Hypotheses for primary energy use, electricity use and CO₂ emissions of global computing and its shares of the total between 2020 and 2030

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Abstract: - There is no doubt that the economic and computing activity related to the digital sector will ramp up faster in the present decade than in the last. Moreover, computing infrastructure is one of three major drivers of new electricity use alongside future and current hydrogen production and battery electric vehicles charging. Here is proposed a trajectory in this decade for CO₂ emissions associated with this digitalization and its share of electricity and energy generation as a whole. The roadmap for major sources of primary energy and electricity and associated CO₂ emissions are projected and connected to the probable power use of the digital industry. The truncation error for manufacturing related CO₂ emissions may be 0.8 Gt or more indicating a larger share of manufacturing and absolute digital CO₂ emissions. While remaining at a moderate share of global CO₂ emissions (4-5%), the resulting digital CO₂ emissions will likely rise from 2020 to 2030. The opposite may only happen if the electricity used to run especially data centers and production plants is produced locally (next to the data centers and plants) from renewable sources and data intensity metrics grow slower than expected.

Key-Words: - carbon dioxide, data centers, electricity, devices, hydrogen, manufacturing, networks, primary energy, production, renewables, steel.

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1 Introduction

There are reasons to believe that global primary energy consumption (GPEC) will increase in this decade. For instance, U.S. Energy Information Administration (USEIA) estimates that GPEC will increase by 28% between 2015 and 2040 and that Coal, Oil, Gas will make up more than 75% of GPEC in 2040 [1]. USEIA also predicted that global energy-related CO₂ emissions will grow 0.6% per year from 2018 to 2050 [2]. In summary, the global demand of Coal, Oil, Gas is expected to grow towards 2050[3]. Here it is hypothesized that between 2020 and 2030 the global CO₂ emissions related to energy conversion increase >10% from ≈36 Gigatonnes (Gt) to ≈40 Gt, i.e. 1% per year. 1% is consistent with the growth rate for global energy related CO₂ emissions reported in [4] from 2007 to 2017.

The motivation for repeating the global energy situation is to put the entire digital sector (hypothetically having similar scale of power use as all kinds of computing/processing) into perspective being ≈3% of GPEC, ≈7% of global electricity use (GEU), and ≈5% of global CO₂ emissions.

Table 1 adapted from [5] shows potential trends of computing power and intensity. Computing intensity is here expressed in Zettainstructions per second which is a common metric for computing capacity [6]. Computing energy efficiency is commonly expressed in instructions per kWh [7]. Computing is assumingly a larger entity than the digital sector but should have similar magnitude as far as power use.

Table 1. Potential historical and future trends for computing and global power.

| Year | Zetta Instructions per second, ZIPs [5] | Gigainstructions per J, GIPJ [5] | GW average power for computing [IPS/IPJ] | GW average power for World (from Table 4) | Share computing |
|------|----------------------------------------|---------------------------------|-----------------------------------------|-------------------------------------------|----------------|
| 2030 | 2606                                   | 5121                            | 560                                     | 4103                                      | 14%            |
| 2029 | 1622                                   | 3297                            | 541                                     | 4023                                      | 13%            |
| 2028 | 941                                    | 2123                            | 487                                     | 3944                                      | 12%            |
| 2027 | 557                                    | 1367                            | 448                                     | 3866                                      | 12%            |
| 2026 | 343                                    | 880                             | 429                                     | 3791                                      | 11%            |
| 2025 | 215                                    | 567                             | 417                                     | 3716                                      | 11%            |
| 2024 | 104                                    | 365                             | 313                                     | 3643                                      | 9%             |
| 2023 | 61                                     | 235                             | 285                                     | 3572                                      | 8%             |
| 2022 | 35                                     | 151                             | 254                                     | 3502                                      | 7%             |
7% is not far from “conventional wisdom” concerning the current share of information processing and computing (excluding wireless and displays) [8] of GEU. Fig. 1 shows the graphical display of Table 1.

Fig. 1. Computing power trends in relation to global power consumption 2010 to 2030.

The digital sector and its infrastructure - belonging to every activity of daily life - cannot easily be compared to other sectors. Moreover, different nations and different companies have totally different starting points regarding electric power infrastructure, growth of gross national product and nature of business growth. The current share – and future evolution - of direct renewable electricity supply – beyond the local mix - to all global data centers and networks is not clear. In 2020 the share is assumed to be close to zero. When considering CO2 emissions created by computing, the locally used grid mix is a significant factor [12][13]. Global e-Sustainability Initiative (GeSI) estimated that energy use related CO2 emissions by the Information and Communication Technology (ICT) sector was 0.8 Gt CO2 in 2019, rising to over 0.9 Gt in 2030 driven by the growth of the sector, especially by electricity use of the transmission networks [14]. The scope for ICT used by GeSI is not evident and likely the 2030 CO2 emissions will be higher than 0.9 Gt as shown in the present prediction. Furthermore, it is not clear how much the digital sector can influence the global emissions, anthropogenic and others. Similarly the Consumer Technology Association reported that 2% of their member companies released 0.792 Gt in 2017 increasing 3% from 2016 [15]. Claims are often made that the solution is that companies shall switch to renewables with no critical discussion on the relation to the development of the power industry. Still, some ICT companies promise that all of their data centers will use 100% renewable electricity before 2030. Such claims need further scrutiny. In this article some new points will be raised: the underestimation of the production of ICT Equipment, hypotheses regarding rising data center power and end-user devices use. Contrary to previous studies [16], the current hypothesis is that data centers will stand out as the drivers for power use and related CO2 emissions.

2 Problem Formulation

In the present research the hypothesis is that the probability is close to 100% that the CO2 emissions from computing and the digital sector will rise between 2020 and 2030.

3 Problem Solution

The proposed solution to test the hypothesis is to look for forecasts of GPEC and GEU and sources for each. Then derive the CO2 intensity for primary energy and electricity sources. Then summarize
forecasts for power use of the major entities of the computing sector. Then add all data into the life cycle assessment software tool SimaPro version 9.0.0.31 which facilitates logic connections between all parameters as well as uncertainty analysis with Monte Carlo simulation. At last test the probability of CO₂ reduction or increase by combining the CO₂ intensities with the energy and electricity uses of computing.

4 Global energy and electricity use from 2015 to 2030

The global energy forecasts of GPEC and GEU are done by several bodies with high validity, e.g. BP[4] and USEIA[2]. Here is summarized and analyzed numbers from BP. Energy, electricity and CO₂ emission forecasts and baselines will never be exact, but trend analyses could be more or less realistic. BPs statistics for energy, electricity and CO₂ seem to be one of the most realistic.

4.1 Global primary energy consumption

Table 2 shows sources for GPEC for 2015 [17] extrapolated to 2020 and 2030 [4]. The hypothesis used to design Table 2 is that the shares (%) for all sources - except “Other renewables” - are expected to grow until 2030 as between 2015 and 2018 and the total GPEC to grow 1.9% per year, consistent with [3]. Then the remaining share is allocated to “Other renewables”. “Other renewables” includes wind, solar, geothermal, biomass, tidal etc.

Table 2. Sources for global primary energy consumption (ExaJoule), 2015 according to BP Statistical Review of World Energy and assumptions for 2020 and 2030

| Source       | 2015 | 2020 | 2030 |
|--------------|------|------|------|
| Coal         | 158  | 158  | 156  |
| Oil          | 182  | 205  | 260  |
| Gas          | 132  | 143  | 169  |
| Nuclear      | 24   | 26   | 31   |
| Hydro        | 37   | 42   | 53   |
| Other renewables | 15  | 29   | 58   |
| TOTAL GPEC (EJ) | 548 | 602  | 727  |
| TOTAL CO₂ (Gt)   | 33.5 | 35.5 | 40.3 |

Table 2 suggests that Coal, Oil and Gas will stay at >80% of GPEC in this decade.

Table 3 shows typical CO₂ intensities assumed to be consistent with the global CO₂ emissions (see Table 2) and usages of Coal, Oil and Gas.

Table 3. CO₂ intensity for sources of primary energy (Gigatonnes/ExaJoule)

| Source       | 2020 | 2030 | Min | Max |
|--------------|------|------|-----|-----|
| Coal         | 0.095| 0.094| 0.096|
| Oil          | 0.064| 0.06 | 0.07|
| Gas          | 0.053| 0.05 | 0.056|

4.2 Global electricity – sources and trends

The hypothesis used to design Table 4 is that the share (%) for all sources - except “Other renewables” - are expected to grow until 2030 as between 2017 and 2018 and the total GEU to grow 2.5% per year. Then the remaining share is allocated to “Other renewables”. “Other renewables” includes wind, solar, geothermal, biomass, tidal etc. Toward 2050 solar power will likely increase rapidly and may provide 27% of GEU [3].

Table 4. Sources for global electricity use in 2017 and 2018 and assumptions for 2020 and 2030

| Source       | 2017[4] | 2018[4] | 2020 | 2030 |
|--------------|---------|---------|------|------|
| Coal         | 9806    | 10101   | 10450| 13098|
| Oil          | 870     | 803     | 772  | 671  |
| Gas          | 5953    | 6183    | 6432 | 8290 |
| Nuclear      | 2639    | 2701    | 2783 | 3417 |
| Hydro        | 4065    | 4193    | 4342 | 5466 |
| Other renewables | 2343 | 2634    | 2872 | 4454 |
| TOTAL GEU    | 25677   | 26615   | 27651| 35395|

Table 5 shows the CO₂ intensities for different sources which are assumed to be consistent with the
general understanding of current total global anthropogenic CO2 emissions from GEU sources.

Table 5. CO2 intensity for sources of electric power (million tonnes CO2/TWh) 2020 and 2030

| Source            | 2020 and 2030 , median | Min    | Max    |
|-------------------|------------------------|--------|--------|
| Coal              | 0.98                   | 0.67   | 1.19   |
| Oil               | 0.89                   | 0.82   | 0.97   |
| Gas               | 0.65                   | 0.56   | 0.79   |
| Nuclear           | 0.008                  | 0.006  | 0.01   |
| Hydro             | 0.006                  | 0.003  | 0.009  |
| Other renewables  | 0.010                  | 0.009  |        |
| Average global CO2 intensity 2020 | 0.543±0.084 |        |        |
| Average global CO2 intensity 2030 | 0.534±0.082 |        |        |

Tables 2 to 5 show that Coal electricity will rise from 28% of total CO2 emissions in 2020 to 32% in 2030.

5 Digital sector latest prediction

Given the hypotheses for global energy and electricity forecasts for this decade mentioned in section 4, how likely is it that the digital industry will be able to reduce “its own” CO2 emissions?

5.1 Data centers use

Data centers – now using around 33 GW - are of large interest as they might use much more power (≈89 GW) in this decade than in the last. Likely, both bottom-up and top-down approaches are required to understand the trends of data center electricity use in this decade. There are some circumstantial evidence that we are heading for much higher global Wattage from computing in the next decade. A recent study[16]–stated161 TWh in China alone from data centers in 2018 -suggests that the global data center electricity use is running along the expected case in[18]. As a result, globally, data centers could possibly have used 400 TWh in 2018. Moreover, the current data center networks using individual fibers are costly, bulky, hard to manage, and not scalable[19]. Also, a new hypothesis is that servers currently deliver only around 30% of their nominal electrical efficiency improvements as reduced electricity costs and carbon emissions [20]. Moreover, between 2010 and 2020 Germany’s data center electricity use grew 3% per year from 10.5 to 14.3 TWh, and 16.4 TWh is predicted for 2025[21]. Scaling Germany’s data center intensityper capita to theglobal population estimate in 2030[22]leads to >2000 TWh for global data centers in 2030. Furthermore, if in 2030 there will be around 800-1000 massive hyperscale data centers (each with around 500 MW capacity) handling most of the Global data center IP traffic and they in 2030 run on average 300 MW (not unrealistic that a 500 MW center will use 60% of its full capacity in 2030) these data centers will use >2000 TWh. This suggests a certain massive growth for global data center electricity use as suggested by[5][16]. Still, the current hypothesisfor 2020 - based on updates of [16] -is that data centers will use around 294±5 TWh emitting 0.16±0.3 Gt CO2. In 2030 this is assumed to rise to 783±190 TWh emitting 0.42±0.12 Gt CO2. The effect of 50% of the data centersusing local renewable power in 2030 - and 50% global average macro grid power –is presented in in Section 6.

5.2 Mobile networks use

The mobile sector is generally waiting for 5G. Mobile networks power use may rise from 2020 (≈11GW) to 2030 (≈36GW) but still not at an alarming rateas the share of mobile networks of the whole digital sector will likely still be manageable by 2030. The currenthypothesis for 2020,based on updates of [16], is that mobile networkswill use around 98±2 TWh emitting 0.054±0.08 Gt CO2. In 2030 this is assumed to rise to 316±130 TWh emitting 0.14±0.06 Gt CO2. The effect of 50% of the mobile networks using local renewable power in 2030 - and 50% global average macro grid power –is presented in Section 6.

5.3 Optical networks use

The forecasts for this decade for fixed networks were heavily overestimated in [16]. The reason is that equipment swapping was not considered appropriately. Optical networks currently use ≈17GW, but that may rise to ≈32 GW in 2030.
The reason is that industry is indicating some concerns for energy efficiency [23]. For Wavelength Division Multiplexing (WDM) systems, the bitrate increase so far has been somewhat faster than the energy-efficiency increase. Therefore, foreseeable WDM generations tend to consume increasing power over time despite in the best case using less than 0.2 nanojoule/bit [23].

The current hypothesis for 2020 based on updates of [16] is that optical networks will use around 150±20 TWh emitting 0.083±0.02 Gt CO2.

In 2030 this is assumed to rise to 284±140 TWh emitting 0.15±0.06 Gt CO2.

The effect of 50% of the optical networks using local renewable power in 2030 - and 50% global average macro grid power –is presented in Section 6.

5.4 Devices use

Devices is a very diverse group of gadgets consisting of phones, portable computers, peripherals, smart home devices, Wi-Fi modems/gateways, and IoT devices. They may use ≈95 GW in 2020 and might decline to ≈89 GW in line with the most popular hypotheses saying that the group uses less and less power. The reason for the popular hypothesis is that a shift to power efficient tablets and smartphones –ins favour of laptops and desktops – reduces the overall power use more than the increased amounts of power efficient devices shipped and installed.

Here the Wi-Fi modems are moved from the Fixed Wired networks entity in [16] and added to this group. Fig. 2 and 3 show the reparation in 2020 and 2030, respectively.

Fig. 2. Shares for devices power use in 2020

The current hypothesis for 2020 based on updates of [16] is that devices will use around 830±200 TWh emitting 0.45±0.12 Gt CO2. In 2030 this is optimistically assumed to decrease to 760±320 TWh emitting 0.4±0.15 Gt CO2.

5.5 Manufacturing processes

Manufacturing of digital equipment will use around 34 GW in 2020 optimistically assumed to slow to ≈27 GW in 2030.

For 2015 it was recently estimated [24] that 1 Gt CO2 are emitted upstream for the production of digital devices including radio, television, communication equipment and apparatus as well as computers and office machinery. Thereby it includes not only the end-user digital devices, but also digital devices which end up in other user products like cars, buildings etc. 1 Gt CO2 per year is several times higher than other estimations of ICT hardware production in 2015 [16]. However, [25] also identified manufacturing as being underestimated, but not as much as [24]. Anyway, Das [26] estimated that IoT semiconductor manufacturing alone used 2 EJ in 2016 and will use 35 EJ in 2025. This means rising from around 0.3% to 5% of GPEC. Using Table 2, the related CO2 emissions would be ≈0.12 Gt (2 EJ×0.06 Gt/EJ) in 2016 and ≈1.9 Gt (35 EJ×0.055 Gt/EJ) in 2025, respectively. Such hypotheses are much in line with those trends presented in [24]. The current hypothesis for 2020 based on updates of [16] is that manufacturing will use around 300±50 TWh emitting 0.17±0.04 Gt CO2. This is 0.83 Gt less than [24] indicating that production electricity CO2 and other CO2 are much underestimated in [16]. In 2030 this is assumed to decline to 240±60 TWh emitting 0.13±0.03 Gt CO2. However, the uncertainty is huge if the findings in [24] and [26] are considered.
If including the production related “truncation error” from [24], the numbers for 2020 are 0.99±0.06 Gt and 0.95±0.05 Gt. If including the hypotheses and findings of Das[26], the “truncation error” for CO₂ emissions would be even higher.

### 6 Results

The main results are obtained by combining the CO₂ intensities in Table 5 with the TWh in Sections 5.1-5.5 for each sector for 2020 and 2030. SimaPro version 9.0.0.31 is used to obtain the uncertainty ranges. Table 6 shows the summary of digital sector CO₂ evolution and the share of the digital Sector of global CO₂ emissions.

Table 6: Approximate million tonnes CO₂ evolution from digital sectors

| Digital Sector          | Year 2020 | Year 2030 0% renewables |
|-------------------------|-----------|-------------------------|
| Data Centers use        | 160±25    | 420±120                 |
| Mobile networks use     | 54±13     | 170±60                  |
| Optical networks use    | 83±20     | 150±60                  |
| Devices use             | 460±110   | 410±150                 |
| Manufacturing processes | 1000±60   | 960±50                  |
| TOTAL (Gt) 0% renewables for Networks and Data Centers in 2020 | 1.76±0.17 | 2.11±0.3 |
| TOTAL (Gt) 5% renewables for Networks and Data Centers in 2030 | 2.08±0.3 |
| TOTAL (Gt) 50% renewables for Networks and Data Centers in 2030 | 1.76±0.35 |

Monte Carlo simulations in SimaPro version 9.0.0.31 - each with 100000 runs - show 3.89%, 4.28% and 18.1% probabilities that the CO₂ will emissions decrease between 2020 and 2030 in the 0%, 5% and 50% renewables scenarios, respectively. This means that the probability is 82% to 96% that CO₂ emissions from the digital sector will increase between 2020 and 2030. Fig. 4 shows a graph for the 0% renewable scenario resulting from the present simulation.
7 Discussion

Several authors in the fundamental semiconductor research area see problems and potential solutions to the increasing power use in computing.

7.1 Drivers and uncouplers

Obviously, Moore’s law does not hold anymore[27]. Still, Das argued that IoT semiconductor devices use stage power will sharply decline until 2025 [26]. Thylen [28] argued that nanophotonics is one of the solutions to the emerging energy per bit problem in data centers and optical networks. Further, material breakthroughs are necessary to change nanophotonics [28]. Moreover, it is very reasonable to assume that there will be several engineering tricks such as replacing

- electronic (de)serializers time division multiplexers with optical space division multiplexing,
- clock and data recovery by synchronizing photonic pulses[28]

However, much of these “tricks” may already have been implemented? Directly modulated low-cost vertical cavity surface emitting lasers (VCSELs) - used as optic links in datacom- use 56–510 fJ/bit[29]. If such efficiencies are comparable to “what it takes” on system level (=50 fJ/operation [5]) it is not all unreasonable that computing will have a reasonable power consumption in this decade. The discussion about implications of current switching energy (J/transistor) roadmaps is hugely important. It has been predicted[5] that even with PUE=1 that we are in need of a new switch or chip architecture. That is, predictions of electricity use per computation for the next decade is key as well as the implications of such predictions when combined with number of computations.

The projected global instructions per second (in CPUs and GPUs) – in 2030 is around 2.6 Yotta (2.6×10^{24}) instructions per second[6] and the instructions per Joule (Instructions per kWh[7]) in 2030 imply thousands of TWh (as shown in Table 1 and Fig.1) for computing in 2030[5]. The often cited formula from Koomey about computing energy efficiency[7], predicting Instructions/kWh may still hold validity[5], but it has not been confirmed lately. Industry is projecting that more and more W is needed per server to reach the required performance. Moreover, the FLOP/s/W for servers and computers are decreasing. Likewise are the operations per second per Watt decreasing. Operations per second per Watt is often used for data center energy performance [5]. More concerningly, the maximum heat fluxes (W/cm²) in commodity CPU / GPUs have been reached, the clock frequencies reached plateaus in the 2010s, and the Voltage reduction is slowing [30]. The relation between the manufacturing CO2 and the use stage CO2 for the whole digital sector has been assumed to be on average 25% manufacturing and 75% use[16]. Using 1 Gt CO2 per year for Manufacturing[24] would either render 4 Gt CO2 per year in total for the digital sector or a 50% share for Manufacturing. Anyway 1 Gt CO2 per year would add around 0.8 Gt CO2 per year, showing a tremendous underestimation of the sector in 2015. Such Gt CO2 per year would be close to worst case scenario of [16] for Production in 2020. Theremarkable hypotheses [26] of 35 EJ for IoT semiconductor manufacturing in 2025 also indicate that manufacturing/production could be largely underestimated in these kinds of CO2 predictions.

Table 7 shows some other TWh results for networks and data centers obtained from updating estimations for 2015 and 2020 [16] and using average of values from [5] for 2025 and 2030. These results are further developed in this article.

Table 7. Approximate TWh evolution from selected ICT Sectors

|                  | 2015 | 2020 | 2025 | 2030 |
|------------------|------|------|------|------|
| Mobile networks  | 152  | 136  | 286  | 700  |
| use stage        |      |      |      |      |
| Optical networks | 179  | 171  | 138  | 146  |
| use stage        |      |      |      |      |
| Data centers     | 220  | 207  | 469  | 799  |
| use stage        |      |      |      |      |

From Table 7 it could already be argued that the CO2 emissions for digital networks will not be reduced easily in the short-term if some global average energy mix is used.

Also there is a need for a better understanding of how everyday online practices are shifting[13]. Take self-driving cars in which 4 persons – which may include the “driver” - watch streamed 8K 4D videos hour after hour. Such business cases may add to the growing video traffic. Also epidemics and pandemics may lead to more video conferences and leisure streaming as a result of quarantine situations.
7.2 Renewables?

Buying renewables “somewhere else” leads to more renewables in the average macro grid mix which reduces CO\(_2\) emissions in the long-run. Hypothetically CO\(_2\) reduction in the short-term can be achieved by local renewable power production which feeds directly the needs of own of facilities and equipment.

As shown in Section 6, 50% local and direct renewable electricity supply to all global data centers and networks in 2030 does not likely (18% chance) reduce the digital sectors own, relatively small, CO\(_2\) emissions between 2020 and 2030.

7.3 Steel production with hydrogen – 10% of GEU in 2030?

In this section the additional electricity use and CO\(_2\) emissions of hydrogen production for steel production is estimated. The motivation is that Steel is an important material constituent also for computing equipment and the need to highlight potential new large electricity demands. In order to reduce the CO\(_2\) emissions from steel production, \(\approx 3.3\) Gt\[31\], it has been proposed to produce steel with hydrogen \[32\][33] instead of coke \[34\].

How much additional electricity would be required globally – and CO\(_2\) emitted - if all global steel would be produced with hydrogen reduction (2) instead of coke reduction (1)?

\[
\begin{align*}
2 \text{Fe}_2\text{O}_3 + 3 \text{C} &\rightarrow 4 \text{Fe} + 3 \text{CO}_2 \quad (1) \\
\text{Fe}_2\text{O}_3 + 3 \text{H}_2 &\rightarrow 2 \text{Fe} + 3 \text{H}_2\text{O} \quad (2)
\end{align*}
\]

In 2018, the total world crude steel production was 1808.6 million tonnes (Mt) and Sweden’s steel production was 4.7 Mt \[35\].

The emissions from steel production is 1.1 Gt CO\(_2\) per year according to (1): \(1.8 \times 10^{12}\) kg Fe\times0.59 kg CO\(_2\)/kg Fe. This shows that (1) is very crude and underestimate the actual CO\(_2\) emissions\[31\].

Anyway, according to (2), producing 1 kg Fe requires \(\approx 0.053\) kg H\(_2\). It takes around 36 kWh electricity to produce 1 kg H\(_2\)[36]. Accordingly, \(\approx 1.93\) kWh/kg Fe, and 3492 TWh \((1.8 \times 10^{12}\) kg Fe\times1.93 kWh/kg), i.e. almost 10% of GEU in 2030.

3492 TWh global annual electricity use derived from (2) would according to Table 5 emit \(\approx 1.85\) Gt CO\(_2\) per year. This represent a 68% increase compared to (1) but a 44% decrease compared to \[31\]. In Sweden, 9 extra TWh (\(\approx 5\) of Sweden electricity use \[3\]) – i.e. corresponding to one more 1000 MW nuclear reactor – will be required. Moreover, the global steel production may grow from 2018 to 2030. The CO\(_2\) balance - using (1) and (2), effect of recycling, etc. - of current and future steel production is beyond the scope of this article. Also the effect on the digital sector and computing footprint of hydrogen production is excluded. The section suggests that the hydrogen economy will require much extra electricity. However, using hydrogen for steel production could make sense from a CO\(_2\) emission viewpoint.

8 Conclusion

The probability is between 82 and 96% that computing and the digital sector will increase its CO\(_2\) emissions between 2020 and 2030. However, at 4-5%, computing and digital emissions will remain a relatively small share of the total global in this decade.

9 Next steps

Obviously there are several assumptions which should be revisited. For instance, it is not self-evident that the overall power used by devices in homes will decline in this decade. The potential effect of waning Moore’s law for the use stage of such consumer devices is only included broadly in \[5\]. However, this effect was neglected by frameworks such as those used by \[16\] and \[25\]. The framework used by \[21\] for end-user devices may include this effect. More global estimations of instructions and operations – and measurements of J/operation - are required to substantially move this field forward. The degree to which home-owners will be able to produce own renewable power, which can run their digital devices, could also be investigated.

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