GREEN 2019

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Birgit Gersbeck-Schierholz, Leibniz Universität Hannover, Germany

GREEN 2019

Forward

The Fourth International Conference on Green Communications, Computing and Technologies (GREEN 2019), held between October 27, 2019 and October 31, 2019 in Nice, France, continues the series of events focusing on current solutions, stringent requirements for further development, and evaluations of potential directions. The event targets are bringing together academia, research institutes, and industries working towards green solutions.

Expected economic, environmental and society wellbeing impact of green computing and communications technologies led to important research and solutions achievements in recent years. Environmental sustainability, high-energy efficiency, diversity of energy sources, renewable energy resources contributed to new paradigms and technologies for green computing and communication.

Economic metrics and social acceptability are still under scrutiny, despite the fact that many solutions, technologies and products are available. Deployment at large scale and a long term evaluation of benefits are under way in different areas where dedicated solutions are applied.

We take here the opportunity to warmly thank all the members of the GREEN 2019 technical program committee, as well as all the reviewers. The creation of such a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to GREEN 2019. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

We also thank the members of the GREEN 2019 organizing committee for their help in handling the logistics and for their work that made this professional meeting a success.

We hope that GREEN 2019 was a successful international forum for the exchange of ideas and results between academia and industry and to promote further progress in the field of green communications, computing and technologies. We also hope that Nice, France provided a pleasant environment during the conference and everyone saved some time to enjoy the charm of the city.

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Saving Energy in Text Search Using Compression

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***Abstract*— The widespread use of text databases and their exponential growth has boosted the interest in developing text compression techniques. These techniques aim at representing text collections using less space, but also at efficiently processing them by providing functionalities such as searching for words and phrases in the compressed text or decompressing just a portion of the text. In this paper, we study compression techniques from the perspective of the savings obtained in energy consumption when searching directly within the compressed text. Our results show that the use of text compression techniques can have an important influence on energy efficiency when the text is processed, for example, for word or phrase searches. Our evaluation compares the energy consumption of both compressed and uncompressed text searches, and the results show that compressing text databases can lead to important energy savings (around 50%).**

Keywords – Text compression; End-Tagged Dense Codes; Energy efficiency; Green software.

I. INTRODUCTION

In recent years, the amount and size of text collections has increased considerably. Although the capacity of new devices to store such a large amount of data is growing quickly, the rate of generation and growth of text collections is even higher. Compression techniques raised as a natural solution to reduce space needs and to save transmission times [1]. However, in a text database, not only space matters but also the ability to efficiently perform queries and to retrieve any part (e.g., decompressing a relevant document) of the whole collection [2][3]. This led to the creation of word-based text compression techniques that not only allowed to reduce the size of the text database to around 30%-35% of the original size but also to efficiently search for any word or phrase directly in the compressed text, avoiding the need for decompressing before searching.

Typically, if one aims at providing efficient access to a document collection, the usual choice is to provide indexed searches that require an additional indexing structure. One could opt for a full-text inverted index that tracks the exact positions where each word occurs within the collection. This index would occupy around 30-40% of the size of the original collection [4], but efficiently supports both word and phrase searches. To save space, document- or even block-addressing inverted indexes can be used instead [4]. For each word, these indexes keep a list of documents/blocks where the word occurs, hence allowing us to directly filter out the documents/blocks where a word occurs. However, solving phrase searches still requires to sequentially scan those documents/blocks containing the words than compose such phrase to verify that they occur in adjacent positions. Consequently, the raise of text compressors that permitted to perform searches directly within the compressed text even faster than when those searches were performed over plain text, boosted the performance of block-addressing inverted indexes [4]-[6] and allowed us to represent the compressed text plus the index in just around 35-45% of the size of the original collection [3] and typically still permit to solve queries within the range of 1-100 milliseconds. In practice, the larger the block size chosen for the block-addressing inverted index, the smaller the index and the longer blocks have to be sequentially traversed at query time.

In this paper, we do not tackle indexing, but we consider a new aspect of text compression techniques. We focus on the energy consumed during the compression process and, more importantly, at search time, where we compare the energy used to perform online searches on both compressed and uncompressed text.

As a matter of fact, the energy consumption of Information Technology (IT) solutions has become in recent years an important concern, and, in particular, software development and maintenance with a “green” perspective in mind [7][8]. If we focus on text databases, energy consumption is a particularly important aspect due to the large number of searches that can be performed on it. Therefore, even small savings in the amount of energy required to perform a single search can be transformed into huge savings when all the searches performed are considered.

We provide experimental results in which we study the energy required when a text collection is compressed and, more importantly, we measure the energy consumption involved when searching both compressed and uncompressed text. Without losing generality, we focus our experimental evaluation on a given compressor, namely End-Tagged Dense Code (ETDC) [6], since it is the best compressor for representing text databases in a compressed form [3][4] while still being able to search for words or sentences in the compressed text without previously decompressing it.

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All our energy consumption measurements were carried out by using an Energy Efficiency Tester (EET) device [9].

The remainder of this paper is organized as follows: Section II briefly presents basic concepts on text compression and describes the ETDC technique. Then, it briefly discusses the search mechanism used to efficiently perform searches for words in both compressed and uncompressed text. In Section III, we explain the main aspects of software sustainability, as well as the framework used to measure software energy consumption. Section IV presents the experimental design framework, and provides the results obtained from our preliminary study. Our main conclusions and future work are discussed in Section V.

II. BACKGROUND

A. Basic concepts on text compression

Word-based compressors represent each word in the text with a code (also called *codeword*) and achieve compression by assigning shorter codes to the most frequent words. By typically using either Huffman [10] (or Dense [6]) coding, the codewords assigned become prefix-free codes. This means that no codeword can be a prefix of a longer codeword and ensures that decoding any codeword can be efficiently performed without the need of any look-ahead.

Huffword [2] is a Huffman-based compressor where each word is given a *bit-oriented* code, that is, the code is a sequence of bits. It yields strong compression ratios, around 25% in English texts, but being bit-oriented, decompression and searches within the compressed text are slow. Plain Huffman [5] assigns *byte-oriented codes* to each word, that is, each code is a sequence of bytes. By using codes made of bytes instead of bits, compression ratios worsen to around 30%, yet byte-wise decoding becomes much faster than that of Huffword, and searches (using a variant of the Shift-Or string matching algorithm [5]) are also largely sped up.

However, Tagged Huffman Codes [5] brought the most important break-through regarding search efficiency within the compressed text. The difference with Plain Huffman is that the first bit of each byte is used to mark if that byte is the first byte of a codeword. In this way, Tagged Huffman Codes became suffix-free (a codeword cannot be a suffix of a longer codeword), what allowed to use the fastest Boyer-Moore [11] string matching algorithms to directly search in the compressed text [5].

By reserving 1 bit of each byte, the compression of Tagged Huffman worsened slightly (compression ratios around 35%) with respect to Plain Huffman. Yet, searches were largely boosted. Indeed, searches for either words or phrases within text compressed with Tagged Huffman can be up to eight times faster than the same searches in uncompressed text [5]. Furthermore, since the beginning of any codeword is now distinguishable, Tagged Huffman also gained self-synchronization capabilities, that is, we can access any byte of the compressed text and start decompression from there on without the need for synchronization from the beginning of the text. Even considering the loss of compression ratio with respect to Plain Huffman, its improved search capabilities promoted Tagged Huffman as the best choice to compress text databases until the proposal of Dense Codes [6].

The ETDC uses the first bit of each byte to mark the last byte of each codeword instead of the first one, as in Tagged-Huffman. This simple idea makes ETDC a prefix-free coding (without the need of applying Huffman coding), and allows ETDC to have all the same interesting properties of Tagged-Huffman but achieving compression ratios closer to those of Plain Huffman (around 31%) which pushed ETDC as the best compressor for text datasets [4]. In summary, the main strengths of ETDC are its good compression, fast compression and decompression procedures, as well as random decompression capabilities (self-synchronization), and the ability to directly search within the compressed text using Horspool algorithm [12].

For these reasons, our empirical evaluation studies, without loss of generality, the energy savings obtained when searching within text compressed with ETDC.

B. End-Tagged Dense Code: compression and search

ETDC [6] is a well-known two-pass word-based byte-oriented statistical compressor. As a two-pass compressor, it processes the source text twice at compression time. A first pass over the text is performed in order to gather both the different words/symbols (the set of different symbols is typically known as the vocabulary of symbols) and their frequency to make up a model of the original text. After that, the vocabulary of symbols is sorted by frequency, and then, as a statistical compressor, ETDC performs a coding stage where shorter codewords are given to the most frequent symbols. As a result of the coding stage, each symbol is associated a unique codeword. ETDC is a byte-oriented compressor, which means that codewords are variable-length sequences composed of 1, 2, or more bytes. The exact encoding mechanism of ETDC will be explained below. After the coding stage, a second pass over the original text is performed again, and, for each symbol of the original text ETDC outputs its corresponding codeword to a new file (compressed-file), hence creating the compressed representation of the original text. In addition, the correspondence symbol⟷codeword (i.e., the list of symbols sorted by frequency in the case of ETDC) must also be kept along with the compressed file (header-file) to allow a further decompression. The overall compression procedure is depicted in Fig. 1. Note that, by replacing the most frequent symbols by the shortest codewords, compression is obtained. In addition, since each source symbol is always replaced by the same codeword, when performing searches for a given word/symbol we can just obtain the codeword associated to such word and then look for the actual positions where the corresponding codeword occur within the compressed file. By using Horspool algorithm [12], searches are efficiently performed [6].

C. Encoding and decoding procedures in ETDC

The encoding procedure of ETDC is very simple [6]. In this case, given a symbol ranked at position i in the vocabulary of words (decreasingly sorted by frequency) ETDC will assign to it a codeword c_i composed of 1 or more bytes (recall ETDC generates byte-oriented codewords).

One of the key-features of ETDC is that it marks the last byte of each codeword with a special flag. ETDC reserves the first bit of each byte from a codeword to mark if that byte is the last byte or not, i.e., the first bit of the last byte of a codeword is set to 1, and the first bit of the remaining bytes is set to 0. Therefore, one-byte codewords will have the form 1xxxxxxx; two-byte codewords have the form 0xxxxxxxx:1xxxxxxx; three-byte codewords follow the pattern 0xxxxxxx:0xxxxxxx:1xxxxxxx; and so on. Note that basically, the numerical byte-values of the ending byte of any codeword are within the range [128,255], whereas the other bytes have values within the range [0,127].

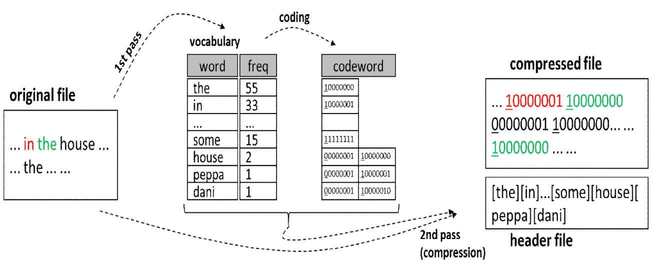

Figure 1. Compression process in ETDC

By marking the last byte of each codeword, ETDC becomes a prefix-free coding. Therefore, despite other well-known Huffman-based compressors [5][10] that reserve some bit-combinations to ensure that the final codewords own the prefix-free property, ETDC can use all the possible bit-combinations of each codeword byte. Actually, the codeword assignment in ETDC is done in a completely sequential fashion (considering the remaining 7 bits of each byte) and does not depend on the actual frequency value of the words, but only on their rank within the sorted vocabulary. The codeword assignment to words decreasingly sorted by frequency is done as follows:

- 1-byte codewords are given to the first 128 words in the vocabulary, i.e., the most frequent word receives codeword 10000000, the second word in the vocabulary is given codeword 10000001, and so on until the word ranked at position 128, which is assigned codeword 11111111. Note that the initial bit is 1 to flag that it is an ending codeword byte, and the remaining seven bits are assigned sequentially from 0000000 to 1111111.
- A 2-byte codeword is given to the next 128x128 words; i.e., word ranked at position 129 receives codeword 00000000:1000000; next word is given codeword 00000000:1000001; and so on until the word ranked at position $128+128^2$ which is given codeword 01111111:11111111.
- A 3-byte codeword is given to the next 128^3 words, from codeword 00000000:00000000:10000000 to codeword 01111111:01111111:11111111.
- If required, 4-byte codewords would be assigned to the next 128^4 words in the same way, and so on.

Codewords are sequentially assigned to words during compression. However, we can know at any moment which codeword corresponds to a given word. This operation is called *encode*, and allows us to search for any word or phrase in the compressed text. We can also know at any moment the word corresponding to a given codeword. This operation is called *decode*, and allows decompressing the text starting at any position.

D. Searching: the Horspool algorithm

Pattern-matching algorithms aim at efficiently finding the positions of a text in which a given *pattern* (a sequence of symbols, for example, a word) appears. A sequential brute-force search would be a simple but very inefficient solution.

The Horspool algorithm [12] searches for the pattern in a sequential fashion but skips parts of the text during the search. The algorithm uses a *search window* of the same size as the pattern we are searching for (see Fig. 2). This search window is moved along the text during the search. At each step, the text under the window is compared with the pattern. If they are equals, the algorithm reports a new occurrence of the pattern. If they are not, the algorithm moves the window to a new position, trying to skip as much text as possible. I.e., if β is the last symbol in the pattern, the skip distance is the number of symbols from the last appearance of β in the pattern to the end of the pattern. If the last symbol only appears in that last position, the skip distance is the size of the pattern. The efficiency of Horspool is given by its capacity to skip large portions of the text. Therefore, the larger the alphabet of symbols, and the larger the pattern, the more chances to skip text, so the more efficient the algorithm will be.

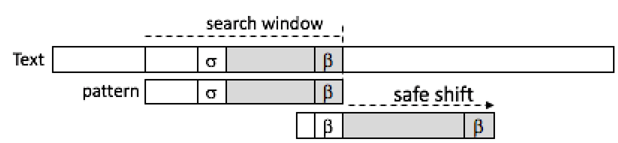

Figure 1. Horspool search algorithm scheme.

Although the Horspool algorithm was thought to be applied in plain text, it can also be applied to text compressed with ETDC. The result of applying this algorithm in text compressed with ETDC is that the searches in the compressed text are much more efficient than searches in the original plain text [5][7].

III. SOFTWARE SUSTAINABILITY

Recent research focused on the proper use of resources required by software has emerged in the area of software sustainability [13]. This resulted in more sustainable and environment-friendly software. According to Calero and Piattini [13], there are three dimensions of Software Sustainability: (i) Human sustainability, which analyzes how software development and maintenance can affect the sociological and psychological aspects of the people involved; (ii) Economic sustainability, which is related to how software lifecycle processes protect stakeholders' investments, ensuring benefits and reducing risks; and (iii) Environmental sustainability, which studies how the development and maintenance, and the use of software affects the use of resources and the energy consumption. This dimension is also known as Green Software.

Our work focuses on the Environmental sustainability dimension. In particular, we analyze how the usage of the ETDC as a text compression technique reduces the amount of energy needed to perform direct searches, compared to the energy needed when directly searching within plain text. To do that, we use FEETINGS (Framework for Energy Efficiency Testing to Improve eNvironmental Goals of the Software) [9], whose objective is to measure and analyze the energy consumed by a software product when it is executed in a computer. This framework is divided into two main components:

- An Energy Efficiency Tester (EET), the hardware device that measures the energy consumption of a software product during its execution. The EET is composed of different sensors that support the measurement of three different hardware elements: processor, hard disk, and graphics card. Furthermore, two additional external sensors quantify the total power consumption of the computer, and that of the monitor connected to the computer (Device Under Test or DUT) where the software is executed.
- A Software Energy Assessment (SEA) application, which automatizes the processing, the analysis, and the visualization of the data collected by the EET.

IV. ETDC Energy Consumption Evaluation

A. *Experimental design framework*

We have carried out a set of experiments to evaluate whether the use of ETDC as the compression method to deal with a text collection not only leads to improvements in space and search times but also entails savings on the amount of energy consumed to perform searches. In addition, we also include results showing the time and energy consumption required to compress such text dataset.

We have used a text collection from [6] composed of a small text named Calgary [14], and several text collections from TREC-2 and TREC-4 [15] (AP Newswire 1988, Ziff Data 1989-1990, Congressional Record 1993, and Financial Times from 1991 to 1994). The size of the dataset is around 1,030 MiB, and when processed with ETDC, the vocabulary obtained has 886,190 different words.

Aiming at performing online searches for single-word patterns, we considered the vocabulary from the collection and we randomly chose words (we assume words are sought with uniform probability by following the same model in [5]) to make up three sets of patterns with varying length. These sets of patterns contain respectively 10 words whose length is 5, 10, and >10 characters. Note that, for this study, we did not filter those words out by frequency.

All our experiments were run on a DUT connected to the EET that was connected to an LCD monitor Philips 170S6FS. The DUT specifications are: (a) Asus M2N-SLI Deluxe motherboard; (b) AMD Athlon tm 64 X2 Dual Core 5600+ 2.81 GHz processor; (c) 4 modules of 1GB DDR2 533MHz RAM memory; (d) Seagate barracuda 7200 500Gb hard disk; (e) GPU Nvidia XfX 8600GTS; and (f) AopenZ350-08Fc 350 W Power supply. It runs Linux Mint 18.3 Cinnamon 32 bits, and the compiler used was gcc version 5.4.0.

We present two main experiments. First, we focus on searches and compare both the performance and the energy consumption obtained when we search for the ten words in each of our query sets, using Horspool algorithm, both over the ETDC-compressed representation of the dataset, and over its plain/original version. Finally, we complete our study showing the amount of energy consumed to compress the dataset with ETDC.

Each experiment was repeated 20 times and then averaged. Being a controlled test environment, 20 measurements are usually a sufficient sample size to mitigate the impact of outliers (such as energy consumption devoted to operating system tasks). Therefore, our time results are presented as average running times, and our energy consumption data are shown in average watt second (W·s). In practice, we will show four different energy-consumption values corresponding to the Hard Disk Drive (HDD), the graphics card (GPU), the processor (CPU), and the Power Supply Unit (PSU), which indicates the total energy consumption of our system.

We performed two-sample t-tests on the measurements we obtained from the experiments, assuming the variance of the samples obtained from measurements in plain text and ETDC are not equal. The test revealed that the means obtained in the two samples are different with a confidence of 99% ($\alpha = 0.005$).

B. *Plain text searches vs. searches over text compressed with ETDC*

In Table I, we show both the average time and the average energy consumption corresponding to searches performed over the original text and over the text compressed with ETDC. Recall that we use the three query sets discussed above corresponding to ten patterns of length 5, 10, and >10 characters, and our times include the overall time corresponding to ten Horspool searches for those ten patterns.

TABLE I. TIME AND ENERGY CONSUMPTION RESULTS WHEN PERFORMING 10 SEARCHES WITH HORSPOOL ALGORITHM OVER BOTH TEXT COMPRESSED WITH ETDC AND OVER UNCOMPRESSED TEXT

Pattern length	Uncompressed Text					Text compressed with ETDC				
	time (s)	Energy consumption (W·s)				time (s)	Energy consumption (W·s)			
		HDD	GPU	CPU	PSU		HDD	GPU	CPU	PSU
5	28.78	470.79	43.27	153.39	4120.08	14.04	230.18	20.53	62.71	1817.83
10	25.17	411.43	36.86	132.29	3647.17	13.00	212.79	19.48	56.50	1684.84
>10	23.87	390.89	34.79	126.29	3465.62	13.54	221.70	18.66	56.35	1771.77

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TABLE II. TIME AND POWER MEASURED BY THE EET. POWER VALUES ARE OBTAINED AS THE ENERGY CONSUMPTION VALUES FROM TABLE 1 DIVIDED BY THE RUNNING TIME (IN SECONDS).

	Uncompressed Text					Text compressed with ETDC				
		Power (watt)					Power (watt)			
Pattern length	time (s)	HDD	GPU	CPU	PSU	time (s)	HDD	GPU	CPU	PSU
5	28.78	16.36	1.50	5.33	143.16	14.04	16.39	1.46	4.47	129.48
10	25.17	16.35	1.46	5.26	144.90	13.00	16.37	1.50	4.35	129.60
>10	23.87	16.38	1.46	5.29	145.19	13.54	16.37	1.38	4.16	130.85

Note that, in Table II, the HDD and GPU consumptions do not vary in the uncompressed and compressed representations. This permits us to conclude that, as expected, it is more energy efficient to perform searches over text compressed with ETDC than over uncompressed text. In particular, we can also see that the most important energy savings (in percentage) are obtained in the processor, followed by the total consumption values drawn by the PSU, and finally the HDD and the GPU are the elements where less savings are reached.

Considering search performance, as expected from [6], the search time is also lower in the compressed scenario (in practice, our compressed searches require from 43% to 51% less time). When we compare how the search times vary with respect to the pattern length, we can see that the longer the pattern, the faster the search is performed, and consequently less energy is required. This is expected since longer patterns lead to longer jumps during the left-to-right traversal in Horspool algorithm.

Even though it could seem rather unexpected, the search times over text compressed with ETDC only marginally depend on the pattern length. Yet, this is true. Given a pattern P, note that on compressed searches we do not search for pattern P, but for the codeword associated to P. Yet, in our dataset, all the words are given codewords of 1, 2, or 3 bytes (recall more frequent words are given shorter codewords). Consequently, the longest "*shift*" during the left-to-right traversal in Horspool will be of only 3 bytes. The average codeword length is 2.9, 3.0, and 3.0 respectively for the patterns in our query sets with patterns of length 5, 10, and >10 characters. This would explain that searches for patterns of length 5 are slightly slower. Yet, we would expect that search performance on patterns of length 10 and >10 should be similar.

In Table II, we have divided the total energy consumption values shown in Table I by the time required to run each experiment. This gives us power values for each component that are independent on the time needed to complete each run. It is interesting to see that both the HDD and the GPU (as expected) have rather constant power needs in both the compressed and the uncompressed scenarios. They require around 16.3 and 1.5 watt, respectively. However, the processor power decreases considerably in the compressed scenario. Not only the searches over compressed text perform faster, but the CPU requires also around 20% less power. On the one hand, Horspool benefits from a lower probability of match between the last character of the pattern, and the rightmost character on the sliding window of the text, and such probability is lower on text compressed with ETDC than on uncompressed text. In [16], it was shown that those probabilities of match are, respectively, around 1/119=0.008 in ETDC and 1/19.3=0.052 in plain text. This is due to the fact that we can find any of the 256 possible combinations of a byte both the compressed text and in the search pattern for ETDC, whereas in plain text less than 100 different byte values are used ([A-Z], [a-z], [0-9], and punctuation symbols). On the other hand, due to that lower probability of match in ETDC, Horspool algorithm wastes much less time comparing (right-to-left) the text and the pattern, and, consequently, most of time is devoted to the main (left-to-right) shift-loop. We conjecture that this makes the execution pipeline simpler and more predictable and reduces the power required by the processor.

C. *Compressing text with ETDC*

As shown above, searching within text compressed with ETDC is more energy efficient than performing searches over uncompressed text. In this section, we also take into account the energy consumption involved when compressing the original text. Table III shows the average time (for 20 repetitions), and the average energy consumption (and power) required to compress our dataset with ETDC.

TABLE III. COMPRESSION WITH ETDC: TIME AND ENERGY ONSUMPTION.

time (s)	Energy consumption (W·s)				Power (watt)			
	HDD	GPU	CPU	PSU	HDD	GPU	CPU	PSU
53.24	876.88	78.94	320.71	6867.21	16.47	1.48	6.02	128.99

As in Table II, we already observe that the power required by both the HDD and the GPU remain rather constant (around 16.5 and 1.5 watt, respectively). The reason is that those consumptions are close to the basal consumption of those devices in the computer. However, the power required by the CPU grows clearly with respect to the values obtained at search time. The CPU uses around 6 watts, whereas for searches over uncompressed text only around 5.3 watt were needed, and those values decreased to around 4.3 watt for searches over text compressed with ETDC. Since the power needs grow, and from the fact that compression takes more time than performing searches, the overall energy consumption increases accordingly.

If we informally analyze the obtained data, we can see that the energy consumption devoted to compress the original text is equivalent to the consumption of performing twenty searches within the uncompressed text. Similarly, from the point of view of energy efficiency, if one is going to search for more than 40 words over a whole large text dataset, it would compensate to keep the text compressed with ETDC, and to perform the searches over such compressed text. This typically can lead to savings around 50% with respect to performing the same searches over the original plain text.

D. *Threats to validity*

The study presented in this work has some limitations that should be taken into account to understand to what extent the results are valid. According to the classification of threats discussed by Wohlin et al. [17] we can identify the following threats:

- *Threats to Construct Validity*: the main threat relates to whether the obtained energy consumption measurements are correct. In our case, we have overcome this threat by using the EET device [9]. This device has been validated and compared with another measuring device in [18]. The energy consumption results obtained by both devices were similar. In addition, EET has previously been used in other similar measurements. Additionally, we have used different patterns of varying length. This fact permitted us to analyze how the length of the pattern influences energy consumption.
- *Threats to Internal Validity*: these threats are mainly related to the configuration of the DUT in which the measurements are made. As it is evident, if we had used a different DUT, we would have obtained different data. However, we believe that, even though the absolute values of the measurements could have varied, the energy consumption relations/conclusions would still remain. Note also that the state of the Operating System (e.g., existence or not of other running tasks) could also be a relevant factor that should be considered. To overcome this possible issue and obtain more stable measurements, each measurement was repeated 20 times.
- *Threats to External Validity*: We have used our own EET as the tool for measuring energy consumption. As indicated above, this device is able to obtain exact measurements of the energy consumed by different hardware elements. Obviously, the measurements obtained are specific for our EET and may differ if we use other mechanisms, such as energy estimation or other devices. Nevertheless, our EET was designed for the actual measurement of different hardware components when a given software is running, and we consider the results obtained to be correct.
- *Threats to Conclusion Validity*: We have analyzed energy consumption when searching a compressed text only by the ETDC algorithm. Therefore, the results obtained cannot be assumed for other text compression algorithms. Yet, as discussed in the future work section, we would expect a rather similar behavior.

V. CONCLUSIONS AND FUTURE WORK

Compression methods have become a widely-used resource nowadays. This is due to the large amount of data that is generated and that must be stored. Undoubtedly, compression permits to store those data within less space. In the scope of text databases, where the ability to perform searches and to retrieve some parts of the text collection is of major interest, End-Tagged Dense Code [6] becomes one of the best compression alternatives due to its reasonable compression ratios (around 30-35%), fast compression and decompression processes, the possibility of performing direct searches on the compressed text very efficiently using Horspool algorithm, and by allowing random decompression (i.e., starting decompression from any random offset of the compressed file).

In this paper, we have also considered a fundamental concern such as the amount of resources used (by means of energy consumption) when performing searches. We have compressed a large text database with ETDC and then performed queries both over the original uncompressed text and over the compressed counterpart. Our results show that compression not only reduces space and searching time, but also leads to less energy being consumed. On the one hand, one could expect that since a faster algorithm requires power during a shorter amount of time, the overall energy consumption would decrease. Our results clearly confirm that. On the other hand, we found a rather unexpected result: the same Horspool algorithm, running over compressed data also required less CPU power than when it ran over uncompressed data.

As future work, we want to extend our study to include other well-known compression techniques for text databases that own similar features to those in ETDC. Among them some good candidates are Tagged and Plain Huffman, or the Restricted Prefix Byte Codes [19]. In this way, we will be able to know which of these techniques requires less energy in compression time, and which one provides more efficient searches in terms of energy. In addition, we intend to expand the study by analyzing CPU utilization when performing text searches (with and without compression), and to determine the relationship between CPU utilization and energy consumption.

Once it is clear that compression permits to reduce energy utilization at search time, another interesting research line involves studying the actual impact of compression in terms of energy within a compact block-addressing inverted index.

ACKNOWLEDGMENTS

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Energy-Aware Design Considerations for Ethernet-Based 5G Mobile Fronthaul Networks

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***Abstract*— Communication networks are not only important to society, they also consume a lot of energy. Recent years research has focused on Cloud-Radio Access Network (C-RAN) to decrease the energy consumption in mobile networks. Hence, this work investigates how to lower the energy consumption in the Ethernet based fronthaul network by choosing the right C-RAN functional split. Different functional splits assign different loads to the fronthaul network, and this work considers how much impact the data load has on the fronthaul network's energy consumption. This work presents a model for the fronthaul energy consumption, which takes the different steps of the Ethernet switch operations into account. The outcome of this model shows the extremely high importance of choosing the right functional split when mobile networks are entering the era of 5th Generation (5G). The impact of switch capacity and size of Ethernet packets is also considered. In a 5G worst case scenario, one switch will consume the same amount of energy as 199 households. The difference in energy consumption between the best and worst case scenario of this paper is 99.32% per switch.**

Keywords- Energy consumption; green networking; Ethernet fronthaul; C-RAN; functional split; 5G.

I. Introduction

The Information and Communications Technology (ICT) sector counts for over 2% of the world's carbon emissions nowadays [1]. However, the energy consumption of the ICT sector is forecasted to increase by 8% by 2030 in the best case scenario, and by 20% in the worst case scenario [1]. The ICT sector covers many areas and one of them is mobile networks. Mobile networks are growing the most, among all ICT sectors, in terms of number of subscribers, traffic demand, connected devices and offered services [2]. The trend in mobile networks is that more and more capacity is required and the coverage should be everywhere. Hence, base stations are widely deployed to cover the largest area possible, in order to satisfy the users' needs. The next generation of mobile networks, the 5th Generation (5G) is approaching and promises more capacity and higher bitrates. Thus, an important parameter to consider is how this growth will affect the energy consumption in mobile networks.

In the mobile network's base stations, the power amplifier takes up most of the energy consumption, next comes the baseband processing and then the cooling [2]. Cloud-Radio Access Network (C-RAN) architectures have been introduced to lower these parameters. In C-RAN, the radio frequency and baseband processing functions from the base station are split in two units referred to as the Radio Unit (RU) and the Centralized Unit (CU). The concept is illustrated in Fig. 1. The RU is located close to the antenna at the antenna mast, thereby it is convection cooled and settles for a smaller amplifier. The CUs from several cells can be gathered in a datacenter, where it is possible for them to share processing powers when not used at the same time. Hence, C-RAN will have the possibility of saving energy consumption in the three most energy consuming parameters of the traditional base station. The RU and the CU are connected by a network segment called the fronthaul network [3]. Originally, only the radio frequency functions were present in the RU, hence the fronthaul network required very large bitrates in order to transport a constant stream of raw In-phase and Quadrature (IQ) data blocks. These blocks of raw IQ data were transported using a special protocol, for example Common Public Radio Interface (CPRI). Recently, the concept of functional splits has been scrutinized, leaving more processing functions in the RU. The more functions are left locally in the RU, the lower the bitrate on the fronthaul network, and gives the possibility of a bitrate varying with user load, but also a larger and more complex RU. Additional information regarding the functional splits is found in [3], which provides an in-depth analysis of the functional splits including latency and impact on fronthaul

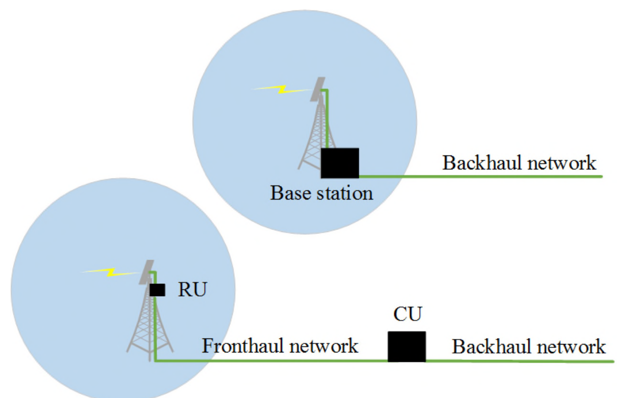

Figure 1. Comparison of traditional base station and C-RAN.

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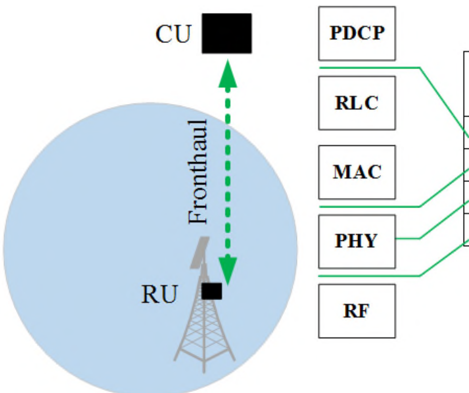

FS	LTE DL FH Bitrate [Mbps]	LTE-A DL FH Bitrate [Mbps]	5G DL FH Bitrate [Mbps]
RLC/PDCP	416	4016	160016
PHY/MAC	420	4133	160800
PHY	538	86016	2752512
RF/PHY	4915	157286	25165824

Figure 2. The functional splits considered and their corresponding fronthaul bitrates for LTE, LTE-A, 5G. The functional splits are illustrated in the LTE protocol stack with upper layer PDCP and lowest RF.

TABLE I. PROPERTIES FOR FRONTHAUL BITRATE CALCULATIONS.

	RATs		
	LTE	*LTE-A*	*5G*
Bandwidth	20 MHz	100 MHZ	400 MHz
# Antennas	2	32	256
# Spatial layers	2	8	12
Modulation order	16 QAM	256 QAM	256 QAM
Sample rate	30,72 MHz	30,72 MHz	614,4 MHz
# Subcarriers	1200	6000	24000
# Resource element blocks	100	500	2000

network. Selected functional split (FS) options are illustrated in Fig. 2. Fig. 2 shows the RU and CU separated by the Fronthaul (FH) network, which is illustrated by a green dotted line. To the right in Fig. 2, the Long Term Evolution (LTE)/LTE-Advanced(LTE-A)/5G protocol stack illustrates the location of the different functional splits selected for this paper. The LTE/LTE-A/5G protocol stack consists of, from the bottom up: the Radio Frequency functions (RF), the physical processing (PHY), the Media Access Control (MAC), the Radio Link Control (RLC) and the Packet Data Convergence Protocol (PDCP). Further description of the protocol stack layers can be found in [3]. On the right side of the figure is a table stating the fronthaul bitrates for LTE, LTE-A and 5G considering different functional splits. These fronthaul bitrates are based on calculations in [4] and extended using the parameters stated in Table I, to also include LTE and 5G. The fronthaul bitrates are only considered for the Downlink (DL) direction.

This work investigates how different functional splits impact the energy consumption in the fronthaul network. The main goal is to investigate how much energy can be saved, when using different functional splits and thereby different bitrates on the fronthaul network. This paper is organized as follows: Section II provides and overview of research in this field. Section III introduces Ethernet fronthaul networks. Section IV outlines a model for energy consumption in the Ethernet fronthaul network. Section V introduces a small case study. Section VI presents the results of energy consumption in the fronthaul network. Section VII discusses the results provided, considering how to obtain an energy efficient fronthaul network for 5G. Section VIII concludes the paper.

II. STATE OF THE ART

C-RAN has been the topic of much research in recent years. A detailed description of the technology is found in [5]. In [6], Sun et al. investigate optimization algorithms to improve the user-centric energy efficiency by jointly allocating resources. Fathy et al. [7] present a power model for a RF/PHY split Passive Optical Network (PON) fronthaul considering sleep mode and active RUs. They find that the average network power consumption is lower using their “greedy selection” algorithm. The work in [8] investigates the energy consumption in the RU considering different functional splits, digital and analogue. In contrast to the previous mentioned papers, this work looks into the energy consumption in the fronthaul network specifically. In [9] Tan et al. analyse the energy consumption in RF/PHY split stating that 90 % of the energy is consumed by the RU, 9% by the CU datacenter and 1% by a 10G Ethernet PON fronthaul network. The work in [10] by Kondepu et al. investigate the energy efficiency for the fronthaul network for a flexible functional split, by switching on and off resources using Software Defined Networking (SDN). This work distinguishes from previous mentioned papers by considering the energy consumption for each of the functional splits and not the best option available. Further, it considers Ethernet for fronthaul transport. With regard to the arguments provided in this section, this work represents an uninvestigated area of looking into the fronthaul energy consumption while considering the different functional splits individually.

III. ETHERNET FRONTHAUL NETWORKS

Fronthaul transport can use many different types of technologies, one of them being Ethernet. The fronthaul

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TABLE II. COMPARISON OF CPRI, ETHERNET AND CPRI OVER ETHERNET FRONTHAUL.

	Selected fronthaul options		
	CPRI	***CPRI over Ethernet***	***Ethernet***
What is transmitted?	Raw IQ samples.	IQ samples encapsulated in Ethernet frames.	Ethernet frames.
Quality of Service	Dedicated user channel.	Shared transmission. Ethernet control management necessary.	Shared transmission. Ethernet control management necessary.
Pros	Simple RU. Capacity, timing and synchronization are guaranteed.	CPRI RUs can be reused. Existing Ethernet network can be used.	Variable/lower bitrate on fronthaul link. Existing Ethernet network can be used.
Cons	Constant high bitrate on fronthaul link increasing by number of antennas.	High Bitrate. Delay can occur. Requires a gateway from CPRI to CPRI over Ethernet.	Delay can occur. Requires new RUs with higher complexity.

network consists of different elements, depending on the type of network. In an Ethernet fronthaul network, the RU and CU are connected by fibers, transmitting Ethernet frames, and Ethernet switches, forwarding Ethernet frames in the right direction. The fibers alone do not consume any energy, they are just pipes, whereas the Ethernet switches require energy in order to function. Ethernet is a packet switched network technology, where it is possible to assign capacity depending on user load. As a fronthaul network, Ethernet benefits in being flexible and already widely used in other network segments. Table II summarizes three options for fronthaul transmission. The option of transmitting fronthaul data using CPRI; this option is most beneficial for functional splits located between the RF and the resource element mapper function, i.e., functional splits having a constant bitrate on the fronthaul link [3]. The same functional splits can be transported over Ethernet using a gateway to encapsulate CPRI into Ethernet frames; this is referred to as CPRI over Ethernet. Another solution is fronthaul transmission over Ethernet. This solution is preferred for functional splits with a variable bitrate on the fronthaul link, i.e., those having the resource mapper included in the RU. Table II represents the current status of the network – the RUs connected using CPRI, and the Ethernet solutions as an option for the future fronthaul network for 5G.

In the future 5G network, the RAN will be expanded with more antennas. This will increase the demands to the fronthaul network even more, as not only higher bitrates shall be transported, but also more streams are present from the higher numbers of RUs and antennas. The following formula can be used for an estimate of the amount of RUs in an area covered by one CU assuming a circular coverage area:

$$N_{RU} = \frac{\pi \cdot D_{MAX}{}^{2}}{\pi \cdot D_{single}{}^{2}} \cdot RATs \qquad (1)$$

D_{MAX} is the maximal distance between the CU and the RU due to fronthaul latency constraints. D_{single} is the maximal transmission distance for one single antenna. Radio Access Technologies (RATs) describe how many RUs are present at each antenna site. They describe whether 3rd Generation (3G), LTE, LTE-A etc. are present in the current area, as each RAT requires its own RU. The amount of RUs found in (1) can be used to find the estimated number of switches covering the current area. Hence, each RU is connected to one ingoing port in an Ethernet switch. Equation 2 expresses the lowest number of switches N_{sw} to cover an area:

$$N_{SW} = \frac{N_{RU}}{N_{port}} \qquad (2)$$

In (2), N_{port} is the number of ingoing ports in each switch.

In 5G networks, more capacity will be provided for the users. More capacity can be obtained e.g. by adding more bandwidth to the system or by adding more RUs for denser coverage and hotspot compliance. If more RUs are added to the system, more switches are necessary in the fronthaul network (as seen in (2)). If adding more bandwidth to increase the capacity, less RUs are necessary leading to less switches in the fronthaul network. The energy efficiency of the Ethernet fronthaul network depends on the number of RUs, the bandwidth available and the number of ports in each Ethernet switch.

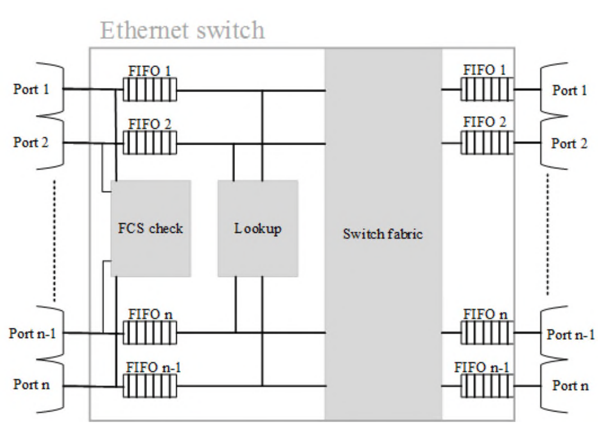

Figure 3. The construction of an Ethernet switch.

IV. AN ETHERNET FRONTHAUL ENERGY CONSUMPTION MODEL

An Ethernet switch consists of different components. Ethernet frames are received in input modules, which type depends on whether the network is optical or electrical. Then

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the Ethernet frames are sent into the switch via receiving ports. When entering the switch, the Frame Check Sequence (FCS) is checked and the frame is stored in a First In First Out (FIFO) queue. Then the address field in the frame is read, and matched in an address lookup process to the right outgoing port. Afterwards the frame is again stored in a FIFO queue, before it is sent to the outgoing ports and transmitted via output modules. Fig. 3 illustrates the composition of an Ethernet switch. All of these processes consume energy depending on the fronthaul link bitrate.

In an Ethernet fronthaul network, each switch consumes energy related to the amount of incoming traffic. This is expressed in (3), where P_{FH} is the total power in W consumed when transmitting data over the fronthaul network between the RU and CU. P_{SW} is the total power consumed by one switch, and that is multiplied by the number of switches N_{SW}.

$$P_{FH} = P_{SW} \cdot N_{SW} \quad (3)$$

Equation 4 determines the power consumed in one switch. $P_{standby}$ is the power always consumed in the switch to keep it running. P_{pk} is the power consumed by the switch when forwarding one packet. P_{bit} is the power consumed by the switch when forwarding one bit.

$$P_{SW} = P_{standby} + P_{pk} \cdot N_{pk} + P_{bit} \cdot N_{bit} \quad (4)$$

To determine the power consumed by the switch when forwarding one packet, requires the power consumed by the process only used once per packet, namely the MAC address lookup (P_{MAC}). This function's power consumption is divided by the maximal number of packets forwarded per second.

$$P_{pk} = \frac{P_{MAC}}{N\ MAX_{pk}} \quad (5)$$

N Max_{pk}, the maximal number of packets forwarded per second, is calculated by dividing the switch's maximum line bitrate by the minimum packet size.

Determining the power consumed by the switch when forwarding one bit, requires the power consumed by the processes where each bit is handled, namely the reception (P_{RX}), the FCS check (P_{FCS}), two FIFOs (P_{FIFO}) and the transmission (P_{TX}). These functions power consumption is divided by the maximal number of bits forwarded per second.

$$P_{bit} = \frac{P_{RX}+P_{FCS}+P_{FIFO} \cdot 2+P_{TX}}{N\ MAX_{bit}} \quad (6)$$

N Max_{bit}, the maximal number of bits forwarded per second, is the switch's maximum line bitrate.

The given model is used for further investigation of the energy consumption in an Ethernet fronthaul network.

V. CASE STUDY

An Ethernet fronthaul limited by 20 km latency [5] using 3-sectorized antennas covering 13 km^2 per 3-sector, would need a total of 291 antennas/ RUs to cover the entire area. If the area is fully covered by four RATs (for example 3G, LTE, LTE-A and 5G) the total number of RUs in the area is 1164, considering (1). Using 24 port switches, this corresponds to 49 switches considering (2). These numbers only provide a rough estimate, but it gives the idea that 50 switches in the area covered by one CU-datacenter is not an unrealistic number.

The calculations in this paper use a Cisco Catalyst 9200 switch for reference. This switch has a standby power of 35 W [11]. The switch has a power consumption of 42,27 W in case of full port traffic and 100% load [11]. The difference between standby and full load is thereby 7.27 W. Dividing this number into four switch processes, those mentioned in the model (FCS, MAC, FIFO, FIFO), a rough assumption is that each process consumes 1.8 W. The switch is assumed to use 24 ports running 1 Gb speed and transmitting/receiving via SFP+ modules consuming 1.5 W each [12].

VI. RESULTS

Based on the bitrate numbers provided in Fig. 2 and the model outlined in Section IV, combined with the switch energy consumption numbers provided in section V, the following results are obtained, illustrated in Fig. 4-8.

Fig. 4 illustrates the input parameters from the model in Section IV. The numbers are based on functional split RF/PHY using 5G RAT for one switch. The energy consumption is illustrated on a logarithmic scale as a function of different packet sizes. The figure illustrates how

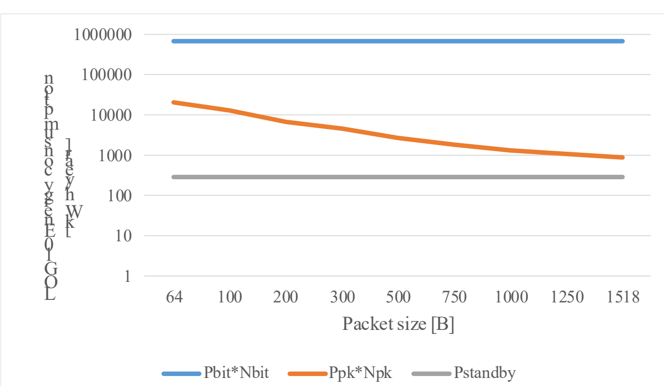

Figure 4. Energy consumption by packet size for the different elements in (3).

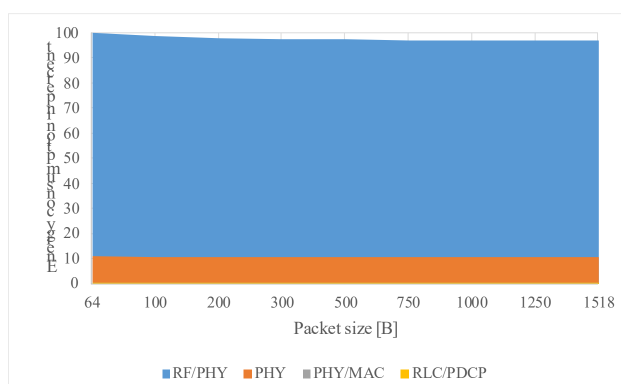

Figure 5. Percentage of energy consumption by increasing packet sizes using 5G RAT.

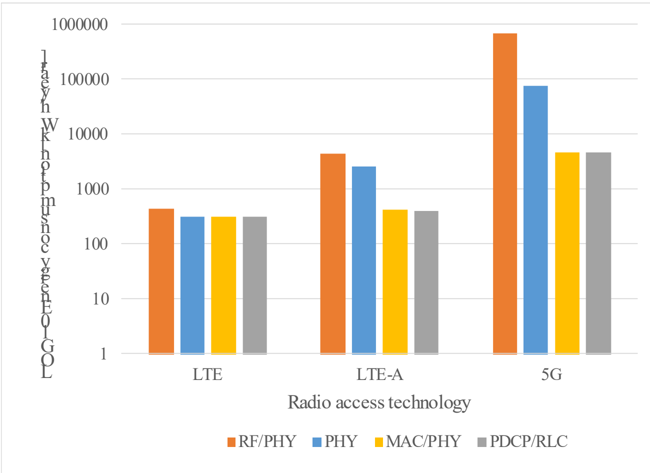

Figure 6. Energy consumption by radio access technology.

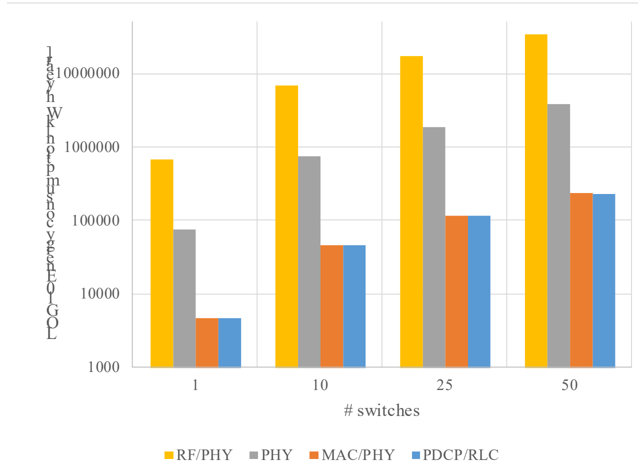

Figure 7. Energy consumption by increasing number of switches in 5G.

different sizes of packets do not affect the total energy consumed by all bits (Pbit*Nbit) and neither the standby power (Pstandby) this is as expected as none of these parameters are affected by increasing packet sizes. However, the energy consumed for all packets (Ppk*Npk) is much affected by different packet sizes. The decrease in energy consumption between transmitting only the smallest possible Ethernet packets, and only the largest possible Ethernet packets is 95.78%.

Fig. 5 illustrates the percentage of total switch energy consumption as a function of the packet sizes. The figure illustrates different functional splits using 5G RAT. It is clear that the RF/PHY split consumes the largest percentage of energy. The figure shows how large effect the packet size has, thus the energy consumption percentage decreases slightly when the packets are larger. It is not possible to see the functional splits PHY/MAC and RLC/PCP in the figure as they consume much less energy. However, in those splits the decrease in energy consumption between transmitting only the smallest possible Ethernet packet, and only the largest possible Ethernet packet is 2.66% in both cases whereas for the RF/PHY split the difference is 2.84%.

Fig. 6 illustrates the energy consumption in the fronthaul network when using different functional splits and different RATs. Note that it is illustrated on a logarithmic scale. This calculation assumes that the packet size is 1518 B. The figure shows the energy consumption in the fronthaul network using LTE, LTE-A and 5G RATs. The figure states huge differences in power consumption for the different functional splits using LTE-A and 5G. In 5G, the energy saving by using split PDCP/RLC compared to split RF/PHY is 99.32% per switch, compared to LTE where the energy saving is only 27.66% between the two splits. Or in other words if assuming one household consumes 3500 kWh per year, then the fronthaul energy consumption in 5G using split RF/PHY covers 199 households per switch, where split PDCP/RLC covers less than 1.5 households per switch. In Fig. 6, the power consumption for LTE does not differ much when comparing the different functional splits, meaning that

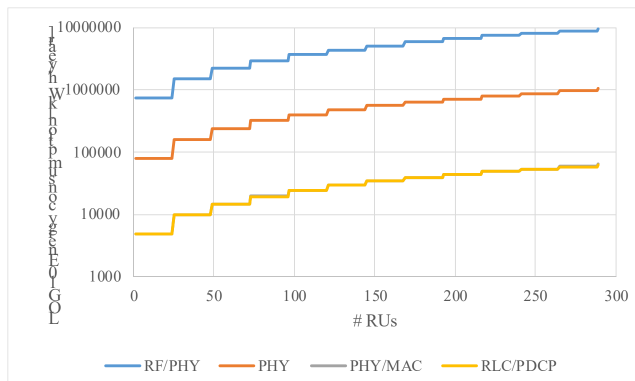

Figure 8. Energy consumption for 5G and different functional split options compared to amount of RUs.

significant energy consumption reductions or increases will not be present using this RAT.

Fig. 7 shows the yearly fronthaul energy consumption in kWh using 5G RAT This calculation assumes that the packet size is 1518 B. The energy consumption is illustrated by increasing number of switches. As the figure shows, then the Energy consumption increases by number of switches in the network. The figure illustrates how much energy is required to run a fronthaul network with many switches, as illustrated in the case study in Section V, where 50 switches did not seem unrealistic in the area covered by one CU-pool.

Fig. 8 illustrates on a logarithmic scale, how the fronthaul energy consumption increases when more RUs are added to the network. In the figure, each switch is assumed to have 24 ingoing ports, and the indent behavior of the graph shows the capacity of each switch.

VII. DISCUSSION

The energy consumption is an important matter considering all areas of the ICT sector. The fronthaul network must never be a bottleneck for the expensive RAN capacity, but neither should it consume more energy than

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necessary. In that regard, the fronthaul network must be carefully aligned. From the results, it seems like there is a large gap in the bitrates and energy consumption between the PHY split and the MAC/PHY split. The MAC/PHY split has the physical processing in the RU and handles all baseband processing in the CU. This means a relatively simple RU and a significantly lower energy consumption.

Results in this work show how the choice of a functional split, the number of RUs and the number of ingoing ports per Ethernet switch has huge impact on the energy consumption in an Ethernet fronthaul network. The energy consumption does not differ much between the different functional splits when considering LTE, but when entering the era of 5G, the fronthaul networks will suffer from large energy consumption. To lower the energy consumption in the fronthaul network, the choice of a functional split becomes very important, together with high capacity Ethernet switches, and packet sizes. Slight decreases are obtained by transmitting larger sized packets even in splits PHY/MAC and PCP/RLC. In this model, a fixed packet size is used which is very optimistic. In reality packets will be of different sizes, and the smaller packets, the more packets are necessary to transmit the same amount of data. At the same time, every packet carries a header, so more packets means more headers. Hence, using smaller packets, more bits have to be transmitted. In relation to that, it might not always be possible to fill up an entire Ethernet packet. Some functions in the protocol stack are time critical, e.g. the HARQ process [13]. In a time critical transmission, the packet might need to be sent before it is filled, leading to smaller packets and more overhead transmission.

Fig. 7 shows the energy consumed by up to 50 switches in a network. According to the roughly estimated calculation of the number of switches in Section III, then 50 switches in the coverage area of one CU is not unrealistic. It depends on several factors, for example, if the area is covered only by three RATs, then the number of switches required is reduced to 37. These assumptions are though not completely realistic. In reality the area might be fully covered by 3G and LTE RATs, and then LTE-A and 5G will be used to cover hotspots. Different cell sizes are not considered. Considering the energy consumption of 25 switches this corresponds to the energy consumption of 4975 households when using split RF/PHY in 5G and split PDCP/RLC covers less than 38 households.

The results representing 5G and the extremely high bitrates and energy consumption related to that is only an extrapolation, but is found useful as a guideline for what can be expected.

VIII. Conclusion

This work investigated energy consumption in Ethernet-based fronthaul networks for current and future mobile networks. The fronthaul network connects the RU at the antenna site and the CU located in a datacenter. A model for the fronthaul energy consumption was presented, taking the different steps of the switching process into account. The outcome of this work shows the extremely high importance of choosing the right functional split, when mobile networks are entering the era of 5G, as significant reductions in energy consumption can be obtained. Many assumptions have been made due to lack of data but the paper gives an overview of the energy consumption now compared to 5G mobile networks, and predicts that in a worst case scenario one switch will consume the same amount of energy as 199 households. Suggestions provided in this paper to lower the energy consumption in the fronthaul network includes: choosing a functional split with lower fronthaul bitrates, development of low energy consuming Ethernet switches with many ports, and attempt to fill up Ethernet packets in order to transmit as large packets as possible and utilize the already used resources to a higher degree.

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Nuclear Energy and Solving Global Environmental Problems

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***Abstract*— This paper shows how nuclear energetics is connected to global environmental problems, such as global climate change, depletion of natural resources, accumulation of industrial and consumption waste, air, water, and soil pollution, deforestation, desertification, and loss of biodiversity. The first six problems are closely intertwined with the planet's energy production. The use of fuels, especially of black coal, leads to a dramatic increase in air, water, and soil pollution levels, as well as to the accumulation of large waste amounts and catastrophic emissions of greenhouse gases. However, nuclear energetics allows harnessing energy without causing greenhouse gases and having the lowest carbon footprint all over its energy generation cycles. Nowadays, the impact of human activity on the biosphere has reached a global scale, changing the cycle of matter, the water balance of the planet, and radically affecting soils, vegetation, and fauna. Global environmental problems have become our reality. Anthropogenic activities have created new sources of pollution of the biosphere, which, ultimately, can create a threat to the existence of humanity itself. The comparison of the ecological effectiveness of various ways to generate energy shows that nuclear energy has an advantage over fuel energy sources with regards to all indicators and, along with water, wind and solar energy, forms the "green square" of the prospective energy development. Being natural-like as all the components of the "green square" nuclear energy is a direct embodiment of the sun's energy on earth.**

Keywords-energy; global environmental problems; climate change; depletion of resources; accumulation of waste; pollution; energy sources.

I. INTRODUCTION

The environmental threat to the existence of human civilization is officially recognized at the highest interstate level. Consumer attitude towards nature has put it on the brink of survival. The predominant patterns of production and consumption lead to environmental depletion increasing the risk to human life and health due to the reduced quality of the environment. Scientific and technological progresses have created a danger of an environmental catastrophe, and the very concept of development has been put into question.

Many scientific works have analyzed problems existing in modern global ecodynamics, including their connection to the growth of the planet's population, food and energy resources scarcity. The key features associated with the sustainable development of the nature-society system have been determined [1]–[3]. Researchers have come to the conclusion that global environmental problems and environmental safety are closely related to energy [4]–[9].

There is an urgent need to revise the scale of human values. For sustainable development, the energy issue needs to be dealt with.

The rest of the paper is structured as follows. Section III presents the state of the art. Section IV details our research and we conclude in Section V.

II. STATE OF THE ART

According to the report of the United Nations Committee on Environment and Development (UNEP – United Nations Environment Program), the prognosis for the development of humanity until 2032 is disappointing. Irreversible changes will occur under the influence of human activity on the planet. More than 70% of the earth's surface will be impacted one way or another, more than a quarter of all animal and plant species will be permanently lost; safe air, clean drinking water, undisturbed landscapes will be in deficit, and the ability of nature to recover from the human impact will diminish [10].

The high quality of the natural environment is a core value for humanity, an unconditional value category, and the essence of global environmental interests. According to the World Health Organization, 80% of all diseases are caused today by consumption of poor-quality drinking water [11]; according to the International Atomic Energy Agency (IAEA) estimates, five million people die from diseases associated with consumption of polluted and poor-quality water every year [12]. Water may become almost the main cause of future armed conflicts, same as oil today.

Statistical data on the ecological condition of Russia give disappointing forecasts. Today, more than a third of the urban population of Russia lives in areas where there is no atmospheric pollution monitoring, and more than half lives in cities with high and very high levels of atmospheric pollution [13].

Russia, along with the entire planet, has been experiencing serious environmental problems. The average air temperature has been growing, the permafrost has been receding, and various manifestations of climate instability have been observed.

V.I. Vernadsky saw the solution to environmental problems in changing worldview and ideological principles, i.e., in the noospheric thinking [14]. Therefore, the teaching of V.I. Vernadsky on the transition from the biosphere into the noosphere has recently become particularly relevant; it can serve as the basis for fundamental research on environmental problems and the practical search for their solution. The research on the patterns of biosphere development is key for rational environmental management.

Noosphere is the area of interaction between society and nature; within its boundaries, the rational human activity becomes the determining factor of development. According to Vernadsky, the basic prerequisites for creating the noosphere are the following:

- unification of humanity
- transformation of the means of communication and information exchange
- discovery of new sources of energy
- social welfare
- equality between all people
- eradication of wars

Vernadsky concluded that humanity would turn into a new powerful geological force transforming the face of the planet with its thought and work in the course of its development.

Technical progress allows performing two main tasks:

- to improve the efficiency of the use of the planet's natural and resource potential;
- to exploit new forces of nature for the benefit of humanity.

The reference to "new sources of energy" and "new forces of nature" is a characteristic feature of Vernadsky's creative heritage.

Today, humanity has come close to the discovery and use of new physical phenomena, which is confirmed by the discovery of the Higgs boson, also referred to as the God particle, which opens the era of practical use of brilliant ideas that interconnect mass and energy. A kilo of matter can be converted into the amount of energy equal to a half of the annual Sayano-Shushenskaya hydroelectric power plant output. The Higgs boson is the golden key to the transformation of mass into energy; and this greatest discovery confirms the correctness of noospheric ideas and strengthens the faith in the power of intelligence.

The noospheric worldview, closely connected with the development of science and education, will develop together with further scientific discoveries. Noospheric thinking outlines ways to use and develop natural forces in the interests of humanity, productivity growth, rational environmental management, and the preservation and development of public health.

Scientific thought offers energetic and material capabilities that allow humanity not only to exploit the biosphere but also to reasonably transform the earth's biosphere itself in order to conserve and multiply all resources, as well as to make them renewable.

For years, we lived without resource shortages because we used to be a part of a self-consistent resource turnover, we were self-sufficient. Over the past 200 years, we have created the technosphere, in which we live. Before that, we were a part of nature, we used muscular strength of our own, of horses, mules, donkeys, and camels; we used the energy of wind and water. We were a part of nature without disturbing its "metabolism". Then, we came up with a steam engine, we invented electricity; as a result, we have built the technosphere, which is absolutely antagonistic to nature. This is a problem because this system is eliminating the resources and it is working against nature itself.

The solution to the problem is the creation of a nature-like technosphere, the use of nature-like technologies. It is necessary to create fundamentally new technologies that can be a part of the natural circulation. The Sun is a thermonuclear energy source and hundredths of a percent of the Sun's energy are converted through the mechanism of photosynthesis into energy, which provides nutriment to everything on Earth. This is a closed resource circulation.

Nature-like technologies and the achievements of scientific and technical progress will solve the problems of sustainable development.

III. RESEARCH

Global environmental problems are closely related to energy problems. If all countries of the world reach energy consumption levels of the United States of America or at least of "saving" Japan in the next 15 to 20 years, the total energy consumption will increase in accordance with the population almost 15 times [15]. The world electric power industry is not ready for such a "great leap". There is not enough organic fuel on the planet. Therefore, we can draw the following conclusion: energy development must explore the use of new powerful sources of energy and abandon burning fossil fuels.

The relationship between global environmental and energy problems is particularly apparent when comparing two indicators: the mass of resources required to produce a unit of energy and the global impact of greenhouse gas emissions on nature.

Figure 1 shows the main characteristics of various energy generation methods with two global indicators, namely greenhouse gas emissions and energy output per unit of weight of a substance. These indicate the efficiency of using the internal energy of substances, i.e., nuclear and thermonuclear energy. The existence of the solar system is based on these; the two reactors—a nuclear one inside the Earth and a thermonuclear one in the Sun—will remain main sources of energy. The proportion of energy harnessed from hydrocarbons will remain the largest. However, the limitedness of oil and gas reserves is obvious. The prospect for their active use is clear only for a few decades. During this time, oil and gas in the energy industry must be replaced by other sources. There are only two alternative options, namely the use of coal or nuclear energy. Modern technologies using both these types of raw materials will allow meeting the growing energy needs of humanity for the next few hundred years.

Nuclear is much more attractive compared to coal in terms of its impact on the environment. Humanity has already exceeded the limit of possible industrial development while maintaining the stability of biological systems and has reached the threshold of self-destruction of the biosphere. Environmental threats, such as the greenhouse effect and irreversible climate change, acid rains, reduction of biodiversity, increase of the content of toxic substances in the environment, require a new development strategy involving the coordinated functioning of the economy and ecosystem.

WAY OF GENERATION		EMISSION OF GREENHOUSE GASES	AMOUNT OF ENERGY PER 1 KG OF SUBSTANCE
burning	coal > 1 kg of coal 567 g of ash	CO_2 = 2.76 t (from burning of 1 t of coal)	7 kWh/kg
burning	natural gas	CO_2 = 1.62 t (form burning of 1 t of gas)	14 kWh/kg
nuclear energy		CO_2 = 0	24,000,000 kWh/kg
thermonuclear energy		CO_2 = 0	60,000,000 kWh/kg
quark-gluon level	Higgs boson	CO_2 = 0	6,940,387,213,578,000 kWh/kg

Figure 1. Global efficiency of different ways of energy generation [13]

In September 2017, at the International Ministerial Conference on Nuclear Power in the 21st century organized by the IAEA, Director General of the ROSATOM State Atomic Energy Corporation Alexey Likhachev emphasized the key role of the nuclear power industry in ensuring sustainable development and the global switch to low-carbon generation: “Everybody understands that the future belongs to green power. Sun, wind, water and atom, while supplementing and strengthening each other, must form the green square which will be the basis of the world carbonless mix…We are not competitors; all green energy sources are parts of the solution to the problem of the global climate change… The nuclear power industry meets all requirements set for the power of the future. This is a source of stable and environmentally friendly pure energy obtained at low cost. Nuclear power along with solar, wind and hydro energy make up the so-called “green square”, which will serve as a basis of the global power balance in the future...”[16].

The concept of “green square” implies that nuclear power is one of the key components of “green” energy. Together with solar, wind and hydropower, nuclear power forms the “green square” which will provide the basis for the world’s future zero-carbon balance and sustainable development.

In addition to the removal of a substance per se, the use of resources, as well as the generation of waste, should be taken into account. For example, a water nuclear power requires the use of water to cool condensates, as any other power plant which uses thermal turbines (coal, oil, gas) does. Other renewable energy sources have a number of advantages in this regard. Water sources where they already exist do not cause unnecessary difficulties, as the water used to cool the condensates is returned to nature.

In addition, nuclear energy is related to the formation of Radioactive Waste (RW). This issue requires special attention [13]. These are nuclear materials and radioactive substances, the further use of which is not envisaged. The problem of RW accumulation is primarily ecological. It is inextricably linked to the legacy accumulated during the period of the country's military arsenal build-up, but at the same time, the solution of the task of the final placement of RW is the key to the development of the nuclear industry in the future. The problem exists and needs to be addressed without shifting to subsequent generations.

Until recently, Russia adopted the practice of long-term storage of RW and delayed resolution of issues regarding their final isolation. That is why the solution of problems with regards to radiation heritage and ensuring the safety of the population and the environment is a serious technical, economic and, above all, environmental and social objective.

In 2015, the Russian Federation submitted the Fourth National Report on the Implementation of Obligations Arising from the Joint Convention, which confirmed that the basic principle of State policy of the Russian Federation in the field of RW is the transition to the practice of burying RW.

The Russian Federation Federal Law No. 190-FZ "On Radioactive Waste Management" initiated the establishment of the Unified State System for Radioactive Waste Management (USS RWM) (Figure 2).

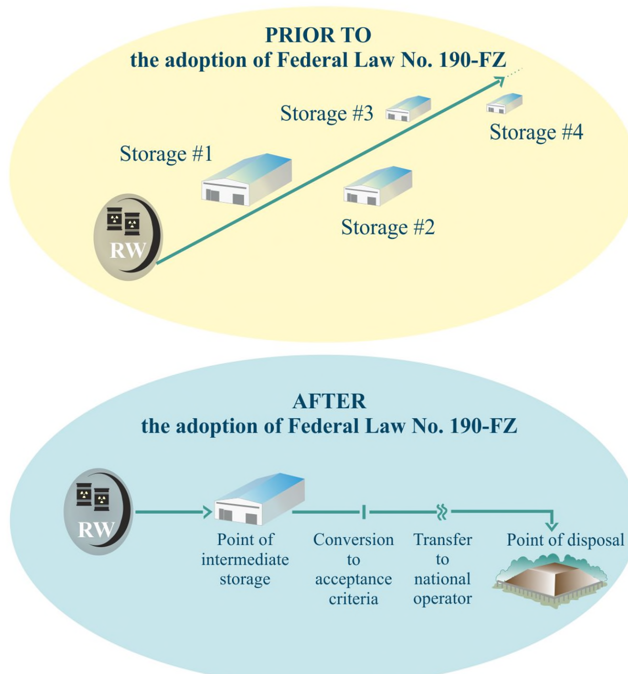

Figure. 2. Change of the system of handling the deleted RW after the adoption of Federal Law No. 190-FZ "On Radioactive Waste Management" [13]

The basic operating principles of USS RWM are:

- Priority to protect the life and health of present and future generations of people and the environment from the negative effects of RW;
- Prohibition of the import into and export from the Russian Federation of RW for the purpose of storage, processing and disposal, except in cases provided for in article 31 of Federal Law No. 190-FZ;
- Responsibility of organizations for ensuring safety in RW management up to their transfer to the national operator and for financial support of RW management works;

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- Accessibility to citizens and public associations of information related to safety and prevention of accidents regarding RW management, as well as other information on RW management.

The main purpose of the USS RWM is to organize and ensure safe and cost-effective management of RW, including its disposal. The Federal Law No. 190-FZ consistently reveals the composition, terms and stages of its establishment, and Government Decision No. 1185 of 19 November 2012 defines the procedure and terms for the establishment of the USS RWM. The formation of the USS RWM required profound changes at all stages of RW management (Figure 3) – starting with the technologies of RW management in organizations where RW is generated, and finishing with the formation of a national disposal operator and components of its structure.

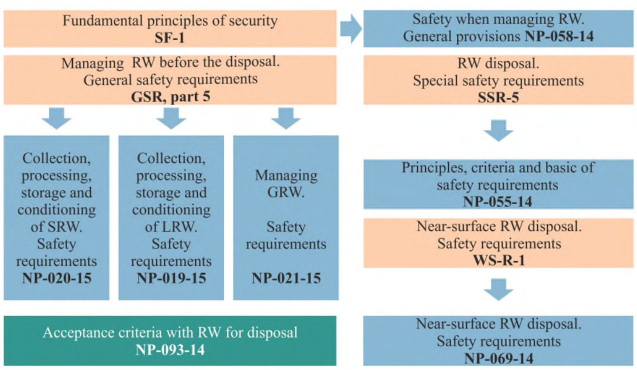

Figure. 3. Interrelation between IAEA safety requirements and Federal rules and standards which regulate safety during RW handling [13]

A fundamental solution to the issue is the transition to a closed nuclear fuel cycle [13]. The objectives of the transition to a closed nuclear fuel cycle are being formulated as follows. The first challenge is to fractionate high-level waste to escape disposal into deep geological formations to ensure safety and environmental acceptability. The second task is to develop industrial technologies of waste-free processing of Spent Nuclear Fuel (SNF), re-involvement of uranium, multiple recycling of plutonium, which is possible in a two-component system when by restoring the isotopic composition of plutonium developed in fast reactors, multiple recycling can be ensured. And the third, crucial task is international cooperation in accordance with the existing roles of countries in the two-component system, to comply with the nonproliferation regime.

Nowadays, it became obvious that the lifecycle of nuclear fuel does not end after it has worked the assigned term in the rector’s core, and then was stored for the required time period in the spent fuel pool. Open nuclear fuel cycle provides for long-term storage of SNF and its further disposal. Closed cycle refers to reusage of nuclear fuel through the processing of SNF and manufacture of secondary fuel. Secondary fuel refers to fuel based on fissile material recovered from SNF. These are not only the residues of uranium-235 (regenerate, regenerated mixture REMIX) but also plutonium-239 accumulated in fuel tablets during the operation of nuclear fuel in the reactor.

It should be noted that countries supporting the concept of SNF reprocessing and recycling are now forming the main agenda for expanding nuclear energy in the world. Indeed, the development of technology and the public desire to support the development of nuclear energy is connected with the decision to process SNF.

Two-component energy refers to the synergistic existence of a reactor fleet on thermal and fast neutrons, which allow to increase the efficiency of using the potential of initial natural uranium by tens of times, due to the fact that in fast reactors the 238th isotope of uranium will be used almost in full. Of course, systems with 100% efficiency do not exist, but the use of natural uranium in a two-component system will increase the efficiency of natural uranium usage by 100-150 times. This is sufficient to meet humanity's need for electricity in the next millennium.

Closing the nuclear fuel cycle requires effective solutions to improve SNF processing technologies, fractionation, inclusion of minor actinides in the fuel and afterburning them (as a possible option) in fast neutron reactors.

Coexistence of reactors on thermal and fast neutrons will make it possible to reduce the cost of nuclear energy generation, in particular for the water-water energetic reactor technology, because it will be possible to abandon boron regulation, zirconium, which will exclude the possibility of zirconium-steam reactions, transition to other fuel element shells.

The schematic diagram of two-component nuclear power can be depicted with rather complex connections, but in reality, is quite simple and understandable at the intuition level. These are existing technologies with conversion, enrichment, fuel fabrication, energy generation, SNF reprocessing and recycling products back to thermal neutron reactors, as well as fuel fabrication for fast reactors, reprocessing their SNF, "leveling" the isotope composition of plutonium for its possible recycle.

When recycled in thermal neutron reactors, the isotopic composition of plutonium is deteriorated. With the initial content of about 1% plutonium in the SNF of these reactors, the 239th isotope in the mass fraction of its isotopes is in the range of 55-60%. As a result of the first recycle in thermal neutron reactors, the proportion of the 239th isotope of plutonium is reduced to 35-40% of the total volume of plutonium contained in the fuel composition. Only the addition of plutonium of fast reactors allows the recovery of isotopic composition and the provision of multiple recycling.

IV. CONCLUSION

This analysis has shown that global environmental problems, such as, first of all, global climate change,

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depletion of resources, waste accumulation, and pollution, are closely intertwined with how humanity harnesses energy.

According to the results of the comparison of various energy sources and from the point of view of influence on the abovementioned environmental problems, the best energy source is nuclear, which along with hydropower, solar and wind energy forms the "green square" of natural energy technologies.

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Electric Vehicle Deployment in China and the Associated Implications on the Electricity Grid and Carbon Footprint: Lessons for South Africa

Fourth Industrial Revolution

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***Abstract*—Currently, there is a global acceptance of transforming the transport industry by replacing conventional vehicles by Electric Vehicles (EVs) as a means of reducing greenhouse gas and mitigating carbon emissions problems associated with conventional vehicles. The year 2017 was a milestone for sustainable automobile production, with electric vehicles deployments going above 100 million units globally. Much of the deployment occurred in China. China has the highest number of electric vehicles per capita in the world. The deployment approach has been very aggressive causing serious strain in its electricity grid and the environment as a result of a large amount of electricity demanded by this fleet of Chinese electric vehicles, and also as deploying electric vehicles in China is highly associated with the carbon emissions from electricity generated from coal. The South Africa automobile industry is preparing for a similar deployment model, in which 50% of all vehicles will be electric by 2050. Noting that South Africa currently suffers from endemic electricity supply inconsistency and as over 90% of its electricity is generated from coal, it is important to have an informed policy on the cost and benefits of the deployment model from lessons learned from China.**

Keywords - electric vehicles; policy approach; policy implication.

I. INTRODUCTION

The United Nation's Sustainable Development Goals (UNSDG) in general have an ambitious and transformational vision for the globe- striving for a world where the environment of humans and other species is safe, resilient and sustainable [1]. The Fourth Industrial Revolution builds on the digital and technological revolution and leads to unprecedented paradigm shifts in the grid warranting a transformation of entire systems. The automobile and transport industry is a significant influence of this shift through the introduction of EVs [2]. Most economies have generally supported that conventional vehicles should be replaced with EVs as EVs have the potentials to significantly reduce gas emissions from the transport sector. Viewing EVs deployment as an effective measure to reduce the climate impact of the transport sector, governments around the world have initiated strategies and frameworks to encourage producers and consumers to drive electric vehicles [3]. This study will be assessing China's policy implications as a road map for the South African deployment policy. China deployment strategy caused strain on its electric grid and increased its carbon footprint. Bearing in mind South Africa's weak electricity grid with typical periodic shortfalls and its significant electricity generation capacity from fossil fuel resources, more knowledge about the challenges ahead will be beneficial.

The rest of the paper is structured as follows. In Section II, we go over related literature review. Section III presents the methodology and Section IV is the results and analysis. The conclusion and future work are listed in Section V.

II. LITERATURE REVIEW

This section presents an overview of the developments to China's EV market and compares trends related to South Africa.

The Electric Vehicles Initiative (EVI) is a multi-government policy designed under the Clean Energy Ministerial (CEM) in 2009 [4]. The primary goal is "dedicated to conducting collaborative activities that support the design and implementation of EV policies and programs" [4]. The EVI currently has 16 member states as partners. The United States, Canada, and China are currently co-leading the EVI.

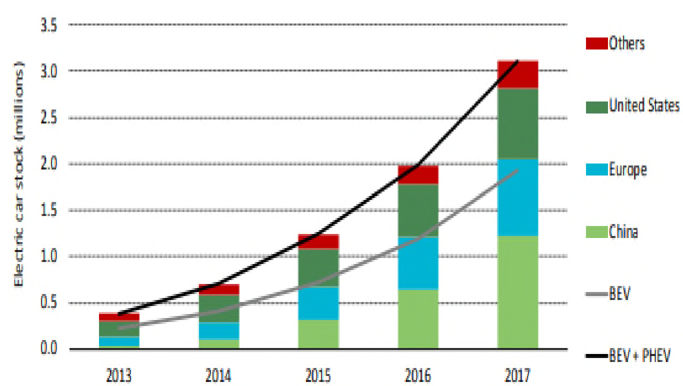

Figure 1. Evolution of the global electric car stock, 2013-2017, IEA [5]

According to [3], China is currently the largest electric car market in the world, accounting for more than 40% of all-electric car sales in the world as of 2016. "In 2016,

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China became the country with the largest electric car stock, with about a third of the global total with more than 200 million electric two-wheelers, 3 to 4 million Low-Speed Electric Vehicles (LSEVs) and more than 300 thousand electric buses" [3]. An increase in EV demand has also led to an increase in public and private charging infrastructure. "In 2016, the annual growth rate of publicly available charging (72%) was higher, but of a similar magnitude, than the electric car stock growth rate in the same year (60%)" [3]. Through the New Energy Vehicle (NEV) program, China aimed at an EV market stock of about 80 million by 2030. The aggressive deployment strategy has some associated implications on the grid and the carbon footprint of the country. South Africa Green Transport Strategy (GTS), with a goal aimed at transforming the transport sector to 50% EV by 2050, seems to be on this same path.

The International Energy Agency (IEA) [6] conducted an extensive research investigating different scenarios for EV deployment in China and the associated implications thereof with regard to energy portfolio, economics, and the environment. It identified that the impact of EVs in terms of CO2 emissions and on-grid capacity at the national level largely depends on the charging strategy and EV design. As a result, the analysis conducted in this paper utilized this important outcome as a basis for assessing the EV impact, by evaluating the effect of two commonly deployed EV designs (PHEV and BEV) in the Chinese market on independent variables.

III. METHODOLOGY

The Ordinary Least Square (OLS) was used to show evidence of a relationship between the independent and dependent variables. The following tests were performed:

- Unit root test
- OLS estimation test
- Serial correlation
- Normality
- Heteroscedasticity

A. *Data Sourcing and Limitations*

The dependent variables (total grid capacity, electricity generated from coal and emission from coal) were sourced from the World Bank. The independent variable (EV demand) was sourced from EV Volumes [8]. The analysis only considered 10 years of yearly data (2009 to 2019) due to a lack of data. The lack of accurate and reliable data has been identified as a significant problem hindering the development of useful EV-grid models and strategies [7].

B. *Model specification*

The Ordinary Least Square (OLS) model was employed in performing multiple linear regressions. A multiple OLS model is denoted as follows:

$$Y_t = \beta_o + \beta_1 X_{1t} + \beta_2 X_{2t} + \beta_3 X_{3t} + \varepsilon_t \qquad (1)$$

With reference to equation (1) indications represented are as follows:

Y_t = Dependent variable

β_o = The intercept of the equation.

β_{1-3} = The slope coefficient of the independent variables.

X_{1t-3t} = The independent variable that is used to predict the dependent variable.

ε_t = The error term.

The model specification (causality between the dependent variable to independent variables) of this paper was then equated as:

$$BEV\ /\ PHEV_t = \beta_0 + \beta_1 GC_t \beta_2 EGC_t \beta_3 EC_t + \varepsilon_t \qquad (2)$$

With reference to formula (2) indications represented are as follows:

PHEV = Plug-in Hybrid Electric Vehicles
BEV = Battery Electric Vehicles
GC = Grid Capacity
EGC = Electricity Generated from Coal
EC = Emissions from Coal

IV. RESULTS AND ANALYSIS

Traditionally, the OLS requires that a cointegration and error term be determined between the independent and the dependent variables through the Engle-Granger analytical technique. However, the technique was not utilized due to limited observations and also because the aim of the paper was mainly to show evidence of a relationship between the independent and dependent variables.

TABLE I. UNIT ROOT TESTS

Variables	ADF P-Values	PP P-Values
PHEV	0.0011	0.0532
BEV	0.0433	0.0633
GC	0.0534	0.0045
EC	0.0061	0.0550
EGC	0.0514	0.0007

TABLE II. ORDINARY LEAST SQUARE ESTIMATIONS FOR VARIABLES

OLS estimation for PHEV		
Variables	t-statistics	P-value
GC	-545.8878	0.0012
EC	187.2888	0.0034
EGC	-35.95261	0.0177
OLS estimation for BEV		
GC	-1345.742	0.0501
EC	3063.620	0.0034
EGC	-80.49225	0.0079

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All conducted unit root tests (Table I) produced a stationary outcome at 1st difference. The p values from all series were below 0.05.

The OLS estimation (Table II) detects if a relationship exists between the independent variables (*PHEV & BEV*) and dependent variables (*GC, EGC & EC*). Outcomes from estimation tests produced a *p-value* of results <0.05. The regression analysis further confirmed reliability by obtaining an R-squared of 94% for PHEV and 60% for BEV.

Table III presents the results of the diagnostic tests. Here, the errors were normally distributed. Serial correlation was not detected. The White's test and the Arch test reflect that the series are homoscedastic.

TABLE III. DIAGNOSTIC TESTS

Test	Measurement	P-values
Normality	Jarque-Bera	0.8762
Serial correlation	Correllogram test at (1st difference)	0.134
Heteroscedasticity	White's test	0.0940
	Arch test	0.1450

V. CONCLUSION AND FUTURE WORK

Replacing conventional vehicles with EV's deployment is a delicate transformation that requires extensive research that would guide policy towards reliable and applicable strategies. Instead of the current ongoing excitement concerning deploying EVs in South Africa as soon as possible, an effective cost-benefit analysis should be conducted on the currently planned deployment goals.

Important topics gathered from this study as lessons for South Africa are as follows:

- It is important to re-evaluate the deployment model to determine the percentage and grid network tolerance. It will be very aggressive to radically transform the transport industry such as 50% of all vehicles should be electric by 2050. South Africa does not have the potential for such a fast pace transformation, but rather a slower transformation with realistic periodic targets.
- End-user efficiency and consumption policing will be fundamental for ensuring consistency between the grid capacity and end-users demand. EVs penetration level of 50 % can cause serious low-voltage levels and grid supply shortfalls in the long-run to end-users.
- Other things to consider include: will the EVs market boom? Is complete automation an option, such as EVs with solar panels? Will the supply from renewable energy sustain the predicted demand?

The reflected evidence from China's case gives information on the importance of developing sustainable automated systems that can precisely monitor the demand of EVs to grid capacity periodically and also assess charging strategies and EV models to grid capacity. This study also aimed at achieving this objective.

In future work, the study will further asses the environmental and economic benefits of EVs technology in China to established evidence on the role of EV deployment to environmental wellness in the case of China.

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