Analysis of Blockchain in Solar Energy Systems

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***Abstract*— This paper is a descriptive review of utilisation of blockchain technology in solar energy (photovoltaic) systems. The 42 studied papers where extracted from the database SCOPUS using the research expression "Blockchain AND (PV OR photovoltaic OR "solar energy")", in titles of the papers, at April 22nd, 2022. A quantitative analysis is elaborated about authors, affiliation, journals, countries and authors keywords. A qualitative analysis of papers is more elaborated manually extracting the main problems encountered in solar energy systems and how blockchain technology brings some solutions. This study may help researchers and practitioners to direct their studies and solutions in a way to take advantage to the emergent blockchain technology.**

Keywords- ***blockchain; renewable energy; solar energy system; photovoltaic; PV, solar energy trading.***

I. INTRODUCTION

By this review, we are trying to shed light on the usage of the blockchain technology in the solar energy systems represented by the photovoltaic systems. The information is extracted from 42 papers from SCOPUS database. We used abstracts and full papers to study quantitative and qualitative aspects. The general principle is self-consuming [1] the solar energy and trading the surplus, this system is called prosumer. Other papers combine PV (Photovoltaic) operators and consumers of energy (Fig.1).

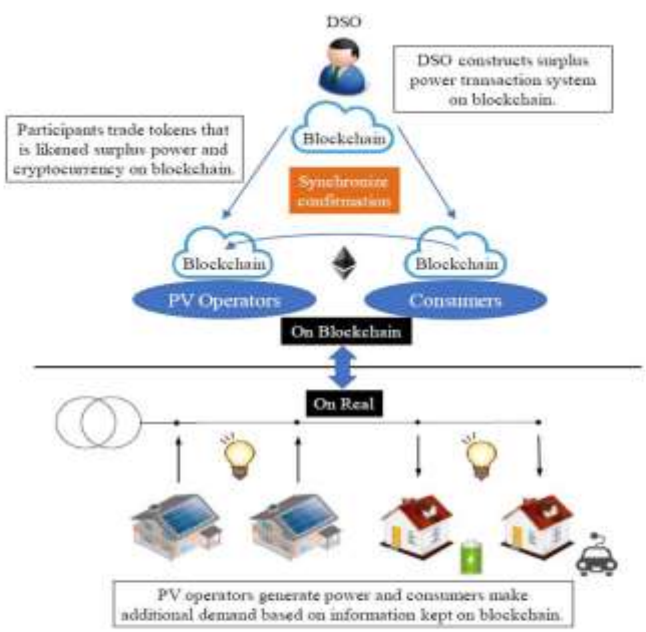


Figure 1. Schema of an example of generation for trading solar energy [8]

The paper treats two aspects. Section 2 offers a quantitative study of the papers (scientific production by year, author, affiliation, country, document type, subject area and citations). Section 3 is a citation analysis of papers, Section 4 is an authors' keywords analysis, then a qualitative analysis containing problematics and their solutions is presented in Section 5. The final section is a conclusion about the limits and trends on applying blockchain on solar systems.

II. SCIENTIFIC PRODUCTION ANALYSIS

In this section we'll show which year was the most productive in term of literature, which authors contributed more, which country is more interested in this topic and many other quantitative properties.

A. Scientific production by year

In the collection of papers, 2019 was the most productive year (13 papers). The decrease of production in 2020 is explained by the crucial pandemic situation. The increase in 2021 comes from the transformation of scientists and industrials to teleworkers. An increasing is expected in 2022, in a post-pandemic situation due to the awareness of industrials and governments about the importance of digitalization and comfort of the citizen's sides of life.

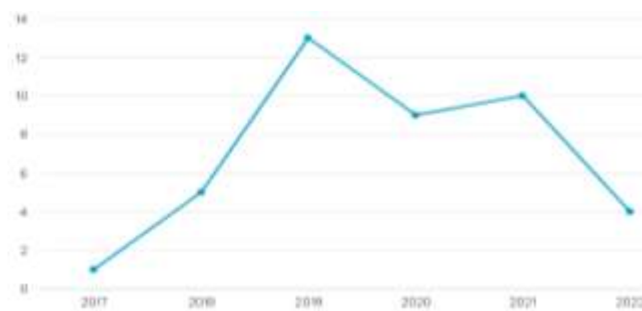


Figure 2. Production by year

B. Number by source

The shape of the graph is monotone; all sources are ex aequo in number of papers (1 paper per source), only one source (the journal of energy reports) has 2 papers related to the blockchain used in PV system. This fairness is explained by the consciousness of all the scientific communities about the advantages of blockchain in the management of PV energy.

Figure 3. Papers by year by source

C. Number by author

The analysis of authors (Fig. 4) shows that the first author in blockchain in PV energy (5 papers) is “Kim Taesic” affiliated to “Texas A and M University-Kingsville, Kingsville, United States” since 2017. His research interests are principally: engineering, energy, computer science and Mathematics.

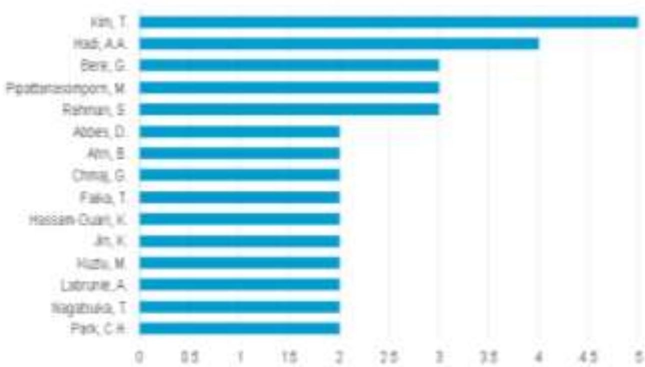


Figure 4. Papers per author

He has an h-index of 16 and 1033 citations on 71 published papers (Fig. 5), on energy and other domains.

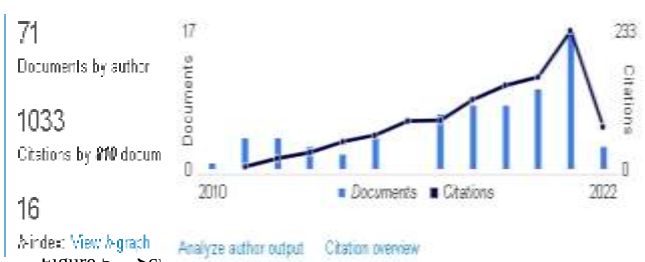


Figure 5. Sci

The second most productive in this collection of papers is “Hadi, Abdullah Al” by 4 papers, also affiliated to “Texas A and M University-Kingsville, Kingsville, United States”. Even his novelty (since 2019) in research, He has 8 papers cited 52 times and an h-index of 4 (Fig. 6). His interests of research are: Engineering, Energy, Computer Science and Chemical Engineering.

Figure 6. Scientific metrics of the author Hadi, Abdullah Al in SCOPUS

In the Third position (with 3 papers in the studied collection), comes the authors shown in Table 1.

TABLE I. AUTHORS IN THIRD POSITION

Author	Affiliation	Papers	h-index	Citations
Bere, Gomanth	Texas A and M University-Kingsville, Kingsville, United States	11	3	24
Pipattana sompon, Manisa	Chulalongkorn University, Bangkok, Thailand	105	35	5362
Rahman, Saifur	Virginia Polytechnic Institute and State University, Blacksburg, United States	365	48	11155

We notice that the fifth and the last author in table 1, has the highest number of citations. Even He is the low productive in Top 5 authors, He has the highest impact on scientific community.

D. Number by affiliation

The universities and laboratories look for the primary ranking positions, to be more visible and attractive to the international scientific competencies of lecturers and researchers.

Figure 7. Papers by affiliaion

The first productive university with 5 papers is "Texas A and M University-Kingsville". The university has a hole institute "institute for sustainable energy and the environment" interested in the issues of renewable energy and blockchain. It is followed by "Virginia Polytechnic Institute and State University" with 3 papers, and, the third position with 2 papers by 8 universities (Fig. 7), and then come the remaining affiliations by 1 paper.

E. Number by country

United States is the most productive country (Fig. 8) with 12 papers among 42, followed by China (10 papers) and India (5 papers).

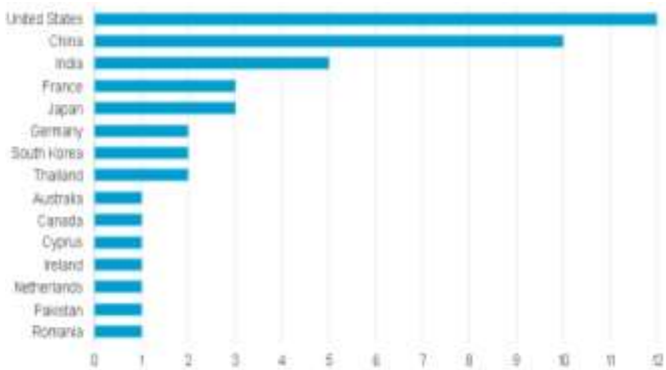
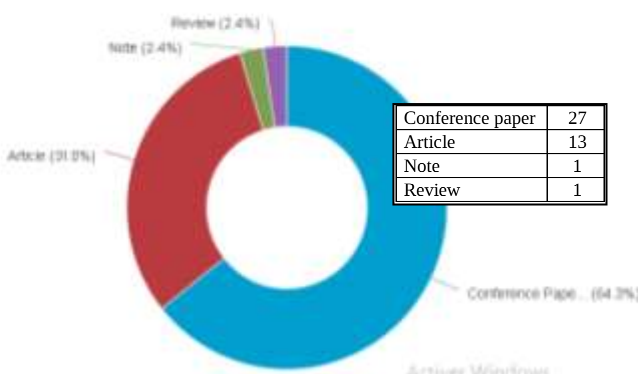


Figure 8. Papers by country

F. Number by document type

The conference papers are majority (64,3%), ie 27, followed by journal articles (31%), ie 13 papers. It is remaining 1 paper as a review and 1 paper as a note (Fig. 9).

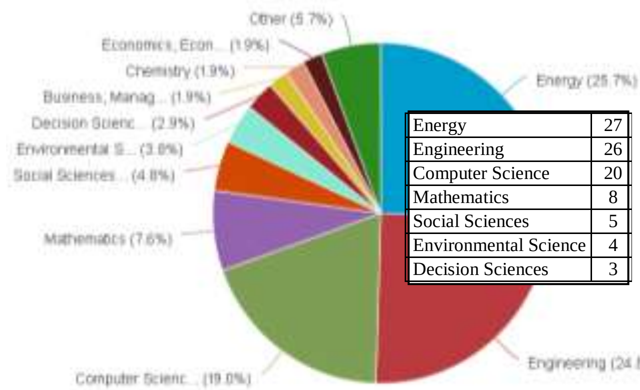


Conference paper	27
Article	13
Note	1
Review	1

Figure 9. Papers by document type

G. Papers by subject area

The papers are divided fairly on the subject areas of energy (27 papers) and Engineering (26 papers), in third position comes the computer science (20 papers). The remaining papers (Fig. 10) are shared on mathematics (8 papers), social science (5 papers), environmental science (4 papers)…etc.



Energy	27
Engineering	26
Computer Science	20
Mathematics	8
Social Sciences	5
Environmental Science	4
Decision Sciences	3

Figure 10. Papers by subject area

III. CITATION ANALYSIS

The citation analysis is the examination of the frequency and impacts of a scientific document over time. In this section we'll show different citation criteria to determine which paper contributed the most and in which year it appeared the most in others scientific documents.

A. Citations by year

Figure 11 shows that the citations are increasing over the years, showing a growing interest in strong and valid papers about energy, energy trading and blockchain technology. This was especially true in 2021 where all eyes were headed towards cryptocurrency and blockchain.

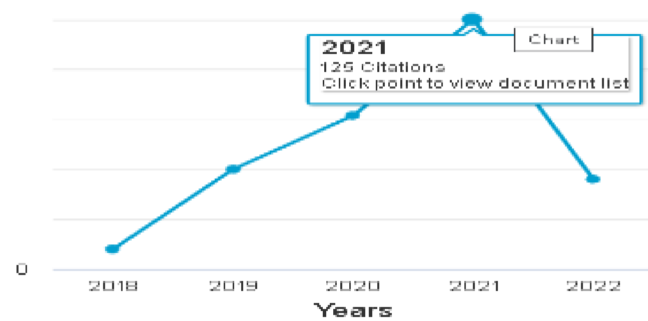


Figure 11. Citations per year

B. Citations by papers

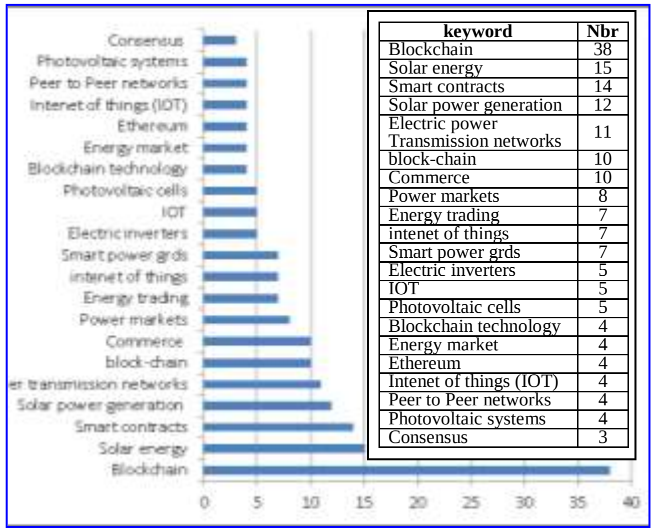
The most cited paper (86 citations) is entitled "Energy trading for fun and profit buy your neighbor's rooftop solar power or sell your own-it'll all be on a blockchain". The reasons are: (1) the notoriety of the paper (2012), (2) the usage of blockchain in managing the photovoltaic system was relatively new, (3) the paper responded to the questions: Would you pay slightly more for your electricity if you knew it was sourced from photovoltaic panels on your neighbor's roof? Or, if you are that neighbor, would you use your solar power to charge a battery and dump that energy back onto the grid at peak hours, when the price was highest? [24]. The second most cited paper [11] is entitled “Applying the blockchain technology to promote the development of distributed photovoltaic in China” (31 citations). Even though it is relatively recent (2018), but it was cited thanks to: (1) it is a review paper, it is more read than other papers, (2) it gives strengthens and weakenesses of the distributed PV system, by region and several environments like economic, social and technical one, (3) It explains what are the threats and how blockchain comes to improve the existing PV system. The third position of citations are two papers concerning the trading of PV energy in a hybrid system (self consumption and injection in a public grid) [23] [25], with 28 and 27 citations respectively (Fig. 12).

	Documents	Total
		300
1	Energy trading for fun and profit buy your neighbor's roofto...	86
2	Applying the blockchain technology to promote the developmen...	31
3	[Photovoltaic Trading Mechanism Design Based on Blockchain-b...	28
4	Distributed Solar Self-Consumption and Blockchain Solar Ener...	27
5	Trading solar energy within the neighborhood: field implemen...	21
6	Implementing blockchain technology in irrigation systems tha...	13
7	Internet of Things (IoT)-Enabled Solar Micro Inverter Using ...	11
8	A Blockchain-based Platform for Exchange of Solar Energy: La...	10
9	Blockchain-Based Communication and Data Security Framework f...	9
10	Comparative Analysis of Blockchain-based Smart Contracts for...	8
11	Application of Blockchain Technology in Peer-to-Peer Transac...	8
12	Blockchain in solar energy	7
13	A Novel Framework for Monitoring Solar PV based Electric Veh...	6
14	Blockchain-based Solar Electricity Exchange: Conceptual Arch...	6

Figure 12. Most cited papers

IV. KEYWORDS ANALYSIS

The keyword analysis is a quantitative and qualitative analysis of a paper. The most used words in the titles are “blockchain” and “solar energy”; of course, they are contained in the request introduced in the research zone in SCOPUS database. “block-chain” is appeared 10 times. The remaining keywords are “Smart contracts” to explaiin the automated rules concerning the generation and trading of the solar energy (Solar power generation, Electric power transmission networks, power markets,…etc.). The keywords also concern “Internet Of Things”, consensus and the most used cryptocurrency in them “ethereum”.



keyword	Nbr
Blockchain	38
Solar energy	15
Smart contracts	14
Solar power generation	12
Electric power Transmission networks	11
block-chain	10
Commerce	10
Power markets	8
Energy trading	7
intenet of things	7
Smart power grds	7
Electric inverters	5
IOT	5
Photovoltaic cells	5
Blockchain technology	4
Energy market	4
Ethereum	4
Intenet of things (IOT)	4
Peer to Peer networks	4
Photovoltaic systems	4
Consensus	3

Figure 13. Authors’ keyword frequencies

We can notice that blockchain is appeared like “blockchain” (38) and like “block-chain” (10) and like “blockchain technology” (4), in total 52 times. We find also that “peer to peer network” (4) is appeared because it supports the blockchain solution.

V. QUALITAIVE ASPECTS OF THE ANAYSIS

The remaining of the paper concerns a qualitative study, concerning aspects extracted after a full exploration of the papers.

A. *Energy generation or energy trading*

Twenty papers treat the problem of trading solar energy jointed to self-consumption. Two among them are surveys and eighteen papers treat the self-consumption of solar energy and other aspects.

Figure 14 shows the sequence diagram for the energy trading.

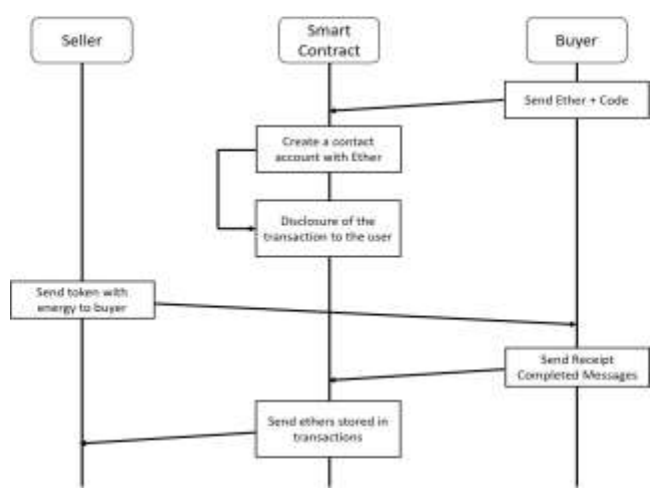


Figure 14. Sequence diagram for the energy trading [2].

In the energy trading platform, some participants have superfluous energy that they wish to sell to the platform as sellers, whereas others do not have sufficient energy to meet their demands and must buy the shortfall from the platform as buyers. Specifically, first, the buyer defines and sends Etherium and code so that smart contracts can be created.

B. Solar Energy System 4.0 (IOT and Blockchain)

Establishing a system using IOT (Internet Of Things) devices that produce the excess of energy. It consists of two parts: energy generation which maximizes the produced energy and energy trading using blockchain trading model ethereum based application. Enegy generation gains 35% [2]. There are 6 papers related to the IOT. [20] Provides continuous monitoring, data exchanging, and optimal operation in smart grid environments and in the IOT-enabled PV systems.

C. Other treated Ploblematics And Solutions

This section illustrates the encountered problems in solar energy systems, proposed solutions and the findings after applying these solutions. To avoid similarities, only 13 papers are explicited.

In [1], none of the existing studies provides a complete blockchain-based multi-dimensional P2P transaction mechanism. Fully open P2P trading mode and decentralized electricity price mechanism are adopted in day-ahead market, and P2P pool trading mode and electricity price mechanism based on supply/demand ratio are adopted in real-time market. The transaction mechanism designed can effectively realize P2P power transactions between producers and consumers, and promotes the enthusiasm of producers and consumers to participate in the P2P day-ahead market in order to maximize the benefits for prosumer target to achieve transactions between users according to different transactions. The objective of [2] is balancing power supplement from the solar energy's intermittent and unpredictable generation. A solar energy generation and trading platform EggBlock is proposed. It achieves reliable and transparent energy trading on the blockchain and converges to the optimal direction with short iterations. The average energy generation gain of 35% is obtained. How to optimise energy exchanges on a local energy community in a distributed way? [5]. It is possible to solve the optimization problem also with a distributed method using game theory, where each element of the grid tries to reach its own objectives, using real consumption and production data. It is possible to determine not only anomalies but also to create clean dashboards that can help on reporting how each classroom/auditorium is being used and who are the biggest offenders when it comes to power consumption and warning with alarms. The integration of distributed energy resources (DER) into centralized power markets on the large scale is challenging. The contribution of [6] is meeting future electricity demand. It provides valuable guidelines for the integration of DER into future sustainable energy markets. How to manage surplus PV output? The aim of [8] is to find consumers of surplus PV output and to match electricity supply and demand with market mechanism. Authors propose a new contract processing algorithm to calculate the nodal price in the area with surplus power transaction.

Abandoning solar energy in rural regions and increasing voltage fluctuation have become more prominent [3]. To increase the local electricity consumption of the photovoltaic generation, the incentive mechanism using an optimal internal electricity price is proposed with blockchain technology. The simulation result shows that the comprehensive revenue is increased, and the local electricity consumption rate of distributed photovoltaic generation is significantly raised.

Alao and Cuffe [12] investigate the impact of the delay resulting from a blockchain, and proposes a promising security measure, for a hierarchical control system of inverters connected to the grid. The blockchain communication network is designed at the secondary control layer for resilience against cyberattacks. A temperature-based weather derivative swap DeFi instrument is proposed in [13], it can serve as an effective volumetric risk hedging instrument at a negligible cost. It is only elucidative of the type of flexible hedging arrangements that can be enabled by blockchain, as any other weather index could be employed if required. In the same context [15], simulation method for smart inverters and blockchain network using a proposed framework as cooperative control approach, responded to different operating conditions.

In [16], authors adopt an appropriate mechanism that allows benefiting from the excess energy produced by these base stations and simplifies the process of energy trading while also making it cost-optimal.

A direct communication-based LCOE (BLCOE) is proposed in [17]; it is a model as the least-cost solution that measures the impact of energy reliability on generation cost. It considers daily variations in the cost of solar modules and battery storage across sub-Sahara Africa (SSA). Simulation results show the reduction of energy costs by approximately 95% for battery and 75% for the solar modules.

To avoid repetitions, the remaining papers are not presented because of the similarities with the presented ones.

VI. CONCLUSION

We saw in this paper how fast intrests in energy are growing. Many papers are published about this topic and many other technologies other than blockchain are integrated, which will lead to a mass distribution of the idea of exchanging excess solar energy with neighbours via a blockchain network using a proper coin. The main barrier here is how to transform a simple consumer to a prosumer. A P2P network is the most adequate architecture to support this platform. A cryptocurrency will make the trading more fluent. The prices of energy generally depend to the rules of offer/demand of the local or metropolitan market of solar energy. Knowing that the blockchain technology itself is a big consumer of energy, it is important to be autonome and a consumer of renewable energy like solar energy. This work may be usefull to developper of blockchain platforms and the producer of energy solar to take benefits both from their combination and to find exactly how to do so since the word blockchain can be difficult to combine with energy production In a future work, we will show other studies aspects from this collection of papers like: used protocols and consensuses, smart contracts, statistical methods, used data in blockchains…etc.

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