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REVIEW

Integrated Planning of New Energy Systems: Environmental Trade-Offs and Sustainability Pathways

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ABSTRACT

The rapid transition toward low-carbon energy systems is creating increasingly complex and interconnected energy structures characterized by high shares of renewable energy, sector coupling, and advanced conversion and storage technologies. To manage these systems while achieving decarbonization, security, reliability, and sustainability goals simultaneously, integrated energy system planning has become essential. However, most existing planning studies primarily emphasize techno-economic optimization and greenhouse gas reduction, while long-term environmental impacts and sustainability considerations remain insufficiently addressed. This review provides a comprehensive assessment of integrated planning approaches for new energy systems, with a particular focus on environmental impacts, trade-offs, and sustainability pathways. It examines major planning frameworks, including optimization-based, simulation-based, and hybrid methods, and evaluates how environmental factors are incorporated into system design. Special attention is given to life-cycle assessment, multi-dimensional environmental evaluation, and the role of sector coupling in shaping system-wide environmental outcomes. By comparing environmental trade-offs across sectors, spatial scales, and time horizons, the review highlights inherent tensions between decarbonization objectives, resource consumption, and ecological impacts. Case studies from China, Pakistan, South Korea, and Malaysia illustrate how integrated planning is applied under diverse socio-economic and policy conditions. Finally, the review identifies key research gaps, emphasizing the need for deeper environmental integration, improved data and model connectivity, and pathway-based planning to support environmentally sustainable and resilient energy transitions.

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1. Introduction

The world energy system is undergoing a dramatic change caused by the necessity to reduce climate change, to improve energy security, and to help in sustainable economic development [1,2]. The international agreements to reduce global temperature increase, and the national net-zero and carbon-neutrality goals have increased the use of renewable energy sources, end-use electrification, and new energy carriers, including hydrogen and synthetic fuels [3]. These changes are all collectively transforming traditional energy systems, which were heavy fossil fuel-based, into more complex and interconnected new energy systems with high proportions of variable renewable energy, distributed generation, and cross-sector coupling. Although this shift promises unprecedented opportunities in deep decarbonization, it also creates serious planning dilemmas in relation to environmental trade-offs and sustainability in the long term.

In the past, energy system planning has been carried out in comparatively closed sectoral frameworks, where the most significant focus has been on the minimization of expenses or the reliability of supply. These boundaries have, however, been blurred by the fast development of renewable sources of energy, energy storage systems, and power-to-X conversion systems. Fuel chains, transport networks, industrial, and heating networks are now closely interconnected with electricity networks and form strong interdependencies between sectors and across spatial scales. Integrated planning has, in this regard, become an essential paradigm in the design and operation of energy systems in the future in a consistent and effective way. Integrated planning aims to jointly maximize several vectors of energy, infrastructures, and demand sectors, and it considers changes over time, space limitations, and policy goals [4,5].

Although integrated energy system planning has increasingly adopted it, it has given little serious attention to the impact on the environment, and its focus on environmental issues has been limited or patchy [6]. The reduction of greenhouse gas (GHG) emissions is often a primary target or a constraint, but other environmental aspects, including air, land, and water usage, biodiversity effects, and material resources degradation, are commonly disregarded or managed afterward. Such a limited perspective would transfer the environmental load instead of eradicating it and put the sustainability objectives of the energy transition in jeopardy. As an illustration, major implementation of renewable energy and battery storage has the potential to eliminate operational emissions to a considerable extent but might have an upstream effect with regard to the extraction of critical minerals, land use, and water usage. Equally, sector couples capable of deep decarbonization, like power-to-hydrogen, can be enacted but would create new trade-offs associated with energy efficiency loss, infrastructure growth, and regional environmental impacts.

This makes it not possible to measure the environmental performance of new energy systems using single indicators or sectoral analyses [7–9]. Rather, it is becoming increasingly apparent that environmental trade-offs are typical of energy system transformation, and should be explicitly determined, measured, and controlled using comprehensive planning strategies. These trade-offs can be made in various dimensions, including between climate mitigation and the quality of the local environment, between short-term operational gains and the long-term sustainability of resources, and between local and global environmental outcomes. The way these complexities are to be addressed is by designing planning frameworks that incorporate environmental assessment techniques, such as life cycle assessment (LCA) and multi-criteria decision analysis, directly into system design and optimization procedures.

Simultaneously, the so-called sustainability pathways have become prominent in energy studies and policy-making. Instead of concentrating on fixed state configurations of the system, sustainability pathways consider dynamic transition paths, which take into consideration technological learning, infrastructure lock-in, policy evolution, and socio-environmental feedback throughout time. In this view, integrated planning is not simply a method of finding the cost-optimal system designs, but a strategic tool of guiding energy systems to the environmentally sound, socially acceptable, and resilient futures. The sustainability pathways emphasize flexibility and adaptability, and resilience in the face of uncertainty, which are especially pertinent in the context of climate change, geopolitical, and technological changes [10].

Over the last few years, there has been a significant amount of literature on the subject of integrated energy system planning that covers a wide range of issues. The literature has reviewed the sector coupling technologies, optimization and simulation, the renewable integration dilemma, and the policy implications of low-carbon transitions [11]. Other analyses have been narrowly based on the methodology of environmental assessment or on the sustainability of specific technologies, e.g., hydrogen or bioenergy, or energy storage. These strands of literature are, however, very much treated independently. Extensive reviews to carefully connect the integrated planning methodologies with the environmental impact assessment, trade-off analysis, and sustainability pathway design have been limited. Specifically, synthesis that critically evaluates the integration of environmental considerations into the planning models, trade-offs across sectors and scales, and the use of the planning results in the long-term sustainability strategies is lacking.

The gaps identified in this review are filled by presenting in a systematic and critical way the body of literature on the integrated planning of new energy systems, especially the area of environmental trade-offs and sustainability pathways [12]. The review takes a holistic approach whereby it considers more than cost and carbon measurements in the design of the energy system because the aspect of environmental sustainability is multidimensional. In a combined analysis of planning structures, modeling techniques, and evaluation strategies, the given article attempts to explain how the environmental goals can be integrated into energy planning systematically and how the conflicting objectives can be reconciled in a practical way.

This review will find applications across a broad spectrum of energy system designs, such as those based on electricity-dominated systems with a high renewable content, those based on multi-energy systems integrating heat, gas, and transport industries, and those based on hydrogen and synthetic fuels [13]. The short-term operational planning and long-term expansion thinking are both taken into account because there is a tendency that environmental trade-offs can have varied forms at various time scales. The three spatial scales include the scales such as local systems and industrial park, city and regional systems, and national and transnational energy systems, while a variety of planning contexts and environmental issues exist.

In terms of methodology, the review encompasses optimization-based, simulation-based, and hybrid planning methodologies, and has a special focus on how environmental indicators are integrated with objective functions, restrictions, or post-processing analysis. The combination of life cycle thinking, multi-criteria assessment, and uncertainty analysis is discussed in-depth with its methodological strengths, limitations, and limitations that need to be developed. Besides that, the review also takes into consideration socio-environmental and policy aspects as it acknowledges that sustainability pathways are not only influenced by technological and economic aspects but also by governance systems, preferences of stakeholders, and societal values.

The rest of the present article is structured in the following way. The conceptual framework of integrated new energy systems is presented in Section 2, including the boundaries of the system, its relevant components, and planning targets. Section 3 discusses integrated planning methodologies in which optimization, simulation techniques, and advanced hybrid strategies are compared. Section 4 comprises the analytical heart of the review, which integrates the environmental impact assessment frameworks, trade-off analysis, and the design of sustainability pathways as integrated planning frameworks. Section 5 will include some case studies and regional visions that show the implementation of integrated planning and environmental concerns in various socio-economic contexts. The significant research gaps and future directions are incorporated in Section 6, followed by the conclusion, including general findings and implications that the research has on the researchers, planners, and policymakers (Section 7).

Through the connections of integrated planning, environmental assessment, and long-term sustainability, this review aims to contribute to the creation of low-carbon, but also environmentally responsible and resilient long-term energy systems.

2. Conceptual Framework of Integrated New Energy Systems

2.1. Definition and System Boundaries

Integrated new energy systems are energy systems that are planned and designed by a considerate choice of several energy conveyors, infrastructures, and domains of demand on a common analytical plane[14]. In comparison to traditional energy systems that are typically designed with one main energy vector, i.e., electricity or fossil fuels, integrated systems explicitly take into consideration the interactions between electricity, heat, gas, hydrogen, and liquid fuels and the conversion and storage technologies thereof. It is not just that they have a variety of technologies, but that they plan and operate interrelated subsystems to accomplish several aims, such as economic efficiency, environmental sustainability, and reliability of the system. The conceptual framework of the integrated new energy systems, as shown in **Figure 1**, indicates how the different sectors of energy carriers, conversion technologies, storage, and end-use interact within specific spatial and temporal constraints.

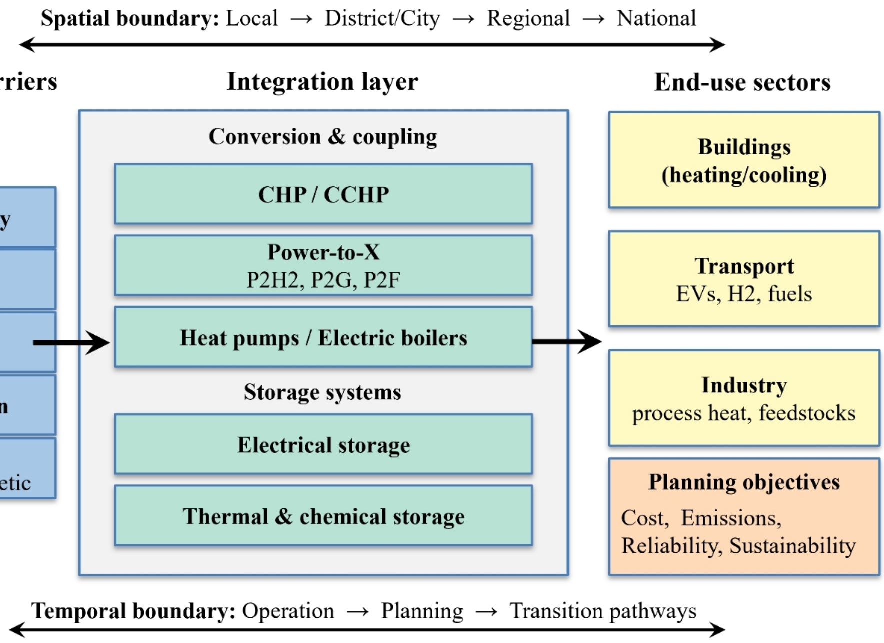

Figure 1. Conceptual framework of integrated new energy systems illustrating multiple energy carriers, conversion technologies, storage options, demand sectors, and planning boundaries across spatial and temporal scales.

System boundaries are also a significant issue in integrated energy system planning because they dictate what interactions and impacts will be included in the analysis. There are spatial and temporal boundaries that can be established. Spatially, integrated systems can be local in scale, i.e., buildings, districts, or industrial parks, or regional, national, or transnational energy networks. The challenges presented by each scale have specific problems in terms of the availability of infrastructures, resource endowment, and environmental consequences. Planning horizons can range from short-term operational scheduling to long-term capacity expansion over a few decades in temporal terms. Short-term analyses tend to focus on the management of system flexibility and variability, whereas long-term perspectives are needed to capture the effects of infrastructure lock-in, technology learning, and cumulative environmental effects. A coherent conceptual framework should then be able to bring spatial and time boundaries into the context of the specific research or policy question under study[15]. **Table 1** provides a brief overview of some conceptual differences between the various systems to define the key distinguishing features of the integrated new energy systems, as well as the difference between the conventional sector-specific energy systems and the integrated new energy systems.

Table 1. Conceptual characteristics distinguishing integrated new energy systems from conventional energy systems in terms of structure, scope, planning horizon, flexibility, and environmental considerations.

Dimension	Conventional Energy Systems	Integrated New Energy Systems
Energy carriers	Single or dominant carrier (e.g., electricity, fossil fuels)	Multiple carriers (electricity, heat, gas, hydrogen, fuels)
Sectoral scope	Sector-specific (power, heat, transport analyzed separately)	Cross-sectoral with strong sector coupling
Planning horizon	Short- to medium-term	Short-term operation and long-term transition pathways
System flexibility	Limited, supply-oriented	High flexibility via storage, conversion, and demand response
Environmental focus	Primarily operational emissions	Life cycle impacts and multi-dimensional sustainability

2.2. Key Components of Integrated New Energy Systems

Integrated new energy systems consist of a wide array of supply, conversion, storage, and demand-side units that, as a group, allow the delivery of flexible and low-carbon energy[14,16]. On the supply side, wind, solar, hydro, and bioenergy are some of the renewable energy technologies that are at the center stage, usually complemented with residual generation of fossil fuels with carbon capture or other mitigation strategies in the transitional stages. The growing use of variable renewable energy resources creates a high rate of temporal variability that cannot be addressed with balancing solutions in isolation and, instead, has to be addressed with system integration. Integration across energy carriers is based on energy conversion technologies. Heat recovery, power-to-heat systems, combined heat and power units, electrolysis to produce hydrogen, and synthetic paths to fuel allow the transfer of energy between sectors according to demand trends and resource availability. The technologies enable sector coupling, which enables excess renewable electricity to be used in heating, transport, or industry to improve the efficiency of the overall systems and curtailment. Meanwhile, conversion processes cause loss of efficiency and the need to have more infrastructure, which has significant effects on both the performance of the system and the environment.

Another element of integrated systems that is also critical is energy storage, which offers a temporal decoupling between the demand and supply of energy[17]. Short-term variability can be met by using electrical storage technologies like batteries, pumped hydro storage, whereas long-term balancing and seasonal flexibility are met by thermal storage or chemical storage in the form of hydrogen or synthetic fuels. Additional demand-side factors, such as demand response, end-use sector electrification, and smart energy management systems, also improve integration by making the system more adaptable. Collectively, these elements create a very networked system where such decisions made about a particular element can lead to further impacts on the other sectors and over time.

2.3. Planning Objectives and Constraints

Integrated new energy systems are multi-objective in their planning, as their goals are diverse and even conflicting with each other in some cases, corresponding to energy transitions[18]. Economic goals are usually to minimize the total system cost, which covers capital investment, operation cost, and, in certain cases, the external cost associated with emissions or resource consumption. Technical targets aim at maintaining the reliability, adequacy, and flexibility of systems that need to accommodate the variability of renewable generation and the changing demand patterns. The scope of environmental objectives is further than reducing greenhouse gas emissions to air quality, land and water use, resource efficiency, and ecology in general.

These aims are sought within a complicated set of constraints that model possible system settings. Resource constraints are a result of the availability of potential renewable energy, the availability of water resources, and the availability of essential materials needed to run energy technologies. Infrastructure limitations are manifested through current networks, the maturity of technology, and physical bottlenecks of transmission, storage, and conversion capacity. Policy and regulatory restrictions, including emission levels, renewable energy requirements, and market design policies, also shape the results of the planning process, putting an emphasis on some technologies or routes as opposed to others. Moreover, the social restrictions associated with societal acceptance, equity, and land-use contradictions are known to have a considerable impact on the implementability of the integrated energy solutions[19].

The interaction of goals and limitations determines the significance of the explicit consideration of trade-offs in the framework of integrated planning. Optimal decisions based on cost or carbon might cause unintended environmental or social impacts when the bigger sustainability aspects are not taken into account. An effective conceptual framework of integrated new energy systems, therefore, needs to have a number of dimensions of planning objectives and have a platform for assessing other system designs in an unbiased and methodical way [4]. This framework is the basis of the planning techniques and environmental analyses to be discussed in the further sections of this review.

3. Integrated Planning Methodologies

3.1. Optimization-Based Approaches

The main part of the integrated planning approaches of the new energy systems is composed of optimization-based techniques, and they are commonly applied to determine system configurations that optimally meet the predefined goals within a series of technical, economic, and environmental constraints [14]. These methods generally encourage the planning issue as a mathematical program where decision variables are investments in generation, conversion, storage, and network infrastructure, and decisions involving the operations over time. The optimization models can take the form of linear, mixed-integer, and nonlinear models, depending on their level of detail and scale of the system. Linear and mixed-integer linear programming are typically used because they can be computed with computational tractability and because they can be used to model large-scale systems, whereas nonlinear formulations are typically used when higher fidelity is needed to model thermodynamic relationships or non-convex system behavior.

The objective function is a decision that is used in determining the outcomes of planning. Single-objective formulations tend to aim to reduce the overall costs of the system or greenhouse gases and assume that the other aspects of performance will be achieved as co-benefits. By comparison, multi-objective optimization directly models trade-offs between competing objectives, including cost, emissions, system reliability, etc., by producing Pareto-optimal sets of solutions. The strategies enable the decision-makers to test the impacts of the addition of small steps to the environmental performance and the potential effects on the economy or technology. Nonetheless, multi-objective formulations are also more complex models that need to be interpreted carefully, especially when the objectives are presented in disparate units or when the stakeholder preferences should be included in the decision-making process [20,21].

Long-term energy planning is a subject of uncertainty, and stochastic and robust formulations have been embraced more often as part of optimization-based energy planning to overcome uncertainties in technology costs, fuel prices, as well as policy evolution and availability of renewable resources [22]. Stochastic optimization is an uncertainty model of having many scenarios with probability assignments, whereas robust optimization aims at finding solutions that will be acceptable in a broad spectrum of future possibilities. Inasmuch as these techniques increase the reality of planning outcomes, they also come with increased computational loads and might necessitate simplification assumptions with respect to uncertainty representation. Consequently, trade-offs are usually made in the choice of model detail, computational capability, and the scope of uncertainty.

3.2. Simulation and Scenario-Based Planning

Another approach that complements optimization in the planning of an integrated energy system is simulation-based techniques [23]. Simulation models are not aimed at finding a mathematically optimal solution, but are used to investigate the behavior of energy systems in a given configuration, operational rules, or under a policy scenario. Such models are especially effective at examining the dynamics of a system, temporal variability, and the interaction of supply and demand among the dynamics of multiple system sectors. Simulation tools are common in integrated planning settings to determine the viability of high-renewable or highly coupled systems in operations, assess flexibility needs, and determine possible infrastructure or control strategy bottlenecks.

Scenario-based planning has strong relations with simulation methods and is an important tool in the search for long-term transition pathways in deep uncertainty [24,25]. Scenarios are usually alternative futures that are defined by various assumptions about the development of technologies, the ambition of policy, socioeconomic changes, and changes in behavior. The ability to compare the performance of systems according to various scenarios will allow planners to know strong strategies that will work in different circumstances, as opposed to using one prediction. Scenario analysis has been specifically useful in evaluating sustainability pathways, which allows the evaluation of the cumulative effects on the environment, the lock-in effects of infrastructure, and when important decisions regarding investments are made over the entire planning horizon.

Simulation and scenario-based methods are limited, nevertheless, in spite of their advantages. Since system settings are frequently pre-established, they can fail to represent the complexity of possible system architectures or determine the cost-efficient investment routes. Moreover, scenario analyses are usually sensitive to assumptions that may be hard to validate or compare studies to study. This means that simulation-based planning is best deployed in conjunction with optimization techniques to give more detailed operational information and qualitative knowledge that supplements quantitative optimization findings [26].

3.3. Hybrid and Advanced Planning Methods

To overcome the drawbacks of optimization- or simulation-based methods in planning, there has been an increase in the literature on hybrid planning methodologies. These models merge the advantages of other modeling paradigms to have a more detailed model of an integrated energy system. One of the typical hybrid strategies is to combine long-run capacity expansion optimization models with short-run operational simulation models [27]. In these frameworks, investment decisions and high-level system structure are determined with the help of optimization and operational feasibility, flexibility requirements, and stability under realistic time conditions, and are evaluated with the help of simulation models. This recurring interdependence enables planners to improve the design of systems and minimize the exposure of systems to infeasibility or over-optimistic designs.

Integrated energy system planning has also been carried out with advanced modeling techniques such as agent-based models and system dynamics, where socio-technical interactions and behavioral factors may be of interest [28]. The agent-based models are described as the individual actors, and this includes the consumers, firms, or policymakers, and their interaction within the energy system is simulated. This method is applicable in the analysis of the dynamics of technology adoption, market behavior, and the impacts of policy instruments on heterogeneous stakeholders. In contrast, system dynamics models focus on feedback, delays, and nonlinear interactions at an aggregate level and provide an understanding of long-term transition dynamics and possible unintended consequences of policy interventions.

More recently, the traditional planning techniques have started to be supplemented by data-driven and machine learning techniques [29,30]. These methods are not intended to fully substitute optimization or simulation frameworks, but are rather mainly applied to improve demand forecasting, renewable generation modeling, and scenario generation. In combination with a well-considered approach, data-based approaches can make computational complexity lower, model accuracy higher, and serve real-time or close to it planning applications. Their use in long-term integrated planning, however, is constrained by the limited availability of data, issues of interpretability, and the difficulty in integrating learning-based models into transparent decision-support systems.

3.4. Comparison and Applicability of Planning Models

The variety of integrated planning approaches indicates the breadth of planning issues, scales of the system, and decision contexts experienced when designing new energy systems [31]. The optimization-based methods can be effectively applied to finding the cost-efficient system configurations and searching among the well-defined goals, especially at the regional or national levels. The simulation and scenario-based techniques are good at studying the dynamics of a system, its operational feasibility, and uncertainty, so they can be used in the study of operations at a detailed level and also long-term transition regarding the system. More complex and hybrid approaches provide a potentially more profitable direction towards the high fidelity of structural and dynamic complexity, at the cost of increased modeling and interdisciplinary skills. The variety of the reviewed planning approaches is based on the different priorities of analysis and situational setting of decisions; **Table 2** gives a comparative summary of the major integrated planning approaches and their scope of application.

Table 2. Comparison of major integrated energy system planning methodologies, highlighting their strengths, limitations, and typical applications.

Methodology	Main Strengths	Key Limitations	Typical Applications
Optimization-based models	Identifies cost- or emission-optimal solutions; scalable	Limited system dynamics; simplified environmental metrics	Capacity expansion, policy evaluation
Simulation-based models	Captures temporal variability and system dynamics	Not inherently optimal; scenario-dependent	Operational analysis, flexibility assessment
Hybrid optimization–simulation	Balances optimality and realism	Higher complexity and computational burden	Integrated investment–operation studies
Agent-based and system dynamics	Represents behavior and feedback loops	Limited quantitative optimality	Technology adoption, policy impact analysis
Data-driven and ML-enhanced methods	Improves forecasting and computational efficiency	Limited transparency; data dependence	Demand prediction, renewable integration

The problem of integrated energy system planning cannot be resolved by one and only methodology. The purpose of the study, the type of data needed, and the computational resources, together with the context of decision making, should hence determine the method to be used. Notably, there is a wide difference between the degree of approach to environmental impacts and sustainability interpretation among methodologies, which affects the detection and evaluation of trade-offs. These differences in methodological approaches are fundamental to the interpretation of the outcomes of planning, as well as the development of integrated approaches that have the potential to assist in facilitating the transition to energy that is environmentally sustainable. It is based on this methodology that the integrated analysis of the environmental impacts, trade-offs, and sustainability pathways that are presented in the next section is derived.

4. Environmental Impacts, Trade-Offs, and Sustainability Pathways in Integrated Energy Planning

4.1. Environmental Impact Assessment Frameworks in Integrated Planning

EIA is an essential part of planning an integrated energy system since it offers the framework in which the proposed system configurations are analyzed in relation to the wider sustainability goals [4,32]. Environmental effects, in the new energy systems, go way beyond the immediate greenhouse gas emissions, including the energy conversion processes. These consist of a broad spectrum of pressures on natural systems, such as emissions of air pollutants, land use, water use, ecosystem perturbation, and extraction and processing of material resources. The challenge to systematize these multiple effects in a systematic and internally consistent way is increasingly being realized in integrated planning frameworks.

Historically, energy planning has relied on a few indicators to carry out environmental assessment, the most significant one being carbon dioxide emissions. Although such indicators are central because they are relevant in mitigating climate change, they are not comprehensive since they depict the performance of the environment. There is potential that high-renewable and highly electrified systems, such as those, can reach high levels of emission reductions and, at the same time, raise pressures on land, water, or essential material supply chains. Integrated planning frameworks, as it is called in environmental assessment, attempt to extend the analytical scope to include various indicators that capture local and global environmental issues [33,34]. The choice of indicators is closely connected to the system boundaries and scales of plans because what is relevant at the local level, air quality or land-use conflicts, is different from what is relevant on the national or global level, climate change, or resource depletion.

One of the main difficulties related to implementing environmental assessment models in terms of integrated planning is making the environmental indicators and energy system models compatible [35]. The model of planning is usually generated at small temporal and spatial scales where the environmental effects can rely on fine-scale processes and site-specific situations. The key to bridging this gap involves making sure that abstraction is done carefully and the representations of indicators are detailed enough to be able to record meaningful differences between system configurations, but are simple enough that they can be handled in large-scale planning models.

4.2. Integration of Life Cycle Thinking into Energy System Planning

Life cycle thinking has become a critical mechanism that can deal with the upstream and downstream environmental effects that relate to new energy systems. The life cycle assessment can offer a broad view of the environmental burdens not reflected by operational metrics by looking at the end-of-life treatment, maintenance, and extraction of raw material, and the manufacture of energy technologies. Life cycle thinking is especially relevant in integrated planning situations when dealing with technologies with low operation emissions and high embodied emissions, e.g., photovoltaic systems, wind turbines, batteries, and hydrogen production infrastructure [36].

Life cycle assessment may be implemented in energy system planning in a variety of ways [37]. Some of the studies use life cycle emission factor or resource intensity coefficient directly in the optimization model, and thus, the life cycle impact may be an objective or a constraint. Life cycle assessment is used in other instances as a post-processing, in which optimized system configurations are ex post evaluated to determine overall environmental implications. Both methods trade analytical rigor against computational feasibility. Direct integration allows the effects of environmental concerns on the planning results to be explicitly considered, although simplified models of life cycle processes are frequently needed. Post-processing methods provide more comprehensive analysis of the life cycle, but there is a risk that the environmental trade-offs will be discovered too late when major decisions of the system design are already taken.

Another audit issue is the selection of the attributional and consequential life cycle perspective. Attributional and consequential assessment assign the effects of the environment to individual technologies or energy flows and, respectively, seek to capture the system-wide impacts of marginal decisions. Within integrated planning, where the emphasis is usually on large-scale system change, as opposed to incremental change, consequential perspectives can provide more avenues of understanding. Nevertheless, they are applied with potent assumptions regarding the reaction of the systems and the market dynamics, creating extra uncertainty. Consequently, the continuous and open-minded incorporation of life cycle thinking is a current field of study in the field of integrated energy planning [36,38].

4.3. Multi-Dimensional Evaluation and Environmental Trade-Offs

Figure 2 schematically depicts the multidimensionality of the environmental effects and how the burden may shift between categories. Balance between various goals is an inherent part of integrated energy planning, and the environmental trade-offs are one of the key aspects of the decision-making. These trade-offs occur when any change in one aspect of the environment results in negative effects on a second aspect, or environmental aims contradict economic or technical aims [39]. As an example, moving towards more decarbonization by mass renewable deployment could lead to more land use and material demand, whereas the use of bioenergy can lead to a decrease in fossil fuel consumption, at the cost of water use and biodiversity effects.

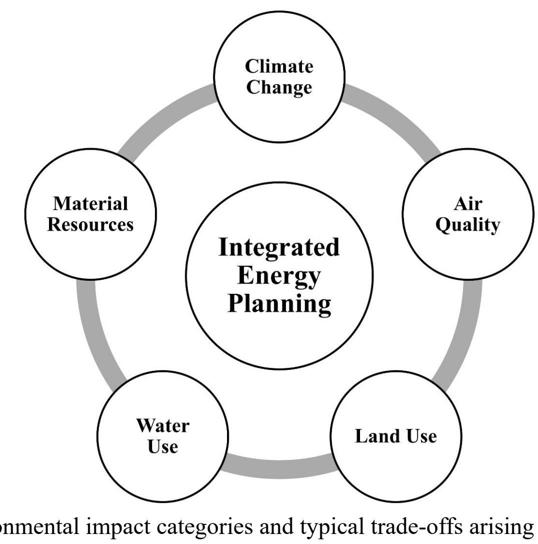

Figure 2. Multi-dimensional environmental impact categories and typical trade-offs arising in integrated energy system planning.

Such trade-offs are intended to be explicit and are achieved using multi-dimensional evaluation frameworks in order to aid the clear comparison of different system designs. Multi-criteria decision analysis is commonly used to consolidate a range of pointers into composite performance metrics or rank system settings in accordance with stakeholder preferences. These methods also allow the investigation of the effect of various weighting schemes or priorities of policy on the perceived desirability of competing pathways in integrated planning studies. Nonetheless, the practice of using aggregated indicators also brings up the issue of subjectivity, since the outcomes can be subject to the weights, normalization procedures, and sets of indicators. In order to organize the discussion of the environmental dimensions and explain the essence of the common trade-offs, **Table 3** is used to summarize the main environmental indicators and the planning tension associated with them reported in the studies [40].

Table 3. Major environmental impact dimensions are considered in integrated energy system planning, and typical trade-offs are identified in the literature.

Environmental Dimension	Key Indicators	Typical Trade-Offs
Climate change	GHG emissions, carbon intensity	Deep decarbonization vs. higher system costs
Air quality	NO_x, SO_2, PM emissions	Electrification benefits vs. upstream emissions
Land use	Land occupation, ecosystem disturbance	Renewable expansion vs. biodiversity impacts
Water use	Water withdrawal and consumption	Hydropower and bioenergy vs. water scarcity
Material resources	Critical mineral demand, recyclability	Storage and electrification vs. resource depletion

Trade-offs do not exist only at the environmental dimension level, but it is usually possible to have relations between environmental, economic, and technical performance [41]. Cost-effective solutions might perform better in terms of environmental impacts in some aspects, whereas the ones that are more environmentally appropriate might demand more investments or be difficult to ensure the reliability of the system. The use of integrated planning frameworks that give clear accounts of such interactions can be useful in understanding the opportunity cost of sustainability goals, in addition to determining trade-off solutions that can be used to balance competing goals. Notably, the problem of trade-offs does not mean that the environmental goals shall be secondary to economic ones, but a well-informed decision-making process must also take into consideration the entire scope of the consequences that various planning options entail.

4.4. Sector Coupling and Cross-Sector Environmental Effects

The new energy systems are characterized by sector coupling, which is crucial in influencing the environmental outcomes [42]. Sector coupling, which can be achieved by converting electricity into heat, transport, and industrial through power-to-heat, power-to-hydrogen, and synthetic fuel systems, is the key to more effective use of renewable energy and deep decarbonization of the entire economy. Concurrently, it opens up new routes through which environmental influences can spread across the sectors.

As a matter of the environment, sector coupling may create synergies and conflict. Emissions in sectors that are difficult to abate (such as heavy industry and long-distance transport) can be lowered by using the excess renewable electricity to produce hydrogen, e.g., Nevertheless, there will be an efficiency loss and infrastructure growth that can drive up the total energy consumption and material consumption. Likewise, the electrification of heating and transport would help in improving the air quality in cities, with an added benefit of displacing emissions and resource requirements higher up the power production and manufacturing lines. The capturing of these cross-sector effects and preventing problem shifting across sectors necessitates integrated planning [43,44].

Environmental concerns of sector coupling are also considerably relevant, and depend on factors including the carbon intensity of electricity supply, the regional supply of resources, and the temporal coincidence between renewable production and demand. Integrated planning models that include an environmental measure of the sectors can assist in determining the circumstances in which sector coupling produces net environmental advantages, and under which circumstances alternative policies might be more sustainable [42].

4.5. Sustainability Pathways and Long-Term System Transitions

In addition to considering the status quo of the systems, integrated planning is important to influence the long-term sustainability directions of the energy system transformation [4]. Sustainability pathways focus on the time aspect of planning by giving credit to the fact that energy systems change over decades as a result of a series of investment choices, policy interventions, and technological shifts. Environmental effects are long-term, and a decision made early in planning can result in lock-in effects limiting future choices or further deteriorating the sustainability problems over the long term. Based on the analysis above, **Figure 3** is a conceptualization of the dynamic nexus between the decisions of integrated planning, environmental assessment, and (long-term) sustainability pathways.

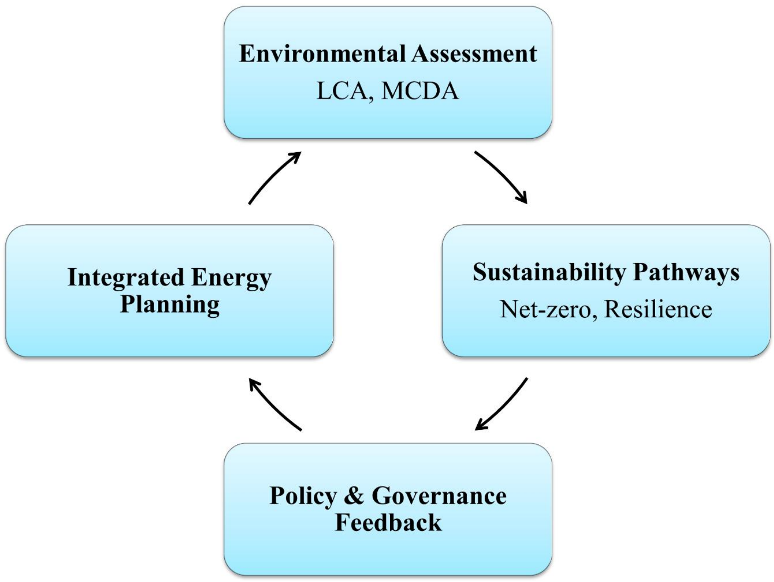

Figure 3. Conceptual linkage between integrated energy system planning, environmental assessment, and long-term sustainability pathways.

The transition dynamics (when to deploy technology, when to expand infrastructure, and when to move out of carbon-intensive assets) can be analyzed using integrated planning frameworks that are based on a pathway-oriented perspective. These analyses point out the significance of flexibility and adaptability to attain environmentally sustainable results, especially when one is uncertain of the future performance of technology, prices, and policy considerations [45]. Pathway-based planning also helps in the evaluation of cumulative environmental effects, which allow insights into short-term trade-offs that result in long-term gains or destroy overall sustainability objectives.

Pathways to sustainability also include social and policy aspects that can affect outcomes in the environment [46]. Transitions are influenced by the possibility and desirability of alternative transition schemes as determined by the public, considerations of equity, and the structures of governance. Planning that takes into consideration these dimensions, as well as environmental and techno-economic factors, can facilitate more comprehensive and resolute decision-making. Combining environmental impact assessment, trade-off analysis, and pathway design into one unified approach, integrated energy planning offers an effective vehicle to assist in navigating the shift towards long-term low-carbon, as well as environmentally responsible and resilient energy systems.

5. Case Studies and Regional Perspectives

5.1. Integrated Energy Planning in China

China offers one of the most comprehensive and rich case study sources on the integrated planning of new energy systems due to its size, fast energy transition, and robust policy-supported approach to decarbonization. China is the biggest energy consumer and the greatest carbon emitter in the world, and hence it has the two-fold challenge of trying to cut emissions and its energy security and economic growth. National strategies including carbon peaking and carbon neutrality, have now become integrated planning, with more and more focus being placed on synchronizing the electricity, heating, transport, and industrial systems [47].

Most of the Chinese case studies are based on large-scale power systems that have large-scale penetration by wind and solar power, energy storage, flexible thermal generation, and an increasing transmission system. The integrated planning models are usually implemented at provincial or regional levels to solve the spatial disjuncture between renewable resource supply and demand centers. In many cases, environmental trade-offs have been studied on the basis of carbon reduction against land use, water consumption, and air pollution emissions, especially in areas where there is a water shortage or where there are large populations.

These trade-offs are not always unidirectional. In a notable counterexample from Western China's desert regions, large-scale PV deployment has produced unexpected ecological co-benefits: reduced soil evaporation, increased vegetation cover, and enhanced conditions for local animal husbandry. This case illustrates that renewable energy, ecology interactions can be synergistic under specific climatic and spatial conditions, here, the PV panels created favorable microclimates by shading and reducing wind speeds. For integrated planning, this finding implies that environmental impact assessments should move beyond assuming negative trade-offs and instead incorporate site-specific ecological feedback mechanisms, which may reveal previously overlooked sustainability pathways. However, such synergies remain context-dependent and should not obscure the general need to manage land-use conflicts and biodiversity impacts in renewable energy deployment [48–50].

More case studies in China of urban and industrial parks show the value of integrated planning at smaller scales. Distributed renewable generation, combined heat and power systems, thermal storage, and demand-side management are frequently combined in these studies to enhance the local-scale energy efficiency and air quality. In such cases, environmental appraisals focus on co-benefits, including changes in the level of particulate matter and the good health of people, in addition to the mitigation of climate. Altogether, Chinese case studies prove that integrated planning can assist in high decarbonization targets, yet they also show the significance of controlling environmental limitations in the region and preventing the transfer of problems across different spheres [51].

5.2. Integrated Energy Planning in Pakistan

Pakistan is an opposite scenario of planning, with the fast rate of growth in demand, a lack of infrastructure, and being extremely susceptible to the danger of environmental and climatic conditions. Pakistan case studies on energy systems are usually targeted at increasing the reliability and affordability of energy systems, as well as decreasing reliance on foreign fossil fuels. In this regard, integrated planning is tied inextricably to such sustainable development goals as access to energy, economic resiliency, and the environment [52].

A large amount of literature looks at hybrid energy systems that integrate renewable energy sources like solar and wind with traditional generation and energy storage, especially in remote areas or underserved ones. Evaluation of trade-offs of cost, reliability, and environmental performance is performed through integrated planning strategies with a high priority on minimizing greenhouse gas emissions and local air pollution. The water-energy nexus is also a burning issue in Pakistan, as the role of hydropower cannot be underestimated, and water resources are also susceptible to climate change. Case studies often point to a dilemma between hydropower development, the effects of hydro on the ecosystem, and the availability of water in agriculture and domestic consumption [53].

On the national level, it is increasingly clear that integrated planning studies can examine the possibilities of sector coupling, such as transport electrification or renewable energy use to power industrial operations. Nevertheless, in such instances, the extent of environmental assessment is usually restricted to carbon emissions because of data limitations and the complexity of the modeling. The Pakistani experience points to the relevance of specific context-based integrated planning frameworks in consideration of development priorities, institutional capability, and environmental vulnerability, and extending the range of the environmental indicators as the data and analytical instruments become advanced [54].

5.3. Integrated Energy Planning in South Korea

South Korea provides case studies that are influenced by high dependence on energy imports, well-established industrial development, and a high level of technological development[55]. In South Korea, integrated energy planning is developed in strong connection with national plans of carbon neutrality and decarbonization of industrial processes, specifically electricity system transformation, hydrogen implementation, and sector coupling.

The South Korean case studies are largely based on how renewable energy can be integrated into a highly urbanized and densely populated setting in which there are limited land reserves, and popular acceptability of the same raises major concerns[56]. Trade-offs between the offshore wind development, grid expansion, and energy storage deployment and the effects on the marine and coastal ecosystems are assessed using integrated planning models. Hydrogen-based routes are especially characteristic of the literature on decarbonization of industry and transport. These papers demonstrate the promise of power-to-hydrogen systems to lower emissions, but also focus on efficiency losses, the cost of infrastructure, and the environmental impacts of hydrogen production in the upstream.

In South Korean case studies, environmental assessments are more likely to be quite comprehensive in nature, usually including life cycle emissions and air quality indicators in addition to cost and reliability metrics. The close relationship between energy planning and industrial policy can be analyzed in detail regarding the cross-sector environmental impact, especially in the steel, petrochemical, and transport industries. In general, the experience of South Korea demonstrates that integrated planning may be able to facilitate technologically advanced sustainability-related approaches, but it should also pay close attention to the management of the spatial limits and social approval[57,58].

5.4. Integrated Energy Planning in Malaysia

Case studies in Malaysia are relevant to the issues and possibilities of energy transitions in emerging economies undergoing increasing demand, with strong renewable resources, and continuing to be dependent on fossil fuels. The Malaysian integration planning is usually concerned with balancing between economic development and environmental protection, and specifically referring to the electricity generation, the use of industrial energy, and urbanization[59].

The case studies often discuss how solar energy, biomass, and natural gas could be integrated into the power system, and there is more and more interest in energy storage and in the management of the demand side[60]. The significant characteristic of Malaysian integrated planning studies is biomass-based pathways, backed by agricultural residues and palm oil by-products. It is commonly evaluated that these pathways can contribute to the reduction in emissions and to the growth of the principles of the circular economy, yet land use change, biodiversity, and competing resource demands are also raised in concern. These trade-offs are assessed using integrated planning frameworks, on which to determine circumstances where bioenergy can positively contribute to sustainability goals.

In Malaysia, Urban and building-scale case studies focus on the integrated planning of electricity, cooling, and distributed renewable generation since cooling demand in a tropical climate is important. In such studies, environmental analysis usually takes into account carbon emissions and energy-saving, with an increasingly strong desire to assess water consumption and local environmental effects. The case studies conducted in Malaysia emphasize the need to coordinate the integrated energy planning with more detailed environmental and land-use policies, especially in places where the energy development overlaps delicate ecosystems[61].

5.5. Comparative Insights from Regional Case Studies

Combined, case studies of China, Pakistan, South Korea, and Malaysia reveal that the context of integrated energy planning is varied and that the environmental trade-offs and sustainability routes are determined by regional factors. Although integrated planning is used in all four countries to facilitate decarbonization, there are significant differences in the priorities, limitations, and environmental issues of all four countries. The Chinese environment is dominated by large-scale integration of systems and regional coordination. Developmental and resilience are the main concepts that guide Pakistan. Technological sophistication and decarbonization of industries are the characteristics that guide South Korea, and resource-based and urban integration are the challenges in Malaysia. To compare the key features of the integrated planning case-studies across the regional situations, **Table 4** summarizes the key features of the integrated planning case-studies of China, Pakistan, South Korea, and Malaysia.

Table 4. Comparative overview of integrated energy planning focus, dominant technologies, and environmental priorities in selected countries.

Country	Planning Scale	Key Technologies	Main Environmental Focus
China	Regional to national	Renewables, storage, hydrogen, sector coupling	Emission reduction, land and water constraints
Pakistan	Local to national	Solar–wind hybrids, hydropower, storage	Energy access, water–energy trade-offs
South Korea	National and industrial	Offshore wind, hydrogen, storage	Industrial decarbonization, land constraints
Malaysia	Urban to national	Solar, biomass, gas, cooling integration	Land use, biomass sustainability

These continental views emphasize the fact that there is no best model of integrated energy planning. Rather, sustainable environmental results rely on a collective arrangement of planning frameworks to local resource endowment, socio-economic and policy goals, and keeping an overall perspective against transfer of environmental loads at cross-sectoral and cross-scale scales [62]. The lessons learned in these case studies are helpful in terms of further development of integrated planning approaches and developing context-specific and environmentally resilient sustainability pathways.

6. Research Gaps and Future Directions

6.1. Methodological Gaps in Integrated Energy Planning

Although there have been great achievements in terms of integrated planning of new energy systems, there are still some significant gaps in methodology that do not in any way allow present models to provide full support of environmentally sustainable decision-making. The treatment of the environmental dimensions other than greenhouse gases is one of the longest gaps. Whereas carbon measures are regularly included in the form of a target or constraint, other environmental consequences, which may be land use change, water stress, biodiversity loss, and material criticality, are typically treated in a partial or simplistic way. Such an imbalance may skew the results of planning towards the direction of paths that are good in terms of emissions reduction, but which cause great environmental pressures in other directions [63].

The other important issue, which is a methodological issue, is the combination of the environmental assessment tools with the planning models. Life cycle assessment, multi-criteria evaluation, and ecological impact analysis are often undertaken as ex post methods, but not as part and parcel of the planning systems. This disconnection constrains the impact of environmental concerns on the core planning decisions and the capacity of models to internalize trade-offs when designing a system. Whole-system methods are still computationally expensive and tend to need broad simplifications of environmental processes, which underscores the importance of the methodological innovations needed in order to balance the depth of an analysis with computability [64,65].

The majority of integrated planning studies also have not adequately addressed the representation of uncertainty. The uncertain nature of technology learning rates, availability of resources, climate, and policy paths makes environmental impacts and sustainability outcomes very sensitive. Even though stochastic and robust optimization methods are more often implemented for techno-economic variables, the uncertainty concerning environmental indicators. Further studies need to come up with systematic methods of proliferating the environmental uncertainty using models of planning, thus enhancing the sustainability evaluation robustness and credibility.

6.2. Data and Model Integration Challenges

The availability and quality of data are one of the biggest obstacles to further development of integrated and environmentally holistic energy planning. There is a high resolution of data about energy demand, performance of technology, and system operation, especially in developed economies. On the other hand, the information regarding the environmental effects, the life cycle base, and other ecological constraints in the region is often incomplete, discontinuous, or old-fashioned. It is particularly these limitations that are the most acute in emerging and developing economies, where integrated planning is most desperately required in order to direct sustainable development[66].

Integration of models is also a further problem since integrated energy planning is increasingly demanding integration between models at different scales and levels of abstraction[67]. Operational simulation tools, capacity expansion models, life cycle assessment databases, and policy analysis frameworks are usually created independently with incompatible assumptions and data structures. The harmonization of boundaries in systems, time, and space resolutions and indicators is one of the areas through which these models have to be aligned. In the absence of such harmonization, the integrated analyses will be in danger of giving inconsistent or misleading results.

The development of digitalization, open data platforms, and interoperable modeling frameworks has some promising opportunities to solve these challenges[68]. Nevertheless, converting these opportunities will demand increased collaboration between the various disciplines and increased incentive to share and be transparent with data. The creation of standardized datasets and benchmarking exercises would go a long way in making the integrated planning studies more comparable and reproducible to make them stronger arguments to policy and practice.

6.3. Emerging Technologies and Planning Paradigms

The fast development of new energy technologies provides both opportunities and challenges to integrated planning[69]. The green hydrogen, synthetic fuels, long-duration energy storage, and carbon dioxide removal technologies can facilitate deep decarbonization of the spheres that are hard to electrify. Simultaneously, the new technologies introduce new environmental and sustainability concerns about energy efficiency, material consumption, land and water use, and long-term ecological effects. The models of current planning do not have the resolution or the scope to represent these technologies and how they interact with the current energy systems properly.

The world of energy planning is also being transformed by digital technologies and artificial intelligence[70]. The machine learning techniques can be used to enhance demand forecasting, renewable resource analysis, and system operation, and more advanced optimization algorithms can be used to enhance the efficiency of computations. Nonetheless, the introduction of data-driven approaches into long-term planning systems leads to concerns about transparency, understandability, and compatibility with the sustainability targets. It is a crucial research problem to ensure that superior planning instruments are interpretable and credible to the decision-makers.

Lastly, an increasing interest in extending integrated planning paradigms to include more clearly social and institutional aspects of sustainability is present. Problems like energy justice, societal acceptance, and governance capacity are becoming the key determinants of successful energy transitions[71]. They should be investigated in future studies into how such factors can be modeled in integrated planning frameworks, either as extended objective functions, or as narratives, or linked to socio-economic models. The role that integrated planning plays in transforming the energy systems to be environmentally sustainable can be reinforced by filling in methodological, data-related, and conceptual gaps and using the approach in future research.

7. Conclusions

The shift towards low-carbon and sustainable energy systems is also radically changing the design, planning, and operation of energy systems. Due to the growing complexity of energy systems, with large proportions of fluctuating renewable energy, extensive sector linkage, and the electrification of end-use sectors, conventional, silo planning strategies will no longer be adequate. As has been shown in this review, integrated planning offers a requisite and, even more, essential structure in dealing with the technical, economic, and environmental issues regarding the new energy systems.

This article reviews the literature on integrated planning methodologies; as such, it demonstrates a wide variety of modeling methods employed to represent multi-energy systems at both spatial and temporal scales. Simulation-based, optimization-based, and hybrid frameworks each have their advantages and disadvantages, but cannot represent all the environmental effects and sustainability issues. Although technological economic performance is still dominant in most planning studies, the review reveals that environmental dimensions are slowly taking center stage, especially with consideration of life cycle thinking, multi-criteria evaluation, and cross-sector environmental assessment.

One key conclusion made in this review is that environmental trade-offs are inherent in the process of transforming the energy system and cannot be removed solely by technological substitution. Greenhouse gas mitigation strategies can create pressure on land, water, and material resources or redistribute environmental impact by sector and area. Integrated planning is very important in ensuring that these trade-offs are made explicit so that decision-makers can compare alternative system configurations and transition pathways in a transparent and systematic way. Instead of seeking the best solution, integrated planning helps to make informed trade-offs and priorities towards achieving sustainability.

The discussion of the environmental effects, trade-offs, and sustainability directions provides reasons to support a long-term approach to energy planning holistically. The sustainability pathways highlight the importance of the timing and sequencing of investments and policies, as well as the coordination of investments and policies, as much as end-state system configurations. Those planning systems that consider transition dynamics, uncertainty, and cumulative environmental impacts are in a better position to prevent infrastructure lock-in and provide adaptive and resilient energy systems. With the addition of the socio-environmental aspects, including equity, general acceptance, and governance ability, the value of integrated planning as a tool to be applied in real-life decision-making becomes even more effective.

The case studies of China, Pakistan, South Korea, and Malaysia in the regions show how the integrated planning is influenced by different socio-economic factors, resource endowments, and the priorities of the policies. These examples show that the concepts of integrated planning are universal, but the local context is the key to sustainability results. In China, extensive system coordination and regional environmental limits predominate the planning issues, developmental and resilience issues featuring in Pakistan, industrial decarbonization and technological assimilation in South Korea, and resource-based and urban sustainability issues in Malaysia. These views combine to indicate that there is a necessity of having flexible and context-dependent planning systems that do not impose environmental costs across sectors or locations.

In prospect, the review provides a number of areas of priority in future research and practice. The methodology may have to be improved in order to incorporate significantly more of the environmental indicators in the basic planning models, to be more careful about the treatment of uncertainty, and to reflect more appropriately the emerging technologies and socio-institutional influences. The future of integrated planning studies will rely on advancements in terms of data availability, model interoperability, and transparency to enhance credibility and policy relevance of such studies. To overcome these problems, interdisciplinary cooperation and better coordination between energy modeling and environmental science and policy analysis will be needed.

In conclusion, integrated planning is not merely a technical exercise, but a strategic tool for guiding energy systems toward environmentally sustainable and socially acceptable futures. By explicitly addressing environmental trade-offs and by supporting robust sustainability pathways, integrated planning can help ensure that the energy transition delivers not only deep decarbonization but also broader environmental and societal benefits over the long term.

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