Hypotheses for primary energy use, electricity use and CO_2 emissions of global computing and its shares of the total between 2020 and 2030

ANDERS S.G. ANDRAE
Huawei Technologies Sweden AB
Skalholtsgatan 9, 16494 Kista
SWEDEN
anders.andrae@huawei.com

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 alongsidefuture and current hydrogen production and battery electric vehicles charging. Here is proposed a trajectory in this decade for CO_2 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 CO_2 emissions areprojected and connected to the probable power use of the digital industry. The truncation error for manufacturing related CO_2 emissions may be 0.8 Gt or more indicating a larger share of manufacturing and absolute digital CO_2 emissions.While remaining at a moderate share of global CO_2 emissions (4-5%), the resulting digital CO_2 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.

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 CO_2 emissions will grow 0.6% per year from 2018 to 2050 [2]. In summary, the global demand of Coal, Oil, Gas is expected togrow towards 2050[3]. Here it is hypothesized that between 2020 and 2030 the global CO_2 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 CO_2 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 asall kinds of computing/processing) into perspective being ≈3% of GPEC, ≈7% of global electricity use (GEU), and ≈5% of global CO_2 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%

2021	22	97	248	3433	7%
2020	13	63	233	3366	7%
2019	8.4	40	230	3300	7%
2018	5.4	26	227	3235	7%
2017	3.4	17	224	3172	7%
2016	2.2	11	222	3110	7%
2015	1.4	6.9	217	3049	7%
2014	0.8	4.5	196	2989	7%
2013	0.5	2.9	197	2930	7%
2012	0.3	1.9	197	2873	7%
2011	0.2	1.2	179	2817	6%
2010	0.1	0.8	146	2761	5%

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.

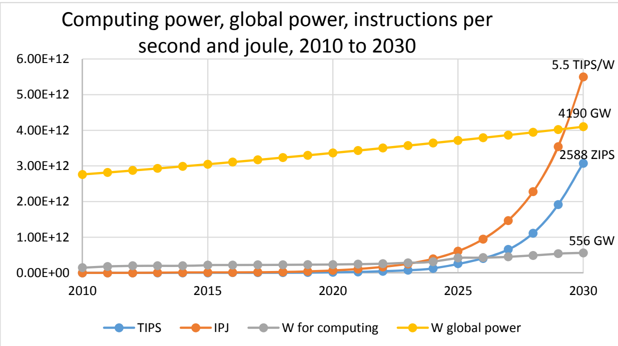

Fig. 1. Computing power trends in relation to global power consumption 2010 to 2030.

The globalconsumption by fuel shows that Coal, Oil and Gas totally dominate occupying>80% of the GPEC and >60% of the GEU[4]. Such non-intermittent and easily accessible fuels are currently the basis for societies moving away from poverty as they provide power independently of the weather. Anyway, hydro and nuclear have a big importance in some nations. It seems very difficult to quickly – in a few decades - stop the use of Coal, Oil and Gas considering current ways of food production, heating and air conditioning. Nuclear seems to be an effective and efficient way of reducing CO_2 emissions, especially if the spent fuel can be reused as in Gen IV nuclear power systems[9][10]. Solar power will be important when the large-scale charging capacity is solved.Sun's energy supply to Earth is ≈23000 TW[11], andcurrent GPEC, ≈167000 TWh, is thereforetheoretically covered by the Sun in just 8 hours.

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 CO_2 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 CO_2 emissions by the Information and Communication Technology (ICT) sector was 0.8 Gt CO_2 in 2019, rising to over 0.9Gt 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 CO_2 emissions will be higher than 0.9Gt 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 beraised: 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 use stage and upstream manufacturing will stand out as the drivers for power use and related CO_2 emissions.

2 Problem Formulation

In the present research the hypothesis is that the probability is close to 100% that the CO_2emissions 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 forforecasts of GPEC and GEU and sources for each. Then derive the CO_2 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 CO_2 reduction or increase by combining the CO_2 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 GEUare 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 CO_2 emission forecasts and baselines will never be exact, but trend analyses could be more or less realistic. BPs statistics for energy, electricity and CO_2 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

	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 CO_2 (Gt)	**33.5**	***35.5***	***40.3***
Global GPEC CO_2 intensity (Gt CO_2/EJ=kg/MJ)	**0.061**	***0.059***	***0.055***

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

Table 3 shows typical CO_2 intensities assumed to be consistent with the global CO_2 emissions (see Table 2) and usages of Coal, Oil and Gas.

Table 3. CO_2 intensity for sources of primary energy (Gigatonnes/ExaJoule)

	2020 and 2030, median	**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 GEUto 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 andassumptions for 2020 and 2030

	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
	25677	**26615**	**27651**	**35395**

Table 5 shows the CO_2 intensities for different sources which are assumed to be consistent with the general understanding of current total global anthropogenic CO_2 emissions from GEU sources.

Table 5. CO_2 intensity for sources of electric power (million tonnes CO_2/TWh) 2020 and 2030

	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 CO_2 intensity 2020	0.543±0.084		
Average global CO_2 intensity 2030	0.534±0.082		

Tables 2 to 5 show that Coal electricity will rise from 28% of total CO_2 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” CO_2 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 CO_2.
In 2030 this is assumed to rise to 783±190 TWh emitting 0.42±0.12 Gt CO_2.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) butstill 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 CO_2.
In 2030 this is assumed to rise to 316±130 TWh emitting 0.14±0.06 Gt CO_2. 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 CO_2.

In 2030 this is assumed to rise to 284±140 TWh emitting 0.15±0.06 Gt CO_2.

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.

5.4Devices 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 topower 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.

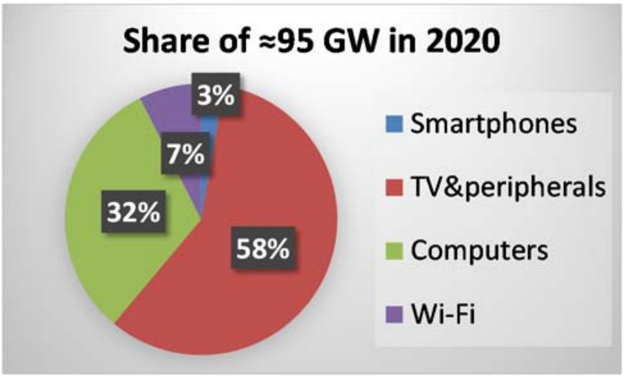

Fig. 2. Shares for devices power use in 2020

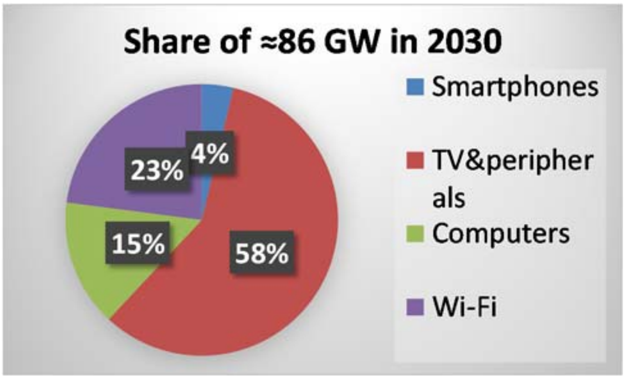

Fig. 3. Shares for devices power use in 2030

The current hypothesis for 2020 based on updates of [16] is that deviceswill use around 830±200 TWh emitting 0.45±0.12 Gt CO_2. In 2030 this is optimisticallyassumed to decrease to 760±320 TWh emitting 0.4±0.15 Gt CO_2.

5.5Manufacturing processes

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

For 2015 it was recently estimated[24] that 1 GtCO_2 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 GtCO_2 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 CO_2 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 CO_2.This is 0.83 Gt less than [24]indicating that production electricity $CO_2$and otherCO_2 are much underestimated in [16]. In 2030 this is assumed to decline to 240±60 TWh emitting 0.13±0.03 Gt CO_2.However, the uncertainty is hugeif 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 CO_2 emissions would be even higher.

6 Results

The main results are obtained by combining the CO_2 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 CO_2 evolution and the share of the digital Sector of global CO_2 emissions.

Table 6: Approximate million tonnes CO_2 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% renewable power for Networks and Data Centers in 2020	1.76±0.17	2.11±0.3
TOTAL (Gt) 5% renewable power for Networks and Data Centers in 2030		2.08±0.3
TOTAL (Gt) 50% renewable power for Networks and Data Centers in 2030		1.76±0.35
Share of Global CO_2 emissions, 0% renewables in 2020	4.7%	5.2%
Share of Global CO_2 emissions, 5% renewables in 2030		5.2%
Share of Global CO_2 emissions, 50% renewables in 2030		4.4%

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 CO_2will 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 CO_2 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.

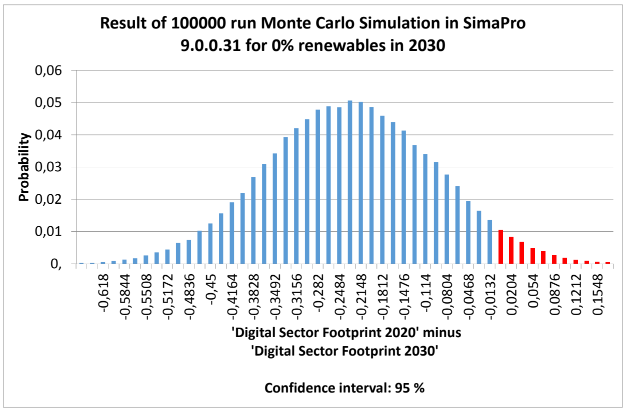

Fig. 4. Monte Carlo simulation result for probability of digital sector CO2 reduction between 2020 and 2030.

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 beenimplemented?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] andthe 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 Wattis often used for data center energy performance [5].More concerningly, the maximum heat fluxes (W/cm^2) in commodity CPU / GPUs have been reached, the clock frequencies reached plateus in the 2010s, and the Voltage reduction is slowing [30]. The relation between the manufacturing CO_2 and the use stage CO_2 for the whole digital sector has been assumed to be on average 25% manufacturing and 75% use[16]. Using 1 Gt CO_2per year for Manufacturing[24]wouldeither render 4 Gt CO_2per year in total for the digital sector or a 50% share for Manufacturing. Anyway 1 GtCO_2per year would add around 0.8 Gt CO_2per year, showing a tremendous underestimation of the sector in 2015. Such Gt CO_2per 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 CO_2 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 use stage	152	*136*	*286*	*700*
Optical networks use stage	179	*171*	*138*	*146*
Data centers use stage	220	*207*	*469*	*799*

From Table 7 it could already be argued that the CO_2 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_2emissions from steel production, ≈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)?

$$2\ Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3\ CO_2 \quad (1)$$

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O \quad (2)$$

In 2018, the total world crude steel production was 1808.6 million tonnes (Mt) and Sweden’s steel production was4.7 Mt [35].

The emissions from steel production is 1.1 Gt CO_2per year according to (1): 1.8×10^{12} kg Fe×0.59 kg CO_2/kg Fe. This shows that (1) is very crude and underestimatethe actual CO_2 emissions[31].

Anyway, according to (2),producing 1 kg Fe requires ≈0.053 kg H_2. It takes around 36 kWh electricity to produce 1 kg H_2[36]. Accordingly, ≈1.93 kWh/kg Fe, and 3492 TWh (1.8×10^{12} kg Fe×1.93 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 ≈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 (≈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 thatthe 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 ofsuch 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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