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Applications of P-graph to Carbon Management: A Mini-Review

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There is utmost urgency to decarbonize the various industry sectors to keep the global temperature increase within adaptable levels. The P-graph framework is a tool that can support the network design and optimization of new and integrated decarbonization and carbon management systems. An advantage of the P-graph is the capability to determine optimal and near-optimal network solutions that aid decision-making. P-graph is commonly applied in planning supply chain networks and designing reaction pathways and mechanisms but can also be used in designing and optimizing systems to reduce carbon emissions. This work surveys the P-graph literature on decarbonization and Carbon Management Networks (CMNs). Bibliometric analysis is used to identify the trends, knowledge gaps, and potential future research areas. P-graph studies related to biomass and renewable energy are dominant research areas in this sub-area of study. Emerging topics include bio-hydrogen renewable energy, Negative Emissions Technologies (NETs), and Carbon Capture and Storage (CCS). Trend analysis suggests that P-graph approaches to biorefineries, product design, uncertainty, and risk analysis will continue to grow. Other combined techniques with P-graph such as the use of sustainability indicators, reliability and criticality analysis, multi-criterion decision analysis (MCDA), Life Cycle Optimization (LCO), and Monte Carlo simulation extend the capabilities of P-graph. A knowledge gap exists in P-graph approaches to green ammonia, solar, hydroelectric, and other renewable energy sources and products, which points to potential research opportunities.

1. Introduction

Human activities have caused the global temperature to increase by 1.1 °C, and further anthropogenic GHG emissions will cause the temperature to rise above adaptable levels (UNFCCC, 2021). In the recent COP26, nations agreed on adaptation and mitigation actions against climate change, highlighting long-term, low greenhouse gas emission development strategies (UNFCCC, 2021). Such strategies include clean power generation and energy efficiency measures (IPCC, 2022). Carbon Dioxide Removal (CDR) or Negative Emissions Technologies (NETs) can also partly address the residual emissions to reach the climate goals (IPCC, 2022). There is utmost urgency to decarbonize the various industry sectors given the rapidly depleting carbon budget (IPCC, 2022). Different approaches to decarbonization include the classic solutions (stretching operating boundaries, optimizing furnaces, heat pumps, process heat recovery), turning to renewable energy, using green chemicals, Carbon Capture Utilization, and Storage (CCS or CCUS), and electrification (IPCC, 2022). Many of these approaches rely on Process Integration (PI), which is defined as an overall design and operation approach to unify the processes (Klemeš, 2022). PI was first implemented in heat recovery systems but further expanded to pollution prevention, renewable energy planning, etc. (Klemeš, 2022). The usefulness of PI in fighting climate change is now recognized.

The application of PI tools like Mathematical Programming (MP) and Pinch Analysis (PA), resulted from the need to solve complex, combinatorial network problems (Klemeš and Varbanov, 2015). Aside from MP or PA, the P-graph framework is a powerful and efficient tool for solving Process Network Synthesis (PNS) (Friedler et al., 1992b) or PNS-like problems (Friedler et al., 2019). An advantage of the P-graph framework is the capability to exhaustively enumerate alternative solutions (Tan et al., 2018). Over the years, P-graph has been applied to

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PNS and PNS-like problems including supply chains, reaction pathways and mechanisms, chemical process synthesis, energy conversion, etc. (Klemeš and Varbanov, 2015). A new book by Friedler et al. (2022) discusses the diverse applications and future directions of P-graph. Focusing on the topic of decarbonization, a review by Lam (2013) underscored the application of P-graph in cleaner production network synthesis and carbon emissions reduction strategies. Since 2015, several papers on this topic have been published. A paper by Tan et al. (2016) established the use of P-graph as an alternative to PA and MP in planning Carbon Management Networks (CMN).

This work surveys the recent developments in the P-graph approach to decarbonization and CMNs. This review differs from previous P-graph reviews as it focuses only on these two research areas. The secondary objective of this work is to identify the trends, knowledge gaps, and map potential areas for future research on this topic using bibliometric analysis. The rest of the paper is organized as follows. Section 2 gives a brief overview of the P-graph framework. Section 3 reports the current P-graph literature on decarbonization and CMNs. Section 4 presents the applications' topical coverage and impact. Section 5 discusses the knowledge gaps and future research potentials. Finally, section 6 gives the conclusions of this work.

2. Overview of the P-graph framework

P-graph was first developed to solve PNS problems in plant design (Friedler et al., 1992b). The framework uses a bipartite graph, representing process units (O-type modes shown as horizontal bars), material streams (M-type nodes shown as solid/hollow circles), and arcs to show the relationship between the process units and materials (Friedler et al., 1992b). Five axioms of the P-graph (Friedler et al., 1992b) were the basis for the development of three efficient algorithms (Friedler et al., 1992a). For any given PNS problem, the Maximal Structure Generation (MSG) algorithm rigorously generates an error-free superstructure of the problem, the Solution Structure Generation (SSG) algorithm enumerates all combinatorially feasible structures, and the Accelerated Branch-and-Bound (ABB) algorithm efficiently determines the optimal solutions (Friedler et al., 1992a). The features of the P-graph improve the computational efficiency compared to MP solvers by multiple orders of magnitude (Klemeš and Varbanov, 2015). Another advantage of using P-graph as opposed to traditional MP is the automatic generation of optimal and near-optimal solutions which can then be subjected to further comparative analysis (Tan et al., 2017). This feature is advantageous to carbon management to provide options for decision makers. Some near optimal solutions may be more practical or more robust compared to the optimal solution. Finding such solutions using MP requires the addition of integer cut constraints (Voll et al., 2015). A detailed tutorial on P-graph algorithms and applications in Process Systems Engineering (PSE) are found in a recent book (Friedler et al., 2022). The free software (P-graph Studio), technical support, and tutorials are available via the website (www.p-graph.com) hosted by the University of Pannonia in Hungary.

3. P-graph for decarbonization and CMNs

This section presents the recent literature on the P-graph approach to decarbonization and CMNs, divided according to sub-topics on renewable energy, efficient energy systems, CCS, and NETs.

3.1 Renewable energy

Several studies have been found on the application of P-graph in designing and optimizing biomass supply chains, biorefineries, and bioenergy parks using dedicated crops or agricultural wastes, and only a few have been found related to other renewable energy sources. A study used P-graph to cluster and synthesize regional energy supply chains using biomass (Lam et al., 2010). Another study on biomass supply chain networks in Malaysia used P-graph to interconnect plant mills, hubs, and plants with palm oil as fuel (Haleem et al., 2015). P-graph was used to design a sustainable agricultural waste-based energy supply chain by introducing emergy as a sustainability indicator (Vance et al., 2015). A large-scale biomass supply chain network was modeled via the decomposition approach to simplify a usually complex problem, and was demonstrated in a case study using various types of biomass and biomass residues (How et al., 2016). P-graph was used to design a biorefinery that converts wood residues into multiple products (kraft pulp and bioenergy) and the profitable products were screened by optimization (Atkins et al., 2016). The framework was also applied in bioenergy parks, which is a network of biomass processing industries (Benjamin, 2017). The model is integrated with a risk-based criticality index, which quantifies the effect of supply-side disruption (Benjamin, 2017). A study used P-graph Life Cycle Optimization (LCO) in green ammonia production as automotive fuel, using carbon and nitrogen footprints (Angeles et al., 2017). The pre- and post-treatment pathway of the anaerobic digestion of lignocellulosic waste was also optimized using P-graph to find the most cost-optimal solution (Fan et al., 2018). A novel debottlenecking approach was developed by incorporating P-graph with Sustainability Indices (SI) in biomass supply chain networks (How et al., 2018). Bioenergy using anaerobic digestion of Municipal Solid Waste (MSW) to reduce carbon footprint was demonstrated in a P-graph model considering circular economy principles (Fan et al., 2020). A study developed a P-graph model for bio-hydrogen synthesis using palm oil mills as the sources and oil refineries and ammonia plants as sinks (Lee et al., 2020). Bio-hydrogen networks were also produced using methane from landfill gas and palm oil mill effluent were also optimized using P-graph (Hemmati et al., 2020). P-graph was also demonstrated in pyrolysis oil biorefineries by introducing new operating units (centrifuge and wet oxidation systems) (Pinheiro Pires et al., 2021). P-graph was applied in Integrated Biorefineries (IBR) producing multiple bioenergy and biochemical products based on various agricultural waste (Sangalang et al., 2021). The Multi-Criteria Decision Analysis (MCDA) tool VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) was integrated into P-graph to further evaluate the optimal and sub-optimal solutions based on multiple criteria in an agricultural waste-based biorefinery (How et al., 2021). The network design and optimization of bio-hydrogen using solar energy, palm oil mill effluent, and wastewater were also addressed (Affery et al., 2021). Only one study was found on the P-graph application to solar energy, which optimized a network of photovoltaic-based microgrids with battery-hydrogen energy storage (Mah et al., 2021).

3.2 Energy efficient systems

Decarbonization can also be achieved through efficient energy systems (IPCC, 2022). P-graph was used to design fuel cell-based cogeneration systems with carbon constraints (Varbanov and Friedler, 2008). P-graph was demonstrated in carbon-constraint energy sector planning for the strategic allocation of limited energy sources to multiple demands (Tan et al., 2016). P-graph was also used in designing smart energy systems, optimizing the energy supply distribution in a district (Maier, 2016). Efficient polygeneration systems generating multiple products (heat, power, cooling, and treated water) were optimized using a fuzzy P-graph model, which considers uncertainties (Aviso and Tan, 2017). The P-graph application in Total Site Heat Integration (TSHI), which integrates industrial clusters resulting in emissions reduction, was demonstrated in the kraft pulp industry (Ong et al., 2017) and in a district case study (Walmsley et al., 2018). Studies on heat integration, wherein simultaneous saving of water and energy is achieved such as in Heat-Integrated Water Network (HIWN), also employed P-graph (Chin et al., 2019). A multi-periodic P-graph was used in synthesizing the energy supply for a manufacturing plant (Éles et al., 2019). Reliability, which is critical in selecting process systems, was taken into account in heat-integrated systems using P-graph (Orosz et al., 2019). An integrated fuzzy P-graph was used in the cogeneration of electricity and heat and addressed multiple conflicting objectives by including indicators for targeting (Tay et al., 2020). A study used P-graph to optimize the heat energy distribution to consumers in a case study, which resulted in a reduction in carbon dioxide emissions (Kuznetsov et al., 2021).

3.3 CCS and NETs

Very few publications have been found applying P-graph to CCS and NETs. The planning of CCS retrofit through source-sink matching was demonstrated using P-graph (Chong et al., 2014). A P-graph and Monte Carlo simulation approach was developed for planning robust CMNs and was demonstrated by a case study on CCS (Tan et al., 2017). Negative emissions biochar networks were optimized using P-graph considering the presence of contaminants in a source-sink model (Aviso et al., 2018). The P-graph framework was also applied using the induction approach in ranking NETs, which bears similarities with Machine Learning (ML) techniques (Low et al., 2020). A negative emissions polygeneration plant with desalination was also designed using a multi-period P-graph model (Pimentel et al., 2021).

4. Topical coverage and impact

The published sources have been analyzed using the Scopus database (2022) by searching the term “P-graph” in the fields of title-abstract-keyword. The documents were screened and out of the 374 original documents, 82 remain under the topic of decarbonization and CMNs. Table 1 shows the distribution of the publications according to the categories of renewable energy, efficient energy systems, NETs, and CCS. The fundamental publications refer to review papers that promote the use of the P-graph in decarbonization and CMNs. The number of citations per group and publication years are also reported in Table 1. Figure 1 shows the yearly publications on P-graph related to decarbonization and CMNs, which shows a steady increase over the years.
Studies on P-graph related to decarbonization and CMNs appear as early as 2001. There is a growing trend in this sub-area, and it is projected that the number of publications will continue to increase. Studies on biomass under renewable energy have the highest number of publications, followed by efficient energy systems. These two topics have been in the literature since 2009 and 2001, respectively, and publications on these two topics have continued to the present. More recent P-graph topics have emerged under renewable energy since 2017, including applications in green ammonia (since 2017), bio-hydrogen (2020), hydroelectric (2020), and solar energy (2021). New topics on P-graph approaches to CCS and NETs also appear in 2017 and 2018, respectively. Trend analysis of the publications from 2015 to the present considering keywords that appear at

least four times shows that other recent popular keywords in this topic include risk and uncertainty analysis, refining, and product design. In terms of impact, the P-graph application in CCS has the highest number of citations per publication (32) although the topic is relatively new. This is followed by biomass renewable energy with 16 citations per publication and efficient energy systems with 10 citations per publication. Although a relatively new topic like CCS, the P-graph approach to NETs has 8 citations per publication.

Table 1: Publications on P-graph (related to decarbonization and CMNs), their impact, and publication years

Topical Group	Publications per group	Citations per group	Citations per Publication	Publication years
Renewable Energy	38	542	14	2009-2021
Biomass	30	495	16	2009-2021
Bio-hydrogen	5	24	5	2020-2021
Solar	1	5	5	2021
Green Ammonia	1	11	11	2017
Hydroelectric	1	7	7	2020
Efficient Energy Systems	33	340	10	2001-2022
NETs	5	38	8	2018-2021
CCS	3	96	32	2017-2019
Fundamentals	3	78	26	2013-2018
Grand Total	82	1,094	13	2001-2022

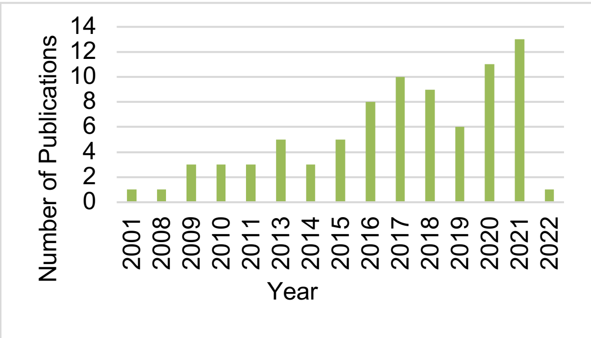

Figure 1: Yearly publications on P-graph approach to decarbonization and CMNs

5. Future research potential

P-graph approach to biomass renewable energy and efficient energy systems dominate the sub-area of study from 2001 to the present. Based on the literature review, P-graph is used for designing and optimizing biomass supply chains and biorefineries using dedicated crops and agricultural waste, as well as optimizing and screening profitable pathways and products based on biomass. Under efficient energy systems, P-graph is used in energy sector planning, energy distribution systems, polygeneration, and other integrated systems. Emerging topics that have a growing number of recent publications identified in Table 1 include P-graph approaches to bio-hydrogen (since 2020), CCS (2017), and NETs (2018). Based on the literature review, popular applications of P-graph in bio-hydrogen include planning hydrogen networks from sources such as palm oil mills and anaerobic digestion. On the other hand, P-graph approaches to CCS include optimization of source-sink retrofitting projects. P-graph approach to NETs includes optimization of negative emissions biochar networks and polygeneration plants with desalination. Novel techniques in combination with P-graphs are also developed including the decomposition approach (How et al., 2016), criticality analysis (Benjamin et al., 2017), debottlenecking and incorporating Sustainability Indices (How et al., 2018). Uncertainty handling by using fuzzy P-graph is also common. The analyses of optimal and sub-optimal solutions are done through MCDA techniques (How et al., 2021) and Monte Carlo simulation (Tan et al., 2017) for robustness. A knowledge gap is identified under renewable energy in the sub-topics of green ammonia, hydroelectric, solar, and other renewable energy sources and products. The small number of well-cited papers on the emerging topics of NETs and CCS also suggests a research direction with significant growth potential.

6. Conclusions

The P-graph framework serves as a valuable computational tool for carbon management. This work surveyed the recent developments in P-graph related to these topics. The dominant topics since the turn of the century are applications to biomass renewable energy and efficient energy systems. Recent topics that have emerged include other renewable energy (bio-hydrogen, green ammonia, hydroelectric, and solar energy), NETs, and CCS. Publication trends were analyzed to identify knowledge gaps and potential future research directions.

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