Comparison of Several Simplistic High-Level Approaches for Estimating the Global Energy and Electricity Use of ICT Networks and Data Centers

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Abstract: Currently the global energy and electricity use of ICT networks and data centers are estimated and predicted by several different top-down approaches. It has not been investigated which prediction approach best answers to the 5G, Artificial Intelligence and Internet of Things megatrends which are expected to emerge until 2030 and beyond. The analysis of the potential correlation between storage volume, communication volume and computations (instructions, operations, bits) is also lacking. The present research shows that several different activity metrics (*AM*) – e.g. data traffic, subscribers, capita, operations – have and can be been used. First the global baseline electricity evolution (TWh) for 2010, 2015 and 2020 for networks of fixed, mobile and data centers is set based on literature. Then the respective *AM* – e.g. data traffic - associated with each network are identified. Then the following are proposed: Compound Aggregated Growth Rate (CAGR) for each *AM*, CAGR for TWh/*AM* and the resulting TWh values for 2025 and 2030. The results show that *AMs* based on data traffic are best suited for predicting future TWh usage of networks. Data traffic is a more robust (scientific) *AM* to be used for prediction than subscribers as the latter is a more variable and less definable concept. Nevertheless, subscriber based *AM* are more uncertain than data traffic *AM* as the subscriber is neither a well-defined unit, nor related to the network equipment which handle the data. Despite large non-chaotic uncertainties, data traffic is a better *AM* than subscribers for expressing the energy evolution of ICT Networks and Data Centers. Top-down/high-level models based on data traffic are sensitive to the amount of traffic however also to the development of future electricity intensity. For the first time the primary energy use of computing, resulting from total global instructions and energy per instruction, is estimated.

Combining all networks and data centers and using one *AM* for all does not reflect the evolution improvement of individual network types. Very simplistic high-level estimation models tend to both overestimate and underestimate the TWh. However, looking at networks and data centers as one big entity better reflects the future converging paradigm of telecom, ICT and computing.

The next step is to make the prediction models more sophisticated by using equipment standards instead of top-down metrics. The links between individual equipment roadmaps (e.g. W/(bits per second)) and sector-level roadmaps need further study.

Keywords: ICT, data centers, data traffic, model, communication networks, electricity, prediction, primary energy, subscribers.

1. INTRODUCTION

Electricity is at ≈44% (electricity production 26614.8 TWh/4.4 ≈ 6050 Million tonnes oil equivalents (Mtoe) of 13800 Mtoe) a huge share of the current global primary energy supply (PES) [1]. The global PES grew by 16 EJ between 2017 and 2018 and 10 EJ between 2016 and 2017 [1]. No predictions are done in [1] which reports factual observations, however, predictions can still be attempted based on historical trends. With the current growth rates [1], extrapolated between 2018 and 2030, global PES would rise from 13800 Mtoe to 16600 Mtoe, and the electricity supply (not PES) from 26000 to 36000 TWh. However, needless to point out, it is important to always critically question forecasts [2]. One important driver for increasing global electricity demand is for millions in poor underdeveloped households to quickly get access to reliable electric power which can replace health damaging direct coke and wood burning [3]. Other important drivers will be electrification of transport and sustainable hydrogen/ammonia production. Electricity is more energy efficient for transport than using primary fuel [4]. Therefore the total global PES could be reduced by using more electric power in the use stage. However, the manufacturing of batteries to be used in electric vehicles requires around 350-650 MJ PES/kWh battery capacity [5], which corresponds to around 200 kWh electric power/kWh. Moreover, until there is charging infrastructure across the globe or batteries that can last for ≈1000 km the World will be dependent on internal combustion engines [6]. ICT is essential in society, the market is expanding fast and there is some concern that ICT might use many times more electric power in the next decade [7]. The driving trends for data traffic and computations are more advanced video, video streaming for gaming, augmented reality, 5G, artificial intelligence (AI) training, autonomous vehicles with streaming cameras, holography, digitalization, advanced commercials, and the need for reliable

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electricity. 5G technology will foster more demand from online gaming, video calling and interactive sports experiences. If the current energy intensity J/bit (≈3-5 pJ/bit [8,9]) – expressed as PES/instruction - does not improve, it is (unrealistically?) estimated that in 2030 the PES use of computing devices could reach ≈60% of the total amount of global PES, i.e. ≈420 EJ. This will become completely unsustainable by 2040 [9,10]. In this research, total global instructions and total global bits are considered equal. Anyway, the scientific method requires clear definitions. Moreover, correct judgement of changes and trends require reliable observations and homogeneous and representative measurements. Global ICT energy and electricity use predictions have neither but still the order of magnitude of the historical TWh electricity use seem commonly agreed and understood. Understanding the trends for energy and electricity demand need more than a couple of years of factual observed data. Maybe something like ten years is required in order to understand if ICT and computing has changed its electricity use.

When in operation, ICT Networks and data centers use around at least 500 TWh electricity estimated by several different approaches [7,18]. Consumer ICT devices, embedded chips and production of ICT equipment could add up another 1500 TWh [7] but this is not explored further in the present research. It has been proposed that training a single AI model - Transformer (213M parameters) with neural architecture search - will require around 660 MWh electricity [11]. Andrae explored how much electricity might be required toward 2030 under certain circumstances which are not at all unrealistic (exploding data due to 5G, Machine Learning and AI + transistor energy problems) [12]. Andrae explored Special Purpose Computing instructions. However, the high-level system-level energy saving is somewhat ignored in such approaches. Anyway, the PES intensity per logic operation (J/bit) and the total global number of logic operations (bits) have not been explored despite work by e.g. Åberg and Mämmela [8] discussing energy limited microelectronics.

Questions explored in the present research:

- Which simplistic high-level approach gives the most credible and systematic predictions for 2030 ICT networks and data centers electricity use in the use stage?
- What is the probability of the electricity use of ICT networks and data centers rising 5-10 times as has previously been suggested [7] ?
- Which models can best mirror what is in the ICT network power calculation?

Table 1: Bases for understanding ICT Sector electricity footprint on a top-down/high-level.

Sections 2 and 3	Basis for prediction, Activity Metric (*AM*)	Reference
“Fixed”	Data traffic	[7]
“Fixed”	Data traffic	[13]
“Fixed”	“Fixed” subscribers	[14]
“Mobile”	Data traffic	[7]
“Mobile”	Data traffic	[13]
“Mobile”	“Mobile” subscribers	[14]
“Data Centers”	Data traffic	[7]
“Data Centers”	Data traffic	[13]
“Data Centers”	“Servers”	[15]
“Fixed”+ “Mobile” + “Data Centers”	Data traffic	This research
Section 4		
“Data Centers”	Historical Compound Aggregated Growth Rate (CAGR) of electricity (TWh)	[16]
“Fixed”+”Mobile”	Historical CAGR of electricity (TWh)	[16]
“Fixed”+ “Mobile” + “Data Centers”	CAGR of Global Capita and TWh/Global Capita	This research
“Fixed”+ “Mobile” + “Data Centers”	Bits, operations, computations, instructions	This research

- Which model helps us understand and predict ICT network power?
- Has the electricity consumption by data centers leveled off in recent years due to efficiency improvements?

The originality of this research is the systematic comparison of prediction results made possible by several different models (Table **1**).

The falsifiable hypotheses for models describing ICT electricity use described in literature are:

- Data traffic numbers from [13] are – if used carefully - the most suitable prediction bases (activity metrics, *AMs*) for networks and data centers electricity use
- Final electricity use (TWh) for all kind of networks is equally sensitive to changes in Data traffic growth and electricity intensity improvement

2. MATERIALS AND METHODOLOGY

In this section it is explained which methods are used to obtain the results shown in section 3.

Equations 1-3 describe the idealized relations between electricity usage for each year from 2021 to 2030, activity metric, and electricity intensity improvement. Electricity usage for 2010, 2015 and 2020, and corresponding activity metric (*AM*), and resulting electricity intensity improvement between 2010 and 2020 are assumed known facts.

$$E_{2021+n} = \left(\frac{AM_{2021+n}}{AM_{2020+n}}\right) \times E_{2020+n} \times EI_{2010\ to\ 2020} \quad (1)$$

$$AM_{2021+n} = AM_{2020+n} \times (CAGR_{AM,2020\ to\ 2030})^{n} \quad (2)$$

$$EI_{2010\ to\ 2020} = \left(\frac{\left(\frac{E_{2020}}{AM_{2020}}\right)}{\frac{E_{2010}}{AM_{2010}}}\right)^{\frac{1}{(2020-2010)}} \quad (3)$$

where

$E_{,2010}$ = electricity usage in networks and data centers in 2010, TWh

$E_{,2020}$ = electricity usage in networks and data centers in 2020, TWh

$E_{,2021}$ = electricity usage in networks and data centers in 2021, TWh

AM_{2020} = Activity metric in 2020, e.g. Exabyte (EB), subscriber etc.

AM_{2021} = Activity metric in 2021, e.g. EB, subscriber etc.

$CAGR_{AM,2020\ to\ 2030}$ = Compound Aggregated Growth Rate (CAGR) for Activity metric in between 2020 and 2030, %

n = 0,1,2,3…,9.

$EI_{2010\ to\ 2020}$ = annual electricity intensity improvement between 2010 and 2020, %

$EI_{2020\ to\ 2030}$ = annual electricity intensity improvement between 2020 and 2030, %

$EI_{2010\ to\ 2020} = EI_{2020\ to\ 2030}$.

$CAGR_{AM,2020\ to\ 2030}$ might differ considerably for data traffic in between literature sources and networks. Table **2** shows baseline values for electricity and data traffic footprint of Networks in 2010, 2015 and 2020.

624 TWh for "Fixed"+ "Mobile" + "Data Centers" for 2010 from [19] is obtained from backward extrapolation of growth rates between 2013 and 2015.

207 TWh for data center global electricity seems very low considering that it was recently estimated that China's data centers alone used 160 TWh [20].

Regarding "fixed" networks use stage, Kyriakopoulos *et al*. demonstrated that for Elastic Optical Networks Based on Signal Overlap there is an almost linear increase in power consumption, when the average data traffic demand increases [21].

Such estimations strengthen the arguments that global data centers and "fixed" networks – despite removing old "fixed" networks" - could use more electricity in the next decade.

3. RESULTS

Here follows a concise and precise description of the results. Table **3** shows the evolution of data traffic, subscribers and TWh for "fixed", "mobile" and "data centers".

Table 2: Baseline Values for Electricity and Data Traffic Footprint of Networks in 2010, 2015 and 2020

Network type	*E* (TWh) and Activity Metrics (*AM*)	2010	2015	2020
"Fixed"	Data traffic, ExaByte (EB) [7]	325	839	2444
"Fixed"	Data traffic, EB [13]	325	839	2568
"Fixed"	"Subscribers", billions [14]	1.75	1.85	2
"Fixed"	Electricity use, TWh [17]	162	179	171
"Fixed"	Electricity use, TWh [18]	80	85	90
"Mobile"	Data traffic, EB [7]	22.6	75	791
"Mobile"	Data traffic, EB [13]	22.6	75	492
"Mobile"	"Subscribers", billions [14]	5.3	7.2	7.9
"Mobile"	Electricity use, TWh [17]	204	152	136
"Mobile"	Electricity use, TWh [18]	70	117	138
"Data Centers"	Data traffic, EB [7]	1403	4803	13761
"Data Centers"	Data traffic, EB [13]	1403	4803	17510
"Data Centers"	"Servers", millions [15]	38	43	48
"Data Centers"	Electricity use, TWh [17]	196	220	207
"Data Centers"	Electricity use, TWh [18]	273	245	231
"Data Centers"	Electricity use, TWh [19] "Sobriety scenario"	227 (323 in 2013)	400	651
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [13]	1403	4803	17510
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh [17]	604	552	514
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh [18]	423	447	459
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh [19] "Sobriety scenario"	624 (757 in 2013)	863	1227
"Fixed"+ "Mobile" + "Data Centers"	Capita, billions [7]	6.85	7.04	7.4
"Fixed"+ "Mobile" + "Data Centers"	Total global instructions, nonillions (10^{30}), (Tables **7** and **8**)	0.15	1.04	7.7

Table 3: CAGR Values for Activity Metrics and Electricity Intensities in and between 2025 and 2030

Network type	E (TWh) and *AM*	Assumed $CAGR_{AM,2020\ to\ 2030}$	2025 result	2030 result
"Fixed"	Data traffic, ExaByte (EB) [7]	26.6%	7693	25901
"Fixed"	Electricity use, TWh [17]	-13.2%. Nonlinear improvement of TWh/EB from -20% in 2022 to -5% in 2030	204	448
"Fixed"	Data traffic, EB [13]	23.43% [13]	7357	21077
"Fixed"	Electricity use, TWh	-18.2% TWh/EB [$EI_{2010\ to\ 2020}$]	179	188
"Fixed"	"Subscribers", billions [14]	1.5% [13]	2.1	2.3
"Fixed"	Electricity use, TWh	-1% TWh/billion subscribers	177	183
"Fixed"	Data traffic, EB [13]	23.43% [13]	7357	21077
"Fixed"	Electricity use, TWh [18]	-17.81% TWh/EB [$EI_{2010\ to\ 2020}$]	97	104
"Mobile"	Data traffic, EB [17]	79%	9722	178324
"Mobile"	Electricity use, TWh. 5G 0.06 TWh/EB	-35.6% [Nonlinear improvement of sub TWh/EB (e.g. 4G TWh/EB) from -20% in 2022 to -5% in 2030] [17]	168	369

(Table 3). Continued.

Network type	E (TWh) and *AM*	Assumed $CAGR_{AM,2020\ to\ 2030}$	2025 result	2030 result
"Mobile"	Data traffic, EB [13]	45%	3157	20257
"Mobile"	Electricity use, TWh	-29.4% TWh/EB (2010 to 2020 CAGR)	153	172
"Mobile"	Data traffic, EB [17]	79%	9722	178324
"Mobile"	Electricity use, TWh	-29.4% TWh/EB (2010 to 2020 CAGR)	439	1413
"Mobile"	"Subscribers", billions	1.25%	8.64	9.5
"Mobile"	Electricity use, TWh	-8.72% TWh/billion subscribers	92	62
"Mobile"	Data traffic, EB [13]	45%	3157	20257
"Mobile"	Electricity use, TWh [18]	-21.36% TWh/EB (2010 to 2020 CAGR)	266	514
"Data Centers"	Data traffic, EB [7]	33.8%	43748	254498
"Data Centers"	Electricity use, TWh [17]	-12.4%. Nonlinear improvement of TWh/EB from -20% in 2022 to -5% in 2030	249	944
"Data Centers"	Data traffic, EB [13]	25%	53438	163078
"Data Centers"	Electricity use, TWh	-22% TWh/EB (2010 to 2020 CAGR)	183	163
"Data Centers"	Data traffic, EB [22]	56%	161778	1494659
"Data Centers"	Electricity use, TWh	-22% TWh/EB (2010 to 2020 CAGR)	556	1495
"Data Centers"	"Servers", millions [15]	1.4%	52	55
"Data Centers"	Electricity use, TWh	-1.77% TWh/ million servers	205	198
"Data Centers"	Data traffic, EB [13]	25%	53438	163078
"Data Centers"	Electricity use, TWh based on [18]	-24% TWh/EB (2010 to 2020 CAGR)	184	146
"Data Centers"	Data traffic, EB [13]	25%	53438	163078
"Data Centers"	Electricity use, TWh based on [19]	-14% TWh/EB (2010 to 2020 CAGR)	952	1393
Combined				
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [17]	33.8%	43748	254498
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh	-15.5% TWh/EB (2010 to 2020 CAGR)	622	1761
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [13]	25% [13]	53438	163078
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh	-24% TWh/EB (2010 to 2020 CAGR)	410	326
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [22]	56%	161778	1494659
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh	-24% TWh/EB (2010 to 2020 CAGR)	1240	2991
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [13]	25% [13]	53438	163078
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh	-17% TWh/EB (2010 to 2020 CAGR)	1486	1800
"Fixed"+ "Mobile" + "Data Centers"	Data traffic, EB [13]	25% [13]	53438	163078
"Fixed"+ "Mobile" + "Data Centers"	Electricity use, TWh, based on [18]	-22% TWh/EB (2010 to 2020 CAGR)	413	472

Table **3** shows that raising the number of "mobile" and "fixed" subscribers by an order of magnitude - which is likely for IoT and other kinds of subscriptions/connections which will be very different from current telecom subscribers - would increase the "fixed" and or "mobile" TWh by an order of magnitude. Data generated by IoT depends on the application. Data traffic is more credible than subscribers for predicting "fixed" and "mobile" networks electricity use, while "servers" and Global IP Data Center traffic [13] are well aligned whenever 2010 to 2020 electricity improvement continue between 2020 and 2030 for data traffic, i.e.

$EI_{2010\ to\ 2020} = EI_{2020\ to\ 2030}$.

While having a tendency to underestimate e.g. mobile traffic, [13] is a transparent basis for simplistic high-level predictions of ICT networks electricity use.

Based on Tables **2** and **3**, Figures **1** to **4** show a graphical summary of the spread of electricity use between 2010 and 2030 obtained by high-level simplistic trend analyses.

4. DISCUSSION

2030 is approaching fast and earlier data traffic based approaches [7,17] might have overestimated the TWh of networks and data centers in 2025 and 2030 as the historical 2010-2020 trend was not assumed to continue.

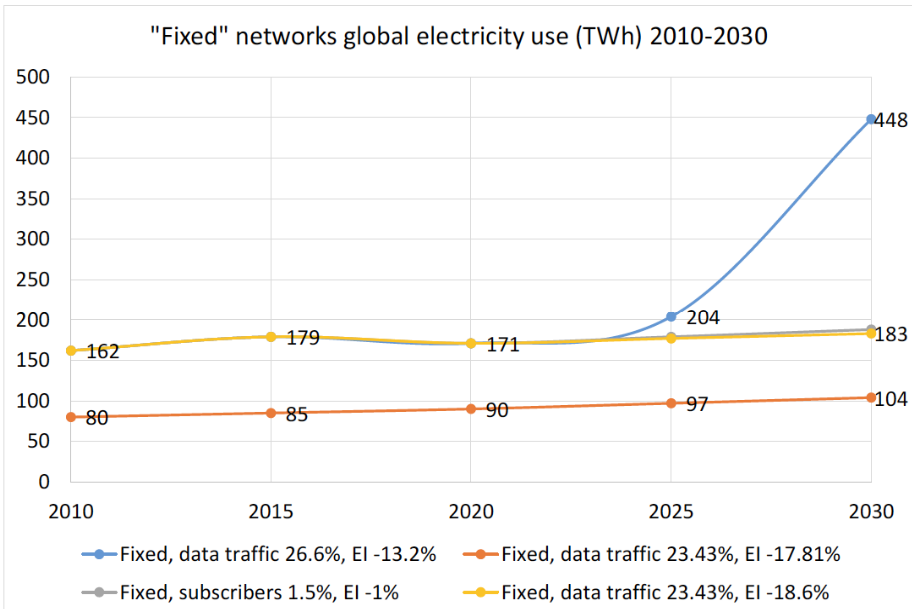

Figure 1: Spread of electricity use for fixed networks 2010-2030.

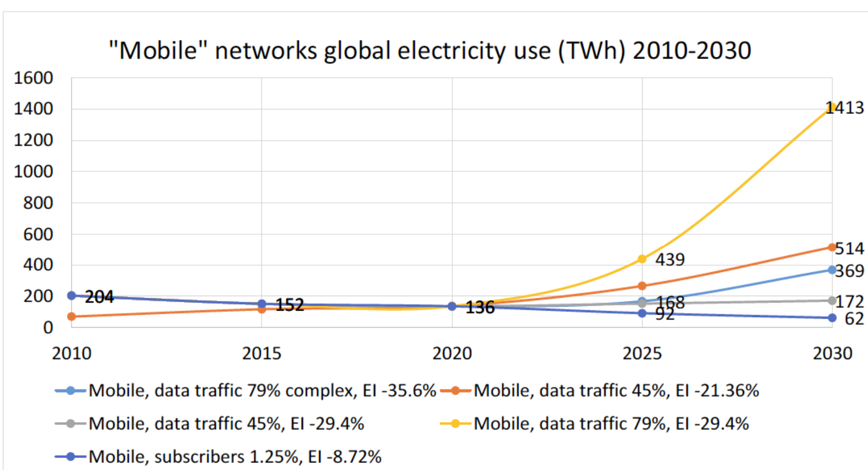

Figure 2: Spread of electricity use for "mobile" networks 2010-2030.

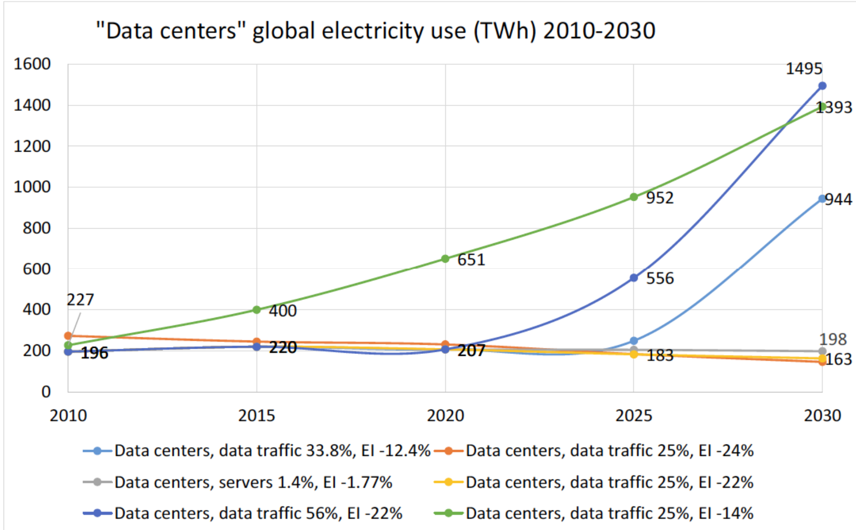

Figure 3: Spread of electricity use for "data centers" 2010-2030.

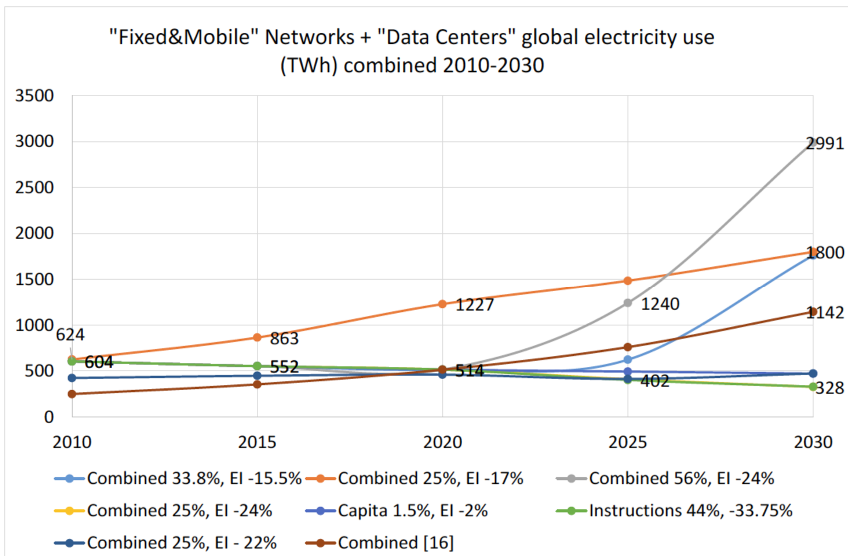

Figure 4: Spread of electricity use for combined "mobile", "fixed", "data center" networks 201+-2030.

Memristors ("memory+transistor") might be one of the game changers that will keep the electricity improvements (*EI)* going 2020 to 2030 [23].

For data centers, if the current developments continue, Hintemann and Hinterholzer argued that the energy consumption of data centers will "only" double by 2030 compared to today [24]. That estimation is more consistent with a waning *EI* than constant *EI* between 2020 and 2030. As shown in Figure **3**, the current data center electricity is quite uncertain [19,20] and a higher starting value in 2020 results in higher electricity use in 2030.

Also, there are estimations of 79% CAGR of mobile data traffic [17] from 2020 to 2030. Using 79% - instead of 45% [13] - with constant *EI* will give >1400 TWh for mobile networks in 2030, instead of 172 TWh. This shows that a more complex model [7] for mobile can be less sensitive to the total traffic and that the total electricity use is very sensitive to data traffic growth in simplistic modelling.

In reality there are many layers of intensity and efficiency at sector, sub-network, and site equipment level.

The convergence of fixed and mobile networks might speak against using separate traffic data, but this is doubtful as long as sources like [13] continue to predict separate network traffic data.

Increased electricity use in the use stage of Networks and Data Centers 2020 to 2030 may be driven by decelerating energy efficiency.

The present research shows that the data traffic modelling approaches are not wrong *per se*, and that the assumptions of gradually slowing *EI* improvement from 2022 – used within the data traffic approaches - are realistic. However, waning Moore´s law - and transistor switching energy challenges [12] - will be mitigated by "smart" engineering and system level design of networks and data centers? On the other hand the demand for ultra-low times required for transmitting a message through the network – i.e. ultra-low latency [25] - could mitigate the trend of building fewer large hyperscale data centers, in turn believed to offer huge overall power saving opportunities. The fundamental conflict in ICT is between capacity, latency and energy efficiency. Moreover for mobile networks it might not be enough to phase out older equipment and switch to "5G" equipment as all spectrums have to be offered simultaneously and each spectrum (e.g. 3.5GHz band) has its own energy efficiency [26]. Additionally the first generation of "5G" equipment might not be optimized as far as power use [31].

Server shipments could well grow faster between 2020 and 2030 than the preceding decade. Servers are also very different. Fuchs *et al.* [27] found that idle server power demand to be significantly higher than benchmarks from ENERGY STAR and the industry-released SPEC database, and SPEC server configurations—and likely their power scaling—to be atypical of volume servers.

Further Diouani and Medromi proposed simplified formulae for energy consumption estimation of cloud data centers [28]. However, no quantification of global energy use of cloud data centers was demonstrated.

Continuation of -22% TWh/EB annual improvement for data centers as a whole (Table **3**) - and for the servers within - between 2020 and 2030 will require a large percentage of hyperscale data centers normally offering higher utilization rate and power use effectiveness including liquid cooling and similar [29].

4.1. "Fixed" + "Mobile"+ "Data Centers" – can the Fixed Mobile Convergence be Forecasted?

Table **4** shows Extrapolation with other approaches from 2020 baseline values to 2025 and 2030 for Networks and Data Centers.

As shown in Table **4**, alternative extrapolation approaches give quite different results for 2030. There will be a manageable increase of the electric power, but according to the scientific method the high-level method can only assume that historically achieved electricity intensities - and data traffic changes - will continue until new observations have been done. It has never been argued by data traffic proponents that the electricity use (TWh) rises at the same rate as the ExaBytes.

The developing world will develop their infrastructure and a thought experiment can include network and data center TWh/capita extrapolation to the World capita.

The high-level approaches – especially those combining all networks and data centers - discussed in the present research likely underestimate the total TWh. Using total global instructions for *AM* give somewhat unrealistic forecasts when based on

Table 4: Extrapolation with other Approaches from 2020 Baseline Values to 2025 and 2030 – Networks and Data Centers

Network type	TWh and Data traffic	CAGR	2025	2030
"Data Centers"	Historical Compound Aggregated Growth Rate (CAGR) of electricity TWh →TWh	4.4% [16]	256	318
"Fixed"+"Mobile"	Historical Compound Aggregated Growth Rate (CAGR) TWh →TWh	10.4% [16]	503	825
"Fixed"+ "Mobile" + "Data Centers"	Historical Compound Aggregated Growth Rate (CAGR) TWh →TWh		759	1143
"Fixed"+ "Mobile" + "Data Centers"	Global Capita, billions	1.5%	8	8.6
"Fixed"+ "Mobile" + "Data Centers"	TWh/Global Capita	-2%	493	471
Fixed"+ "Mobile" + "Data Centers"	Total global instructions, nonillions	44% (Tables 7 and 8)	48	298
"Fixed"+ "Mobile" + "Data Centers"	TWh/nonillion instructions	-33.75% for TWh/nonillion bits	402	328

historical trends as demonstrated by 402 and 318 TWh in 2025 and 2030, respectively. Similar results are obtained by using [13] total global data center IP traffic (Table **3**, Combined). The main reason is that each network and data center type has its own energy efficiency characteristics which are lost in calculation which combine all types into one score.

4.2. "Fixed"+"Mobile"

Van Heddeghem *et al*. [16] proposed growth rate for electricity use observed by 2007 to 2012 may not have continued until 2020. Therefore it is questionable if those growth rates - 10.4% for networks and 4.4% for data centers - can be used for 2020 to 2030.

4.3. Metrics for Data Center Activities – can one Activitry Metric be Used as Proxy for Others?

Do data center activities based on i) data storage, ii) data traffic and iii) computations, track each other consistently so that one of these could be used as a proxy for all three?

Tables **5** and **6** show that Global data center IP traffic [13] and communication volume [30] are well suited for acting as proxy for other metrics.

Data center IP traffic is expected grow at a Compound Annual Growth Rate (CAGR) of 25 percent from 2016 to 2021 [13]. Overall data center workloads and compute instances are predicted to more than double (2.3-fold) from 2016 to 2021 [13]. The growth rate of workloads seems to be slower than the data traffic. Xu's [30] instruction/s growth rate and Cisco's compute instances growth rate [13] are not consistent.

The historical improvements may continue and it looks much better for data centers than previously estimated thanks to heavy focus on energy efficiency research and implementation. The awareness is strong and the engineers are smart. However, the 2020 global baseline for data centers is much more than 200 TWh if [19,20] are accurate.

4.4. Rationale for Data Traffic Method Using Published Estimations

There are several reasons why data traffic is a better activity metric for forecasting electricity use of ICT Networks. Here follows four main reasons:

1. Personalized usage profile for same subscriber type.

How can a user making phone a phone call be compared to a user watching 4K video? Both these

Table 5: Data Center Activities Expressed as Data Storage, Communication Volume and Instructions Per Second [30]

Year	Global Storage volume [30]	Global Communication volume [30]	Global Instructions per second [30]
1986	21 PetaByte(PB)	59 PB	0.74 Peta
2007	277 ExaByte (EB)	537 EB	195 Exa
2010			
2015			
2020			
2025	31.2% CAGR between 2007 and 2030	31.2% CAGR between 2007 and 2030	51% CAGR between 2007 and 2030
2030	*140 ZettaByte (ZB)*	*272 ZB*	*2588 Zetta*

Table 6: Data Center Activities Expressed as Data Storage, Data Traffic and Workloads [13]

Year	Storage volume [13]	Communication volume	Global Data center IP traffic [13]	Overall data center workloads and compute instances [13]
1986			?	
2007			?	
2010			1.37 ZB	
2015	600 EB		5.4 ZB	1
2020	2.6 ZB		16.6 ZB	2.3
2025	32% CAGR between 2016 and 2021		25% CAGR between 2016 and 2021	18% CAGR between 2016 and 2021
2030				

users can be the same type of subscriber (follow the same subscriber package with an operator), but can they both declare the same network electricity consumption?

2. Human and other types of subscribers

A company could be a subscriber of public cloud. A vehicle could be a subscriber. How do they compare with a human subscriber? There will be many different types of subscribers – and more quantity - in the future than humans. A company having one fixed broadband service (subscription) has several fixed users of the same service.

3. Communication era is changing to big data era

Data processing will increase faster than data transportation. For legacy networks, the access networks is the biggest part of the electricity consumption and that in turn is well correlated to "subscribers". However, for the big data era, data processing and storage will be higher than traditional telecom, i.e. ICT and not only communication.

4. Lack of dependence between power and subscribers in the 5G era

AMs like the area covered, the number of subscribers, or the amount of data traffic have had a small impact on the amount of electricity used by 1G, 2G, 3G, and 4G mobile networks. Frenger and Tano argued that 5G could change this and make the network energy much more proportional to the actual network load (=amount of data) [31].

The number of subscribers will reach a limit, and therefore data per capita is probably the best *AM* if data and human subscribers are to be combined.

4.5. Computing Share of Total Primary Energy Supply

The rationale for the calculating the total global number of bits (instructions) is not clear. Cisco's total ZettaByte data traffic served will - in itself if translated to bits - render too few bits to result in 8% as share of computing if multiplied with e.g. 5 pJ/bit. Barlage mentioned 7-10% of computing of current total PES and current 3 pJ/computation [9]. The amount of data will increase different amount of times between 2020 and 2030 depending on which measure is used (data volume, global data center IP traffic, instructions, logical operations, computations).

In summary:

1. Data traffic and data traffic intensity will be much more related to energy usage of networks and data centers than subscribers.

2. Data traffic can more sophistically forecast future energy usage levels than subscribers.

3. Data traffic work well at sub-sector level and data [13] are available.

4. The development of data traffic intensity roadmaps will work well on company level.

5. Data traffic and data traffic intensity evolution is applicable and relevant to all companies in the sub-sector.

6. Data traffic and data traffic intensity is adequate for past, present and future development.

7. Data traffic and data traffic intensity respond very well – much better than subscribers - to significant changes in technology and its deployment.

8. Data traffic is very easy to understand and interpret.

4.6. Roadmaps for J/Instruction

Tables **7** and **8** show a new model for estimation of the primary energy use of computing.

Table **7** shows that instructions/byte increases 15% per year. Table **8** shows that the total global instructions might increase 44% per year and the shares of computing of primary energy supply (PES) considering various roadmaps for J/instruction [8].

The instructions in Table **8** is obtained by multiplying instructions/byte [30] in Table **7** with Cisco Global IP Data Center Traffic [13], 17.1 ZettaByte (expressed as 1.6×10^{23} bits) in 2020 and 159 ZettaByte (expressed as 1.5×10^{24} bits). Miller [33] argued that we should move from energies for ~1 cm to~10 m interconnects that are currently in the range of pJ (or larger) total energy per bit, down towards ~10 fJ or lower total energy per bit. This argumentation is reflected in Table **8**. Nevertheless, the ZettaBytes might be much higher in 2030 [22].

Data centers have and will probably develop along the best case scenario in [7]. Best case, Figure **4** in [7]

Table 7: Increase of Instructions Generated Per Data Volume 2007 to 2030

	Xu Instructions/year [30]	Xu Data volume, Byte/year [30]	Xu Instructions/Xu Byte
2007	7.1×10^{27}	9.38×10^{20}	7.55×10^{6}
2010	2.4×10^{28}	2.12×10^{21}	1.16×10^{7}
2015	1.9×10^{29}	8.25×10^{21}	2.35×10^{6}
2020	3.5×10^{30}	5.53×10^{22}	4.79×10^{7}
2025	1.2×10^{31}	1.24×10^{23}	9.74×10^{7}
2030	9.6×10^{31}	4.86×10^{23}	1.98×10^{8}

Table 8: Estimation of Primary Energy Supply of Computing from Total Global Instructions and Energy Per Instruction

	Total global Instructions/year = Xu Instructions/ Xu Byte × Global IP data center traffic [13]	J/instruction [8]	J	EJ	Total Primary Energy Supply (PES), EJ [1, 32]	Share Computing of PES
2020, 5 pJ/instruction (i)	4.79×10^{7} (Table **7**)×17510(Table **2**)×2^{60} ×8 bits/Byte=7.7×10^{30}	5×10^{-12}	3.9×10^{19}	38.5	600	6.4%
2030, 5 pJ/i	3.0×10^{32}	5×10^{-12}	1.5×10^{21}	1500	790	189%
2030, 0.3 pJ/i	3.0×10^{32}	3×10^{-13}	9.6×10^{19}	90	790	11%
2030, 10fJ/i	3.0×10^{32}	1×10^{-14}	3.2×10^{18}	3	790	0.38%
2030, 10aJ/i	3.0×10^{32}	1×10^{-17}	3.2×10^{15}	0.003	790	≈0%
2030, 3zJ/i	3.0×10^{32}	3×10^{-21}	9.6×10^{11}	≈0		≈0%

is the most probable for data centers as also suggested in Figure **3** by three different calculations.

Estimation results from somewhat more comprehensive models than those investigated in the present research – made with some updates of [7,17] - for mobile networks and others are shown in Table **9**.

As shown in Table **3**, the TWh are much lower if no waning of Moore's law is factored in. Also a new assumption is that 5G – starting at 0.06 TWh/ExaByte [7] - will not use historical improvement of the TWh/EB factor between 2010 and 2020 as assumed by [7]. 2030 5G TWh are calculated as: 12 months×94% share 5G×2537 EB/month×0.06 TWh/EB×0.229 (accumulated improvement factor in 2030 with waning Moore's law. Compare the 0.229 accumulated improvement factor to 0.78^{10}=0.083 with no waning and 0.053 in [7]) = 393 TWh.

4.7. Solutions to Counteract the Increases in Global Energy and Electricity Usage in ICT Networks and Data Centers

There are some ways in which the electricity use of networks and data center can be reduced. Suggestions are energy efficient software coding, neural networks which mimic the human brain and moving the memory storage closer to the computation [9]. Others are timers on Wi-Fi modems shutting them down during night time

Table 9: Forecasts of Electricity Use (TWh) of the Entire Internet Including ICT Networks 2020 to 2030

	"Fixed" networks use	"Mobile" networks use	"Data centers" use	Consumer devices use incl. TV&TV peripherals	"Wi-Fi" use	Manufacturing of ICT	TOTAL
2020	171	98	299	966	72	382	1988
2025	200	116	412	918	99	304	2049
2030	428	446	974	839	234	313	3234

[34]. Others are to phase out older energy inefficient fixed networks equipment [18] and optimize the data use itself [35].

4.8. Sensitivity Analyses

The sensitivities $\left(\frac{dE}{dEI_{2010\ to\ 2020}}\right)$ and $\left(\frac{dE}{CAGR_{AM,2020\ to\ 2030}}\right)$ are tested by increasing $EI_{2010\ to\ 2020}$ and $CAGR_{AM,2020\ to\ 2030}$ 1% and determine how E changes in 2025 and 2030. Mobile networks in Table **2** and **3** – with $CAGR_{AM,2020\ to\ 2030} = 45\%$ and $EI_{2010\ to\ 2020} = 29.4\%$ are chosen. The baseline values are $E_{2025} = 153\,TWh$ and $E_{2030} = 172\,TWh$. When $CAGR_{AM,2020\ to\ 2030}$ is changed to 46.45% the following is obtained: $E_{2025} = 161\,TWh$ and $E_{2030} = 190\,TWh$, i.e. $\left(\frac{dE}{CAGR_{AM,2020\ to\ 2030}}\right)$ is +5.2% for 2025 and +10.4% for 2030.

When $EI_{2020\ to\ 2030}$ is changed to 29.7% the following is obtained $E_{2025} = 150\,TWh$ and $E_{2030} = 160\,TWh$, i.e. $\left(\frac{dE}{CAGR_{AM,2020\ to\ 2030}}\right)$ is -2% for 2025 and -7% for 2030.

This suggests that the resulting TWh is more sensitive to traffic growth than electricity improvement.

5. CONCLUSIONS

The conclusions for top-down prediction methods for ICT networks and data centers global electricity use are:

- Data traffic numbers from [13] are – if used carefully - the most reliable prediction bases for networks and data centers electricity use.

- TWh for all kind of networks is not equally sensitive to changes in Data traffic growth and electricity intensity improvement.

In summary both hypotheses set up in Section 1 could not be falsified. The present research has proven that using data (traffic) – being close to an SI unit – can give robust and reasonable prediction results for ICT Networks and data center electricity use. There is not a precision problem with historical [7] data based prediction approaches, however the actual change potential of the electricity intensity has not been implemented carefully enough. It cannot be ruled out that the electricity intensity improvement will continue in the next decade thanks to smart engineering, and then there is no issue of power costs. Subscriber based *AM* worked well historically but is not well-suited for an uncertain future in which the main certain fact is that data traffic will increase heavily. Capita based *AM* can only give order of magnitude indications, but are too crude for well-founded predictions. Global data center IP traffic [13] can be used as a proxy for other *AM*.

Data traffic numbers [13] (having relatively low uncertainty) and historical TWh/Exabyte improvement numbers are the best data known in this field. How these numbers might deviate between 2020 and 2030 is to be the key discussion.

The main argument of this research is that a data traffic approach does indeed give very reasonable numbers for the main global ICT Networks and data centers energy and electricity evolution.

6. NEXT STEPS

Each model has very few factors compared to a rather complex reality. However, measuring ICT power consumption is a hands-on problem which might involve smart meters.

The relative results (Tables **3** and **4**) might look very different to each other suggesting that simplistic approaches have challenges. The next step is to translate the top-down electricity intensity improvements to product equipment targets. The top-down *EI* improvements are more suitable for network operator targets setting than equipment manufacturer roadmaps. The first assumption is that equipment – e.g. servers and base stations – are expected to have the same roadmap as the data centers and mobile networks of which they are parts. “Billion shipped memories and processors” and “billion connections” are worthwhile for *AM* analysis.

Scaling up the effect of AI training and the shifting tide towards edge computing on total electricity use is in the cards.

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AUTHOR CONTRIBUTIONS

Anders S. G. Andrae wrote the paper.

CONFLICTS OF INTEREST

The author declares no conflict of interest. The views of this paper is the authors own and not those of the company.

REFERENCES

[1] BP Statistical Review of World Energy. June 2019. 68th Edition. [cited 2019 Sept 25]: Available from: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[2] Dyson F. The need for sustainable heretics. In: Madhavan G, Oakley B, Green D, Koon D, Low P, (Eds.) Practicing Sustainability. Springer, New York, NY, 2013; 71-76. 2013. https://doi.org/10.1007/978-1-4614-4349-0_14

[3] Lee JY, Kim H. Ambient air pollution-induced health risk for children worldwide. The Lancet Planetary health 2018; 2, e285-e286. https://doi.org/10.1016/S2542-5196(18)30149-9

[4] Wikipedia. Energy efficiency in transport. [cited 2019 Sept 25]: Available from: https://en.wikipedia.org/wiki/Energy_efficiency_in_transport

[5] Romare M, Dahllöf L. The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries. Stockholm. [cited 2019 Sept 25]: Available from: http://www.ivl.se/download/18.5922281715bdaebede95a9/1496136143435/C243.pdf

[6] Kalghatgi G. Is it really the end of internal combustion engines and petroleum in transport?. Appl Ener 2018, 225, 965-74. https://doi.org/10.1016/j.apenergy.2018.05.076

[7] Andrae ASG, Edler T. On global electricity usage of communication technology: trends to 2030. Challenges 2015; 6: 117-57. https://doi.org/10.3390/challe6010117

[8] Åberg M, Mämmelä A. End of Moore's law: performance limited to energy limited microelectronics. 2016. [cited 2019 Sept 25]: Available from: https://www.vttresearch.com/Documents/Eemeli/21st%20Eemeli/15%20Åberg%20Eemeli21_MÅ_03_16.pdf

[9] Barlage D. Impact of the Digital Revolution on World Wide Energy Consumption. [cited 2019 Sept 25]: Available from: https://aroundtheworld.ualberta.ca/portfolio/douglas-barlage/

[10] Techxplore. Light: A possible solution for a sustainable AI. [cited 2019 Sept 25]: Available from: https://techxplore.com/news/2019-07-solution-sustainable-ai.html

[11] MIT Technology Review. Training a single AI model can emit as much carbon as five cars in their lifetimes. [cited 2019 Sept 25]: Available from: https://www.technologyreview.com/s/613630/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes

[12] Andrae ASG. Prediction Studies of Electricity Use of Global Computing in 2030. Int J Sci Eng Invest 2019; 8: 27-33. [cited 2019 Sept 25]: Available from: http://www.ijsei.com/papers/ijsei-88619-04.pdf

[13] Cisco Global Cloud Index. November 19, 2018. [cited 2019 Sept 25]: Available from: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.html#_Toc503317524

[14] International Telecommunication Union. [cited 2019 Sept 25]: Available from: https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx

[15] Statista. Global Server Shipments by Vendor. [cited 2019 Sept 25]: Available from: https://www.statista.com/statistics/267390/global-server-shipments-by-vendor

[16] Van Heddeghem W, Lambert S, Lannoo B, Colle D, Pickavet M, Demeester P. Trends in worldwide ICT electricity consumption from 2007 to 2012. Comput Commun 2014; 50: 64-76. https://doi.org/10.1016/j.comcom.2014.02.008

[17] Andrae ASG. Projecting the chiaroscuro of the electricity use of communication and computing from 2018 to 2030. [cited 2019 Sept 25]: Available from: https://www.researchgate.net/publication/331047520_Projecting_the_chiaroscuro_of_the_electricity_use_of_communication_and_computing_from_2018_to_2030

[18] Malmodin J, Lundén D. The energy and carbon footprint of the global ICT and E&M sectors 2010–2015. Sustainability 2018; 10(9): 3027. https://doi.org/10.3390/su10093027

[19] The Shift Project. Lean ICT – Towards Digital Sobriety. [cited 2019 Sept 26]: Available from: https://theshiftproject.org/wp-content/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf

[20] Computer World. [cited 2019 Sept 25]: Available from: https://www.computerworld.com.au/article/666183/power-consumption-china-internet-usage-grow-two-thirds-by-2023/

[21] Kyriakopoulos CA, Nicopolitidis P, Papadimitriou GI, Varvarigos E. Fast Energy-Efficient Design in Elastic Optical Networks Based on Signal Overlap. IEEE Access 2019; 7: 113931-41. https://doi.org/10.1109/ACCESS.2019.2935328

[22] Shi W, Pallis G, Xu ZW. Edge Computing [Scanning the Issue]. Proc IEEE 2019; 107(8): 1474-81. https://doi.org/10.1109/JPROC.2019.2928287

[23] Gnawali KP, Mozaffari SN, Tragoudas S. Low Power Artificial Neural Network Architecture. [cited 2019 Sept 25]: Available from: https://arxiv.org/abs/1904.02183

[24] Hintemann R, Hinterholzer S. Energy consumption of data centers worldwide. [cited 2019 Sept 25]: Available from: http://ceur-ws.org/Vol-2382/ICT4S2019_paper_16.pdf

[25] Chen H. Abbas R, Cheng P *et al.* Ultra-reliable low latency cellular networks: Use cases, challenges and approaches. IEEE Commun Mag 2018; 56(12): 119-125. https://doi.org/10.1109/MCOM.2018.1701178

[26] Huo L, Jiang D, Lv Z. Soft frequency reuse-based optimization algorithm for energy efficiency of multi-cell networks. Comput Elect Eng 2018; 66, 316-31. https://doi.org/10.1016/j.compeleceng.2017.09.009

[27] Fuchs H, Shehabi A, Ganeshalingam M, Desroches LB, Lim B, Roth K, Tsao A. Comparing datasets of volume servers to illuminate their energy use in data centers. Energ Effic 2019; 1-14. https://doi.org/10.1007/s12053-019-09809-8

[28] Diouani S, Medromi, H. How energy consumption in the cloud data center is calculated. Proceedings of International Conference of Computer Science and Renewable Energies (ICCSRE); 2019: Agadir, Morocco: IEEE; 2019. https://doi.org/10.1109/ICCSRE.2019.8807458

[29] Nadjahi C, Louahlia H, Lemasson S. A review of thermal management and innovative cooling strategies for data center. Sustain Comput Inform Systems 2018; 19: 14-28. https://doi.org/10.1016/j.suscom.2018.05.002

[30] Xu ZW. Cloud-sea computing systems: Towards thousand-fold improvement in performance per watt for the coming zettabyte era. J Comput Sci Technol 2014; 29(2): 177181. https://doi.org/10.1007/s11390-014-1420-2

[31] Frenger P, Tano R. More Capacity and Less Power: How 5G NR Can Reduce Network Energy Consumption. Proceedings of 2019 IEEE 89th Vehicular Technology Conference

(VTC2019-Spring); 2019: Kuala Lumpur, Malaysia: IEEE: 2019: p. 1-5. https://doi.org/10.1109/VTCSpring.2019.8746600

[32] US Energy Information Administration. EIA projects 28% increase in world energy use by 2040. [cited 2019 Sept 25]: Available from: https://www.eia.gov/todayinenergy/detail.php?id=32912

[33] Miller DA. Attojoule optoelectronics for low-energy information processing and communications. J Lightwave Technol 2017; 35(3): 346-96. https://doi.org/10.1109/JLT.2017.2647779

[34] Terry N, Palmer J. Trends in home computing and energy demand. Build Res Inform 2015; 44(2): 175-87. https://doi.org/10.1080/09613218.2015.1040284

[35] Morley J, Widdicks K, Hazas M. Digitalisation, energy and data demand: The impact of Internet traffic on overall and peak electricity consumption. Energ Res Soc Sci 2018; 38: 128-37. https://doi.org/10.1016/j.erss.2018.01.018

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