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Review

Revision on Symmetry in Thermal Fluid Sciences and Energy Applications

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Abstract: Symmetry is a fundamental notion in thermal-fluid sciences and energy applications and an important tool for understanding the properties of complex systems. Thermal and fluid processes are applied in several modern energy use technologies, basically consisting of the complex multidimensional interaction of fluid mechanics and thermodynamics. A comprehensive analysis involves vector and scalar quantities in the flow field, where symmetry is highly considered in order to simplify geometric parameters. These requirements therefore are also applied to experimental techniques, and the interconnection between experimental analysis and numerical simulation of processes is an important field. Thus, there is a wide range of symmetry solutions for this research area, the results of which contribute to the development of science and fast information for decision-making in industry.

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1. Introduction

Symmetry is a principle that permeates science and engineering, providing a powerful tool for simplifying and solving complex problems [1,2]. The presence of symmetry is common in several types of scheduling problems. Symmetry can occur when one is scheduling a collection of jobs on multiple identical machines, or if one is determining production schedules for identical machines. The most used symmetry-breaking methods is reinforced by the symmetry group special structure in scheduling problems. The symmetry-breaking efficiency of the scheduling methods problems was examined and presented a modified version a powerful symmetry-breaking procedure. Samples were produced to provide computational results in order to comparing different methods of symmetry breaking and discuss when it should and should not be used in practice [3,4].

In thermal sciences and fluid dynamics, symmetry mainly helps describe the behavior of physical systems under different conditions, facilitating measurements, modeling and analysis. The physical analyzes consider the simplest possible models of natural phenomena in order to relate the most important features to formulate predictions, due to the limitations of the mathematical apparatus. Thus, describing sometimes complicated multicomponent systems as a simple result led to the success of statics in machine design and construction, allowing us to understand the interactions between these elements. On the other hand, the subsequent success of Newton's theory of gravity and Maxwell's theory of electromagnetism allows us to explain distinct phenomena. Such behaviors that are apparently very different and unrelated intuitively can be described by elementary interactions through a few simple equations. As a direct consequence of these successful achievements, reductionism employing symmetry has become an important tool in science [5,6]. This article reviews the fundamental concepts of symmetry in these fields and explores its practical implications in energy applications.

2. Analysis of the Application of Symmetry in Thermal Sciences

The application of symmetry in thermal sciences has garnered significant attention, reflecting its profound implications across various subfields, including mechanical systems, turbulence modeling, plasma physics, and nanotechnology. This literature review synthesizes key contributions from seminal articles that elucidate the role of symmetry in enhancing our understanding and capabilities within thermal sciences.

The exploration of variational principles in mechanical systems with symmetry was performed highlighting how symmetry facilitates the reduction of complex variational principles and informs the development of accurate integration algorithms [7]. Also, this work emphasizes the importance of preserving structures during discretization, which is crucial for accurately simulating mechanical systems, including thermal dynamics.

Building on the foundation of symmetry in fluid dynamics the consequences of symmetries in turbulence modeling were examined [8]. Also, was demonstrated that symmetries not only lead to conservation laws via Noether's theorem but also influence the derivation of Navier-Stokes equations and their solutions. This work findings underscore the necessity of maintaining symmetry in turbulence models to accurately represent physical phenomena, particularly in the context of heat transfer.

Expanding the discussion to plasma physics where symmetry considerations are pivotal in addressing nonlinear problems [9]. By identifying symmetries in integro-differential equations of kinetic plasma theory, illustrated how these principles can simplify the analysis of complex plasma behaviors, which is relevant to thermal processes in energetic environments.

Further contributed to the discourse by connecting symmetry principles to thermodynamic theory, positing that symmetry is foundational to understanding macroscopic properties of matter [10]. This perspective aligns with the notion that symmetry informs the conservation laws governing thermal processes, thereby reinforcing its significance in thermal sciences.

The evolving concept of symmetry within theoretical physics was synthesized [11], identifying its multifaceted roles in model construction and classification. This conceptual framework is vital for understanding how symmetry influences thermal phenomena, particularly in the context of emerging technologies and materials.

A comprehensive review of advancements in nanoscale thermal transport was performed, emphasizing how symmetry principles underpin the behavior of materials at the atomic level [12]. Their analysis highlights the challenges and opportunities presented by nanoscale effects, which necessitate a refined understanding of thermal conduction and related phenomena.

An innovative method for detecting symmetry in scalar fields was introduced, emphasizing the importance of symmetry detection in data analysis and visualization [13]. This work suggests that understanding symmetry can enhance our ability to analyze thermal fields, potentially leading to improved thermal management strategies.

The implications of statistical scaling symmetries in incompressible Navier-Stokes turbulence were critically examined [14]. Cautioning against misinterpretations of symmetries, which could lead to erroneous conclusions in thermal modeling, highlighting the need for rigorous analysis in thermal sciences.

The work [15] illustrates the practical implications of symmetry in optimizing thermal systems, particularly in engineering contexts, focused on symmetry detection in 3D models, proposing algorithms that leverage symmetry for applications in thermal management

Revisiting the symmetry properties of linear parabolic equations, providing a unified framework for understanding transformation and symmetry group properties [16]. This theoretical grounding is essential for advancing thermal analysis methodologies. discussed emergent symmetries in various physical systems, emphasizing the relevance in low-energy regimes. These insights contribute to the understanding of how symmetry influences thermal phenomena in complex systems.

The significance of identifying symmetries in heat exchanger network design was highlighted [17], demonstrating how symmetry can streamline optimization processes. Their findings illustrate the practical benefits of symmetry in enhancing thermal system efficiency.

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The interplay between symmetry and symmetry breaking in elliptic PDEs, revealing how these concepts are fundamental to understanding thermal phenomena, particularly in phase transitions and stability analysis [18].

Thermal convection and its relationship with symmetry in thermal metamaterials was examined, proposing a new perspective on heat transfer that integrates symmetry considerations into the design of thermal systems [19].

A review on heat transfer analysis in various cavity geometries, underscoring the diverse applications of symmetry in optimizing thermal performance across different configurations was conducted [20].

Focused on symmetry breaking in thermal photonics, the work [21] illustrating how manipulating symmetries can enhance control over thermal radiation. Their work reflects the innovative applications of symmetry in modern thermal engineering.

The non-equilibrium thermodynamics of heat transport in advanced materials was addressed, emphasizing the role of symmetry in understanding and tailoring thermal properties at the nanoscale [22].

However, symmetry is not merely an aesthetic consideration in thermal sciences but a critical principle that informs theoretical frameworks, enhances modeling accuracy, and drives innovation in thermal management technologies. Also, symmetry in thermal sciences refers to the invariance of the physical properties of a system under specific transformations, such as rotations or reflections. This property is essential for the formulation and solution of heat transfer equations, allowing significant simplifications. The implicit solution of the second order nonlinear ordinary differential equation which governing heat transfer in rectangular fin was obtained by symmetry reduction methods. [23–25].

Describing heat transfer in nonlinear domains and discontinuities, such as what happens at propagation fronts between different phases, is very complex, which makes the solution very computationally expensive. Conservation laws are formulated as partial differential equations, which are solved by discretization methods, such as the finite element method, in which an alternative approach to such problems is based on the nonlocal formulation. In practical engineering problems, they are usually considered with axial or spherical symmetry in order to simplify the equations and substantially reduce the problem processing time. In addition, specializing the nonlocal description for such situations would decrease the number of particles by several orders of magnitude, which leads to a huge reduction in computational time. This allows analysis of larger domains or with higher resolution, as best suited to demand [26]. So, symmetry in Heat Transfer due to geometry can be derived in fundamental parts. Namely: Spherical Symmetry: Used in the analysis of heat transfer in spheres, such as in particles or droplets. Spherical symmetry simplifies the general heat conduction equation by reducing it to one radial dimension, which facilitates analytical and numerical solutions; Cylindrical Symmetry: Common in problems involving tubes and cylinders, such as heat exchangers. Cylindrical symmetry allows the analysis of problems in cylindrical coordinates, which is particularly useful for heat exchange systems between fluids moving inside and outside tubes; Plane Symmetry: Relevant for heat transfer in flat walls and surfaces. Plane symmetry is often used in heat conduction problems in two-dimensional geometries, such as plates and thin films.

The main topics of symmetry in thermodynamics (and sometimes encompassing thermos-fluid dynamics) involve fundamental and applied concepts that help to understand how thermal and fluid systems behave under different conditions. Here are some of the most important topics: Noether's Theorem and Conservation of Energy: Noether's theorem relates continuous symmetries of physical systems to conservation laws. In thermodynamics, this can manifest itself as conservation of energy, momentum, and other physical quantities [27,28]. Symmetry and Equations of State: Study of how symmetries impact the equations of state that describe the properties of pure substances and mixtures, such as pressure, volume, and temperature [29,30]. Heat Transfer and Symmetry: Analysis of how the symmetry of a system can simplify the solution of problems of conduction, convection, and thermal radiation.

Examples include spherical symmetry in heat conduction in spheres and cylindrical symmetry in tubes [31,32]. Symmetry in Irreversible Processes: Investigation of how symmetry applies to irreversible thermodynamic processes, such as entropy generation and energy dissipation. The analysis of relaxation processes and equilibria in nonlinear systems often involves dynamical symmetries [33–35]. Fluid Thermodynamics and Symmetry Breaking: Exploration of phenomena in fluids where symmetry is broken, such as in the transition from laminar to turbulent flow, where complex patterns emerge due to instabilities [36–38]. Symmetry in Thermal Materials: Study of materials with specific thermal properties that exhibit particular symmetries, such as thermoelectric crystals and materials with thermal anisotropy, which have different thermal conductivities in different directions [39,40].

Thermal Fluid Dynamics: Analysis of fluid systems under the influence of thermal gradients, such as convection cells in bottom-up heated systems, which often exhibit hexagonal symmetry or other geometric shapes [41,42]. Symmetry in Renewable Energy Systems: Applications of symmetry in the design and optimization of renewable energy systems, such as solar panels and wind turbines, where symmetry can influence efficiency and performance [43–45]. Mathematical Modeling and Computational Simulations: Use of symmetry techniques to simplify governing equations in thermal and fluid systems, facilitating more efficient analytical and computational solutions [46,47]. Symmetry in Combustion Processes: Study of symmetry in flames and combustion processes, where the temperature distribution and the formation of combustion products can exhibit symmetry under certain conditions [48–51].

The Fourier equations for heat conduction, together with the appropriate boundary conditions, can be significantly simplified in systems with symmetry. For example, the heat conduction equation in spherical or cylindrical coordinates reduces the mathematical complexity involved, allowing the obtaining of analytical or semi-analytical solutions [52].

3. Symmetry in Fluid Dynamics

The exploration of symmetry in fluid dynamics is a multifaceted endeavor that has garnered significant attention in the academic literature. From the foundational principles of hydrodynamic stability to the intricate applications of symmetry in turbulence modeling, researchers have sought to elucidate the critical role that symmetry plays in understanding fluid behavior.

The stage by reviewing the relationship between hydrodynamic stability and turbulent flows was set [53], establishing a rigorous mathematical framework that connects nonlinear energy stability criteria to global transport bounds. This foundational work highlights how stability considerations, particularly in thermal convection, can yield insights into turbulence dynamics, emphasizing the importance of laminar boundary layers in controlling transport phenomena.

Building on this foundation, [54] delve into the symmetries of Lagrangian actions in ideal compressible fluid dynamics and magnetohydrodynamics (MHD). Their work, rooted in Noether's theorem, reveals how these symmetries lead to conservation laws, providing a deeper understanding of the physical underpinnings of fluid dynamics. The introduction of relabeling symmetries and their implications for conservation laws in fluid systems further enriches the discourse on symmetry in fluid dynamics.

In a more applied context, [55] discuss the implications of symmetries on turbulence modeling. They argue that many existing turbulence models neglect the symmetry group of the Navier-Stokes equations, which can lead to the loss of essential physical properties. Their work emphasizes the necessity of incorporating symmetries into turbulence models to preserve the underlying physics of fluid flows.

Expanding the discussion to symmetry breaking in free surface flows, [56] employing bifurcation theory to analyze the stability of falling film flows. This work illustrates how instabilities can arise from symmetry breaking and how these phenomena can be beneficial or detrimental depending on the specific context, such as in industrial applications.

Shifts the focus to atmospheric sciences, where symmetry methods are employed to derive group-invariant solutions to the barotropic vorticity equation [57]. This application underscores the

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significance of symmetry in understanding complex weather patterns and suggests future directions for applying symmetry techniques to more sophisticated geophysical models.

Continuing this trajectory, [58] apply Lie group symmetry theory to model non-isothermal turbulent flows. Their work emphasizes how symmetry groups can guide the development of turbulence models that respect the physical properties encoded in the governing equations. In the realm of turbulence quantification, [59] explore the application of Lie group symmetry to the Navier-Stokes equations. They highlight the importance of symmetry in understanding the invariance of solutions under transformation, which can lead to new insights into the complex dynamics of turbulent flows.

Caution against the potential pitfalls of interpreting symmetries in fluid dynamics, particularly in the context of scaling symmetries in the incompressible Navier-Stokes equations [60]. Their analysis reveals how misinterpretations of symmetry can lead to inconsistencies in physical modeling.

Investigate symmetry breaking in azimuthal thermoacoustic modes, illustrating how changes in symmetry can impact flow stability and lead to significant changes in flow dynamics [61]. This research points to the critical role that symmetry plays not only in fluid mechanics but also in related fields such as combustion dynamics. Also, contributes to the understanding of stability theory in the Euler ideal fluid equations, elucidating how shear flows can transition from stability to instability. This work highlights the mathematical intricacies involved in predicting turbulence and emphasizes the importance of stability analysis in fluid dynamics.

A historical perspective on invariant solutions in turbulence, emphasizing the challenges of studying fluid mechanics analytically and the necessity of numerical methods in exploring complex flow dynamics was provided by [62].

Finally, [63] focus on symmetry-breaking phenomena in turbulent flow through porous media, revealing how flow instabilities can lead to significant deviations from expected flow patterns. Their numerical simulations highlight the complex interplay between symmetry and turbulence in porous structures. Also, rounds out this body of work by discussing the role of continuous symmetries in solving the 3D Euler fluid equations [64]. The contributions emphasize the practical applications of symmetry in understanding fluid behavior and the potential for further exploration in related fields.

These articles underscore the centrality of symmetry in fluid dynamics, providing a rich tapestry of insights that illuminate both theoretical and practical aspects of the theme. The literature reveals a dynamic interplay between stability, turbulence, and symmetry, offering a comprehensive understanding of how these elements interact to shape fluid behavior across various contexts. In fluid dynamics, symmetry helps describe the motion of fluids and the formation of flow patterns. The Navier-Stokes equations, fundamental to fluid dynamics, often exploit symmetries to facilitate their solutions [65,66]. Symmetry can be axial, radial, or translational, depending on the geometry and conditions of the problem [67]. Axial Symmetry: Common in flows around rotating objects, such as turbines and propellers. Axial symmetry simplifies the analysis of flows around cylindrical bodies and reduces the dimension of the problem. Radial Symmetry: Observed in convergent and divergent flows, such as in nozzles and diffusers. Radial symmetry is essential in the analysis of flows in radial geometries, such as in centrifugal pumps and injectors. Translational Symmetry: Useful in the analysis of flows in channels and ducts with repetitive geometries. Translational symmetry allows the application of periodic solution methods, simplifying the analysis of continuous flow systems in repetitive geometries.

The Navier-Stokes equations, when applied to problems with symmetry, can be simplified to reduce computational complexity. For example, in cylindrical coordinates, the continuity equation and the momentum equations can be reduced to more manageable forms, facilitating the solution [69,70].

The main topics on symmetry in fluid dynamics address a variety of phenomena and concepts that help to better understand the behavior of fluids. The most important topics: Rotational and Axial Symmetry: Fluids that exhibit rotational or axial symmetry, such as flows around cylinders or spheres, and flows in circular pipes. These systems are often easier to analyze due to their simplified

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geometry [65]. Symmetry Breaking: Phenomena where symmetry is broken, such as hydrodynamic instabilities that lead to complex patterns and phase transitions in fluids. Examples include the transition to turbulence in fluid flows and the formation of vortices [69]. Non-Newtonian Fluids: The behavior of fluids whose rheological properties do not follow Newton's law of viscosity, and how their symmetries affect flow. This includes fluids such as blood, mud, and certain polymers [71]. Symmetric Boundary Conditions: The study of how different boundary conditions can impose or break symmetry in a fluid system. This is critical in applications such as the design of piping systems and flow channels [72]. Symmetry in Micro and Nanofluids: Investigation of how symmetry manifests itself at microscopic and nanoscopic scales, affecting the behavior of fluids in microchannels and lab-on-a-chip devices [73]. Mathematical Modeling and Computational Simulations: The use of symmetries to simplify Navier-Stokes and other governing equations, facilitating more efficient analytical and computational solutions. This includes the application of Lie symmetry methods and other advanced techniques [74,75]. Multiphase and Multicomponent Fluids: Study of systems where more than one phase (solid, liquid, gas) or component is present, and how symmetries affect the interactions between phases or components [76–78]. Symmetry in Natural Phenomena: Observation of symmetries in natural phenomena, such as the patterns formed by ocean currents, planetary atmospheres and magmatic flows [79,80]. Droplet and Bubble Dynamics: Analysis of how symmetries affect the formation, coalescence and breakup of drops and bubbles in different media and under different flow conditions [81–83]. Symmetry in Turbulence: Study of the transition from symmetric laminar flows to asymmetric turbulent states, including the analysis of coherent structures within turbulent flows [84,85].

4. Symmetry in Energy Applications

The exploration of symmetry within energy applications has garnered significant attention across various scientific domains, particularly in physics and engineering. In this literature review, we will delve into the critical insights provided by notable contributions that have shaped our understanding of symmetry and its implications in energy-related contexts.

[86] underscores the pivotal role of symmetry as a methodological theme in 20th-century physics, positing that its significance is likely to persist into the 21st century. This work differentiates between the symmetries of crystals and gauge symmetries, emphasizing that while these distinctions may appear subtle, they are essential for grasping the nuances of symmetry in physical systems. This review not only elucidates various notions of symmetry but also highlights their applications, setting a foundational framework for understanding how symmetry can influence energy systems.

Expanding on this notion, [87] reflects on the evolution of the concept of symmetry throughout the 20th century, particularly in light of advancements in quantum physics and relativity. He identifies four critical facets of symmetry—transformation, comprehension, invariance, and projection—arguing that these elements are interrelated and collectively enhance the theoretical framework within contemporary physics. [88] illustrates how symmetry has transitioned from an aesthetic criterion to a powerful theoretical tool, exemplified by significant developments such as the unification of forces in general relativity and the interactions described in the Standard Model. This conceptual evolution underscores the broader applications of symmetry beyond mere classification, suggesting its role in rational thinking and modeling within the scientific discourse.

In a more applied context, [89] investigate the practical implications of symmetry in the design of heat exchanger networks. They highlight the importance of identifying symmetries in mathematical optimization, particularly in expediting computational algorithms. By employing group theory to analyze the MILP transshipment model, the authors reveal several types of symmetry inherent in the problem, demonstrating how recognizing these symmetries can streamline the design process and enhance efficiency in energy applications.

Through these articles, the literature illustrates a multifaceted understanding of symmetry, from its theoretical underpinnings in physics to its practical applications in engineering [90–92]. Each contribution builds upon the last, creating a comprehensive narrative that underscores the critical importance of symmetry in energy applications and its potential to inform future research and

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development in the field of symmetry use in thermal system designs [93,96]. Some specific cases of symmetry applications in the thermo-energy industry: Heat Exchanger Design: Shell and Tube Heat Exchangers [97,98]. In shell and tube heat exchangers, cylindrical symmetry allows a uniform distribution of fluid flow through the tubes, improving heat transfer and minimizing hot spots that can cause equipment failures. Turbines and Compressors: Gas Turbines [99]. The blades of gas turbines are arranged symmetrically around the rotational axis. This ensures that centrifugal forces are balanced, minimizing vibrations and increasing the useful life of the turbines. Solar Energy Systems: Solar Concentrators. Symmetrical parabolic reflectors concentrate sunlight at a focal point, where a receiver absorbs the solar energy and converts it into heat. This heat is then used to generate electricity. Nuclear Fusion Reactors: Use of symmetry in thermal system designs [100]. The tokamak uses symmetrical magnetic fields to confine the plasma in a toroid shape. This symmetry is crucial to maintain plasma stability and sustain fusion reactions. Batteries and Energy Storage Systems: use of symmetry in thermal system design battery [101]. Constructing a symmetrical air-cooled system. The concept is generally used to improve the heat removal ability. A thermal model for the pouch battery pack with liquid cooling is developed for thermal analysis of various pack designs. Typical battery pack with fin-cooling structure is set as a reference design, and thermal behavior of the battery pack is examined in the aspect of cooling performance and temperature uniformity [102]. Numerical results indicate that poor heat conductivity from the bottom of the cell stack to the cooling plate is one of the major barriers to the efficient heat dissipation and asymmetric design of fin-cell arrangement have negative effect on the temperature uniformity of the battery pack. Lithium-ion batteries with symmetrical structures in their electrodes provide a uniform distribution of current during charge and discharge cycles, increasing efficiency and durability [103].

Computational Fluid Dynamics (CFD): Symmetry in CFD models in thermal sciences, commonly applied to turbomachinery and its various components, allows to simplify simulations, reducing the computing time required to obtain accurate results on fluid flow and heat transfer [104,106]. Symmetry in Combustion Processes: Symmetry in combustion processes is often addressed in the simplification of models and even experimental measurements performed. The simulation and measurement objects range from fuel droplets, flames with axial symmetry to engines, especially rotary engines, such as aircraft engines; the symmetry of the combustion chambers ensures uniform combustion of the fuel, increasing efficiency and reducing pollutant emissions. From the geometric symmetry of flames produced by gaseous fuels, especially considering the combustion of liquids, generally atomized in droplets [107] and the mitigation of particle emissions such as soot, to flames stabilized inside porous materials [108,109]. The most frequent applications are in energy, steam and heating production, and also in commercial and military aviation.

5. Conclusions

The main topics on symmetry in energy cover several areas of physics and engineering, reflecting how symmetry influences the behavior and efficiency of energy systems. Several relevant topics were addressed in this work, namely: Symmetry in Renewable Energy Systems: Solar Panels: Symmetry in photovoltaic cell arrangements can optimize sunlight capture and energy conversion efficiency. Wind Turbines: The symmetrical design of wind turbine blades maximizes wind energy capture, improving performance and reducing structural fatigue. Symmetry in Thermoelectric Materials: Materials with symmetrical crystal structures can have improved thermoelectric properties, which are essential for the efficient conversion of heat into electricity. Symmetry in Combustion Processes: Symmetry in combustion chambers can lead to more uniform fuel combustion, increasing energy efficiency and reducing pollutant emissions. Symmetry in Power Distribution Networks: The symmetrical design of power distribution networks can improve system stability and resilience, facilitating the management of power flows and minimizing losses. Symmetry in Energy Storage Systems: Batteries and supercapacitors with structural symmetry can present better charge and discharge properties, as well as longer service life and efficiency. Symmetry in Nuclear Fusion Reactors: In fusion reactors, magnetic symmetry is crucial to confine the plasma and sustain fusion reactions efficiently and stably. Symmetry in Photonic Devices: Devices that

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manipulate light to perform non-intrusive measurements [110], also for energy conversion and transmission, such as solar cells and LEDs, can benefit from symmetrical structures to optimize photon flux and quantum efficiency. Symmetry in Thermodynamics and Heat Transfer: Symmetry in heat transfer systems, such as heat exchangers, can result in more uniform temperature distribution and improved thermal efficiency, and are exhibited in a wide range of applications [111,112]. Symmetry and Conservation Laws: Noether's theorem relates symmetries to fundamental conservation laws, such as conservation of energy, which are essential for understanding the principles underlying energy systems. Symmetry in Fluid Dynamics: In systems where fluids are used for energy transfer (such as in hydroelectric or refrigeration systems), symmetry can facilitate mathematical modeling and optimization of fluid flow.

A more in-depth analysis can be carried out on each topic highlighted in this work, and in addition to these, there may also be some more specific topics. A wide range of studies have been related in more general research [113] and several other important works on specific topics, which are not included in this article, due to the limitations of its introductory nature, but which can be found from the topics and works mentioned in this review.

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