - But Belkhir et al. claimed 8% while it seems closer 20-25%
- Fibers and NOC negligible $\rightarrow$ mostly switches and routers that do electronic to signal conversions

Aslan, J., Mayers, K., Koomey, J. G., France, C.
Electricity intensity of Internet data transmission : Untangling the estimates.
Journal of Industrial Ecology 22.4 (2018) : 785-798.

Objective, methodology, key results

- Average electricity intensity of transmitting data through the Internet $\rightarrow$ focus on usage and not production
- Surveys 14 previous studies (2000-2016) :
- Existing estimates for 2000 to 2015, vary up to 5 orders of magnitude
  - from 136 kilowatt-hours (kWh)/GB in 2000 (Koomey et al. 2004)
  - to 0.004 kWh/GB in 2008 (Baliga et al. 2009)

Key finding : scope of study plays a role !



Across the 14 studies, 8 combination of subsystems – see Table 2 before

Key finding : Halving of intensity every 2 years.

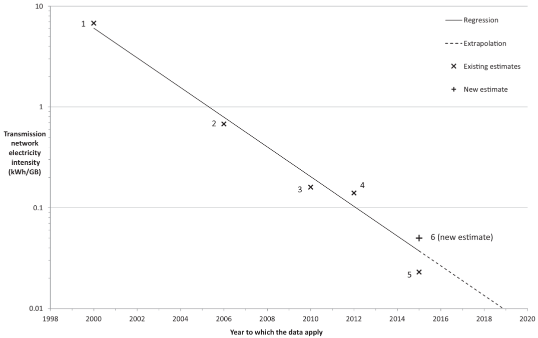


Figure 3 Graph to show estimates for electricity intensity for the transmission network system boundary only, identified from the criteria derived in this study. The y-axis shows the value of electricity intensity (kWh/GB) for each estimate; note the Log_{10} scale. The x-axis shows the year in which the data for each estimate is based. Regression uses average estimates for years in which a range is given and uses all data points on the graph from 2000 to 2015 (including our newly derived estimate for 2015). Data points: (1) median estimate of 6.5 to 7.1 kWh/GB derived from Taylor and Koomey (2008) estimates for the year 2000; (2) median estimate of 0.65 to 0.71 kWh/GB derived from Taylor and Koomey (2008) estimates for the year 2006; (3) estimate of 0.16 kWh/GB for 2010 derived from Malmodin and colleagues (2014); (4) estimate of 0.14 kWh/GB for 2012 derived from Krug and colleagues (2014); (5) Estimate of 0.023 kWh/GB from Malmodin and Lundén (2016); and (6) estimate of 0.06 kWh/GB for 2015 is a new estimate proposed in this study, based on Krug and colleagues (2014) with updated data for 2015 from Krug (2016). kWh/GB = kilowatt-hours per gigabyte.