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Abstract

Sector coupling (SC), the integration of energy vectors and end-use sectors, is increasingly central to the net-zero transition but remains conceptually fragmented. This fragmentation causes modeling inconsistencies, hinders cross-study comparison, and undermines energy policy coordination. We address this gap through a structured mapping of existing definitions, categorizing them along three dimensions, namely, structural, functional, and electricity-centric, and analyzing their limitations. Drawing on these insights, we propose a coherent definition that captures SC in its full diversity and complexity: SC is the establishment of physical or non-physical interconnections, in any direction, among energy-carrying vectors, among energy-consuming end-use sectors, between vectors and sectors, and within the layers that link them (energy processing, transfer, markets, and policy). This framing clarifies what constitutes a "sector", distinguishes "sector coupling" from related concepts such as "flexibility", and encompasses the entire spectrum of interlinkages in a sector-coupled energy system. Building on this definition, we organize the SC interlinkages into six categories based on their driving mechanisms: vector coupling, end-use sector coupling, vector-shift coupling, network coupling, market coupling, and policy coupling. Together, our definition and classification provide a shared conceptual foundation for the SC field. The framework's modular architecture enables extension to new end-use sectors, non-energy material flows, and material-energy circularity pathways. It can enable modelers to avoid unintentional mismatches in model scopes, standardize SC implementation in models, and trace cascading, system-wide interactions. It can also support policymakers in designing structured scenarios, identifying which SC pathway works best in specific settings, and coordinating cross-sector cross-vector policies. By synthesizing fragmented concepts into a coherent and comprehensive whole, this work advances the theory of the SC domain.

Keywords: sector coupling, definition, energy vectors, end-use sectors, flexibility, electrification, interlinkages, energy system modeling, policymaking, decarbonization, taxonomy

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1. Introduction

Rising emissions and worsening climate impacts require an urgent transformation of our energy systems by integrating more renewables on the supply side and shifting to low-carbon vectors on the demand side. Realizing the full potential of these strategies requires coordinated systems-wide interactions between previously siloed energy vectors and end-use sectors. This is the premise of sector coupling (SC): the interlinking of energy vectors (e.g., electricity, gas, heat, molecules) and end-use sectors (e.g., mobility, industry, residential, services). During the past decade, SC has emerged as a whole-energy system strategy central to achieving a flexible and cost-effective net-zero energy transition.

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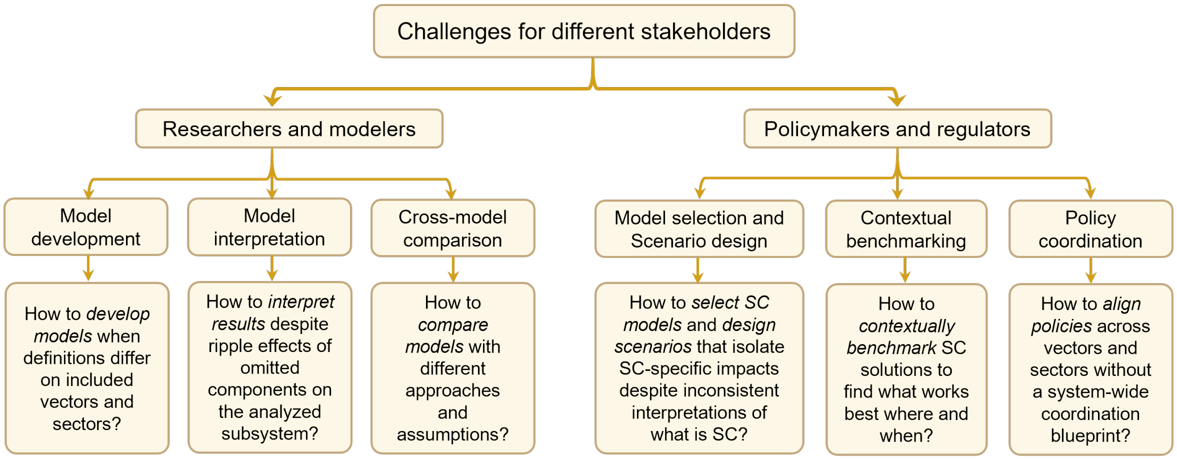

Figure 1: Challenges for different stakeholders arising from the absence of a unified conceptual framework for sector coupling.

Practical applications of SC are not a recent phenomenon. Innovations such as battery electric vehicles (BEVs) and combined heat and power (CHP) systems, which link energy vectors and end-use sectors, date back to the 19th century. CHP systems first appeared in the United States in the 1880s, when urban power plants began utilizing excess steam to heat nearby buildings. However, the advent of long-distance alternating current transmission and large-scale generators relocated power plants away from urban centers, limiting the feasibility of utilizing waste heat [1]. Similarly, BEVs were introduced in the United States and Europe starting in the 1880s but were eclipsed by the affordability of mass-produced internal combustion engine vehicles (ICEVs), leaving these early SC applications largely dormant [2]. By the late 20th century, both technologies re-emerged. Electricity market liberalization enabled decentralized CHP units [3], whereas battery improvements and tightening emission norms revived BEVs [4].

During the last two decades, SC has grown beyond practice to become a key lever for decarbonization across policy levels. At the national level, Germany's Climate Action Plan 2050 explicitly acknowledged SC's importance in 2016 [5]. At the EU level, SC was recognized in the 2018 report of the European Parliamentary Committee [6], reinforced by the European Green Deal's emphasis on smart sector integration [7] and further formalized through the European Commission's strategy for cross-sector decarbonization [8]. Recently, the EU's "Call for Cross-Border Renewable Energy (CB RES) projects" emphasized SC projects, including power-to-gas (P2G) systems [9]. SC has also gained political traction beyond the EU, as exemplified by Australia's "Modeling Sectoral Pathways to Net Zero Emissions" initiative [10]. In parallel, regulators have endorsed SC through measures such as joint planning of electricity and gas grids [11, 12].

Despite a long history of practical applications and growing policy relevance, SC's theoretical development has lagged behind. Foundational efforts such as the energy hub model in the late 2000s [13], along with more recent contributions [14–20], have helped initiate formal academic discourse around SC. Nevertheless, SC's theoretical conceptualization remains fragmented, offering no unanimously acknowledged definition of the term 'sector coupling' [21–23]. While some definitions narrowly equate SC with the electrification of end-uses, others adopt a broader view, including even non-electric energy flows such as waste heat and biofuels. Even the term "sector" is interpreted inconsistently, with different SC definitions including different sectors. Some encompass services, agriculture, and forestry, while others exclude them. Additional ambiguities exist in distinguishing 'supply-side sectors' from 'demand-side sectors', with 'electricity' classified variably in different SC definitions.

The absence of a unified SC framework impacts different stakeholder groups across the energy transition landscape in distinct ways (Figure 1). For modelers and researchers, it presents specific challenges along key stages of energy system modeling. During *model development*, inconsistent SC interpretations create ambiguity regarding which vectors, end-use sectors, and interlinkages to include, leading to divergent system boundaries across tools. While *interpreting* model results, it is difficult to trace how changes in one component propagate throughout the system or how modeling only a sub-system may distort the results due to the impact of excluded components. Moreover, *cross-model comparison* is challenging, as variations in modeling approaches and internal assumptions affect key model outcomes, such as emissions, system costs, and flexibility.

Policymakers and regulators are equally affected. First, while *designing scenarios*, the ambiguity over what constitutes SC blurs the distinction between SC applications (such as BEVs) and flexibility-only measures (such as batteries), both of which offer temporal flexibility. Since both are often bundled together in scenarios, their functional overlap can make it difficult to isolate and assess SC-specific impacts, undermining the relevance of the scenarios designed. Second, *contextually benchmarking* SC applications, i.e., determining "what" works best in which context, presupposes a consistent definition of "what" constitutes SC in the first place. Finally, in the absence of a system-wide blueprint of SC interlinkages, policymakers lack a common reference to identify adverse interdependencies and align synergies across energy vectors and end-use sectors, hindering *policy coordination* and limiting the systemic benefits SC can offer.

To address these challenges, this paper aims to advance the conceptual evolution of SC by synthesizing fragmented perspectives into a coherent, yet broadly applicable analytical framework that rests on two pillars: (a) a consistent definition of *both* "sector coupling" and "sectors", and (b) a comprehensive classification of SC interlinkages. To this end, it pursues three objectives.

1. First, it reviews and systematizes existing SC definitions, identifying key limitations such as ambiguous scope, internal dichotomies, and narrow applicability.
2. Second, it proposes a coherent, value-neutral definition of SC rooted in real-world mechanisms that drive SC interactions.
3. Third, it develops a comprehensive classification scheme based on six distinct coupling mechanisms, thereby integrating diverse SC applications observed in practice into a structured theoretical construct. The categories of SC interlinkages identified are: vector, end-use sector, vector-shift, network, market, and policy coupling.

Together, our aim is to establish a comprehensive yet consistent conceptual foundation for SC, enabling researchers and policymakers to enhance model fidelity and inform policy design.

2. Classification of existing sector coupling definitions

To develop our conceptual framework, we systematically explore the sector coupling literature using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [24], filtering for studies that are both grounded in SC and theoretically informative. Detailed methodology for this process is provided in the Appendix A1. To critically examine the corpus of existing SC definitions so compiled, we introduce a three-dimensional classification framework and apply it to each definition. Table 1 presents the results, dissecting each definition along three axes:

1. *Structural dimension*, which captures SC's system topology: the sectors and grids which SC interlinks;
2. *Functional dimension*, which reflects SC's objectives;
3. *Electricity-centric dimension*, which highlights SC's vector dependency on electricity.

As the table reveals, many existing definitions span more than one dimension. Partitioning and re-arranging the definitions along the three inductively derived dimensions helps us perform a step-wise critique: first, we distill in this section the common traits among the definitions that feature each dimension; next, we identify their shared conceptual gaps and propose ways to address them (Section 3); finally, we consolidate these insights into a coherent definition of SC (Section 4).

Table 1: Classification of the existing SC definitions along three distinct dimensions.

Study	Definitions and conceptualizations (paraphrased)	Structural dimension	Functional dimension	Electricity-centric dimension
Schaber et al. [25]	Interconnection of power, heat, hydrogen, and gas sectors to absorb the temporary surplus from variable renewable sources in an economic manner.	POW, NG, HEAT, H2	DECARB, FLEX	✓
BMWi [26]	Integration of energy sectors enabling the power sector to meet demand for energy in households, transport, industry, trade, commerce and services; contributes to energy transition through efficient use of renewable electricity and substitution of fossil fuels; offers flexibility to the markets and the grid but "should not be misunderstood as a targeted instrument to take up surplus electricity from renewables."	POW, MOB, IND, HOU, TCS	DECARB, FLEX, EFF	✓
Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU) [5]	Interaction between the different sectors in Germany's Climate Action Plan 2050, i.e., energy, buildings, transport, trade and industry, agriculture, and forestry, via renewable electricity to support CO_2 neutrality; coordination of different energy infrastructures to form an efficient overall system; can also improve flexibility.	ENE, MOB, IND, TCS, AGR, LULUCF	DECARB, FLEX, EFF	✓
BDEW [27]	The technical and economic linking of electricity, heat, mobility, and industry and their infrastructures with the aim of decarbonization, while simultaneously making energy use more flexible in industry and commercial/trade, households and transport under the premises of economic efficiency, sustainability and security of supply.	ELEC, HEAT, MOB, IND, HOU, TCS & GRIDS	DECARB, FLEX, EFF, SoS	✗
Robinius et al. [28]	Renewable-dominant energy systems will experience temporary power surpluses;[1] SC is an approach to productively absorb this surplus, enabling holistic transformation across all sectors; it relies fundamentally on increasing the use of renewables to reduce emissions.	MOB, IND, RES, TCS	DECARB	✗
Ausfelder et al. [29]	Integrated optimization of the entire energy system leading to the linking and convergence of electricity, mobility, and heating sectors; includes four pathways: (i) direct electrification, (ii) power-to-hydrogen, (iii) power-to-synthetic fuels, and (iv) expanded use of biomass, solar thermal, and geothermal.	ELEC, MOB, HEATING	✗	✓[2]
Van Nuffel et al. [6]	Involves "the increased integration of energy end-use and supply sectors with one another" to improve flexibility, efficiency, reliability, adequacy, and reduce costs of decarbonization; referred initially to end-use electrification or 'end-use sector coupling' that involves the interaction between energy supply sector (mainly electricity) and end-use sectors; now broadened to include supply-side sector integration or 'cross-vector coupling' which involves the integrated use of vectors and their infrastructures.	Energy supply sectors and end-use sectors	DECARB, FLEX, EFF, ADEQ, REL, COSTS	✗
Wietschel et al. [17]	Ongoing process of substituting fossil fuels with predominantly renewable electricity or other sustainable sources (e.g., waste heat) in new cross-sector applications or through increased use of known cross-sector applications; electricity-based pathways include either direct electrification (e.g., power-to-heat, power-to-move) or power-to-X (e.g., power-to-gas, power-to-liquid); also includes interlinking classic consumption sectors (households, industry, transport, trade, commerce and services) via grid infrastructures; main goal is emission reduction; co-benefits include flexibility, efficiency, degrees of freedom for optimization.	Supply sectors (ELEC, HEAT, FUELS), consumption sectors (MOB, IND, HOU, TCS) & GRIDS	DECARB, FLEX, EFF, degrees of freedom for optimization	✓[3]
Scorza et al. [16]	**Narrow definition**: Use of electricity in consumption sectors or applications where it currently plays little or no role (e.g., BEVs in mobility). **Broad definition** (after Wietschel et al. [17]): Includes both couplings between the electricity and consumption sectors and between consumption sectors themselves (e.g., industrial waste heat reused for power generation). Both definitions see SC as contributing to fossil fuel substitution across various sectors, though to varying extents. The authors classify two types of sectors: (i) the electricity sector, covering both electricity generation and current demand from original electricity applications, and (ii) the consumption sectors of transport, industry, and buildings.	ELEC, MOB, IND, BUILDINGS	DECARB, FLEX	✓

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Study	Definitions and conceptualizations (paraphrased)	Structural dimension	Functional dimension	Electricity-centric dimension
IRENA [30]	SC is electrification of other energy sectors (i.e., heat or transport). However, "electrification and SC are not equivalents. SC will take place only if the electrified resources are used in a way that favours VRE integration."	✗	✗	✓
Fridgen et al. [31]	Holistic, multi-dimensional concept for governing cross-, inter-, and intra-sectoral energy flows — including all networks that transport energy in any form (e.g., electricity grids, gas pipelines, roadways, waterways, railways, communication networks), energy conversion, and energy storage systems — to reduce spatial transport losses and new infrastructure investments, enhance flexibility, and support a future energy system based on renewables.	ALL GRIDS	FLEX, EFF	✗
Münster et al. [32]	A system-of-systems approach to planning, designing, and operating infrastructures and processes by leveraging synergies and complementarities across co-existing energy sectors to optimize resources and improve efficiency. SC involves converting electricity into other energy forms that are then: (i) stored more easily outside the electric system for later re-conversion into electricity or to shift demand in time and space, (ii) consumed in another sector if cheaper or cleaner than energy forms typically available for that sector, either temporarily (through operational optimization) or permanently (through electrification), or (iii) transported as heat, gas, or molecules when doing so is more efficient, convenient, or faster than expanding electric grids, which requires building authorizations, environmental permits, and public acceptance.	✗	DECARB, FLEX, EFF, COSTS (SC goals are implicit)	✓
Hughes et al. [33]	Integrating energy-consuming sectors such as buildings (heating and cooling), transport, and industry with the power supply sector to increase system flexibility and achieve a higher renewable share; involves energy conversion across sectors to facilitate the storage, usage and transport of energy in non-electric forms if they are cheaper/cleaner.	POW, MOB, IND, BUILDINGS (heating and cooling)	DECARB, FLEX	✗
Ramsebner et al. [22]	SC originates from the need to integrate variable renewable electricity into the energy system and therefore excludes non-electric renewable sources (e.g., biofuels, waste heat), which fall under the broader concept of energy system integration (ESI). SC applications can be: (i) direct (electricity used in its original form) or indirect (electricity first converted to heating/cooling, gas, or liquid fuels); and (ii) centralized (large-scale, distant from end-user) or decentralized (small-scale, near end-user).	MOB, IND, RES, TCS	✗	✓
Sadeghian et al. [34]	Integration of different fuels (e.g., fossil fuels, hydrogen, biofuels), infrastructures (e.g., electricity, natural gas, hydrogen, district heating), energy sectors (e.g., residential, transport, industry, commercial, agriculture), and energy systems (e.g., microgrids, energy hubs, virtual power plants) to coordinate centralized and distributed supply and storage systems using coupling technologies (e.g., CHPs, heat pumps); serves to meet diverse energy demands while improving environmental performance, efficiency, economics, flexibility, reliability, and to manage a high share of renewables and sudden failures through optimal linking and switching between energy sources.	MOB, IND, RES, COMM, and AGRI and GRIDS (ELEC, NG, H2, HEAT)	DECARB, FLEX, EFF, REL, COSTS	✗
IRENA [23]	SC goes beyond merely enhancing power system flexibility; it facilitates an integrated transformation of the energy system towards a 100% renewable-based, reliable energy supply and demand across all sectors by combining different sectors of energy demand and production (e.g., electricity, heating, cooling, transport, and industry); it is a "a strategy to optimize the energy system . . . through direct or indirect use of electricity across applications in end-use sectors with the aim of accelerating the transformation towards 100% renewable energy."	ELEC, MOB, IND, H&C	FLEX, REL, 100% RES-based system	✓
Rodi and Kalis [35]	"SC describes the interconnection and interlocking of sectors, i.e., the unimpeded flow of energy and the cooperation of infrastructures. "Sectors" describes energy production and (end) consumption categories, such as electricity, buildings and mobility. Sector coupling leads to the interdependence of otherwise independent sectors and aims at creating unhindered energy flows in an integrated energy system."	Energy production and consumption sectors	✗[4]	✗
Bardow et al. [36]	"SC is the interconnection between (and within) the energy supply and/or energy demand sectors." It leverages synergies among sectors with the ultimate goal of deep decarbonization, while also serving as an additional source of system flexibility. SC interconnections can be of two types: (i) those *across* energy supply and demand sectors, and (ii) those *within* the supply sectors or *within* the demand sectors.	Energy supply and energy demand sectors	DECARB, FLEX	✗

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Study	Definitions and conceptualizations (paraphrased)	Structural dimension	Functional dimension	Electricity-centric dimension
Komarnicki et al. [37]	SC is a bundle of technical and organizational measures aimed at enabling most future energy consumption to be met with renewable sources (mainly wind and solar). These sources are first converted into green electricity, which is then used directly (e.g., BEVs) or indirectly (e.g., power-to-X) to meet energy demands across the sectors of end-use. This creates a direct coupling between renewable energy and all sectors via renewable electricity as the intermediate energy carrier. Since the same renewable electricity can serve all sectors, it also enables energy exchange among them, resulting in strong coupling between sectors themselves.	Energy sector (extraction and distribution of COAL, NG, HEAT, ELEC) and sectors of end-use (MOB, IND, HOU, TCS)	✗	✓

Notes: POW: power; ELEC: electricity; NG: natural gas; H2: hydrogen; MOB: mobility; IND: industry; HOU: housing; RES: residential; TCS: trade/commerce/services; COMM: commerce; AGRI: agriculture; LULUCF: land use, land use change, and forestry; DECARB: decarbonization; FLEX: flexibility; EFF: efficiency; ADEQ: adequacy; REL: reliability; SoS: security of supply. [1] The authors acknowledge that whether future energy systems will exhibit surplus renewables is a broader question beyond the scope of their work. [2] Implicit in three out of four pathways. [3] The authors acknowledge multiple vectors but emphasize renewable electricity. [4] The authors emphasize the need to divorce the normative goals or functions which SC is intended to serve from its objective definition.

2.1. Sector coupling definitions featuring the structural dimension

Definitions that exhibit a structural dimension typically describe SC as the interconnection between the energy-producing supply-side sectors and the energy-consuming demand-side sectors. While many of these definitions focus primarily on the sectoral scope of SC, some also extend the structural emphasis to include grid-level interconnections [31, 34, 35]. Thus, what unites these structurally oriented definitions is their shared emphasis on delineating system boundaries, identifying which sectors and grid infrastructures fall within the conceptual scope of SC. Table 1 lists these definitions, along with the specific sectors and grids they identify, summarized under the column 'structural dimension'.

2.2. Sector coupling definitions featuring the functional dimension

From a functional perspective, SC is defined in terms of the systemic roles it is expected to serve in the energy transition. As shown in the column 'functional dimension' of Table 1, these definitions embed political objectives (i.e., *why* SC should be pursued) into the very conceptualization of SC itself. Among the various roles attributed to SC, decarbonization emerges as the most frequently cited. For example, Scorza et al. [16] note that both narrow and broad interpretations of SC converge on the goal of replacing fossil fuels with renewables, although to varying degrees. Similarly, IRENA [23] defines SC as a key to achieving a 100% renewable-based energy system. In parallel to decarbonization, flexibility and efficiency are frequently highlighted co-functions of SC [16, 17, 23, 26, 27, 31, 33, 34]. While Wietschel et al. [17] prioritize decarbonization and position flexibility and efficiency as "secondary co-benefits" of SC, Fridgen et al. [31] consider flexibility and efficiency as the primary SC functions A smaller segment of the literature also highlights reliability and security of supply as defining functions of SC [23, 27, 34].

2.3. Sector coupling definitions featuring the electricity-centric dimension

The definitions under the column 'electricity-centric dimension' of Table 1 emphasize electricity, particularly renewable generation, as the primary vector driving SC interlinkages. For example, Schaber et al. [25] and Robinius et al. [28] frame SC as a mechanism to absorb *surplus* renewable electricity. On the other hand, BMWi [26] cautions against limiting SC to a *surplus* management tool, stressing that many SC applications like BEVs and heat pumps must operate on demand, not merely when excess power is available. The study instead argues that SC's long-term significance lies in enabling the sustained use of renewable electricity across diverse end-use sectors. This system-wide pro-renewable shift as a defining feature of SC is also echoed by IRENA [30], which describes SC as a form of electrification that actively supports renewable integration, thus distinguishing SC from general electrification.

Scorza et al. [16] refine the electricity-centric dimension by distinguishing between narrow and broad SC definitions. The narrow perspective interprets SC as expanding electricity use in previously unelectrified end-use sectors, while the broader view frames SC as the process of replacing fossil fuels with renewable electricity *or* other sustainable vectors, such as biofuels and waste heat. Ramsebner et al. [22] endorse the narrow SC view, arguing that SC emerged in response to the increasing grid-penetration of renewable electricity and therefore should exclude non-electric vectors from its definitional scope. In contrast, Wietschel et al. [17] advocate the broader view by including even non-electric vectors within SC, but still position renewable electricity as the central vector by identifying two main SC pathways: (i) direct use of electricity (e.g., BEVs, power-to-heat), and (ii) indirect use of electricity by conversion to other vectors such as hydrogen (in form of P2G or synthetic fuels) power-to-liquid (P2L), collectively termed P2X. Similarly, IRENA [23] and Komarnicki et al. [37] define SC as a strategy to interlink renewable electricity and end-use sectors, either directly or indirectly. Lastly, even more nuanced SC conceptualizations, such as that of Thellufsen et al. [38], retain electricity's central position by conceptualizing SC as a bidirectional mechanism, where renewable electricity extends to end-use sectors that, in turn, provide balancing and flexibility services back to the power grid.

3. From fragmentation to coherence: Overcoming conceptual gaps in existing definitions

3.1. The structural dimension: Gaps and resolutions

Definitions that exhibit a structural dimension capture the system topology by describing SC in terms of the sectors and grids that are interlinked. These definitions exhibit two important inconsistencies.

3.1.1. Supply-demand dichotomy in classifying sectors

The first drawback is their bifurcation of sectors into: (i) ‘supply side’, where energy sources are extracted (e.g., coal and oil mining) or transformed into end-use compatible forms (e.g., electricity, refined fuels, or heat), and (ii) ‘demand side’, where energy is consumed to deliver end-use services. This supply–demand dichotomy poses three conceptual limitations.

First, it implies that generation and consumption are spatially segregated. While this segregation was representative of traditional, centralized, unidirectional energy systems, it no longer holds in modern, decentralized, bidirectional systems. For example, a rooftop PV can directly charge a BEV parked beneath it, or a biogas plant can fuel CHP units that supply electricity/heat for on-site use. In such prosumer configurations, generation and consumption are spatially co-located and locally matched, making the strict supply-demand bifurcation obsolete. Although Bardow et al. [36] recommend placing such prosumers on both the ‘supply’ and ‘demand’ sides, doing so would create classification dilemmas and redundancies.

Second, the dichotomy often underpins the classification of SC applications into ‘centralized’ and ‘decentralized’ forms. For example, Bloess et al. [39] classify centralized power-to-heat (P2H) systems as large-scale heat pumps that first convert electricity to heat off-site and then distribute it to the point of demand using heat networks. In contrast, decentralized P2H systems comprise small-scale heat pumps within households, operating on-site to meet the heat demand. In practice, there are intermediate configurations such as neighborhood-scale thermal networks that convert energy into heat “near-site” of the heat demand [1], blurring the centralized-decentralized distinction and thus revealing the inadequacy of rigid supply–demand bifurcation.

Third, the dichotomy creates conceptual ambiguity about whether electricity should be treated as a vector or as a sector. Several SC definitions [16, 23, 27–29, 33] refer to an ‘electricity or power sector’, but without consistent boundaries. Some classify ‘electricity’ as a typical supply-side sector [6], some position it as an atypical energy-consuming sector that includes end-user sales and transport losses between the supply and demand ends [40], while still others conflate both electricity supply (i.e., generation) and its demand within an ‘electricity sector’ [16]. This conceptual inconsistency creates modeling dilemmas: whether direct electrification applications, such as BEVs and electric arc furnaces, should be grouped under the ‘electricity sector’ or under their functionally relevant sectors like ‘mobility’ and ‘industry’, or under both.

To resolve these discrepancies in existing SC definitions, we propose replacing ‘supply-side sectors’ with ‘energy-carrying vectors’ and ‘demand-side sectors’ with ‘end-use sectors’. ‘Energy-carrying vectors’ refer to the different forms in which energy is converted, stored, or transported, such as electricity, heat, natural gas, and molecules. ‘End-use sectors’ represent distinct consumer segments who utilize energy for specific end-use applications and are distinguished by a characteristic consumption profile, such as mobility, industry, and building H&C (more on ‘sectors’ in 3.1.2). This terminology eliminates the spatial bias of the supply–demand dichotomy, while still conveying the dynamism of energy flow through the use of words such as ‘energy-carrying’ and ‘end-use’. It also clarifies the treatment of ‘electricity’, which now falls clearly under the category of ‘energy-carrying vectors’ rather than ‘end-use sectors’. This classification ensures that direct electrification applications are correctly assigned to the relevant end-use sectors based on their application, instead of being grouped under an ambiguous ‘electricity sector’. Overall, this shift from a rigid ‘supply–demand’ typology to a ‘vector and end-use sector’ construct provides a clearer and more consistent foundation for representing and analyzing modern sector-coupled energy systems.

3.1.2. Economy-technology dichotomy in classifying final energy consumption

The second drawback of SC definitions featuring the structural dimension is their lack of consensus on what constitutes a “sector” [17, 22, 28, 29, 35] in the context of sector coupling. Different definitions consider different sectors while defining SC and vary widely in the inclusion of domains such as trade/commerce/services, agriculture, land use, and forestry. We trace this discrepancy to a deeper distinction between the economic and technological interpretations of SC [22]. Definitions that approach SC from an economic perspective [e.g. 27] align with official energy balances, which classify the final energy use based on *who* (or which economic actor) consumes it. These definitions thus aggregate consumer segments into categories such as private households, transport, industry, trade, commercial and public services, agriculture, forestry, and fishing. In contrast, SC definitions grounded in a technological perspective [e.g. 23] categorize the final energy use based on *what* application it serves. For example, these definitions consolidate all demands for space and water heating applications into a single ‘heating’ sector. This definitional dichotomy cascades into the modeling landscape. Energy-economy models such as NEMS [41] and TIMES [42] retain the demands for space and water heating within the respective 'residential' and 'service' sectors. In contrast, technologically oriented models, such as PyPSA-Eur [43] and DIETER [44], bundle these demands into a separate 'heating' sector. These inconsistencies underscore the need for a standardized definition of the term "sectors".

While Ramsebner et al. [22] advocate for the economical classification of "sectors", Scorza et al. [16] argue for adopting the technological perspective. To bridge this gap, we propose combining the *who consumes* (economical perspective) with the *for what* (technological perspective) and define end-use sectors as *distinct consumer segments within an energy system who utilize energy for specific end-use applications and are distinguished by a characteristic consumption profile*. Including the consumption profile is essential, as it captures sector-specific temporal patterns. For instance, in the EU, the 'residential' sector typically shows stronger seasonality, with daily electricity peaks shifted to later in the evening and daily thermal peaks advanced to earlier in the morning compared to the 'industrial' and 'commercial' sectors [45]. Building upon our definition of 'end-use sectors', we propose a two-dimensional classification scheme that maps different sectors to their respective constituent economic actors and end-use applications. Accordingly, future SC studies could benefit from focusing on one or more of the following five end-use sectors: 'mobility', 'industry', 'residential', 'services or tertiary', and 'building H&C' (Table 2).

Table 2: Proposed framework for classifying end-use sectors based on the combined logic of *"who"* consumes and for *"what"* purpose[†].

End-use sector	**Energy consumed *by whom* (economic perspective)**	**Energy consumed *for what* (technological perspective)**
Mobility	Passengers and freight	Transport across road vehicles, rail, air, and maritime modes
Industry	Extraction, construction, manufacturing, processing, and assembly facilities	Mining and quarrying, building and demolition of infrastructure, process heating and cooling, space and water heating and cooling, electro-mechanical drives, and electro-chemical processes. *Excludes non-energy feedstock (e.g., petrochemicals used as raw materials rather than fuels)*
Residential	Households	Lighting, ventilation, powering appliances, cooking. *Excludes building-related heating and cooling*
Services or Tertiary	Trade, commercial, and public service institutions such as shops, hotels, offices, schools, colleges, banks, hospitals, water and waste utilities, data centers[*]	Lighting, ventilation, computing, office equipment, appliances, refrigeration, process heating and cooling, light machinery, water supply, waste, and remediation. *Excludes building-related heating/cooling*
Building Heating and Cooling	Buildings in the residential and services (or tertiary) sector	All building-related heating and cooling end-uses, including space/water heating and cooling, delivered via decentralized systems (e.g., heat pumps) or centralized networks (e.g., district heating)

[†] Sectors such as 'agriculture', 'forestry', and 'fishing' together account for a small share (<3%) of the EU's final energy use [46]. Given their limited impact on system-wide dynamics, SC models may exclude them for computational efficiency. Nonetheless, our framework remains flexible enough to include these where needed.

[*] In the EU Statistical Classification of Economic Activities (NACE Rev. 2), the 'commercial services' sector includes (a) water supply, sewerage, waste management, and remediation activities, and (b) information and communication, including data processing services [47]. Similarly, the US energy balance places sewage treatment and data centers under the 'commercial' sector [40, 48].

Our proposed 'end-use sector' framework offers the following key benefits.

First, we propose a distinct 'building heating and cooling' end-use sector. While a few existing SC definitions do refer to 'buildings' as a separate sector, they often lack a clear specification of the constituent demand flows [5, 29, 49]. To address this gap, we take a cue from Scorza et al. [16]. We extract building-related heating and cooling (H&C) demands, comprising space and water H&C, from 'residential' and 'tertiary' end-use sectors, and aggregate them into a distinct 'building H&C' end-use sector. This grouping serves to analyze SC interlinkages involving the heat vector. The approach finds precedents in several sector-coupled energy system models. Some models fully integrate building thermal demands across 'residential' and 'commercial' boundaries: EnergyPLAN and GENeSYS-MOD group them into 'heating' and 'cooling' demand segments rather than by building type (residential vs. commercial) [50, 51]. Others adopt hybrid approaches that partially aggregate building thermal demands. PyPSA-Eur bundles 'residential' and 'commercial' demands for district heating, but maintains separate buses for individual heating in each of these sectors [43]. Even models which retain completely separate ‘residential’ and ‘commercial/services’ sectors in their structure often aggregate them at the output into a unified ‘buildings’ sector for policy reporting (e.g., TIMES [42], PRIMES [52] and NEMS [53]).

Modelers can construct the ‘building H&C’ end-use sector using either official energy statistics or established methods for end-use energy disaggregation. Official statistical agencies such as the US’ EIA and the EU’s Eurostat routinely report disaggregated end-use energy consumption in the ‘residential’, ‘commercial’ and ‘service’ sectors, including space heating, space cooling, and water heating [41, 54]. Models requiring exogenous demand inputs can synthesize a ‘building H&C’ end-use sector by regrouping thermal end-uses from the standard categories in official statistics, while models generating demand endogenously (e.g., MESSAGEix-Buildings [55]) can disaggregate their ‘building H&C’ demand back to standard categories in official statistics for model validation. When disaggregated thermal data are unavailable, weather-based methods combining heating/cooling degree-days with building physics can isolate thermal demand from total building energy consumption with high accuracy [56]. The basis for such separation lies in the distinct temperature-driven dynamics of thermal demand compared with the stochastic, occupancy-dependent end-uses such as lighting and appliances. Thus, our ‘building H&C’ end-use sector is not a replacement for conventional ‘residential’ and ‘service’ sectors, but a transparent and reversible modeling construct that spans these official categories to analyze SC interlinkages. Our categorization has several merits:

1. It aligns with the growing policy momentum that treats building thermal demand as an integrated decarbonization challenge spanning residential, commercial, and public buildings. This is evident in national-level building-focused initiatives across several EU countries, such as Austria [57], France [58, 59] and Germany [60], along with the UK’s Energy Act (2023) designating Ofgem as the future heat networks regulator [61]. Key examples at the EU and international level include Article 26 of the Energy Efficiency Directive recast (2023) [62], the Energy Performance of Buildings Directive (EPBD) recast (2024) [63], IEA’s Breakthrough Agenda (2024) [64], and Australia’s Built Environment Sector Plan (2025) [65]. The EU’s REPowerEU plan and associated Heat Pump Accelerator Platform further underscore this momentum by targeting 30 million additional heat pumps by 2030 and calling for 750,000 new installers [66, 67].
2. Building-related H&C demands constitute a dominant energy flow, comprising nearly 80% of the ‘residential’ [54], 53% of the ‘tertiary’ [68], and 32% of total final energy consumption in the EU [69]. A dedicated ‘building H&C’ sector captures this systemic significance and provides a clearer basis for tracking decarbonization progress of building-related H&C end-uses. This is particularly important as electrification of heating accelerates under net-zero pathways and demand response in buildings becomes a key flexibility option for integrating higher renewable shares.
3. It improves analytical outcomes across policy, research, and industry. For policymakers, a dedicated ‘building H&C’ sector supports the preparation of targeted interventions through improved modeling of policy levers, such as retrofit programs and gas boiler phase-out regulations [70, 71]. For researchers, it enables more accurate modeling of P2H interactions, which have been shown to outperform fossil-based alternatives in flexibility and efficiency [39, 72, 73]. For instance, it allows explicit modeling of building thermal mass as a ‘virtual battery’ for thermal flexibility [74]. For industry, a dedicated ‘building H&C’ sector offers clearer signals on emerging heat market opportunities (e.g., heat pump deployment trajectories) and associated workforce demand [49]. These signals have already prompted scaled-up heat pump manufacturing, including over USD 4 billion in announced capacity expansions, and installer training programs [75, 76].

Second, we propose retaining all industrial thermal flows, both process- and building-related, within the ‘industry’ end-use sector, rather than reallocating the latter to the ‘building H&C’. Although the extent of such thermal integration varies, many industrial facilities are increasingly leveraging operational synergies between process- and building-related thermal systems to improve efficiency and reduce costs, for example, through shared CHP steam lines or recovery of residual process heat for on-site space comfort and hot water [77–79]. Thus, modeling these flows as a unified thermal block can avoid double-counting of energy demands, simplify system representation, and support a more accurate assessment of decarbonization and efficiency improvement potential in the ‘industry’ sector. Also, this integrated thermal accounting has already been adopted in models such as GENeSYS-MOD [51], EnergyPLAN [50], and PyPSA-Eur [43].

Third, our ‘end-use sector’ classification is adaptable, allowing the incorporation of new sectors in response to evolving research and policy priorities. For example, the growing literature on electricity-water interactions [80–83] has highlighted ‘water’ as an emerging end-use sector. Our end-use sector classification allows adding a new ‘water’ sector that encompasses energy consumed *by* distinct consumer segments, such as desalination plants and wastewater treatment facilities, *for* specific end-use applications, such as freshwater generation and wastewater purification. In addition, these water facilities have a continuous but time-shiftable load profile due to intermittent pumping and batch-based treatment cycles. Likewise, ‘data centers’ could be considered another prospective end-use sector, where energy is consumed *by* data processing facilities *for* information technology services such as cloud computing, data storage, and big data analytics. These facilities exhibit a load profile with multi-scale flexibility arising from deferred computing tasks, thermal storage units, and waste heat reuse [84, 85]. By satisfying the criteria of distinct consumer segments with specific end-use applications and characteristic load profiles, both ‘water’ and ‘data centers’ can be justifiably incorporated into SC models, enabling modular expansion of the SC framework without compromising conceptual clarity or modeling coherence.

3.2. The functional dimension: Gaps and resolutions

Definitions with a functional dimension highlight the systemic roles that SC is expected to fulfill, such as decarbonization, flexibility, or efficiency. These definitions introduce four crucial conceptual challenges.

3.2.1. Prescriptive-descriptive and normative-positive dichotomy

A fundamental difference between normative and positive science is that the former concerns *what ought to be* while the latter deals with the knowledge of *what is*. As Milton Friedman cautioned,“confusion between them is common and has been the source of many mischievous errors” [86]. Functional definitions exhibit precisely this tendency. They merge prescriptive goals (i.e., what SC *ought to* achieve) with descriptive content (i.e., what SC *is*), imposing normative judgments about what constitutes desirable “desirable” SC on an otherwise positive definition offering an unbiased account of SC’s scope and mechanisms. Such conflation introduces two problems.

First, it adds subjectivity, making SC vulnerable to conflicting disciplinary interpretations [35]. Climate scientists may emphasize emission-reducing interconnections as SC, energy engineers may argue that only emission-reducing and flexibility-enhancing interconnections qualify as SC, while economists may prioritize efficiency as the defining criterion. Each discipline, viewing SC through its own normative lens, might arrive at a different definition, possibly hindering interdisciplinary dialogue [87].

Second, a normative definition has limited applicability across diverse national contexts. The World Energy Council’s Trilemma framework recognizes that countries balance energy security, energy equity (affordability and access) and sustainability differently depending on divergent priorities [88]. In developing countries with constrained electricity infrastructure, efficiency may be prioritized to reduce costs and extend access (energy equity), since, saving energy through efficiency upgrades is cheaper than installing new renewables [89]. In contrast, industrialized countries with already high shares of renewables may emphasize system flexibility to maintain grid stability (energy security). Thus, embedding any single normative goal in the SC definition might produce disciplinary and geographical fragmentation, ultimately compromising the conceptual neutrality required for a universally applicable framework.

Beyond these theoretical concerns lies a more fundamental empirical problem. The three common functions most commonly attributed to SC, decarbonization, flexibility, and efficiency [17, 23, 26, 35], are not inherent properties of SC, but contingent outcomes that depend on implementation. SC applications can, under certain conditions, fail to deliver, or even undermine, these functions.

3.2.2. SC and decarbonization

Decarbonization is often cited as a key function of SC, yet not all SC applications deliver it in practice. The climate effectiveness of a particular SC application depends on how it is implemented and the energy sources it utilizes. Some SC applications may even raise emissions. For example, combined-cycle gas turbines (CCGTs), may raise emissions if they are fueled by fossil-methane (instead of bio-methane or green hydrogen) and are frequently dispatched to balance renewable intermittency. Similarly, electrolyzer may increase emissions if the *additional* electricity they demand is supplied by marginal fossil generators higher up the merit order curve, rather than *additional* renewable installations [90]. Steam methane reforming (SMR) does not decarbonize hydrogen production unless paired with carbon capture and storage. Thus, decarbonization is not an intrinsic feature of SC but a context-dependent outcome that requires deliberate policy design to achieve.

3.2.3. SC and flexibility

SC is often promoted as a tool to deliver energy system flexibility, yet, in contrast, some SC applications may increase system-wide flexibility needs [91]. For example, overhead line electric trucks operate with minimal load-shifting capability, which increases not only the system's flexibility needs but also the overall electricity demand [17]. Likewise, while BEVs can provide flexibility, this benefit materializes only if grid- and system-aware smart charging behaviors are incentivized. Otherwise, simultaneous charging during peak hours may necessitate unnecessary grid and generation capacity expansion, driving up system costs. Thus, an "ideal" SC application should actively reduce, rather than increase, system-wide flexibility needs [26].

3.2.4. SC and efficiency

While SC involves energy conversion between vectors, it does not inherently guarantee efficiency gains. Some SC applications, especially those involving multiple conversion steps, incur significant energy losses. For example, converting electricity to hydrogen (P2G) and subsequently using it in fuel cell electric vehicles (FCEVs) is far less efficient than direct electrification alternatives such as BEVs. These high-efficiency options exemplify "desirable" SC from a functional dimension and should therefore be prioritized to minimize the demand for additional renewables and associated system costs.

However, energy efficiency is not the sole criterion. The authors in [26] highlight a trade-off between 'energy efficiency' and 'economic efficiency', noting that the former may be sacrificed if it results in significantly higher costs or emissions. For example, in industrial processes requiring high-temperature heat, low-cost but energy-inefficient heating rods may be a more viable decarbonization option than energy-efficient but costlier heat pumps, especially if usage is limited to a few hours annually. Which efficiency criterion takes precedence, energy or economic, thus depends on context-specific factors such as usage patterns. Efficiency, then, becomes a multidimensional criterion for evaluating which SC applications are "desirable" in a particular context, not a defining characteristic of SC itself.

3.2.5. Toward a value-neutral SC definition

The effectiveness of SC in achieving goals such as decarbonization, flexibility, and efficiency is highly context-dependent. What constitutes "desirable" SC (or "good" SC, in the terms of [35]) thus varies across contexts. To define SC consistently, we argue for separating the descriptive (fact-based) from the prescriptive (goal-driven) elements, the positive (value-neutral) from the normative (value-laden) considerations [35]. Here, 'value-neutrality' means definitional independence from objectives like decarbonization, flexibility, or efficiency, not because these are unimportant, but because embedding them within the core definition introduces disciplinary biases and limits cross-context applicability.

Accordingly, we propose decoupling these objectives from the core concept of SC. We further propose that the value-neutral definition can serve as a *diagnostic tool* for identifying all potential SC interlinkages, while the policy goals can provide *selection criteria* for filtering which interlinkages are "desirable", and hence should be prioritized, in specific contexts. This approach positions SC as an analytically neutral *means* using which researchers across different disciplines and policymakers across different nations can pursue context-appropriate *ends*, ensuring the definition's broad applicability (see Appendix A2.2.5).

3.3. The electricity-centric dimension: Gaps and resolutions

The electricity-centric definitions emphasize electricity, particularly from renewables, as the direct or indirect driver of SC interlinkages. These definitions suffer from four critical limitations.

3.3.1. Narrow scope

The first drawback is their restrictive framing of SC, which excludes all interlinkages not involving electricity. Even broader electricity-centric interpretations, such as Wietschel et al. [17], which allow non-electric vectors within SC, still regard electricity as the central vector driving SC. However, Thellufsen et al. [38] emphasize that realizing SC's full potential requires a system-wide perspective encompassing not just electricity, but also other vectors like gas and heat, along with their associated transport grids. For example, relying solely on electrification-based SC overlooks more synergistic and cost-effective pathways, such as leveraging existing district heating grids for the reuse of industrial waste heat. Similarly, Bardow et al. [36] argue that SC should capture interlinkages not only between vectors and end-use sectors but also among them. Thus, we propose extending SC's scope beyond electricity vector and electricity-based interconnections to include other vectors and a broader set of interconnections: vector-to-vector, sector-to-sector, network-based, and non-physical couplings involving markets and policies (see Figure 2).

3.3.2. *Input-dependent SC status*

The second limitation of these definitions is their inconsistent identification of SC applications, particularly due to their exclusive focus on renewable electricity. For example, an FCEV may run on hydrogen produced from either renewable electrolysis or biomass. Similarly, an electrolyzer may use renewable or fossil electricity. However, the electricity-centric logic excludes bio- and fossil-fuels and thus recognizes only the renewable-input versions of FCEV and electrolyzer as SC examples [17]. This raises a dilemma: should an application's SC status vary with the renewable status of its input? Such unpredictability complicates policy design and implementation. For example, incentives and tariff structures require that SC applications are categorized consistently and predictably at all times. To achieve this, we suggest anchoring our SC definition in the 'interlinkages' which an application creates, rather than in the input vector it consumes. This input-agnostic approach ensures that an application qualifies as SC if it interconnects vectors and sectors, regardless of whether its input is renewable-, fossil-, or bio-based. For example, the FCEV remains an example of molecules-to-mobility coupling, whether powered by electrolysis- or biomass-derived hydrogen. Similarly, an electrolyzer represents electricity-to-hydrogen coupling, regardless of whether its input electricity is renewable- or fossil-based.

3.3.3. *Narrow decarbonization toolkit*

Third, the electricity-centric dimension implicitly assumes renewable electricity to be the sole vector capable of decarbonization, thereby narrowing the available levers for reducing emissions. However, SC applications can still reduce emissions when powered by fossil-dominant electricity, provided they replace more carbon-intensive vectors or less energy-efficient alternatives. For example, shifting from gasoline-driven ICEVs to BEVs charged with a fossil-dominant electricity mix can still yield net emissions savings, if the grid electricity has lower *carbon intensity* (i.e., emits fewer gCO_2/kWh) than gasoline combustion and BEVs demonstrate higher *efficiency* (i.e., consume fewer kWh/kilometer) than ICEVs [92]. Moreover, as Cole et al. [93] demonstrate, eliminating the final few percent of fossil generation in a nearly 100% renewable system causes nonlinear cost spikes and requires building rarely used firm capacity, suggesting that retaining a small share of fossil capacity ensures flexibility and security of supply during low-renewable periods.

To resolve this contradiction, we recommend treating SC interlinkages as structurally neutral mechanisms whose climate impact depends on the relative *carbon intensities* of the vectors and *efficiencies* of the applications they interconnect. This approach makes the full decarbonization toolkit available to researchers and policymakers, allowing them to consider transitional or efficiency-prudent (but not low-carbon) alternatives often prematurely excluded by electricity-centric approaches. As the World Bank observes, countries have different energy needs and resources, and the context fundamentally shapes which energy transition pathways are viable where and when. In some regions, solar PV may offer the least-cost pathway, while in others, natural gas may be more appropriate [94]. Similarly, countries in the early phases of their development cycle need to balance economic growth with decarbonization, and may therefore choose to transition cooking in rural areas from wood to biogas until electrification solutions mature [89]. An electricity-centric SC definition would exclude such transitional pathways despite their legitimate role in reducing emissions and improving energy access.

3.3.4. *Unidirectional SC*

Finally, most of these definitions imply a directional constraint, conceptualizing SC as a one-way energy flow from the electricity vector to different end-use sectors. This interpretation overlooks several 'reverse' and 'recursive' interlinkages that are becoming increasingly integral to modern energy systems. Reverse interlinkages refer to flows originating from end-use sectors back to vectors. For example, flexible heat pumps in the 'building H&C' sector [95] or BEVs in the 'mobility' sector [96] could provide balancing services to the electric grid. Recursive interlinkages involve feedback loops within the same vector or end-use sector. Intra-vector loops include applications such as hydrogen-to-methane conversion through the Sabatier process, where the energy remains within the 'molecules' vector. Intra-sector loops include cyclic applications such as waste-to-energy (W2E) plants that can convert waste from an end-use sector into electricity/heat used by the same sector. By disregarding such multidirectional dynamics, the electricity-centric dimension underrepresents the complex interdependencies that SC entails. We address this gap by removing the directional constraint and accommodating SC interlinkages in all directions, forward, reverse, or recursive, thereby offering a more accurate and inclusive depiction of modern energy system interdependencies than one-dimensional electricity-centric approaches.

4. Towards a consistent definition of sector coupling

Building on our critical analysis of the gaps in existing SC definitions, across the structural, functional, and electricity-centric dimensions, we now consolidate our proposed resolutions into a coherent definition of SC. In particular, we recommend: (i) replacing the outdated 'supply–demand' dichotomy with 'vector/end-use' terminology, (ii) avoiding normative goals in definition, and (iii) offering an input-agnostic, direction-neutral, and comprehensive yet conceptually concrete framing. To contextualize our definition, we first outline the structural anatomy of a sector-coupled energy system, comprising three principal elements.

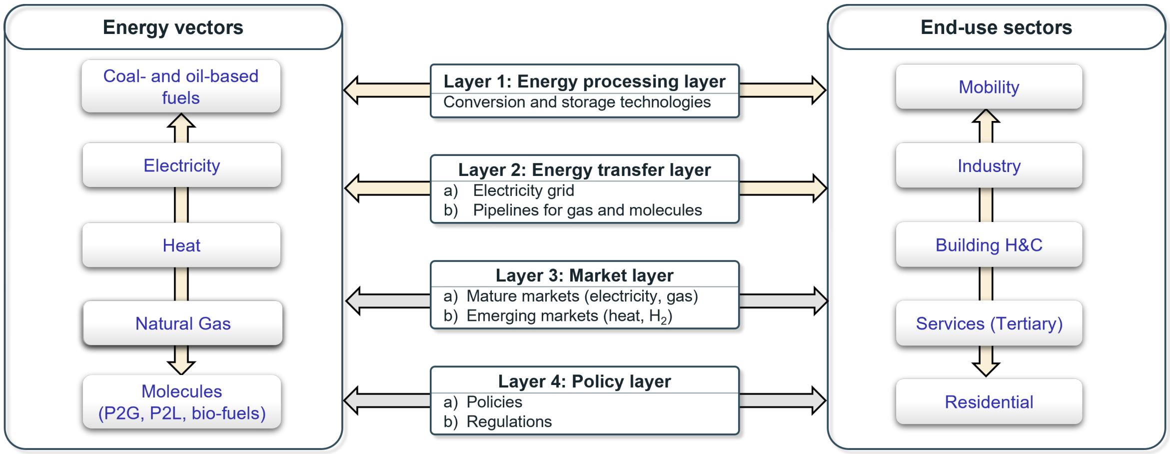
1. Firstly, there are tradable 'energy-carrying vectors' including coal- and oil-based fuels, electricity, natural gas, heat and molecules (left part, Figure 2).
2. Secondly, we find energy-consuming 'end-use sectors', namely mobility, industry, building H&C, services (or tertiary), and residential sectors (right part, Figure 2).
3. Thirdly, four intervening layers link the vectors and end-use sectors (center part, Figure 2):
    (a) The energy processing layer includes technologies that transform or store energy in any form (e.g., power plants, electrolyzers, thermal storage);
    (b) The energy transfer layer refers to the physical infrastructure which moves energy from one place to another (e.g., electricity grids, gas and hydrogen pipelines, district heating and cooling networks);
    (c) The market layer represents the arrangements through which different energy vectors and related services are traded, including mature markets such as electricity and gas, as well as emerging markets such as hydrogen and heat;
    (d) The policy layer covers policies, regulatory frameworks, and governance mechanisms that enable, constrain, or steer the functioning of the preceding layers (e.g., emissions trading schemes, integrated planning for electricity and gas networks).

Building on this structural visualization, we define sector coupling in energy systems as follows: *Sector coupling is the establishment of physical or non-physical interconnections in any direction, which may occur (i) among energy-carrying vectors, (ii) among energy-consuming end-use sectors, (iii) between the vectors and end-use sectors, and (iv) within any of the four interconnecting layers linking these vectors and end-use sectors. The mechanisms driving sector coupling are diversification of vectors, leveraging by-products from one end-use sector in another sector, electrification (both direct and indirect), network sharing, market integration, and policy coordination, with the electricity system acting as the backbone.*

Linkages between energy vectors and end-use sectors can be either physical (beige arrows, Figure 2) or non-physical (grey arrows, Figure 2). Together, these six arrows illustrate six distinct types or forms of sector coupling interlinkages (see Section 5).

To further contextualize our SC definition, we position it relative to the adjacent concept of flexibility and established energy accounting frameworks, and highlight its value-neutral orientation.

First, the above definition clarifies the distinction between the related concepts of 'sector coupling' and 'flexibility'. While SC involves establishing interlinkages between and among vectors and end-use sectors, flexibility refers to the system's ability to handle residual load fluctuations arising from the intermittency of renewables and the outages of generation and transmission assets. While SC and flexibility applications overlap, they are not equivalent. Many flexibility measures, such as power-to-power battery storage, grid expansion, time-of-use tariffs, cross-border electricity trade over interconnectors, and demand-side management with only electric loads, do not interconnect vectors and sectors, and thus fall outside the scope of SC [91]. Conversely, SC applications do not necessarily enhance flexibility and may even reduce it if implemented without coordination (see Section 3.2.3). Moreover, while a storage application that operates entirely with a single vector, such as a battery storing and discharging electricity without



P2G = power-to-gas, P2L = power-to-liquid, H&C = heating and cooling

Figure 2: Structural elements of a sector-coupled system

conversion, represents only temporal flexibility [32, 91], storage preceded by vector conversion, such as a power-to-X-storage application, represents *both* flexibility and SC as it can not only time-shift demand, but also interconnect vectors.

Second, our vector-based terminology complements the established energy statistical conventions. Energy balance methodologies (IEA [97], Eurostat [98], and UN [99]) traditionally organize energy flows along a transformation chain, from 'primary energy' (extracted from natural sources) through 'secondary energy' (transformed from primary sources) to 'final energy' (delivered to end-users) and ultimately 'useful energy' (the energy actually available for end-use). Whereas this terminology classifies energy by transformation stage, tracking energy as it progresses through extraction, processing, delivery, and end-use, our 'vector' framework classifies energy by the physical form through which it flows, regardless of its position in the transformation chain. Crucially, a given vector can span multiple stages of the energy chain. For example, electricity as a vector can be considered as primary energy when generated directly from natural flows without fuel combustion (RES → electricity), as secondary energy when produced through the transformation of combustible fuels in thermal power plants (fuel → heat → electricity), as final energy when delivered to end-consumers, or as useful energy after deducting end-use application losses. Similarly, heat as a vector can be primary (from geothermal or solar thermal), secondary (produced in CHPs), final (district heating delivered to a building), or useful (the thermal comfort actually delivered). Likewise, coal and oil products encompass both primary resources (coal, crude oil) and secondary derivatives (coke, refined petroleum). Thus, the same vector appears at multiple stages of the energy chain.

This orthogonality between the two classification schemes makes our vector-based framework better suited to SC analysis. The conventional stage-based classification answers the question 'how far energy has progressed', which is useful for tracking losses and energy accounting. In contrast, the form-based classification tells us 'what can connect to what', which is essential for mapping SC pathways. SC applications create interlinkages between carrier forms, and these interlinkages exist regardless of where in the transformation chain the associated carrier forms occur. A heat pump couples the electricity and heat vectors irrespective of whether the electricity is primary (renewable) or secondary (thermal-generated); an electrolyzer couples electricity and molecule vectors regardless of the hydrogen's downstream classification. Our framework thus complements established energy accounting frameworks by offering a carrier-form perspective that SC analysis requires.

Third, the value-neutral framing of our definition warrants clarification. SC's recent prominence in the decarbonization discourse as an instrument for absorbing surplus renewables has led some scholars to define SC by its decarbonization function alone, excluding interconnections that do not advance emissions reduction [21, 22]. We take a different approach, decoupling the definitional core of SC from its policy objectives [35]. Real-world energy systems comprise legacy infrastructure, transitional technologies, and emergent low-carbon pathways. Mapping this heterogeneous landscape requires identifying *all* interlinkages, including fossil-based ones, without presupposing desirability. Pre-filtering based on decarbonization criteria risks omitting connections that, while climate-undesirable, remain operative and shape transition dynamics. Overlooking such linkages could yield incomplete models that fail to capture incumbent system inertia or path dependencies constraining the pace of change (e.g., "carbon lock-in") [100, 101].

We further emphasize that while the task of *defining* SC needs to remain value-neutral, SC *policymaking* is necessarily value-laden. Policies need to selectively promote SC applications that are functionally effective in advancing system goals such as emissions reduction or flexibility provision. For example, the EU's Renewable Energy Directive (RED III) prioritizes P2G applications that produce green hydrogen from "additional" renewable generation over those that produce grey hydrogen from fossil sources [35, 102, 103]. Likewise, the EPBD recast (2024) incentivizes flexibility-enhancing SC applications (e.g., smart and bidirectional BEV charging) over options that merely increase electricity demand [63]. Notably, neither RED III nor EPBD redefine SC; both apply functional selection criteria atop the full menu of SC options. Thus, the *definition* identifies SC interlinkages, while *policy* determines which to incentivize. The classification of SC interlinkages that follows (Section 5) demonstrates the diagnostic utility of this approach, systematically mapping the full spectrum of coupling mechanisms that a value-neutral definition renders visible.

5. Classification of sector coupling interlinkages

5.1. Existing classifications

Previous attempts at classifying SC types have been limited, often lacking the consistency and comprehensiveness needed to capture the full range of SC applications. In its simplest form, SC has traditionally been categorized into direct and indirect electrification [17, 23]. Direct SC uses electricity in its original form, while indirect SC transforms it into another vector, such as heat, hydrogen, or liquid fuels. Moving beyond this basic distinction, Bloess et al. [39] divided P2H applications as centralized or decentralized as discussed earlier (Section 3.1.1). Merging these, Ramsebner et al. [22] proposed a four-fold classification of SC applications: direct and indirect electrification, centralized and decentralized. Expanding the scope further to incorporate both vectors and end-use sectors, Van Nuffel et al. [6] categorized SC into two distinct types: (a) end-use sector coupling, representing linkages between energy vectors (primarily electricity) and different end-use sectors, and (b) cross-vector integration, representing interconnections among energy vectors themselves. To this classification, Bardow et al. [36] added a third category, recognizing couplings among end-use sectors as well.

However, these studies neither provide a clear rationale for their SC categorizations nor do they capture the full scope of SC, necessitating a more comprehensive framework. Also, while they do attempt to provide schematic depictions of interactions in sector-coupled systems, none, to our knowledge, offer a structural classification that systematizes these interlinkages into a taxonomy suited for systemic analysis.

5.2. Classification based on our sector coupling definition

As discussed earlier, a unique strength of our SC definition is that it captures not only the inter-linkages within an energy system but also the mechanisms driving these interconnections. This dual focus provides a systematic foundation for categorizing these inter-linkages into six distinct types based on their driving mechanisms. As illustrated in Figure 3, these interconnections are first categorized by their nature as either physical or non-physical. Physical interconnections are further subdivided into four categories, while non-physical interconnections comprise two sub-categories.

5.2.1. Energy vector coupling

Interconnections can occur between two different types of vectors, one of which is typically electricity (Figure 4, left side). These are referred to as 'energy vector couplings'. The underlying mechanism of vector coupling is the diversification of energy vectors, which facilitates the conversion of electricity into other vectors (e.g., gas, heat, or molecules) and vice versa, so that the vector at the output differs from that at the input. The analytical focus is the vector-to-vector interface within the energy processing layer (Layer 1), independent of the end-use application for which the output vector is used. For example, an electrolyzer represents electricity-to-hydrogen vector coupling

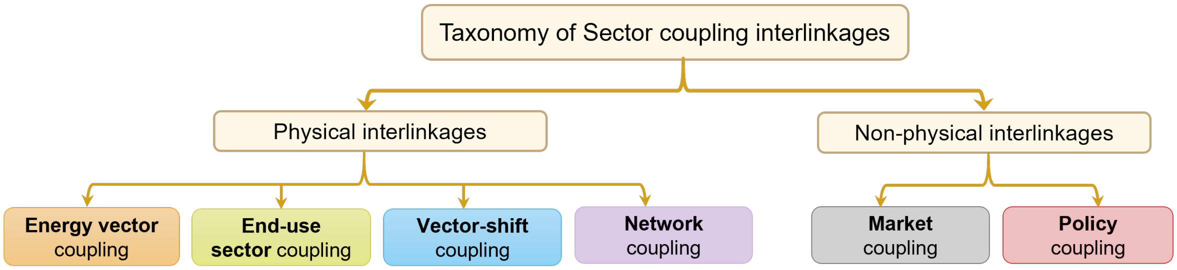


Figure 3: Mechanism-based classification of sector coupling interlinkages into six distinct types, organized by their physical or non-physical nature.

Table 3: Examples of SC applications representing energy vector coupling

Number of vector couplings represented	SC application	Type of vector coupling
Single vector-to-vector coupling	Electrolyzers	electricity-to-hydrogen
	Fuel cells	hydrogen-to-electricity
	Sabatier process	hydrogen(+CO_2)-to-synthetic methane
	[#]CCGTs	methane-to-electricity
Multiple vector-to-vector couplings	CHP systems	gas-to-electricity and gas-to-heat
	Hybrid heat pumps	electricity-to-heat and gas-to-heat
	[†]Direct CO_2 hydrogenation	hydrogen(+CO_2)-to-synthetic hydrocarbons

[#] Typically, methane input to CCGT can be sourced from either natural gas or synthetic methane. Additionally, CCGTs designed to operate on hydrogen–methane blends or pure hydrogen have emerged as a promising technology for decarbonizing gas-fired power generation [104].

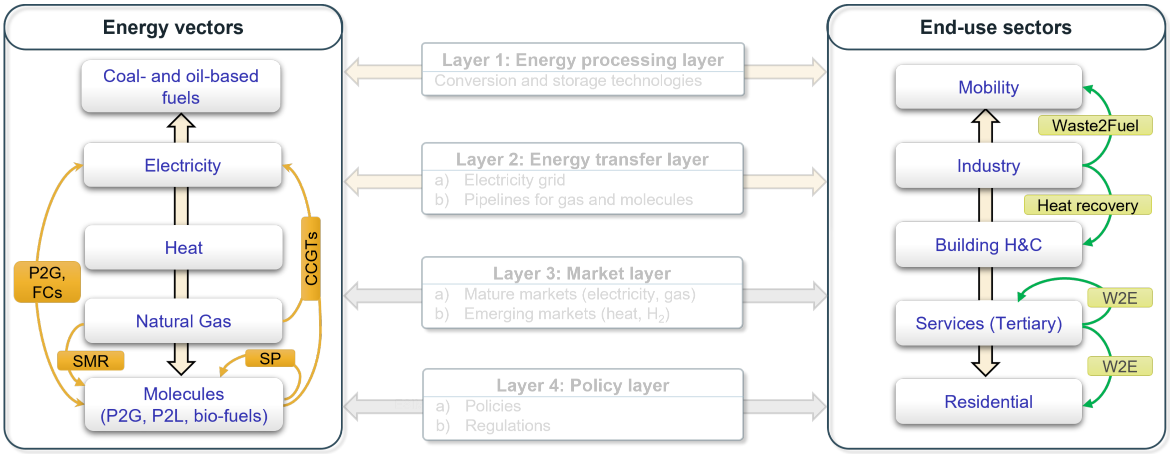
[†] Direct CO_2 hydrogenation exemplifies a multi-input vector coupling, combining green hydrogen with captured CO_2 to produce synthetic hydrocarbons (e.g., methanol, naphtha) [105]. While hydrogen serves as the energy vector, CO_2 acts as a material feedstock and is therefore shown in parentheses.

regardless of whether the output hydrogen is subsequently used in FCEVs (mobility end-use sector) or steel-making (industry end-use sector). A few key SC applications demonstrating vector coupling are summarized in Table 3.

Non-energy material flows interact with contemporary energy systems through applications such as P2X and carbon capture and utilization. Molecules like hydrogen and ammonia, which have long been established as chemical feedstocks, now also serve as energy carriers [106, 107]. Our framework attempts to bridge the gap between material and energy flows by framing 'molecules' (hydrogen, ammonia, synthetic hydrocarbons) as a distinct energy vector. This categorization enables the P2X applications (e.g., electrolysis, direct CO_2 hydrogenation) to be modeled as 'vector coupling', thereby capturing the energy conversion step that often sits upstream in broader material-energy value chains.

At the energy-material interface, energy and material flows cross in both directions. In the energy-to-material direction, the output molecules from 'vector coupling' may be used in downstream material applications. For instance, green hydrogen produced via electrolysis may subsequently serve as feedstock for ammonia-based fertilizers, while synthetic naphtha from CO_2 hydrogenation may feed into plastics production. Since these downstream non-energy applications of 'molecules' fall outside final energy consumption, they are excluded from our SC classification. In the material-to-energy direction, non-energy substances can enter P2X pathways as material inputs. For instance, CO_2 serves as a feedstock in hydrogen(+CO_2)-to-synthetic methane 'vector coupling'. Thus, our framework captures the energy-material *interface* where SC occurs, while leaving the material-material transformations downstream outside its current scope. This is consistent with the distinction between 'final energy consumption' and 'non-energy use' in the IEA and Eurostat energy balance frameworks [98].

Importantly, the modular architecture of our framework, with clearly described vectors, end-use sectors, and coupling categories, provides a foundation for future extensions that incorporate material-energy interactions more



P2G = power-to-gas, P2L = power-to-liquid, H&C = heating and cooling, FCs = fuel cells, CCGTs = combined cycle gas turbines, SP = Sabatier process, SMR = steam methane reforming, W2E = waste-to-energy

⟶ Energy vector coupling ⟶ End-use sector coupling

Figure 4: Energy vector coupling (yellow) and end-use sector coupling (green). Both coupling types represent interlinkages occurring respectively among vectors and among sectors, rather than across the vector-sector interface.

comprehensively. We envision adaptations that explicitly model non-energy material flows, treating them as coupling agents across sectors and vectors. For example, CO_2 reuse pathways and synthetic hydrocarbons spanning both the energy and the petrochemical industries could be systematically integrated. Thus, our framework is adaptable enough to be expanded to cover both energy and material domains, reflecting the increasingly intertwined nature of energy systems and industrial value chains in the net-zero transition.

5.2.2. *End-use sector coupling*

Sector coupling applications can also link distinct end-use sectors, referred to as “end-use sector couplings” (Figure 4, right-hand side). These couplings aim to leverage the by-products or waste from one (or more) end-use sector(s) to meet the energy demands of other sector(s), thereby promoting circular economy principles within the energy system. Examples of end-use sector coupling include:

- Industrial waste heat re-use for residential heating (industry-building H&C coupling) [77, 108].
- Bio-fuel producing applications like anaerobic digestion that harness organic waste from food processing industry to produce hydrocarbon fuels like bioethanol for mobility sector (industry-mobility coupling) [109, 110].
- Waste-to-energy (W2E) plants that use waste from one or more end-use sectors (e.g., residential, services) to meet the energy demands of the same or different end-use sectors (multiple end-use sector couplings possible) [8, 111].

While our framework embraces circular economy principles for *energy* flows, other circular economy measures involving purely *material* flows, such as plastics recycling or steel scrap reprocessing, lie outside the scope of SC, as they involve no energy interlinkages between vectors or end-use sectors. However, as discussed in Section 5.2.1, the modular architecture of our framework allows for future extensions to incorporate applications where material flows intersect with energy systems. For instance, chemical recycling of plastics, which converts waste polymers into hydrocarbon feedstocks via pyrolysis, requires significant energy input and produces outputs that re-enter the petrochemical value chain [112]. Similarly, hydrogen-based direct reduction of steel scrap represents an emerging pathway where material recycling and energy system decarbonization converge [113]. These examples illustrate how applications of the material circular economy interact with the energy circular economy. As Kirchherr et al. [114]

emphasize, comprehensive conceptualizations of ‘circular economy’ encompass both material recovery and energy recovery, suggesting a future direction for extending SC frameworks to encompass material-energy circularity.

5.2.3. Vector-shift coupling

This category of SC links an end-use sector traditionally reliant on fossil-based vectors to a *new vector*. The underlying mechanism of vector-shift coupling is the substitution of one input vector for another to serve the same (or functionally equivalent) end-use. The analytical focus is thus on the vector-to-sector interface. For example, replacing a gas boiler with an electric heat pump shifts the input vector from gas (traditional vector) to electricity (new vector) while preserving the end-use service of space heating. If the new vector is electricity, the interconnection represents vector-shift coupling through direct electrification (Figure 5a). If the new vector is an electricity-derived molecule (e.g., hydrogen, methanol), the linkage constitutes vector-shift coupling via indirect electrification (Figure 5b). The latter category, i.e., indirect electrification, follows a two-step pathway that engages *two* coupling categories in sequence.

- Step 1 (Vector coupling): P2X applications convert electricity to an electricity-derived molecule or an intermediate vector (e.g., hydrogen via electrolysis). The underlying mechanism is vector-to-vector conversion, and the distinguishing question is whether a new vector is now produced at the output.
- Step 2 (Vector-shift coupling): The intermediate vector substitutes for a fossil-based input in an end-use application (e.g., hydrogen replaces natural gas in steel furnaces, thus shifting the input vector powering the same industrial heating end-use). The underlying mechanism is input vector substitution at the vector-to-sector interface, and the distinguishing question is whether a new vector now powers the same end-use.

Which coupling category applies thus depends on the underlying mechanism being analyzed. When evaluating electrolyzer deployment as a means of hydrogen production, the operative mechanism is vector-to-vector conversion, and the interlinkage is thus classified as ‘vector coupling’. When assessing the same hydrogen as a substitute for natural gas to decarbonze steelmaking, the operative mechanism is input vector substitution at the vector-to-sector interface, and the interlinkage is thus classified as ‘vector-shift’ coupling. This multi-step character of indirect electrification helps capture the sequential engagement of distinct coupling mechanisms in today’s complex energy systems.

Traditionally fueled by petroleum, the mobility end-use sector is now being increasingly integrated with the electricity vector. BEVs[1], which facilitate grid-to-vehicle energy flows, and vehicle-to-grid (V2G) applications, which enable reverse energy flows, together represent the electricity-mobility vector-shift coupling via direct electrification. On the other hand, indirect electrification involves electrolysis to produce hydrogen (electricity-hydrogen vector coupling), followed by its use in fuel-cell electric vehicles (hydrogen-mobility vector-shift coupling).

Similarly, the industry end-use sector, conventionally reliant on coal and natural gas, exhibits electricity-industry vector-shift coupling through both direct and indirect pathways. Direct electrification involves technologies such as electric furnaces for process heat, enabling the direct replacement of fossil fuels with electricity. Indirect electrification occurs through electrolysis-based hydrogen production (P2G vector coupling), where first renewable electricity is used to produce hydrogen, which is subsequently utilized for process heating in hydrogen-fired furnaces and burners (hydrogen-industry vector-shift coupling) [115, 116].

5.2.4. Network coupling

The fourth category of sector coupling, called ‘network coupling’, arises from interactions between two distinct energy vectors, while they are being transported through the energy transfer layer. We identify three primary driving mechanisms behind ‘network coupling’. The *first* mechanism is the co-transport of distinct vectors over a shared physical infrastructure (Figure 6). A prominent example is hydrogen blending into natural gas pipelines, where low percentages of hydrogen are injected into existing methane grids to decarbonize the gas supply without major infrastructure overhauls. This illustrates gas-hydrogen network coupling. The *second* driving mechanism is infrastructure sharing, where the transport infrastructure built for one energy vector is used to carry another. This mechanism is

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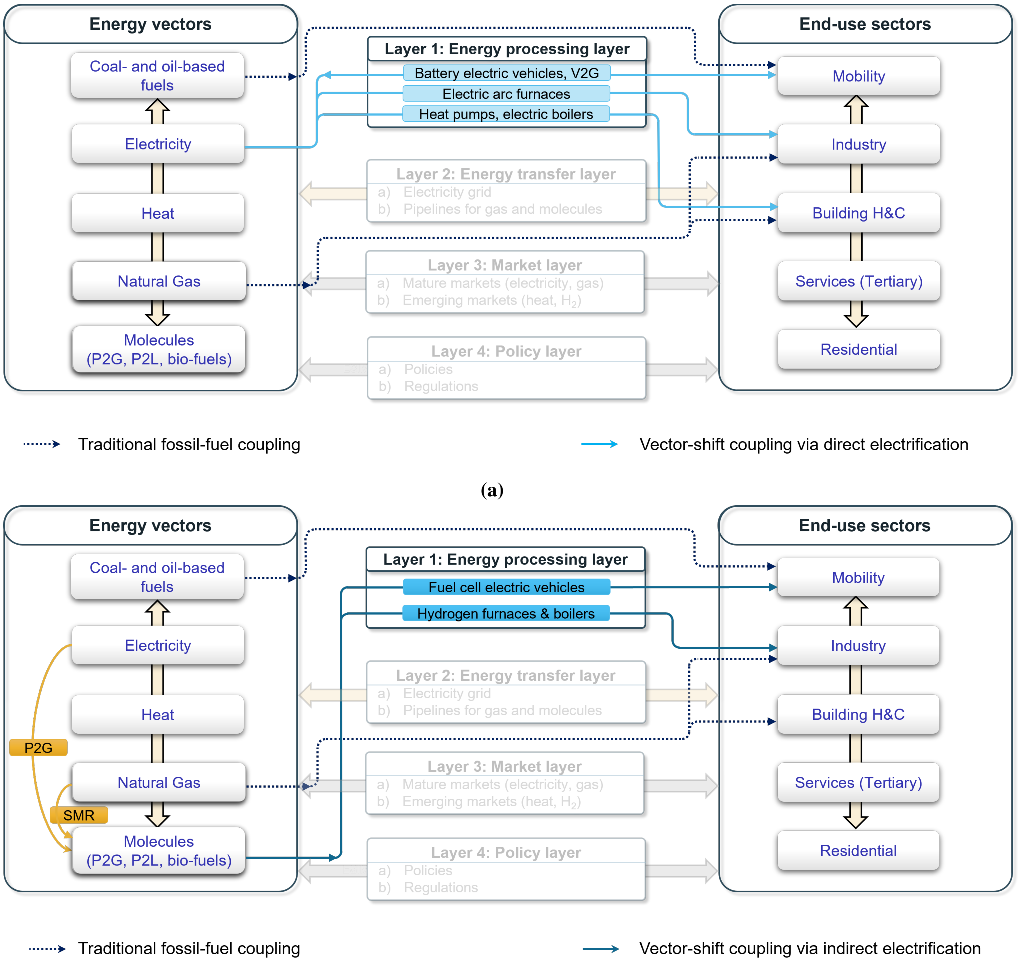
[1] Vehicles, including BEVs, V2G, and FCEVs, are placed within the energy processing layer because they primarily function as distributed energy storage or conversion units. While they do interface with charging or fueling networks in Layer 2, they do not transport energy and are not part of the transfer infrastructure.



(a)

(b)

Figure 5: Vector-shift coupling via (a) direct electrification (light blue), which links fossil-reliant end-use sectors to the electricity vector in a single step, and (b) indirect electrification (dark blue with yellow), which follows a two-step pathway. The yellow arrows in (b) represent the vector coupling step that produces molecules such as hydrogen as an intermediate carrier, which then displaces fossil fuels in end-use sectors.

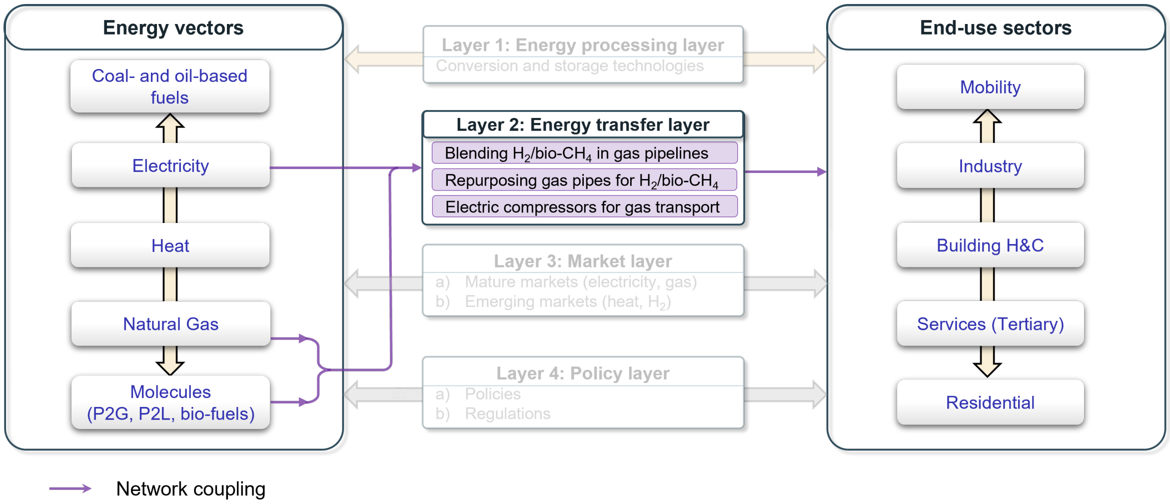


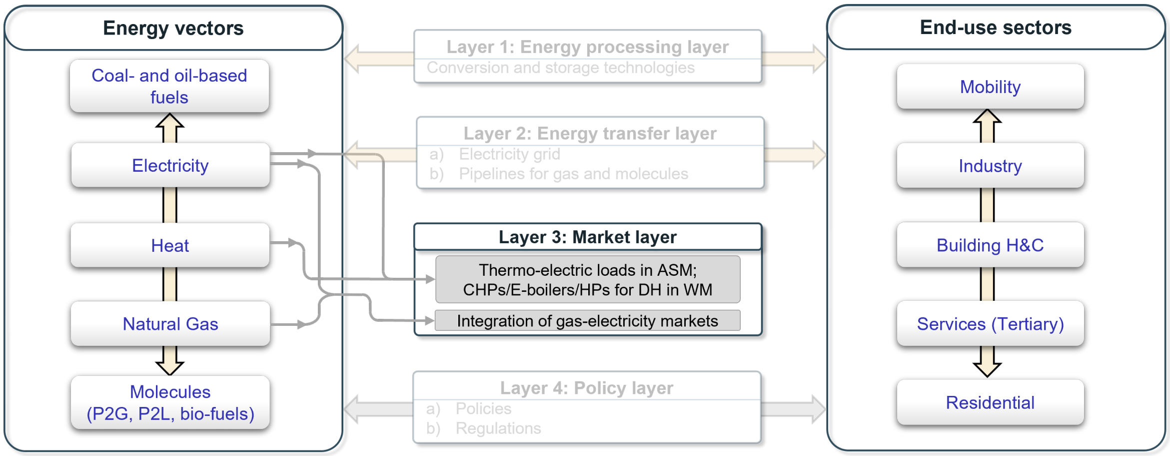
Figure 6: Network coupling (purple). Physical interlinkages arise within the energy transfer layer through co-transport of vectors, infrastructure repurposing, or operational interdependence.

particularly value when transporting energy as a non-electric vector is more efficient than transmission of electricity itself [33]. For instance, the phasing out of natural gas has created opportunities to re-purpose existing gas pipelines for hydrogen transport [117]. A prominent example of such 'network coupling' in action is the European Hydrogen Backbone, an initiative to create a cross-border hydrogen network by repurposing parts of the existing natural gas grid [118]. Likewise, injecting upgraded biomethane into gas pipelines exemplifies natural gas-biomethane network coupling [27]. *Thirdly*, 'network coupling' also stems from operational interdependence, where the movement of one energy vector through its infrastructure is enabled by another vector [119]. For example, gas pipelines depend on electric compressors to pressurize and move gas along the network [120, 121], while district heating systems rely on electric pumps to circulate hot water [122]. These represent electricity-gas and electricity-heat network couplings, respectively.

The final two categories of sector coupling, market coupling and policy coupling, are non-physical in nature. The distinction from physical interlinkages lies in *what* mechanism creates the cross-vector, cross-sectoral linkage. Physical interlinkages operate through technological assets and infrastructure that create energy conversion pathways across vectors (vector coupling), waste energy utilization pathways across sectors (end-use sector coupling), vector substitution pathways serving a given sector (vector-shift coupling), or interdependencies across transport infrastructure (network coupling). In contrast, non-physical interlinkages create coordination mechanisms, either economic (market coupling) or regulatory (policy coupling), that shape the operational (e.g., dispatch, scheduling, trading) and investment decisions regarding those physical assets and infrastructure. Markets create such coordination through price-mediated exchange, providing platforms where different actors exchange energy commodities or services in response to price signals. Policies create coordination through regulatory alignment, harmonizing rules, incentives, or mandates across previously siloed vectors and end-use sectors.

5.2.5. Market coupling

Market coupling involves non-physical linkages within energy markets and can occur in two distinct ways, as illustrated in Figure 7. The *first* mechanism involves interconnecting two different markets for two different energy vectors, such as electricity and gas. The resulting configurations can range from loosely integrated markets with synchronized clearing times to a fully integrated market featuring joint clearing for gas and electricity [123]. The *second* mechanism arises when an application, originally deployed to meet the demand for one energy vector, participates in the market of another vector. Heat-electricity market coupling offers several examples of this second mechanism. Heat pumps and thermal energy storage (TES), installed primarily to satisfy the demand for heat, are increasingly used to deliver ancillary services for electricity, a market for a different energy vector [124–126]. Similarly, Danish CHP



ASM = ancillary services markets for electricity; WM = wholesale or spot market for electricity; DH = district heating;
CHPs = combined heat and power plants; E-boilers = electric boilers; HPs = heat pumps.

⟶ Market coupling

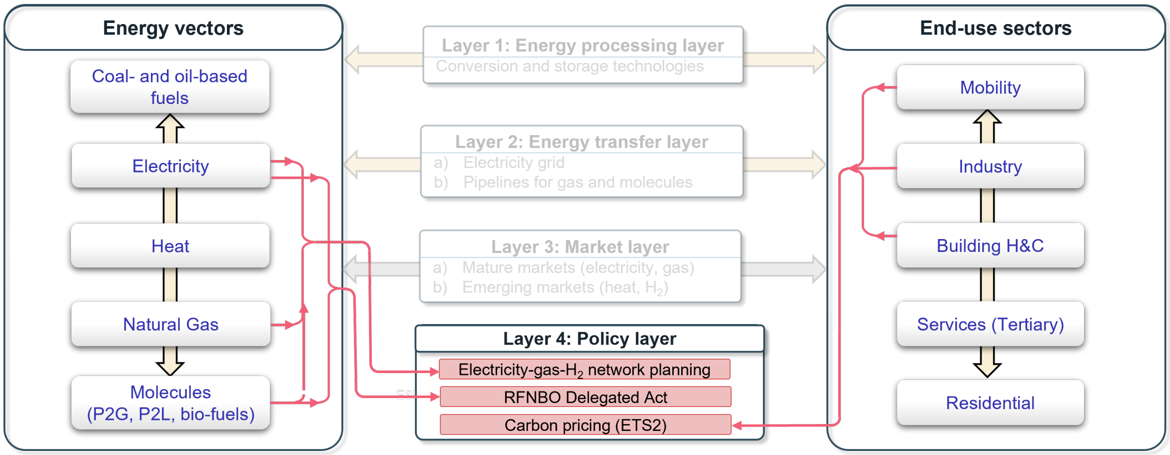
Figure 7: Market coupling (grey). Non-physical interlinkages arise within the market layer through cross-vector market integration or participation of one vector's assets in another vector's market.

plants combined with TES exemplify this coupling at a system scale. Although installed primarily to supply district heating demand, these plants participate in the Nord Pool electricity spot market, optimizing their power dispatch based on price signals. During low-price or high-wind periods, TES allows CHP plants to reduce power output while meeting heat demand from stored energy. Conversely, during high-price periods, they increase electricity sales while accumulating heat for later use. In both cases, assets deployed for one energy vector (heat) generate revenue streams in the market of another vector (electricity) [127, 128]. Likewise, when electrolyzers, installed to meet the demand for a hydrogen vector, provide frequency response by acting as flexible loads, they exemplify hydrogen-electricity market coupling [129, 130]. In contrast, electric loads that provide demand response solely within electricity markets do not constitute an SC application, as the underlying mechanism involves time-shifting consumption within a single vector's subsystem, without establishing any cross-vector market linkages.

5.2.6. Policy coupling

The final category of SC is the policy coupling, which refers to non-physical interconnections that align policies, regulatory frameworks, and business models to address multiple energy vectors or end-use sectors in a coordinated fashion rather than in isolation. Policy coupling manifests across several domains: infrastructure planning, carbon pricing, fiscal frameworks, and sectoral regulations. Infrastructure planning is a key domain in which policy coupling plays a decisive role. As emphasized by IRENA [23], effective SC requires regulatory arrangements that support integrated planning of energy systems. The prevailing approach of optimizing the networks for each vector in isolation risks leading to costly misdimensioning of individual grids. In contrast, SC "results in an integrative planning of expansion projects concerning all grids (i.e., overall optimization)", which increases the degrees of freedom in infrastructure design and improves systemic cost-efficiency [31]. An example of such integrated planning is the joint development of electricity, natural gas, and hydrogen networks [131]. In Europe, this planning approach has been institutionalized through formal communication channels between electricity and gas network operators at both the EU and national levels (Figure 8). The outcome is the joint Ten-Year Network Development Plan (TYNDP) Scenarios, collaboratively prepared by ENTSO-E and ENTSOG for the electricity, natural gas, and hydrogen vectors [12]. These scenarios exemplify a multi-vector approach to long-term infrastructure planning. Similarly, the Australian Energy Market Operator (AEMO) oversees network operation, market management, and long-term planning for both electricity and gas vectors under a unified institutional structure [132].

Carbon pricing offers another avenue for policy coupling. The extension of the EU Emissions Trading System (EU



ETS2 = Emissions Trading System 2; RFNBO = Renewable Fuels of Non-Biological Origin.
⟶ Policy coupling

Figure 8: Policy coupling (red). Non-physical interlinkages arise within the policy layer through coordinated regulatory frameworks addressing multiple vectors or end-use sectors.

ETS2) to road transport, buildings, and small industry establishes a unified carbon price signal across these end-use sectors, aligning decarbonization incentives system-wide rather than through fragmented, sector-specific approaches [133]. Complementing this, the proposed revision of the EU Energy Taxation Directive aims to harmonize taxation across energy carriers by taxing fuels based on their energy content and environmental performance rather than by volume. This approach addresses the current asymmetry wherein taxes and levies on electricity significantly exceed those on fossil fuels, creating a distortion that disadvantages electrification-based SC applications [134].

At the sectoral level, the revised Energy Performance of Buildings (EPBD) Directive exemplifies policy coupling by establishing coordinated building decarbonization targets that simultaneously affect both the 'mobility' and 'building H&C' sectors. It incentivizes installation of smart and bidirectional BEV charging infrastructure in residential and commercial buildings (where vehicles are typically parked for extended periods) alongside heat pump deployment and building envelope renovation [63]. Likewise, the Delegated Act on Renewable Fuels of Non-Biological Origin (RFNBO) establishes electricity-hydrogen policy coupling by linking green hydrogen certification to renewable electricity criteria. To qualify as renewable, hydrogen producers must demonstrate additionality (sourcing electricity from new, unsubsidized renewable capacity), temporal correlation (producing hydrogen when renewable electricity is being generated), and geographical correlation (locating electrolyzers in the same or neighboring bidding zone as the renewable source) [103]. These requirements coordinate investment signals across the electricity and hydrogen vectors, ensuring that increased hydrogen production stimulates additional renewable electricity deployment.

The above examples illustrate how regulatory frameworks create non-physical interlinkages that shape investment signals and enable market outcomes across multiple vectors and sectors. In contrast, regulations that govern only a single vector, such as electricity grid codes or gas quality standards, do not constitute policy coupling, as they lack cross-vector or cross-sectoral scope.

Having presented the six categories of SC interlinkages, we briefly reflect on how the classification can serve both modeling and policy practice. Readers are encouraged to consult Appendix A2, which develops detailed use cases for researchers and modelers (spanning model development, interpretation, cross-model comparison) and for policymakers (covering scenario design, contextual benchmarking, and policy coordination). Unlike previous schematic depictions [8, 19, 22, 28, 36, 37], our classification systematizes the complex web of cross-vector and cross-sector interactions into a structured blueprint for causal analysis of system-wide interdependencies. This visual taxonomy can help modelers trace how perturbations in one system component cascade through multiple couplings, and how omitting system components in models (for computational tractability) can distort the modeling results. This not only improves the interpretability of internal model dynamics but also enhances overall modeling transparency by making causal interdependencies explicit. Simultaneously, our taxonomy can support policymakers by clarifying how sectoral policies might interact, helping align sectoral objectives and avoid counterproductive overlaps. Thus, in both modeling and policymaking, the framework fosters a system-of-systems perspective essential for managing the complexity of sector-coupled transitions.

6. Conclusion

Although sector coupling has seen increasing practical deployment and growing policy attention, its theoretical conceptualization remains underdeveloped and fragmented. The varied definitions of SC in the literature can be broadly grouped along three dimensions: structural, functional, and electricity-centric. Definitions featuring the structural dimension describe SC by which sectors or infrastructural grids are interconnected. Yet, they vary widely in sectoral scope and often obscure the supply-demand distinction, leading to ambiguous system boundaries. Definitions with the functional dimension frame SC by its intended goals, such as decarbonization, flexibility, or efficiency. Yet, they conflate what SC is with what it should achieve, limiting objectivity and applicability across disciplines. The electricity-centric definitions portray SC as a means of integrating renewable electricity into end-uses like BEVs and heat pumps. Yet, they exclude non-electric interlinkages, underrepresenting the full diversity of SC.

This fragmentation is not merely an academic concern. It directly constrains key stakeholders. For modelers and researchers, inconsistent definitions lead to divergent system boundaries, hinder internal model transparency, and limit comparability across models. For policymakers and regulators, the absence of a common SC framework blurs the distinction between SC and non-SC applications during scenario design, impedes the identification of context-appropriate SC solutions, and weakens policy coordination. Our proposed framework, anchored in a consistent definition and mechanism-based classification, addresses these challenges. By establishing clear sectoral and system boundaries, the framework provides researchers with a shared foundation that can enable (i) standardization in the SC modeling landscape, (ii) greater modeling transparency through clearer interpretation of internal model dynamics, and (iii) improved cross-study comparability. For policymakers, it can support (i) a role-based approach to distinguish SC from non-SC applications and combine them in scenarios, (ii) a structured basis to benchmark SC pathways relative to their context, and (iii) a whole-system perspective to identify synergies and avoid adverse interactions in coordinated SC policymaking. These practical applications, illustrated through worked use cases in Appendix A2 demonstrate how conceptual clarity translates into tangible gains in modeling fidelity and policy design.

Existing definitions tend to lean toward two extremes. Narrow SC definitions, especially those with an electricity-centric dimension, restrict SC to select vectors and sectors by focusing on integrating electricity, directly or indirectly, with limited end-use sectors like ‘mobility’ or ‘building H&C’. This perspective overlooks non-electric vectors (e.g., waste heat, geothermal heat, biofuels) and critical couplings between end-use sectors and through ‘network’, ‘market’, and ‘policy’ layers. At the other extreme, some broad SC definitions, especially those featuring the structural dimension, extend SC to non-energy infrastructures like roadways or communication networks. This over-generalization blurs SC’s boundaries and dilutes its practical utility by shifting attention to unrelated non-energy issues.

In contrast, our definition offers a balanced conceptual scope. It is inclusive enough to accommodate the full diversity of vectors, sectors, and interlinkages in modern energy systems, yet focused enough to preserve analytical clarity. This balance is achieved through two design choices. First, we extend the scope of SC beyond physical interlinkages. While existing SC definitions largely cover only physical interlinkages (e.g., ‘vector coupling’ and ‘vector-shift coupling’), our definition includes not only additional physical interlinkages (e.g., ‘end-use sector coupling’ and ‘network coupling’), but also non-physical interlinkages (e.g., ‘market coupling’ and ‘policy coupling’). Correspondingly, our taxonomy visualizes six mechanisms underlying SC interconnections: vector-conversion, byproduct or waste energy usage, vector-substitution, network sharing, market integration, and policy coordination, thereby capturing SC’s full operational *diversity*. Second, we remove the directional constraint implicit in most existing definitions. Rather than treating SC as a one-way energy flow from vectors-to-sectors, we explicitly allow interlinkages to occur ‘in any direction’, including ‘reverse’ (sectors-to-vectors) and ‘recursive’ (intra-vector or intra-sector) interactions, thereby capturing SC’s full operational *complexity*. Together, these choices make *explicit* a comprehensive and logically organized toolkit of SC options, systematically including often-overlooked applications such as waste heat reuse and biofuels. Furthermore, while our framework is broad enough to capture SC in its full diversity and complexity, it is sufficiently bounded to distinguish SC from functionally overlapping but distinct concepts like ‘flexibility’. This distinction matters: while SC establishes interlinkages between and among vectors and end-use sectors, flexibility refers to the system's ability to handle residual load fluctuations.

Crucially, while we have expanded SC's conceptual frontiers, we have done so methodically, leaving our framework agile enough to accommodate future scope expansion without diminishing analytical clarity. Its modular architecture, with clearly delineated vectors, end-use sectors, and coupling categories, provides a foundation for systematic extension along three dimensions. First, new end-use sectors can be incorporated as priorities evolve. For example, both 'water' and 'data centers' satisfy our definition of end-use sector, where final energy is consumed *by* distinct consumer segments *for* specific applications, with characteristic load profiles. Thus, these can be added as end-use sectors without requiring any redesign of our framework. Second, non-energy material flows can be integrated within the existing framework. Our categorization of 'molecules' as a distinct energy vector already captures the dynamics at the energy-material interface via P2X pathways. In the energy-to-material direction, a P2X pathway often represents the upstream vector conversion that produces feedstocks for downstream non-energy applications (e.g., hydrogen from electrolysis used for ammonia-based fertilizers). Conversely, non-energy material inputs like CO_2 already feature as feedstocks in P2X pathways, as reflected in the parenthetical notation of hydrogen(+CO_2)-to-synthetic methane 'vector coupling'. Future extensions could make such non-energy feedstock flows explicit, systematically integrating CO_2 capture and reuse pathways into the framework. Third, material-energy circularity can be modeled by extending the framework to applications where the circular economies of materials and energy converge. Examples include direct hydrogen-based reduction of steel scrap, where material recycling and energy system decarbonization intersect. Together, these extension pathways indicate that our framework can evolve alongside the energy transition rather than remain a static snapshot.

Our proposed SC framework synthesizes existing ideas into a new coherent whole that is both conceptually rigorous and practically applicable, with the ultimate goal of advancing the body of knowledge within the SC domain. By offering a structured approach to understanding SC, it seeks to foster a shared interpretation for future researchers and policymakers alike. We do not claim to settle definitively the debate surrounding the term 'sector coupling', nor would such closure be desirable in an evolving field. Rather, our aim is to provide a coherent foundation that can catalyze productive discussions within the SC domain for improved modeling and policy design toward the net-zero transition.

Declaration of Interests

The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for proofreading and language editing. No scientific content, analysis, interpretation, or conclusions were generated by AI. All text produced with the assistance of this tool was carefully reviewed, revised, and approved by the authors, who take full responsibility for the content of the publication.

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Sector Coupling Reimagined: Synthesizing Fragmented Perspectives into a Unified Framework

Appendix

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A1. Methodology for literature identification

To ensure a transparent and reproducible selection of literature, we construct a search string and use it with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [24]. Our search string focuses on two concepts, (1) sector coupling in energy systems, and (2) conceptual framing, to identify studies that are not only relevant but also theoretically informative (Figure A.1a). Concept 1 ensures that the retrieved studies (A) explicitly mention sector coupling or its synonyms, (B) refer to enabling mechanisms such as electrification or Power-to-X (P2X), and (C) address at least one energy sector or SC application. This avoids power system-only studies and irrelevant hits, such as multi-sector dynamics in sustainability science or biomedical studies on P2X receptor proteins. Concept 2 filters for papers offering (A) definitional clarity, (B) conceptual typologies, or (C) meta-level insights. The Boolean logic (1A AND 1B AND 1C) AND (2A OR 2B OR 2C) thus produces technically focused and conceptually rich SC studies.

Next, we follow the PRISMA process, comprising identification, screening, and eligibility assessment (Figure A.1b). The search string is applied across Web of Science, Scopus (filtered for topics in energy, engineering, and environment), and IEEE Xplore, without restrictions on year, geography, or journal type. The results are exported to EndNote for deduplication. After removing duplicates, we screen titles and abstracts to exclude out-of-scope records, retractions, and highly applied studies that focused solely on short-term scheduling, long-term planning, or market clearing in sector-coupled systems. The remaining articles are reviewed in full. Studies are included if they (i) define or classify SC, (ii) model SC pathways and examine systemic interactions (e.g., competition between SC and non-SC applications), or (iii) refine or challenge existing SC concepts. Studies are excluded if they have a narrow sectoral focus, emphasize operational flexibility, or present modeling tools without engaging SC pathways. This yields n = 72 studies identified via databases. In parallel, we manually search Google Scholar, project databases, and gray literature, and apply the same three-stage process to 82 additional studies. This dual-track process yields a systematically identified corpus of 114 studies. To ensure comprehensive coverage, we also conduct backward and forward snowballing. The resulting set of studies constitutes an adequate and representative basis for analyzing how SC is defined, conceptualized, and modeled in the energy systems literature.

A2. Enhancing SC modeling and policy design through a unified framework

A2.1. Challenges without a unified framework

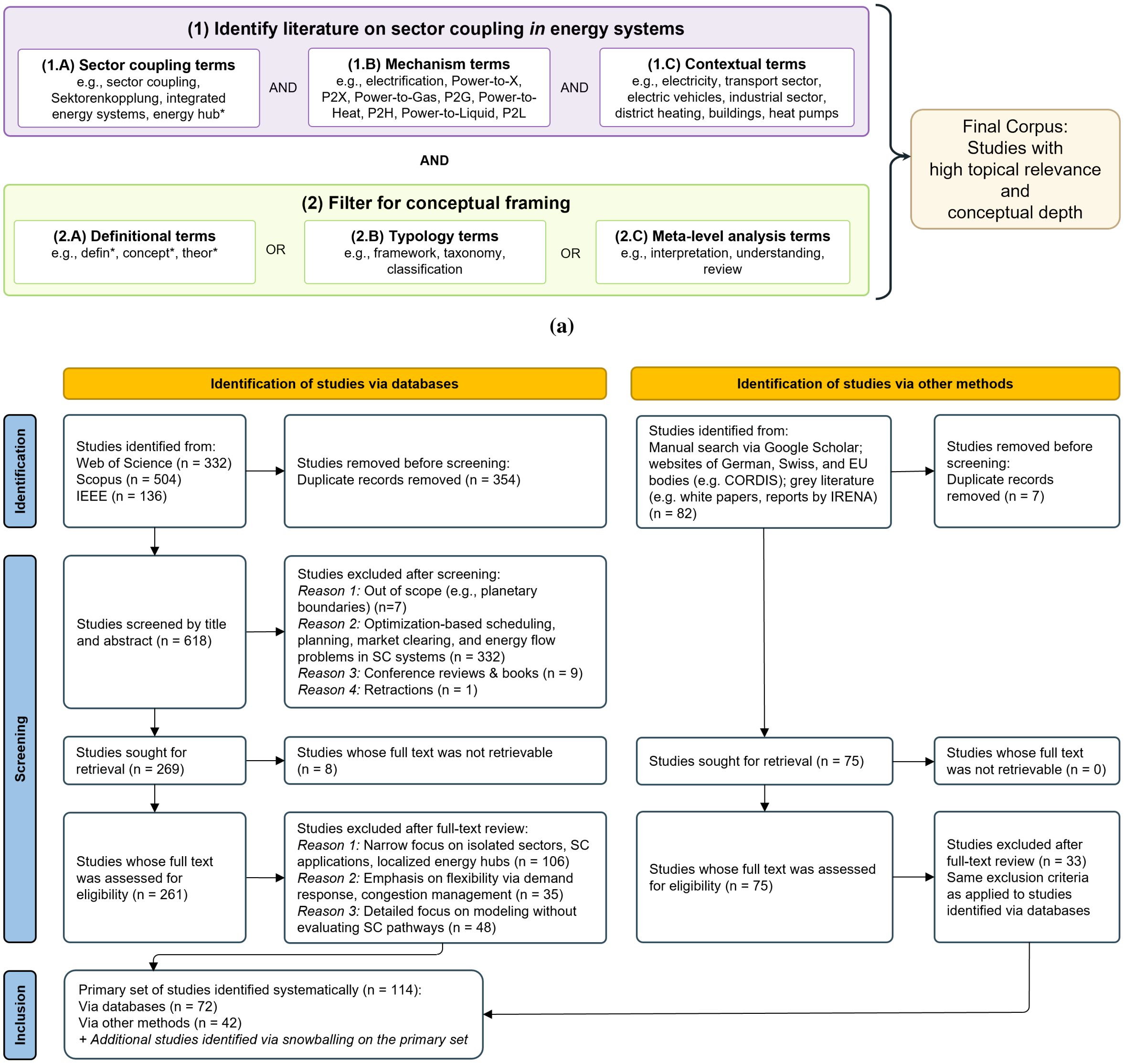
The theoretical underdevelopment of SC is not merely an academic concern, but directly affects: (i) energy system modelers and researchers, and (ii) policymakers and regulators.

A2.1.1. Challenges for energy system modelers and researchers

The absence of a unified SC framework presents challenges to modelers and researchers at various stages of energy system modeling, such as *model development*, *interpretation*, and *comparison*.

Designing future energy system pathways requires integrating SC into state-of-the-art modeling tools [21]. However, inconsistent SC definitions have created a significant barrier between the conceptual understanding of SC and its implementation in modeling tools. This issue is especially problematic during *model development*, where differing SC interpretations lead to ambiguity about which energy vectors, end-use sectors, and SC applications to include, resulting in varying system boundaries across models. For example, the modeling framework REMix excludes end-use sectors [135], while PyPSA includes them within its system boundary and even models inter-sectoral linkages, such as industry-building H&C coupling by accounting for the industrial waste heat reused for district heating [136]. Compounding this challenge is the absence of a shared modeling vocabulary. Key terms such as “sector” are interpreted inconsistently across studies, unlike disciplines such as electrical engineering, where basic concepts have standardized meanings, for example, “ node” is universally understood as a junction of two or more circuit elements. These conceptual ambiguities hinder communication between modeling communities and limit the transfer of methodological innovations across tools, thus undermining standardization in the SC modeling landscape.

Next, the absence of a unified SC framework compromises *model interpretability*. Without a macro-level map of potential SC interlinkages between and among energy vectors and end-use sectors, researchers struggle to trace how changes in one component ripple through the entire system (e.g., how reducing output of ‘industrial’ sector may



(b)

Figure A.1: Overview of the literature identification process.

(a) Schematic representation of the search string construction, wherein sector coupling-related terms (1A–1C) were combined with conceptual framing terms (2A–2C) using the Boolean logic: (1A AND 1B AND 1C) AND (2A OR 2B OR 2C). (b) PRISMA flow diagram illustrating the systematic identification, screening, and inclusion of studies. At each stage, records removed (e.g., duplicates, retractions) were excluded before advancing the remaining corpus to the next step.

may impact the deployment of heat pumps in 'residential' sector or BEVs in the 'mobility' sector). Additionally, since researchers frequently model only a subset of the system for computational tractability or analytical purposes, it becomes crucial to clarify how the excluded components influence the dynamics of those included [137]. For instance, including heat pumps but omitting electrolyzers necessitates an explanation of how such omissions could skew the results. Without a standardized taxonomy of possible SC interlinkages, the complex web of interactions that characterizes sector-coupled energy systems becomes difficult to interpret.

Given SC's theoretical nascency and the different conceptual starting points of various modeling communities, even minor differences in theoretical understanding can cascade into major variations in how SC is implemented in models. This impairs *cross-model comparability*, which is critical for multi-model ensemble analysis — a practice that synthesizes outcomes from multiple tools to mitigate model-specific blind spots and yield insights unavailable to any one tool alone [138, 139]. Yet, differences in SC implementation, particularly in modeling approaches and internal assumptions, hinder meaningful comparison and integration of model outputs. For example, different models operationalize SC using different approaches: EnergyPLAN implements SC through optimization of operations and simulation of alternative investment pathways [50], REMix formulates SC as a deterministic optimization problem spanning both investment and operation [135], while GENESYS-2 applies SC via rule-based heuristic logic [140]. Discrepancies in internal assumptions further affect key outputs, including system costs, flexibility, curtailment, and emissions. For instance, Zwaan et al. [141] show that under identical climate scenarios, models assuming direct use of H_2 in end-use sectors (e.g., REMIND) yield deeper decarbonization outcomes compared to models that restrict H_2 to indirect liquid fuel pathways (e.g., Euro-Calliope) due to the projected decline in liquid fuel demand by 2050. Such heterogeneity of SC implementations makes it difficult to benchmark models, both individually against reference scenarios and comparatively against one another.

A2.1.2. Challenges for policymakers and regulators

Inconsistencies in SC conceptualization disrupt decision-making throughout the policy cycle, affecting how *scenarios* are designed, and SC pathways are *benchmarked* and policies *coordinated* (Figure 1).

First, the absence of a unified SC definition hinders both *model selection* and *scenario design*. Selecting the appropriate tool(s) requires a transparent methodology to evaluate a model's ability to represent the energy vectors, end-use sectors, and their interlinkages, relevant to the specific policy [21]. However, in the absence of a unified SC definition, decision makers with different SC interpretations may prioritize different models to answer the same policy question, leading to inconsistent and opaque model choices. For example, to design SC pathways for unlocking system flexibility, a decision maker with a narrow perspective may favor models that capture only electricity-heat and electricity-mobility interlinkages, while another with a broader perspective may seek tools that also include biofuels or waste heat reuse. Beyond model selection, SC's vague conceptual boundaries complicate scenario design by blurring the line between SC and non-SC applications. For example, emissions reductions may result from SC options like heat pumps or from non-SC measures like building retrofits. Similarly, flexibility can arise from SC applications such as BEVs or from flexibility-only measures like battery storage (temporal flexibility) and grid expansion (spatial flexibility) [91]. Notably, Brown et al. [142] argue that under sufficient transmission capacity, V2G coupling can significantly reduce (or even displace) stationary storage. Such competition or substitution between SC and non-SC applications underscores the need to attribute system impacts carefully. However, when these functionally overlapping applications are intermixed in scenarios without a structured logic for which combinations to include and why, it becomes difficult to isolate and assess SC-specific effects. This hinders decision makers from evaluating SC effectiveness and weakens the credibility of scenario-based insights.

Another key challenge is designing sector-coupled pathways tailored to national/regional conditions. The effectiveness of SC pathways depends on context-specific factors such as renewable availability [143], demand profiles [45], infrastructure constraints [144], market structures [145], and target timeframes [146]. This requires planners to *benchmark SC pathways* relative to their context to identify *what* works best where and when. However, without a consistent definition of *what* constitutes SC, such benchmarking remains difficult. For instance, BEVs-based electrification pathways (narrow definition) may suit a country with established wholesale and retail power markets [145]. In contrast, network-based solutions, such as blending renewable gases in natural gas pipelines or repurposing them for transporting renewable gases (broad definition), may be preferable for a country phasing out natural gas [117, 147]. A policymaker with a narrow view may overlook network-based SC pathways, thereby missing cost-effective opportunities to decarbonize hard-to-electrify end-uses for example, by shifting high-temperature process heat in industry from natural gas to hydrogen using the same pipeline network [116]. In addition, such insights on SC performance remain difficult to transfer across contexts. Thus, definitional inconsistencies risk producing SC policies that are not context-sensitive.

Finally, effective implementation of SC solutions requires *coordinated policymaking* across erstwhile independent energy vectors and end-use sectors [148]. Yet, in the absence of a system-wide coordination framework, policy efforts often remain siloed, addressing vector- or sector-specific challenges in isolation, and undermining SC's synergies [35]. For example, Glenk and Reichelstein [149] argue that while wind farms and electrolyzers may be economically unviable when deployed independently, integrated investment in both can yield synergistic benefits. However, if their deployment rates are not coordinated, accelerated wind expansion may increase curtailment during low demand, while standalone electrolyzers' installation may worsen grid congestion [150]. This need for coordination is also evident in Luderer et al. [151], which demonstrate that combined modeling of the electricity and hydrogen can better optimize the energy system and thus reduce costs. Similarly, policies promoting BEVs and heat pumps need to be aligned. If pursued independently, their simultaneous adoption may overload the distribution grid, especially during winters [152]. Although some degree of policy divergence is expected due to differing political mandates or sector-specific priorities, the conceptual fragmentation in SC's theory institutionalizes regulatory fragmentation in practice. Thus, institutions overseeing different vectors and sectors often operate without strategic alignment, limiting systemic benefits of SC.

A2.2. Applying our framework to enhance SC modeling fidelity and policy design

A2.2.1. Clarifying model boundaries, harmonizing technical scopes, and fostering a common language

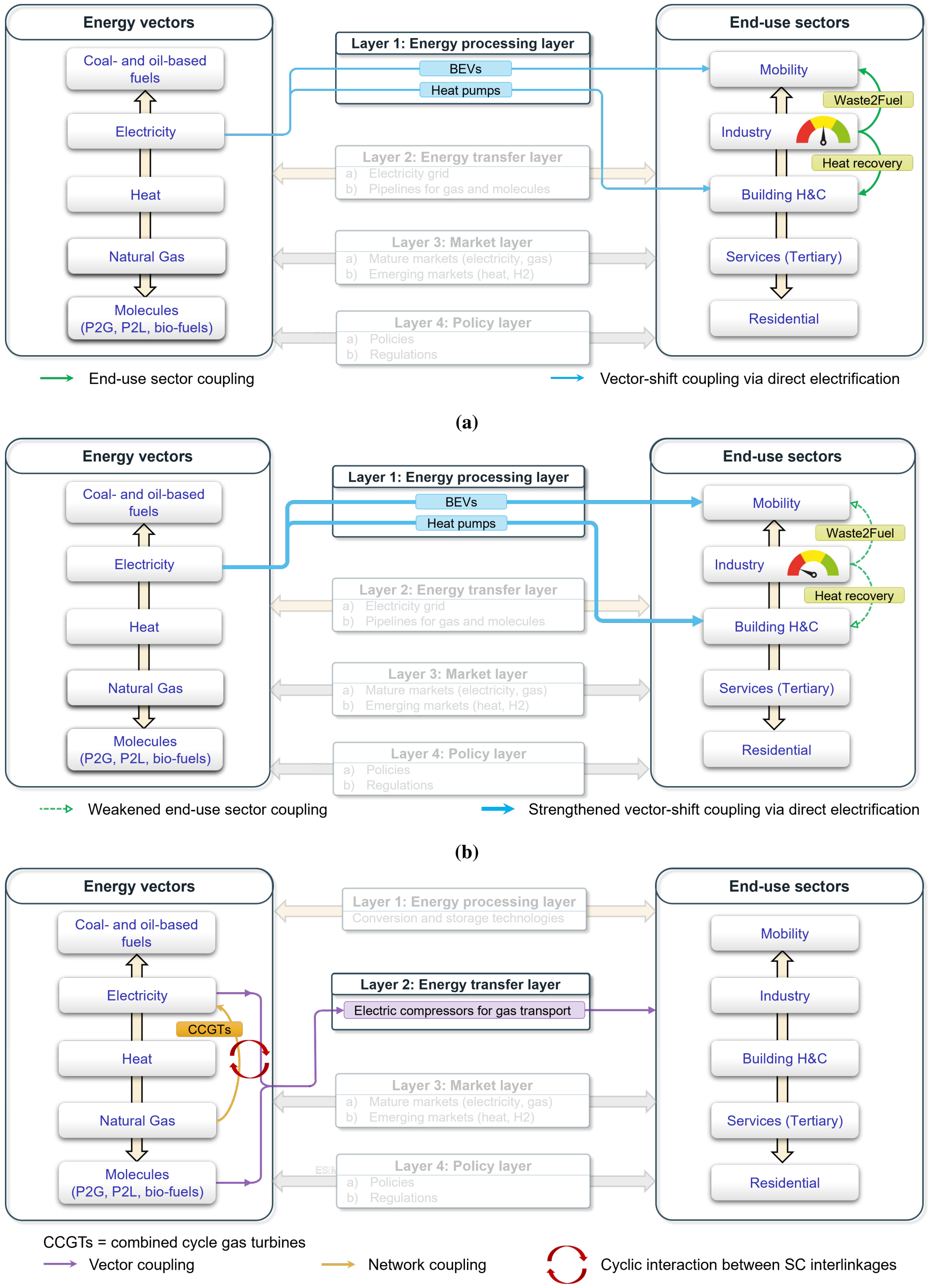
Our unified SC framework bridges the gap between the conceptual understanding of SC and its *model development*. By clarifying what constitutes SC, it guides modelers in selecting which vectors, end-use sectors, and applications to include, reducing unintentional mismatches in system boundaries. Where divergences in scope are intentional, such as those resulting from differing research aims, our framework can provide a structured basis for articulating and comparing them, thus encouraging modeling transparency. Additionally, our framework cultivates a shared SC vocabulary by resolving pertinent dilemmas such as: What differentiates "sector coupling" from "flexibility"? What is meant by "sector"? Should "electricity" be modeled as an energy-carrying vector or an end-use sector? And where and how should W2E plants, data centers, or hydrogen blending in gas pipelines be positioned within the model architecture? This common lexicon can streamline model building, improve documentation clarity for model users, and help exchange methodological innovations across different modeling communities [153], thus fostering greater coherence and standardization in the SC modeling landscape.

A2.2.2. Tracing system-wide interactions

Our taxonomy of interlinkages enhances *model interpretability* by providing a systems-level blueprint of potential SC interconnections between and among vectors and sectors. This structured visualization helps researchers diagnose how perturbations in one component snowball through the system. We illustrate this diagnostic power using three representative use cases.

When tuning model parameters during sensitivity analysis, changes in a single parameter can induce ripple effects in multiple couplings. For example, the output of the 'industry' sector can simultaneously impact four distinct couplings: (i) industry-residential end-use sector coupling through waste heat reuse, (ii) industry-mobility end-use sector coupling through biofuels, (iii) electricity-building H&C vector-shift coupling through heat pumps, and (iv) electricity-mobility vector-shift coupling through BEVs. A reduction in the industrial output parameter (e.g., to reflect lower GDP projections) can induce system-wide structural adjustments as illustrated in Figures A.2a and A.2b. Our interlinkages typology can help modelers intuitively trace such interdependent cause-effect chains that may otherwise remain obscure.

When analyzing partial systems, our taxonomy assists researchers in interpreting how modeling choices, such as omitting sub-systems for computational tractability, can lead to biased results. For example, both electrolyzers and heat pumps compete for renewable electricity. If a modeler excludes electrolyzers but includes heat pumps, our taxonomy reveals that this choice may underestimate downstream deployment of FCEVs due to lower-than-expected hydrogen production. By surfacing such latent system-wide interactions, our taxonomy can help modelers clearly attribute outcomes and rationally justify their model boundaries.



(c)

Figure A.2: System-level propagation of changes and disruptions across a sector-coupled energy system. Panels (a) and (b) show the sensitivity of SC interlinkages to changes in industrial output, while panel (c) illustrates adverse systemic interactions between two different SC interlinkages. **Panel (a):** With moderate industrial output (gauge at mid-level), the 'industry' sector partially meets waste heat and biofuels demands of other sectors, sustaining end-use sector couplings with moderate strength (medium-width arrows), while electrification-based vector-shift couplings through BEVs and heat pumps also remain moderately active. **Panel (b):** A reduction in industrial output (gauge at low level) diminishes the availability of waste heat and biofuels, weakening end-use sector couplings (thinner, dotted arrows), and prompting stronger electricity-based couplings (thicker arrows) to meet residual heat and transport demand through additional heat pumps and BEVs, respectively. **Panel (c):** Feedback loop between electricity-gas 'vector coupling' and electricity-gas 'network coupling', exemplified by the 2021 Texas blackout. Power outages disabled electric gas compressors (network coupling), which disrupted gas delivery to CCGTs (vector coupling), causing further power outages and reinforcing a cascading failure loop.

Lastly, our interlinkages taxonomy can also help SC models anticipate cascading failures across coupled infrastructures (Figure A.2c). For example, during the 2021 Texas blackout, electric outages to the gas transport infrastructure like electric pumps and compressors (i.e., a failure in electricity-gas network coupling), subsequently disrupted gas delivery to CCGTs (i.e., a failure in electricity-gas vector coupling). The resulting curtailment of CCGTs' generation, in turn, triggered further electric outages to the gas infrastructure, reinforcing a self-amplifying disruption loop with gas shortages leading to electricity outage and vice versa [154]. By explicitly distinguishing such couplings, our taxonomy enables a granular assessment of cascading failure pathways and system-level resilience gaps.

In effect, by helping track system-wide causal interdependencies, our framework improves the understandability of internal model dynamics, which is a core pillar of modeling transparency [155]. While prior studies provide schematic depictions of interactions in sector-coupled systems, none, to our knowledge, offer a structural classification that systematizes these interlinkages into a taxonomy suited for systemic analysis.

A2.2.3. Tracing how SC implementation shapes model outcomes

Our SC framework assists in *cross-model comparability* by providing a consistent conceptual reference point. A common reference helps disentangle whether models differ in their *conceptualizations* of SC or in their *implementations* of SC. When models vary in their SC implementations, whether in approaches or internal assumptions, our SC framework helps researchers to transparently document and systematically compare these methodological variations. Model comparison or 'model benchmarking' can take two distinct forms. 'Benchmarking *of* models' assesses an individual model's performance against a reference scenario or standardized test case to validate its internal consistency or real-world representativeness. Here, our interlinkages taxonomy can help design reference scenarios by clarifying which SC interlinkages may be relevant for inclusion. This provides a systematic basis for evaluating whether the model adequately captures the desired SC dynamics. On the other hand, 'benchmarking *across* models' involves running multiple tools under harmonized input data to isolate how variations in SC implementation affect model outcomes. For example, the model DIETER treats the heat pump coefficients of performance (CoP) as temperature-dependent, whereas ISAaR assumes a constant value [156]. However, by placing both temperature-dependent and constant CoP formulations within the same electricity-to-building H&C vector-shift coupling category, our taxonomy makes the underlying assumptions transparent. This conceptual alignment can help modelers attribute differences in output (e.g., optimal heat pump capacities) to divergent SC implementations (e.g., contrasting CoP assumptions) rather than different system dynamics due to inconsistent SC conceptualizations. This attributional clarity enables clearer articulation and comparison of implementation-induced differences across models.

A2.2.4. Structuring scenarios around SC functions and clarifying model selection

Our SC framework improves *scenario design* through two key contributions: *identifying* appropriate applications and *combining* them with a clear rationale.

First, our SC definition serves as a consistent conceptual yardstick for *identifying* SC applications and distinguishing them from non-SC ones. SC measures are those that establish interlinkages between and among vectors and sectors. Based on this distinction, building retrofits, for instance, are efficiency measures falling outside the SC domain. Similarly, battery storage and time-of-use tariff-based demand response represent non-SC options for temporal flexibility, while grid expansion and cross-border electricity exchange are examples of non-SC measures for spatial flexibility. This conceptual segregation supports a more deliberate and systematic selection of applications when constructing scenarios. It also enhances *model selection*: decision makers can use our definition and taxonomy to assess whether candidate SC models encompass the full range of vectors, end-use sectors, and interlinkages relevant to their needs.

Second, it offers a role-based rationale for *combining* non-SC and SC applications when designing scenarios. Assessing the effectiveness of SC applications requires isolating their specific impacts on system outcomes. A typical approach for this is 'scenario switching', i.e., comparing outcomes from a scenario with both SC and non-SC applications against one with only non-SC applications [157]. However, this "with and without SC" scenario approach has inherent limitations: SC and non-SC measures within a scenario often interact non-linearly, making attribution difficult. For example, Nagel et al. [157] show that in Europe, heat pumps (SC) and transmission expansion (non-SC) *compete* under moderate climate targets by providing substitutable flexibility services, but *complement* each other in strict climate targets since an expanded grid enables heat pumps to access low-cost renewable electricity and replace phased-out fossil heat sources. To ensure that designed scenarios can clearly attribute SC-specific impacts, we propose a two-step scenario design method based on system roles, which provides a logical basis for determining which applications to combine or exclude across scenarios.

In the first step, group relevant applications according to (i) whether they qualify as SC or non-SC, and (ii) the system functions they serve, such as temporal flexibility, spatial balancing, or emissions reduction. In the second step, construct scenarios by using non-SC options as the baseline and incrementally adding SC applications (or vice versa) to test their complementarity or competition. For example, decision makers may pair residential batteries (non-SC) with BEVs (SC) to examine their contribution to temporal flexibility, or transmission expansion (non-SC) with BEVs (SC) to assess their spatial balancing trade-offs, while designing such structured scenarios.

By supporting such functionally structured scenario trees, our framework transforms SC scenario design from an arbitrary technology bundling process into a logical process anchored in system functions, thereby strengthening the credibility and policy relevance of model outcomes attributed to SC.

A2.2.5. Assessing SC performance in context

Our SC framework supports decision makers in evaluating sector-coupled pathways relative to their context and identifying *what* performs best in specific settings. First, it provides a coherent conceptual understanding of *what* constitutes SC, including clear sectoral boundaries and a typology of interlinkages. Second, it guides harmonizing assumptions to help align different modeling environments. Third, it introduces consistent criteria to evaluate SC pathways, such as emissions reduction, cost-effectiveness, system flexibility, and renewable curtailment. These criteria are the functional goals of SC that we decoupled from existing definitions (Section 3.2). Although the precise formulation of such criteria lies beyond the scope of this paper, our SC framework underscores the need to develop standardized metrics tailored to sector-coupled systems, for example, extending flexibility indicators such as loss of load expectation (LOLE) and expected energy not served (EENS), which exist for electricity-only systems, to sector-coupled systems. Together, these three elements, namely conceptual clarity, harmonizing assumptions, and emphasis on functional criteria, can provide a structured basis for assessing performance of SC pathways. With the conceptual and modeling alignment they provide, decision-makers can more confidently attribute a SC pathway's performance to contextual factors, such as the local electricity mix, infrastructure constraints, demand profile, and policies, and thereby identify which SC pathway is most effective for a given context.

This contextual benchmarking yields three key benefits. First, it helps compare SC applications across contexts. For example, if BEVs reduce emissions by 50% in Country A and heat pumps by 30% in Country B, contextual benchmarking prevents simplistic generalizations like "BEVs perform better than heat pumps". Instead, it provides context-aware insights, such as "BEVs perform better than heat pumps *in Country A*". This may be attributable to factors specific to Country A, such as a low-carbon electricity mix, short-range mobility patterns, developed charging infrastructure, and BEV-focused policies like tax rebates. Second, it improves the transferability of SC applications to peer regions with similar settings. For example, policymakers in Country C can identify similarities with Country A and *adopt* BEV-focused strategies, or conversely, note the lack of enabling conditions and *adapt* accordingly. Third, it strengthens policy credibility. For example, policymakers can compare the same SC application across different contexts and trace why it succeeds in a particular context, improving reproducibility of and trust in model-based policy recommendations.

In this way, rather than imposing one-size-fits-all prescriptions, our SC framework enables evidence-based comparisons that empower decision-makers to design more adaptive and regionally-grounded SC strategies.

A2.2.6. Enabling coordinated governance of SC solutions

Lastly, our SC taxonomy of interlinkages juxtaposes vectors and end-use sectors, mapping the potential interlinkages between and among them, thereby fostering a whole-system mindset. This system-of-systems approach supports what Olbrich et al. [150] term "system building": an overarching perspective on the energy system to address emerging implications in a systemic manner (e.g., by planning transition processes at a system level). Such system building can help decision-makers reconcile competing objectives, identify synergies, and avoid counterproductive overlaps between vectors and sectors. It can thus facilitate harmonized cross-vector, cross-sector planning by ensuring that policies targeting one vector/sector account for their ripple effects on others. For example, aligning wind and electrolyzer policies by co-locating electrolyzers in wind-rich regions [149], and introducing market mechanisms to synchronize their operation (e.g., joint bidding by wind–electrolyzer systems in ancillary services markets)

[129], can reduce wind curtailment and increase hydrogen yield. Similarly, coordinating BEV and heat pump policies through home energy management systems that optimally schedule smart charging and thermal storage [96], and market instruments (e.g., dynamic tariffs, non-firm connections, local flexibility markets), can mitigate adverse simultaneity effects and ease their concurrent deployment without grid stress [158]. In this way, our unified SC framework allows policy levers to be designed in tandem, unlocking synergistic benefits otherwise missed in fragmented policy landscapes.

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