

Felder, Frank A.

Working Paper

A net-zero energy system with liberalized markets and regulated transportation and delivery

OIES Paper: EL, No. 59

Provided in Cooperation with:

The Oxford Institute for Energy Studies, Oxford

Suggested Citation: Felder, Frank A. (2025) : A net-zero energy system with liberalized markets and regulated transportation and delivery, OIES Paper: EL, No. 59, ISBN 978-1-78467-272-0, The Oxford Institute for Energy Studies, Oxford

This Version is available at:

<https://hdl.handle.net/10419/324426>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

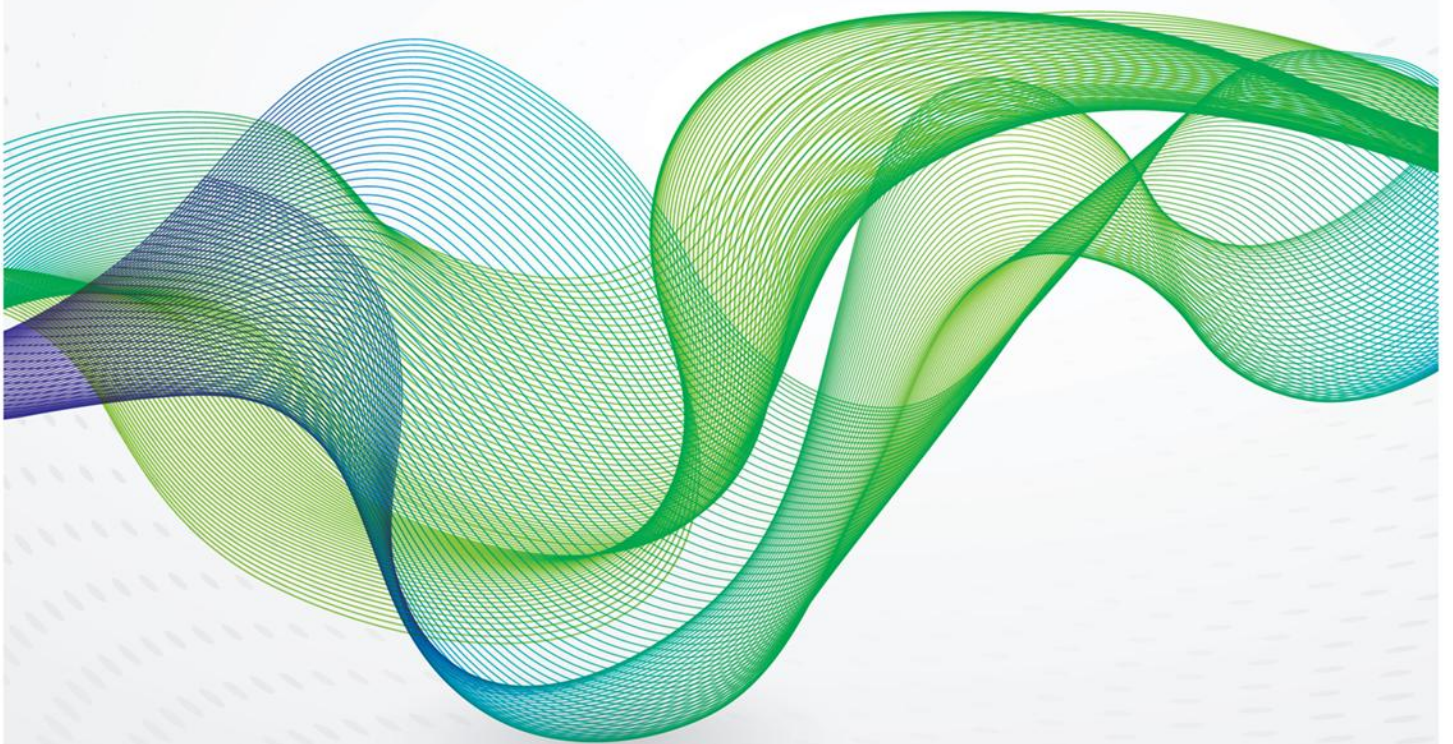
Documents in EconStor may be saved and copied for your personal and scholarly purposes.

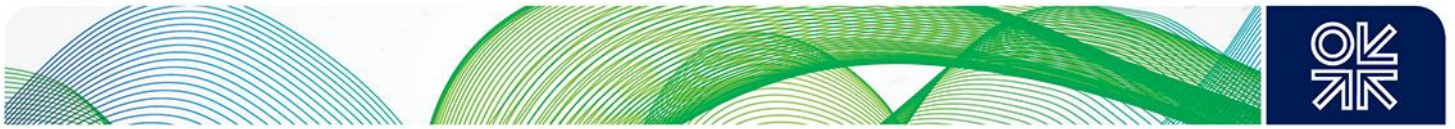
You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

May 2025

A Net-Zero Energy System with Liberalized Markets and Regulated Transportation and Delivery





The contents of this paper are the author's sole responsibility. They do not necessarily represent the views of the Oxford Institute for Energy Studies or any of its members.

Copyright © 2025
Oxford Institute for Energy Studies
(Registered Charity, No. 286084)

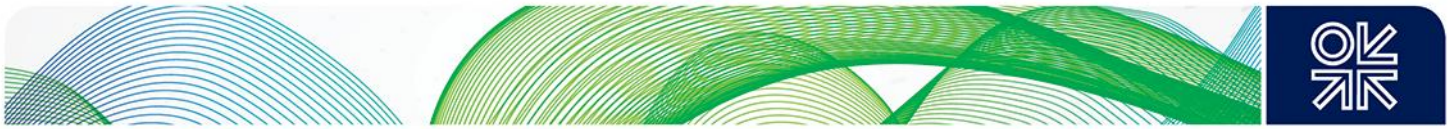
This publication may be reproduced in part for educational or non-profit purposes without special permission from the copyright holder, provided acknowledgement of the source is made. No use of this publication may be made for resale or for any other commercial purpose whatsoever without prior permission in writing from the Oxford Institute for Energy Studies.

ISBN 978-1-78467-272-0



Acknowledgements

The author would like to thank the reviewers for their comments and suggestions.



Abstract

Achieving net-zero greenhouse gas emissions in the energy system requires substantial electrification of transportation and many industrial applications, utilizing net-zero generation resources in conjunction with net-zero gas and heat systems. This paper describes and evaluates a centralized net-zero energy system with liberalized electricity, gas, and heat production facilities, a regulated network utility, and the operator of the net-zero system. Existing market-based electricity systems in Europe and the United States provide the starting point for transitioning to a net-zero energy system and inform the design choices needed to enable that. Such centralized net-zero energy systems may improve system efficiency and reliability through jointly optimizing electricity and gas operations and planning, while accommodating regional policy and governance preferences. Their success depends on whether existing market and regulatory practices can be extended, and new practices developed, to satisfy the multiple policy objectives of net-zero energy systems, accommodate emerging net-zero energy technologies, successfully optimize markets with multiple energy products, efficiently regulate markets and network investment, and implement effective governance.



Contents

Acknowledgements	ii
Abstract	iii
Contents	iv
Tables and figures	iv
1. Introduction and Policy Context	1
2. Net-Zero Energy System Literature Review	1
2.1 Objectives of Net-Zero Energy Systems	2
2.2 Net-Zero Energy Technologies	3
2.3 Market and Economic Regulation	3
2.4 Governance of Net-Zero Energy Systems	4
3. Architecture and Description of the Market and Regulatory Structure of the Net-Zero Energy System	6
3.1 Existing Transmission System Operator and Regional Transmission Operator/Independent System Operator Architecture	6
3.2 Extending the TSO and RTO/ISO Models to the Energy System Operator	9
4. Conclusions, Policy Implications, and Further Research	12
Abbreviations	14
References	15

Tables and figures

Table 1: The end-state net-zero energy system is layered and intertwined	2
Table 2: Generic taxonomy of the objectives of net-zero energy systems	2
Table 3: Summary of existing TSO and RTO/ISO architectures.....	7
Table 4: The governance-regulatory-policy context that affects the optimization of electricity markets and transmission in RTOs/ISOs	9
Table 5: Summary of some major design variations of the TSO and RTO/ISO models	9
Figure 1: Example of integrated net-zero energy system (Davis et al., 2018)	10



1. Introduction and Policy Context

Up to 145 countries worldwide have or are considering net-zero energy emission targets, namely, an energy system that emits at most no greenhouse gases after accounting for emission absorption and/or the capture and storage of emissions from the atmosphere. Similarly, 24 states in the United States (U.S.) and the U.S. District of Columbia are committed to transitioning to net-zero energy systems. These targets aim to eliminate net greenhouse gas emissions and be consistent with other objectives regarding the affordability of energy and the security of energy supply. The starting point for countries and states of the transition is the electric power system, given that it offers the most numerous and cost-effective options compared with other sectors for achieving net-zero emissions. Additionally, through electrification, it can extend its impact into other major sectors such as transportation, heating, and industrial processes.

A whole-system approach that includes electricity and other energy sources and carriers, such as natural gas, hydrogen, carbon dioxide-derived fuels, and heat (steam and hot water) networks, is considered. A centralized system's approach serves two purposes. First, it is a conceptual model that provides a benchmark for evaluating the efficiency of a net-zero energy system (NZES). Second, it is a starting point for practical proposals that are premised on centralized market and network optimization. For example, in response to the United Kingdom's 2023 Energy Act, the National Energy System Operator replaced the National Grid Electricity System Operator so as to accelerate the net-zero energy transition (United Kingdom Department for Energy Security and Net Zero, 2024; Chyong, 2025).

At the outset, it is important to discuss terminology and abbreviations. The paper extends the terms and concepts of the electric power system to the NZES. For instance, the term energy is used in lieu of electricity, and also covers multiple gases, steam, and hot water.¹ Whereas NZES refers to the physical system, the corresponding terms for independent system operators/regional transmission operators (ISOs/RTOs) and transmission system operators (TSOs) are extended to the energy system operator (ESO), the *regional* energy transportation operator (RETO), and the *transportation* energy system operator (TESO). Transportation refers to the long-distance transmission of energy carriers and their local distribution. The term 'social welfare' is the sum of consumer and producer surplus and does not include broader societal objectives, such as distributional impacts or environmental justice. The term 'liberalized' refers to markets for energy products and carriers, but with a monopoly utility transportation and delivery system subject to economic regulation, such as cost-of-service or incentive-based regulation. Other extensions of nomenclature that apply to existing electric, natural, and heating systems are introduced throughout the paper.

The remainder of the paper is organized as follows. Section 2 is a literature review of NZES. Section 3 describes and analyzes the architecture of independent energy system operators (IESOs), regional energy system operators (RESOs), and TESOs. Section 4 summarizes the findings and identifies avenues for additional research.

2. Net-Zero Energy System Literature Review

The literature is replete with NZES proposals (DeAngelo et al., 2021). Net-zero emissions is more than a physical definition; it also includes multiple objectives as it is operationalized within economic, social, and political systems (Fankhauser et al., 2022). Although the specifics of these proposals vary geographically, depending on the available resources, priorities, and political contexts, there are important similarities. The proposals include increased electrification, the ability to manage the variability of power generation from wind and solar photovoltaic (PV) panels, integration with gas and heating systems, a hybrid market and public utility regulatory structure, and governance, including stakeholder involvement and regulatory oversight. As discussed further below, an NZES encompasses layered technologies, markets, economic regulation, and governance, as presented in Table 1 (Clarke et al., 2022; Felder, 2014).

¹ Various terminology is used in the literature such as *power-heat-gas* and *electricity-heat-gas*.



Table 1: The end-state net-zero energy system is layered and intertwined

Net-zero energy system layer	Net-zero energy system elements and description
Objectives	Energy trilemma: energy security, sustainability, and affordability
Technologies	Electrification (much of transportation, heating, and industrial processes), wind and solar PV panels, nuclear (large-scale and small modular reactors), energy storage, transmission and distribution, transformers, power lines, grid enhancing devices net-zero emission gases (hydrogen, gas, and ammonia), heat (steam and hot water), and demand response
Markets and economic regulation	<ul style="list-style-type: none"> • Wholesale energy commodity markets • Retail energy markets • Economic regulation (cost-of-service, incentive-based, performance-based) of the net-zero energy network with cost-reflective tariffs
Governance Stakeholders Regulators Political process	<ul style="list-style-type: none"> • Role of stakeholders (informational, consultation) • Energy and environmental • Regulatory structure and appointments, legal statutes and review, political environment and support

The following subsections review the literature on NZES objectives, technologies, market and economic regulation, and governance.

2.1 Objectives of Net-Zero Energy Systems

A standard but not universal taxonomy of net-zero energy system goals is the energy trilemma: affordability, energy security, and sustainability (Pliousis et al., 2019). In many countries and U.S. states, NZES objectives also include economic development, that is, creating and expanding industries, supply chains, employment, and tax revenues within the realm of pursuing an NZES (IEA, 2024). The other objectives of an NZES may also have sub-objectives, as illustrated in Figure 1. Figure 1 is not meant to be exhaustive but to illustrate that there are multiple policy objectives and layers to NZES.

Table 2: Generic taxonomy of the objectives of net-zero energy systems

Objectives of net-zero energy systems					
<u>Economic</u>		<u>Environmental and public health</u>		<u>Energy security</u>	
Affordability	Economic development	Greenhouse gas emission reductions	Additional sustainability objectives (air, water, land)	Reliability	Resiliency

There are three generic approaches to addressing the multiple policy objectives. One approach is to reduce all the objectives and sub-objectives to a common numerical metric, such as cost (Webb and Ayyub, 2017). The second is to select one objective, typically minimizing cost or maximizing economic social welfare, while adhering to certain limits in order to enable other policy objectives to also be achieved. The third is to analyze the tradeoffs between the distinct objectives through multi-criteria methods (Hobbs and Meier, 2012).

For the purposes of this paper, and consistent with the economic literature on TSOs and ISOs, social welfare maximisation is assumed to be the objective. It accounts for the price elasticity of demand



subject to constraints on environmental and energy security.² To maximize social welfare, meaningful demand response from energy loads is necessary, supported by cost-reflective tariffs (FTI Consulting, 2025; Felder and Athawale, 2014). If energy demand is incorrectly assumed to be perfectly inelastic, then social welfare maximization reduces to cost minimization (Creti and Fontini, 2019).³ Energy affordability, equity, and environmental justice are assumed to be addressed through the broader political process that encompasses the energy sector, and public safety and health systems.

2.2 Net-Zero Energy Technologies

NZES involves integrating multiple existing and emerging technologies, starting with the electricity sector. The transition to net-zero greenhouse gas emissions depends in part on the deployment of large amounts of wind and solar PV energy (IRENA, 2023; United States Department of Energy, 2024b). Wind resources are generally located at remote locations that may be far from existing transmission facilities. Typically, solar PV resources are available near the distribution system and in areas requiring transmission development. Integrating these variable and intermittent resources requires additional transmission and distribution capacity, energy storage, and demand response to reduce the cost of near-instantaneously balancing supply and demand, which is required to ensure the reliability of the electricity system (Aghaei et al., 2018; Tagliapietra et al., 2019).

Expanding transmission and enabling multiple types of energy storage are also critical for achieving net-zero emissions for three reasons (Joskow, 2021). First, electricity demand loads, such as from data centers, for transportation, and industrial electrification, are increasing (Berkeley Lab, 2024; IEA, 2025). Second, as mentioned, the grid is integrating ever-increasing amounts of variable renewables, such as wind and solar PV. Third, electric transmission systems are ageing, and a slate of grid-enhancing technologies is emerging as cost-effective solutions for increasing transmission capacity (Chao and Wilson, 2020).

Electrification may not be suitable for all industrial and commercial applications that consume natural gas or require process heat. Therefore, NZES may require gases with net-zero or negative emissions, such as biogas, biogas with carbon capture, and net-zero hydrogen, and appropriate storage solutions (Leicher et al., 2024; Davis et al., 2018). That some of these gases can be produced using net-zero electricity sources, and the substitutability of electricity with these gases in some applications, indicates that an already interdependent electricity-natural gas system may evolve into an even more interdependent energy system. This system could incorporate multiple energy sources and carriers that would benefit from the centralized optimization of operations and investment (Hong, de León, and Zhu, 2018; Raheli, Wu, Zhang, and Wen, 2021; Zhao, Conejo, and Sioshansi, 2017). The NZES could use the centralized RTO/ISO unit commitment and dispatch strategy or the decentralized European TSO strategy that schedules suppliers and consumers through exchanges (Ahlqvist, Holmberg, and Tangerås, 2022).

2.3 Market and Economic Regulation

The existing electricity and natural gas sectors in the U.S. and Europe are a hybrid of markets and economic regulation. The commodity production of electricity and natural gas are considered competitive, or potentially so with appropriate legal and regulatory oversight, and therefore can be market-based. Market-based means that, for the most part, individual electricity and natural gas producers decide whether to invest in or retire their assets, and how to operate them in response to market conditions and prices, subject to antitrust laws, power market rules, and reliability requirements. In NZES, the premise is that the production of electricity, gas, and heat is market-based, and natural gas is replaced with net-zero energy carriers. The sale of retail energy can be either economically regulated or market-based. The benefits of liberalizing the electric system depend on the successful mix of markets, transmission, and distribution (Felder, 2020).

² For textbook treatments, see Creti and Fontini (2019), and Biggar and Hesamzadeh (2014).

³ For a review of the viability of demand response of electricity customers, see Spees and Lave (2007).



Transmission and distribution investments in Europe and the U.S. are almost exclusively economically regulated and not market-based. The assumption underpinning this is that the transportation of electricity and natural gas for a given region is most efficiently performed by a single entity, namely an economically regulated network monopoly subject to public utility regulation. Such a system's regulator requires the regulated entity to serve all customers based on a tariff, the costs of which the regulator determines and approves (Posner, 1978). The NZESO with an independent energy system operator (IESO) or a transmission energy system operator (TESO) extends this assumption by having a single electricity, gas, and heat systems operator.

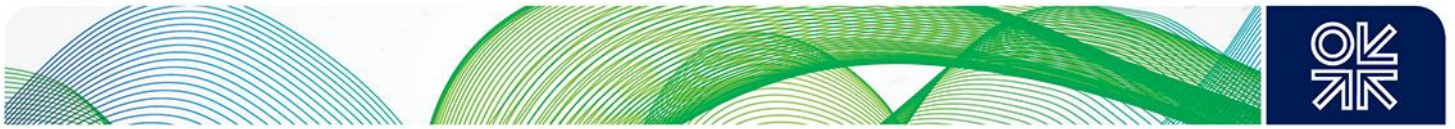
Efficiently reconciling these two investment regimes – regulatory and markets – has been a fundamental challenge within the electricity sector and will continue to be so for the net-zero energy (NZE) transition to succeed.⁴ The electric transmission and distribution systems need to be significantly expanded to accommodate dispersed renewable resources and additional demand from increased electrification (European Union, 2023; U.S. Department of Energy, 2023; Clean Air Task Force, 2024; Centre on Regulation in Europe, 2024; de Lima et al., 2024). The motivations for expanding distribution systems are to address load growth and increase the installation of distribution-level generation, such as solar PV and energy storage (Centre on Regulation in Europe, 2024; de Lima et al., 2024). The ongoing falling costs of distributed energy resources (DERs), and the introduction of policies to encourage their installation are resulting in electric utilities conducting integrated distribution planning (U.S. Federal Energy Regulatory Commission, 2020; Berkeley Lab, 2025). Integrated electricity distribution planning applies a generation and transmission framework similar to integrated resource planning but for the distribution system, using DERs and distribution assets. Furthermore, the question of how to accommodate DERs into electricity markets is also important (U.S. Department of Energy, 2024a; Gerard, Puente and Six, 2018).

The corresponding electricity, gas, and heat transportation infrastructure is likely to be substantially different from its present form. In contrast to an expanding electricity transmission and distribution system, major parts of a natural gas system may shrink while being converted to a system that can ship net zero-emission gases, such as hydrogen and ammonia, as well as steam, heat, and carbon dioxide emissions for storage (Center on Global Energy Policy, 2021; Frontier Economics, 2024; Metaxas, 2024; Saad et al., 2025). The expansion of the electricity system and the gas system conversion need to be tightly coordinated to be efficient and secure (Von Wald et al., 2022). This includes coordinated transportation and delivery expansion policies, which should be designed in anticipation of transitioning to multiple energy system sources and carriers. The fundamental question bedevilling the electric power sector of how to efficiently achieve the broader coordination of market-based investments and economically regulated ones is also pressing for NZES.

2.4 Governance of Net-Zero Energy Systems

The existing governance of ISOs/RTOs and TSOs provides some insights into the need, scope, and approach to the governance of ESOs, whether IESOs or TESO (Anaya and Pollitt, 2017). There are competing models of governance and incentive design. A transactional economics perspective underscores the need for the governance of power systems, given their fundamental structure (Felder, 2002). Incentive design, in contrast, uses economic and financial mechanisms to induce stakeholders to maximize social welfare. The term 'layered governance' is used to include stakeholder governance and consultation, regulatory policy, and the broader public policy. The term 'stakeholder governance and consultation' refers to the processes regulators initially use to govern ISOs/RTOs and TSOs. 'Stakeholder governance' refers to formal governance structures where stakeholders have explicit powers to govern, such as in the U.S. ISOs/RTOs, and 'consultation' refers to regulators obtaining formal input from stakeholders but limited to informational purposes.

⁴ For a collection of papers on transmission investment in liberalized electricity markets, see Hesamzadeh, Rosellón, and Vogelsang (2020).



Presently, ISOs/RTOs and TSOs are subject to both governance and incentive-based approaches. Governance consists of multiple tiers, including stakeholder governance and consultation, regulatory oversight, and the political process. These tiers manage the competing incentives among market participants, aiming to avoid the system operator principal-agent problem (Felder, 2012). The behavior of the system operator is determined in part by whether it owns transmission and the type of economic regulation it is subject to, such as cost-based regulation or incentive regulation (Strbac et al., 2014). The competing incentives of utilities and other stakeholders are also managed, alongside those of market participants, ideally to achieve energy security, economic, and environmental objectives at the lowest cost.

The combined market-economic regulatory strategy is twofold. The first focuses on setting up market and regulatory rules that align the incentives of the various energy system entities to achieve social efficiency (Hogan, 2002a). This necessitates having sufficiently competitive energy commodity markets such that the cost of fixing market imperfections exceeds the inefficiencies caused by these imperfections (that is to say, they are *workably competitive*).

The second part of the strategy focuses on the governance of the ISOs/RTOs and TSOs. Stakeholder governance can be used as a tool to aid the regulator, that is, the stakeholders perform some of the functions that a regulator would otherwise undertake in lieu of any stakeholder governance. Stakeholder governance aids in addressing the principal-agent problem, and furthering buy-in by stakeholders helps avoid regulatory and legal challenges. Stakeholder governance without regulatory oversight, however, is insufficient because stakeholders are self-interested and undertake their governance roles to further their own objectives.

A major governance problem for existing ISOs/RTOs and TSOs is the planning of competing generation resources and their interconnection to the transmission and distribution grid. This problem is challenging, given that every new interconnection can adversely impact the ability of existing and planned generation to deliver electricity. Furthermore, there is also a longer planning horizon for major transmission compared with generation, different incentives for merchant and regulated network providers, various distributed effects on participants of transmission versus generation investments, and divergent cost allocation approaches (Chao and Wilson, 2020).

The principal-agent problem regarding the need and size of proposed expansions has resulted in both over- and under-investment by transmission utilities (Athawale and Felder, 2023; FERC 2024a; Complainants, (2024)). Furthermore, there are long-term uncertainties in transmission and distribution planning (for instance, load growth, renewable deployment, technological advances, and the impacts of climate change on the electric system). Identifying, quantifying, and analyzing the benefits of transmission and distribution investments are challenging and has contributed to transmission under investment (FERC 2024b; Mavroeidis, 2015). Expanding transmission and distribution also raises equity and social justice priorities, which are at the nascent stage of being considered and modeled within the planning framework. As mentioned above, there is a need to integrate power generation markets with transmission and distribution regulation.

Unlike the implementation of RTOs/ISOs and TSOs, where the electricity transmission and distribution systems were already in place, the establishment of an ESO, whether an IESO or a TESO, requires a fundamental expansion of the electricity system and a likely shrinkage and reconstitution of the natural gas system for it to become net zero. Thus, it is necessary to delve into the proposals aimed at facilitating large energy transportation investments.

The proposals and policies aimed at reconfiguring the transmission system to enable it to achieve net-zero energy goals start with improving the planning process (Joskow, 2021). Examples of this include Federal Energy Regulatory Commission (FERC) Order 1920, which implemented a series of reforms, including identifying and expanding the list of transmission benefits that should be considered, conducting a scenario analysis that captures the value of transmission, for example under extreme weather conditions, requiring the consideration of grid enhancing technologies and not just new transmission lines, and the improved facilitation of stakeholder input, including U.S. states, in the planning process (FERC 2024b; Complainants, (2024)).



Another proposal is anticipatory transmission planning, which aims to address the coordination challenge between generation investment and transmission investment (Groppi and Fumagalli, 2014). Given that transmission planning usually takes much longer than generation planning and that the locations of grid-scale renewables are well-known, the thought is that the transmission system can be expanded to those likely locations in anticipation of the development of renewable resources.

Cost allocation proposals are also considered fundamental to expanding the transmission system. Some find that 'beneficiary pays' is the only cost allocation method that avoids free ridership (Macey and Mays, 2024; Rotger and Felder, 2001). Others argue that transmission costs should be socialized to reduce the rate impact on individual stakeholders. This should help in gaining broad support because the financial burden is spread across all constituents, remedying the fact that many of the benefits of transmission expansion are experienced regionally and inter-regionally. Seams issues between RTOs/ISOs and TSOs reduce the benefits of transmission because, if the transactions are uneconomic, the value of the interconnections is negative (Simeone and Rose, 2024). Barriers to transmission expansion include a lack of coordination of transactions and a lack of resource adequacy sharing.

Additional barriers to transmission expansion include differing regional political objectives, stakeholder agreement, diverse organizational arrangements, cost allocation, cost determination, and local opposition for multiple reasons (Joskow, 2021). Although the governance of an NZES is not sufficiently broad enough to address these issues directly, it nonetheless needs to be responsive to them. Consumer protections are also important. They include market power, market manipulation, and fraud at the wholesale and retail levels (Felder, 2024a).

This literature review of the development of NZES, informed by the pursuit of net-zero emission policies by electricity markets with an ESO, highlights several points. First, although the objective function of the NZES is to maximize social welfare, this policy objective is pursued within a broader policy framework of energy security, and economic and environmental objectives. Second, the need for an ESO to efficiently manage economic dispatch and congestion also supports the need for a central NZES operator (NZESO), given the existing and future interdependencies of the electricity, natural gas, and heating systems. Third, efficiently integrating a market-based production system with an economically regulated network system is a major challenge for NZES. Fourth, a broad and layered governance system is needed to manage a range of problems that cannot be completely addressed through incentive mechanisms for market participants, system operators, and utilities.

Based upon the above literature review, the next section describes and analyzes the physical, market, and governance architecture of the NZES that serves as the basis for the findings discussed in the final section.

3. Architecture and Description of the Market and Regulatory Structure of the Net-Zero Energy System

After describing RTOs/ISOs and TSOs, this section depicts the basic architecture of the NZESO and several important variations. The premise is that a single regional NZESO that includes net-zero electric, gas, heat, and transportation is more efficient than alternative structures that do not combine all these functions. There are two reasons for this premise. First, the non-linear electricity flows depend on conditions and constraints throughout the system, making electricity system decentralized operation inefficient (Hogan, 2002b; Mansur and White, 2007). Similarly, the close coupling of electric and gas operations due to the interconnections of both systems supports integrated operations and planning (Peng and Poudineh, 2016; Guerra et al., 2021; Farrokhifar et al., 2020; Schwele et al., 2020; Li et al., 2023).

3.1 Existing Transmission System Operator and Regional Transmission Operator/Independent System Operator Architecture

The starting point for the analysis is two existing electricity models, the European TSO model and the U.S. RTO/ISO model (Pollitt, 2012). Both models structurally separate generation investment and



ownership from the system operator. The TSO model combines system operations with transmission ownership, whereas the RTO/ISO model separates the system operator from the transmission owner. RTOs/ISOs are non-profit utilities whose cost-based budget is approved by their regulators with input from their stakeholders. In contrast, TSOs are generally for-profit utilities regulated by national authorities. Table 3 summarizes these two structures, with the caveat that any such summary omits important exceptions and nuances.

Table 3: Summary of existing TSO and RTO/ISO architectures

Function	European electricity market and regulatory structure	U.S. RTO/ISO structure
<u>Objectives</u>		
Overall objective	Promote European Union climate and renewable integration policy via the European Network of Transmission System Operators for Electricity (ENTSO-E)	Achieve just and reasonable wholesale electricity rates via wholesale markets that maximize social welfare, but in practice, the focus is to minimize costs
<u>Electricity technologies</u>		
Fossil fuel generation	Market and regulatory structure designed around dominance of fossil fuel generation	Market and regulatory structure designed around dominance of fossil fuel generation
Net-zero technologies	Market and regulatory structure modified over time to accommodate increasing shares of net-zero technologies	Market and regulatory structure modified over time to accommodate increasing shares of net-zero technologies
Grid Enhancing Technologies (GETs)	Focus on traditional transmission, although accommodating GETs	Focuses on traditional transmission, although accommodating GETs
Distributed Energy Resources (DERs)	Focuses on grid-scale generation, although accommodating DERs	Focuses on grid-scale generation, although accommodating DERs
<u>Market and network regulation</u>		
Generation ownership	Separate from TSO	Separate from RTO/ISO
Transmission ownership	Owned and operated by TSO	Separate from RTO/ISO, although subject to RTO/ISO requirements, such as scheduling planned outages and operations
Distribution ownership	Separate from TSO	Separate from RTO/ISO
Fuels	Electricity only in most cases, but multiple fuels are used for the UK's National Energy System Operator	Electricity only
Wholesale electricity market	Forecasting, balancing markets, congestion management, and reserve capacity markets run by nominated electricity market operators (NEMOs)	Forecasting, economic dispatch, unit commitment, auctions for transmission congestion contracts, financial settlements, credit policy, market monitoring and mitigation



Function	European electricity market and regulatory structure	U.S. RTO/ISO structure
System operations	TSO based on portfolios of offers, load serving entities' bids, and transition system status	RTO/ISO based on generation unit offers, load serving entities' bids, and transmission system status
Products	Energy, capacity, ancillary services, and transmission congestion contracts	Energy, capacity, ancillary services, and transmission congestion contracts
Generation interconnection policies	Administers the interconnection process	Administers the interconnection process
Market monitoring and market power	TSO and regulators perform these functions	Independent market monitoring and mitigation
Transmission planning – local	Utilities conduct local transmission planning	Limited role of RTOs/ISOs in local transmission planning
Transmission planning - regional	TSOs conduct transmission planning	Conducts regional transmission planning and participates in inter-regional transmission planning
Reliability	NEMOs	Rules developed by the North American Electric Reliability Organization (NERC) and approved in the U.S. by the Federal Energy Regulatory Commission (FERC)
Retail electricity market	No explicit role, but can accommodate countries that have retail electricity markets	No explicit role, but can accommodate states that have retail electricity markets
<u>Governance</u>		
Governance	Formal stakeholder consultations	Formal stakeholder input and governance
Network regulation	Sector regulated by European and national electricity codes with cost-of-service or incentive-based transmission rates	RTOs/ISOs regulated by FERC tariff (except for the Electricity Reliability Council of Texas [ERCOT]) with cost-of-service transmission rates

There are many variations within and among the RTO/ISO and TSO models (Rious et al., 2008; Imran and Kockar, 2014). The fundamental reason for these variations is that policymakers have different views regarding competing design choices (Imran and Kockar, 2014). These differences could be due to differing technical assessments, practical considerations, or valuations of the associated tradeoffs. The basis for the general claim that all these variations can be addressed within an NZESO framework is that underlying an efficient RTO/ISO and TSO is a set of technical optimization problems (examples being economic dispatch, unit commitment, transmission congestion contract [TCC] revenue maximization, and optimal transmission planning). The discussion below illustrates how some of these variations can be extended to the NZESO models. There are also a set of governance and economic regulatory issues (like the principal-agent problem, transaction cost economics) similar to those of an NZESO that must be addressed.

The optimization problems may not explicitly account for the governance-regulatory-policy context but are nonetheless affected by it. For instance, economic dispatch and unit commitment performed by



RTOs/ISOs do not have explicit constraints in their formulation that restrict generation ownership. Their inputs, however, reflect the regulatory policy that limits generation ownership through mergers and the approval of market-based rates (Helman, 2006). The explicit optimization problems occur within the broader governance-regulatory-policy context of RTOs/ISOs, summarized in Table 4.

Table 4: The governance-regulatory-policy context that affects the optimization of electricity markets and transmission in RTOs/ISOs

Governance-regulatory-policy context
<ul style="list-style-type: none"> • Role of stakeholders in RTO/ISO and TSO decision making • Regulatory and legislative policy
Explicit optimization problems
<ul style="list-style-type: none"> • Economic dispatch/generation portfolio optimization • Unit commitment • Transmission congestion contact revenue maximization • Transmission planning

There are many examples of existing design variations in RTOs/ISOs and TSOs. For instance, the RTO/ISO for almost all of Texas, ERCOT, does not have capacity markets and instead implements an operating reserve curve (Zarnikau et al., 2020).⁵ Furthermore, there are multiple transmission planning and interconnection policies that TSOs and RTOs/ISOs can select. These include options across the spectrum from planning new transmission on the basis of existing generation to anticipatory planning policies, from ‘check and connect’ to ‘connect and manage,’ local to interregional planning, and transmission to non-transmission alternatives. Another variation is in how congestion is managed, using either locational marginal pricing or zonal pricing. All RTOs/ISOs use locational marginal pricing except for the New York ISO (NYISO), which started with some form of zonal pricing. European TSOs use zonal pricing. Another problem is how to economically regulate the TSOs, RTOs/ISOs, and utilities. The alternatives span from cost-of-service regulation to incentive-based regulation. Table 5 summarizes some of the major variations of the TSO and RTO/ISO models.

Table 5: Summary of some major design variations of the TSO and RTO/ISO models

Function	Variations
Congestion pricing	Nodal vs. zonal
Resource adequacy	Capacity remuneration mechanism (Bublitz et al., 2019) vs. energy-only market
RTO/ISO/TSO regulation	Cost-of-service with or without performance vs. incentive-based
Generation interconnection	First-come, first-served queue
Transmission planning	Anticipatory planning
Internalizing the social cost of carbon	Greenhouse gas (GHG) tax, GHG cap and trade, renewable portfolio standards, tax credits, and subsidies

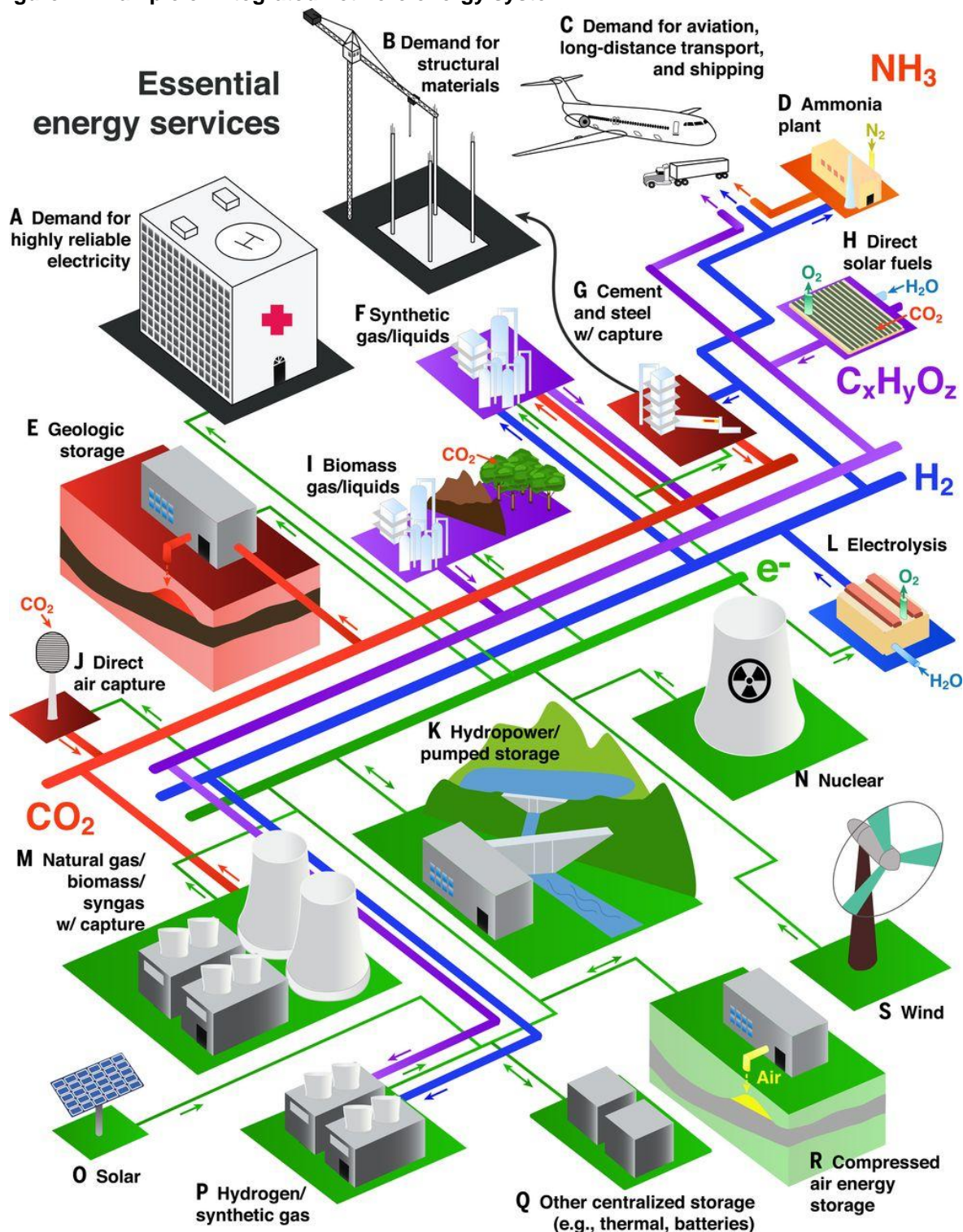
3.2 Extending the TSO and RTO/ISO Models to the Energy System Operator

This section describes how system operator models, and their significant variations can be extended to include NZE transportation and delivery systems. The focus is on RTOs/ISOs, but analogous extensions apply to TSOs. Figure 1 illustrates the physical components and connections of such a system, focusing on the production of energy carriers and carbon dioxide flows. Figure 1 shows the production of these

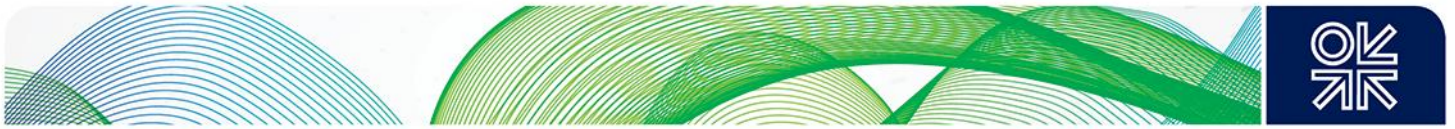
⁵ Since the large-scale blackout in ERCOT in February 2021, Texas has been exploring and implementing additional measures to ensure resource adequacy beyond its operating reserve demand curve.

energy carriers from multiple energy sources through transportation and delivery. It does not, however, include steam and water and does not illustrate the meshed network of the combined system with multiple injection points, transportation and delivery paths, and withdrawal points.

Figure 1: Example of integrated net-zero energy system



Source: Davis et al., 2018



The major players in the NZES are energy producers, energy storage owners and operators, the ESO, electric and gas transmission and distribution utilities, energy service companies (ESCOs), energy consumers, and energy regulators. The market-based participants, including the TESO, are maximizing profits subject to their technological constraints, the joint constraints of the NZES, and the regulations applicable to them. The regulated IESO maximizes the management's utility (say, compensation, prestige, and level of effort) subject to its budget and regulatory mandates. Industrial and commercial energy buyers make energy purchases as part of their profit maximization, and residential buyers do so as part of their utility maximization.

The following subsections generalize the electricity locational marginal pricing model to a four-carrier (electricity, net-zero gas, steam, and hot water) energy system. This generalization assumes that such a system can be modeled with sufficient accuracy by a tractable convex optimization model that maximizes social welfare, with its dual yielding a set of four prices at each node on the system every five minutes. System nodes that can only provide some of the four energy carriers' prices have, in effect, infinite prices for the energy carriers that are not available at those nodes. This assumption regarding model accuracy is one of two fundamental premises for adopting a hybrid market-regulatory structure for a multi-carrier, net-zero energy system (Leslie and Billimoria, 2025). The other assumption is that a hybrid structure using a combination of optimization and oversight is more efficient than a centralized regulatory one or a decentralized market-regulatory structure.

The development of a market-regulatory NZES can both identify and characterize the key tradeoffs among alternatives. The tradeoff dimensions are the following: First, there is a tradeoff between economic regulation and the hybrid model (regulation versus markets). Second, there is a tradeoff among types of economic regulation (cost of service versus incentive-based versus regulation versus performance-based regulation). Third, a tradeoff exists between centralization and decentralization (a single multi-carrier system versus multiple single-carrier systems). The following discussion focuses on extending the U.S. RTO/ISO model to a liberalized NZES.

3.2.1 Energy Markets

The extension of locational marginal and zonal pricing for IESOs and TESOs is straightforward. Based upon an assumed tractable and well-behaved mathematical model, each of the four energy carriers has unit prices for each location (for example, the node or zone) that vary every five minutes in the real-time market, and every hour in the day-ahead market. These prices reflect the marginal cost of producing one more unit of each energy source at that location or zone. These prices are a generalized economic dispatch of the system that satisfies the demand up to the value of lost load (VOLL) for each carrier at each location. The real-time prices can be defined as either *ex-ante* or *ex-post* (Zheng and Litvinov, 2010). At each energy carrier source and sink, there would be a vector of four prices (in many cases, some of the elements of these vectors would be infinite, reflecting the impossibility of producing or consuming one or more energy carriers at that location). In a zonal model, collections of nodes, referred to as hubs, could be defined in which the hub price is the average of the nodal prices. In a zonal model, sets of these locations would be grouped together to determine the zonal price.

The 24-hour day-ahead market is based on unit commitment. Presently, its premise is the start-up time of thermal generators, which is mostly less than 24 hours, and the shapes of the daily electricity load. With the expansion of renewable resources that do not have start-up times because they are not heating up water to produce steam and energy storage, the periodicity of the day-ahead market may change to improve market performance, and there may be a need to have multiple unit commitment markets.

RTOs/ISOs do not limit themselves to conducting unit commitments only once every 24 hours (Nicholson, 2014). Instead, they may perform additional unit commitments in response to generation and transmission contingencies. Similar situations may arise with the combined hybrid system, and these additional unit commitments will be integrated into the process of real-time dispatch. Bilateral contracts of various types can be agreed upon among willing parties based on expected real-time and day-ahead energy prices, and these can be settled financially either between the negotiating parties or using the IESO's settlement system.



This nodal or zonal multi-carrier pricing structure (real-time market and day-ahead hour) supports many policies advancing the energy transition. Pricing greenhouse gases directly or via a cap-and-trade program would be internalized in the prices of the various energy carriers and, therefore, the relevant optimization problems of the market participants and the IESO. Other transition policies, such as renewable portfolio standards and tax incentives, also work. Unlike pricing greenhouse gases, these policies result in revenue streams for some of the market participants that are not internal to the NZES, leading to price suppression (Felder, 2011).

3.2.2 Reliability, Resiliency, Resource Adequacy, and Capacity Markets

Electricity and gas systems currently have reliability and resiliency requirements, and the NZESO would need to integrate these policies into a coherent system. This section describes how this can be done.

Typically, the reliability of the wholesale electricity system is divided into resource adequacy and security.⁶ The amount of resource adequacy is determined using a resource adequacy model that satisfies a loss-of-load-probability (LOLP) or an unserved energy standard (Felder, 2024b). For an NZES that chooses to have a capacity requirement, this resource adequacy framework for the single energy carrier, electricity, can be extended to the other energy carriers. A straightforward extension is for each energy carrier to have an LOLP or unserved energy standard and a resource adequacy model that assesses the need for reserves to satisfy this standard. In the case of natural gas, some jurisdictions already use a planning standard that sets the amount of gas that local distribution companies must purchase, typically based on a design day (Goldman et al., 1993). As the NZES becomes increasingly integrated, it may make sense to have an integrated LOLP standard and resource adequacy model for the entire system. The other prong of reliability is the electricity system's ability to withstand the failure of any single component or the N-1 criterion. This criterion can be extended to each of the energy carriers so that the NZES is planned and operated to satisfy this requirement (Niu et al., 2025).

Policymakers are increasingly concerned about resiliency, which considers the system's ability to withstand and respond to severe events (Felder and Petit, 2022), and resiliency policies could be applied to the NZES. Common-cause failures, also referred to as correlated failures, are the failure modes that lead to prolonged electricity outages and, by extension, energy outages (Felder, 2001). Including resiliency and having an integrated NZES increases the importance of identifying and quantifying common-cause failure increases.

3.2.3 Ancillary Services

The provision of ancillary services that support the NZES starts with the typical existing services for the electricity system, namely operating reserves (10-minute spinning, 10-minute non-spinning, and 30-minute), black start (ability to restart generation units without using electricity from the grid during a blackout), and automatic generation control. Similar ancillary services may be necessary for the non-electricity carriers. For each ancillary service, a determination would be made as to whether it should be provided via markets, as is done with operating reserves and automatic generation control, or through a regulated mechanism. As the NZES develops, there may be a need to define new ancillary services or redefine existing ones. For example, repressurizing the gas system is a challenge, and there may be a need for the equivalent of a black start for the gas system.

4. Conclusions, Policy Implications, and Further Research

Based on a literature review and extending the analysis of electricity markets to NZES, there are three primary findings. First, a whole-systems approach that covers electricity and multiple other energy sources such as natural gas, hydrogen, carbon dioxide-derived fuels (e.g., methane or methanol), and

⁶ Security refers to the ability of the electric power system to continue to operate without disconnecting firm electricity load due to the failure of generation or transmission components (Billimoria, Mancarella, and Poudineh, 2020).

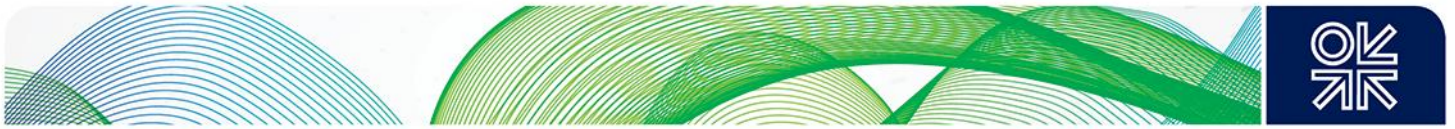


heat networks is necessary to achieve net-zero objectives efficiently. As the energy landscape becomes increasingly interconnected, addressing issues in the electricity grid often requires a broader perspective that includes other energy sources, carriers, technologies, and sectors. The objective of an NZESO should be to maximize social welfare to be as efficient as possible so that other and more important societal objectives, such as equity and environmental justice, can be pursued. Two important areas in which these broader societal objectives can be addressed are retail energy access and pricing, and the siting of energy facilities.

Second, a centrally optimized, liberalized energy market with a regulated network is a useful conceptual model and, potentially, a viable market-regulatory construct. Such centralized net-zero energy systems may improve efficiency and reliability through the joint optimization of electricity, net-zero gas, and heating operations and planning, while accommodating regional policy and governance preferences.

Third, the success of an NZESO depends on its ability to extend existing market and regulatory practices and develop new ones to satisfy the multiple policy objectives of net-zero energy systems, accommodate emerging net-zero energy technologies, successfully optimize markets with multiple energy products, efficiently regulate markets and network investment, and implement effective governance. Existing market-based electricity systems in Europe and the U.S. provide the starting point for transitioning to a net-zero energy system and inform the design choices needed to enable it. There are many important design choices for the NZESO, including whether the system operator owns the network (IESO versus TESO), whether to have a capacity market, and the strategy for network investment. Many of these design choices have already been made by existing ISOs and TSOs, based upon national and regional considerations, and can therefore be extended to the centralized NZESO.

By elaborating on the design of the NZES, this paper identifies three key assumptions necessary for it to be efficient. First, meaningful demand response by energy loads is necessary to achieve the objective of social welfare maximization, and not just cost minimization. Adopting cost-reflective tariffs and enhancing the price responsiveness of electricity, net-zero gases, and heating consumers improves the efficiency of the NZESO. Second, the optimization model used by the NZESO to calculate energy prices needs to accurately approximate the physical system. Third, the governance of the network utility and the system operator must minimize the exercise of market power by market participants and the principal-agent problem of the utility and system operator regarding system operation and network investment.



Abbreviations

DER – Distributed energy resources

IESO – Independent energy system operator

NZE – Net-zero energy

NZES – Net-zero energy system

NZESO – Net-zero energy system operator, referring collectively to IESO and TESO

RTO/ISO – Regional transmission operator/independent system operator

TESO – Transportation energy system operator

TSO – Transmission system operator



References

- Aghaei, J., Nikoobakht, A., Mardaneh, M., Shafie-Khah, M., and Catalã, J. P. (2018). 'Transmission switching, demand response and energy storage systems in an innovative integrated scheme for managing the uncertainty of wind power generation', *International Journal of Electrical Power and Energy Systems*, 98, 72-84.
- Ahlqvist, V., Holmberg, P., and Tangerås, T. (2022). 'A survey comparing centralized and decentralized electricity markets', *Energy Strategy Reviews*, 40, p.100812.
- Anaya, K., and Pollitt, M. (2017). 'Regulating the electricity system operator: Lessons for Great Britain from around the world', Working Papers EPRG 1718, Energy Policy Research Group, Cambridge Judge Business School, University of Cambridge, <https://www.repository.cam.ac.uk/items/f5fa942f-067d-4d75-a38e-cd2c24b2d504>.
- Athawale, R., and Felder, F. A. (2023). 'Overbuilding transmission: A case study and policy analysis of the Indian power sector', *Energy Policy*, 174, p.113437
- Berkeley Lab. (2024). '2024 United States Data Center Energy Usage Report', December, LBNL-2001637, <https://eta-publications.lbl.gov/sites/default/files/2024-12/lbnl-2024-united-states-data-center-energy-usage-report.pdf>.
- Berkeley Lab. (2025). 'Integrated Distribution System Planning', <https://emp.lbl.gov/projects/integrated-distribution-system-planning>.
- Biggar, D. R., and Hesamzadeh, M. R. (2014). *The economics of electricity markets*, West Sussex: John Wiley and Sons.
- Billimoria, F., Mancarella, P., and Poudineh, R. (2020). 'Market design for system security in low-carbon electricity grids: from the physics to the economics' (No. 41), OIES Paper, <https://www.oxfordenergy.org/publications/market-design-for-system-security-in-low-carbon-electricity-grids-from-the-physics-to-the-economics/>.
- Bublitz, A., Keles, D., Zimmermann, F., Fraunholz, C., and Fichtner, W. (2019). 'A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms', *Energy Economics*, 80, 1059-1078.
- Center on Global Energy Policy (2021). 'Investing in the U.S. Natural Gas Pipeline System to Support Net-Zero Targets', April, CGEP Report, <https://www.energypolicy.columbia.edu/publications/investing-us-natural-gas-pipeline-system-support-net-zero-targets/>.
- Centre on Regulation in Europe (2024). 'A Balanced Path to a Net Zero Future: Expansion, Flexibility, Integration and Innovation', October, CERRE Report, <https://cerre.eu/publications/a-balanced-path-to-a-net-zero-future-expansion-flexibility-integration-and-innovation/>.
- Chao, H. P., and Wilson, R. (2020). 'Coordination of electricity transmission and generation investments', *Energy Economics*, 86, p.104623.
- Chyong, K. (2025). 'Decarbonization in Europe: Modelling Economic Feasibility and the Glidepath for Gas'. OIES Paper: NG 197.
- Clean Air Task Force (2024). 'A Vision for the EU Net-Zero Transition', April, CATF Report, <https://www.catf.us/resource/a-vision-for-the-eu-net-zero-transition/>.
- Complainants. (2024). Complaint of Consumers for Independent Regional Transmission Planning for All FERC-Jurisdictional Transmission Facilities at 100kV and Above, 19 December.
- Creti, A., and Fontini, F. (2019). *Economics of electricity: Markets, competition and rules*. Cambridge University Press.
- Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C.



B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., Ingersoll, E., Jaramillo, P., Lackner, K. S., Mach, K. J., Mastrandrea, M., Ogden, J., Peterson, P. F., Sanchez, D. L., Sperling, D., Stagner, J., Trancik, J. E., Yang, C.-J., and Caldeira, K. (2018). 'Net-zero emissions energy systems', *Science*, 360(6396)..

de Lima, T. D., Lezama, F., Soares, J., Franco, J. F., and Vale, Z. (2024). 'Modern distribution system expansion planning considering new market designs: Review and future directions', *Renewable and Sustainable Energy Reviews*, 202, p.114709.

DeAngelo, J., Azevedo, I., Bistline, J., Clarke, L., Luderer, G., Byers, E., and Davis, S. J. (2021). 'Energy systems in scenarios at net-zero CO₂ emissions', *Nature Communications*, 12(1), 6096.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., and Wetzler, T. (2022). 'The meaning of net zero and how to get it right', *Nature Climate Change*, 12(1), 15-21.

Clarke, L., Wei, Y. M., de la Vega Navarro, A., Garg, A., Hahmann, A. N., Khennas, S., Lima de Azevedo, I. M., Löschel, A., Singh, A. K., Steg, L., Strbac, G., and Wada, K. (2022). 'Energy systems', in *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report*, Cambridge University Press, 613-746.

European Union (2023). 'Commission sets out actions to accelerate the roll-out of electricity grids', 27 November, Press Release, https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_6044/IP_23_6044_EN.pdf.

Farrokhifar, M., Nie, Y. and Pozo, D. (2020). 'Energy systems planning: A survey on models for integrated power and natural gas networks coordination', *Applied Energy*, 262, 114567.

Federal Energy Regulatory Commission (FERC). (2024a). 'Consumers for Independent Regional Transmission Planning for All FERC-Jurisdictional Transmission Facilities at 100kV and Above.'

Federal Energy Regulatory Commission (FERC). (2024b). 'FERC Order 1920: Building for the Future Through Electric Regional Transmission Planning and Cost Allocation', 13 May.

Felder, F. A. (2001). "An Island of Technicality in a Sea of Discretion": A Critique of Existing Electric Power Systems Reliability Analysis and Policy', *The Electricity Journal*, 14(3), 21-31.

Felder, F. A. (2002). 'The need for governance of restructured electric power systems and some policy implications', *The Electricity Journal*, 15(1), 36-43.

Felder, F. A. (2011). 'Examining electricity price suppression due to renewable resources and other grid investments', *The Electricity Journal*, 24(4), 34-46.

Felder, F. A. (2012). 'Watching the ISO watchman', *The Electricity Journal*, 25(10), 24-37.

Felder, F. A. (2014). 'Climate change mitigation and the global energy system', *Villanova Environmental Law Journal*, 25, 89.

Felder, F. A. (2020). 'Market versus planning approaches to transmission and distribution investment', *Transmission Network Investment in Liberalized Power Markets*, 257-274.

Felder, F. A. (2024a). 'Distributed Energy Resources Participation in Wholesale Markets', Docket No. L-2023-3044115.

Felder, F. A. (2024b). 'The challenges of incorporating consumer reliability preferences into electricity markets with a capacity requirement', OIES Paper EL54, May, <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/05/EL54-The-Challenges-of-Incorporating-Consumer-Reliability-Preferences-FF.pdf>.

Felder, F. A., and Athawale, R. (2014). 'The life and death of the utility death spiral', *The Electricity Journal*, 27(6), 9-16.

Felder, F. A., and Petitet, M. (2022). 'Extending the reliability framework for electric power systems to include resiliency and adaptability', *The Electricity Journal*, 35(8), 107186.



Frontier Economics (2024). 'Ensuring Resilience in the European Energy Transition: Strategic Use of Gases to Meet EU Climate Ambitions', November, <https://www.frontier-economics.com/media/1tpnnbsm/frontier-economics-ensuring-resilience-in-the-european-energy-transition.pdf>.

FTI Consulting. (2025). 'A roadmap for cost-reflective electricity network tariffs in the EU', March, https://smarten.eu/wp-content/uploads/2025/03/FTI-Consulting-Report_smartEn_03-2025_DIGITAL_V2.pdf.

Gerard, H., Puente, E. I. R., and Six, D. (2018). 'Coordination between transmission and distribution system operators in the electricity sector: A conceptual framework', *Utilities Policy*, 50, 40-48.

Goldman, C., Comnes, A., Busch, J., and Wiel, S. (1993). 'Primer on Gas Integrated Resource Planning', <https://emp.lbl.gov/publications/primer-gas-integrated-resource>.

Groppi, A., and Fumagalli, E. (2014). 'Network expansion by a proactive transmission system operator: A case study', *Energy Policy*, 69, 610-623.

Guerra, O. J., Sergi, B., Craig, M., Pambour, K. A., Brancucci, C. and Hodge, B. M. (2021). 'Coordinated operation of electricity and natural gas systems from day-ahead to real-time markets', *Journal of Cleaner Production*, 281, 124759.

Helman, U. (2006). 'Market power monitoring and mitigation in the U.S. wholesale power markets', *Energy*, 31(6-7), 877-904.

Hesamzadeh, M. R., Rosellón, J., and Vogelsang, I. (Eds.). (2020). *Transmission network investment in liberalized power markets* (Vol. 79). Cham, Switzerland: Springer.

Hobbs, B. F., and Meier, (2012). *Energy Decisions and the Environment: A Guide to the Use of Multicriteria Methods*, Vol. 28. Springer Science and Business Media.

Hogan, W. (2002a). 'Financial transmission right formulations', Mimeo, JFK School of Government, Harvard Electricity Policy Group, Harvard University, https://www.lmpmarketdesign.com/papers/FTR_Formulations_033102.pdf.

Hogan, W. (2002b). 'Electricity Market Design and Structure: Avoiding the Separation Fallacy Comments', Report Submitted to the Federal Energy Regulatory Commission, Docket RM01-12-000, Washington, DC.

Hong, T., de León, F., and Zhu, Q. (2018). 'Optimal Dispatch of Electrical Transmission Systems Considering Interdependencies with Natural Gas Systems', *Game Theory for Security and Risk Management: From Theory to Practice*, 203-222.

Imran, K., and Kockar, I. (2014). 'A technical comparison of wholesale electricity markets in North America and Europe', *Electric Power Systems Research*, 108, 59-67.

International Energy Agency (IEA). (2024). 'Clean energy is boosting economic growth', 18 April, <https://www.iea.org/commentaries/clean-energy-is-boosting-economic-growth>.

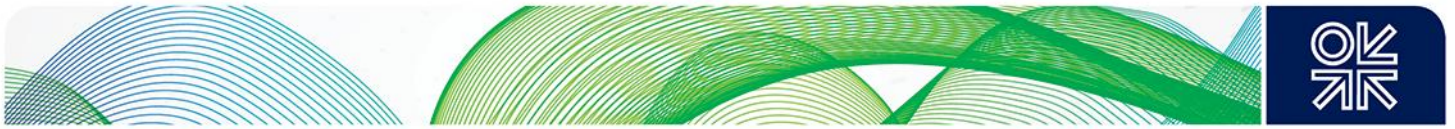
International Energy Agency (IEA). (2025). 'Electricity 2025: Analysis and forecast to 2027', <https://www.iea.org/reports/electricity-2025>.

International Renewable Energy Agency (IRENA). (2023). 'World Energy Transitions Outlook 2023', <https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023>.

Joskow, L. (2021). 'Facilitating transmission expansion to support efficient decarbonization of the electricity sector', MIT Center for Energy and Environmental Policy Research, <https://economics.mit.edu/sites/default/files/2022-09/Facilitating%20Transmission%20Expansion%20to%20Support%20Efficient%20Decarbonization%20of%20the%20Electricity%20Sector.pdf>.



- Leicher, J., Giese, A., and Wieland, C. (2024). 'Electrification or Hydrogen? The Challenge of Decarbonizing Industrial (High-Temperature) Process Heat', *J*, 7(4), 439-456.
- Leslie, G., and Billimoria, F. (2025). 'How new (and old) power system operating constraints map to Australia's wholesale electricity market model', 20 February, https://drive.google.com/file/d/1fhTC_GAX9iNQMYOzdW9b3ejq0N9rf2BY/view.
- Li, , Jiang, L., Zhang, C., Wang, J., Wang, N., Liu, H., Dou, Z., Pan, Y., Zhou, X., and Zeng, (2023). 'Coordinated planning of integrated electricity-heat-gas energy system considering renewable energy consumption', *IET Generation, Transmission and Distribution*, 17(14), 3232-3244.
- Macey, J., and Mays, J. (2024). 'The law and economics of transmission planning and cost allocation', *Energy Law Journal*, 9 November, <https://www.eba-net.org/wp-content/uploads/2024/11/7-Macey-Mays209-249.pdf>.
- Mansur, E. T., and White, M. W. (2007). 'Market organization and market efficiency in electricity markets', <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ae760108abdde08037f7708b66a6ba00b50def9c>.
- Mavroeidis, N. (2015). 'Transmission Expansion Planning Under Uncertainty', Delft University of Technology, MSc Thesis, https://repository.tudelft.nl/file/File_001fda3e-65b7-4e16-9fce-58d1e4bfd5bc?preview=1.
- Metaxas, A. (2024). 'On the way to EU's clean energy transition: new approaches and challenges for Gas Regulation in the EU', *The Journal of World Energy Law and Business*, 17(1), 69-86.
- Nicholson, E. (2014). 'Operator-initiated commitments in RTO and ISO markets', FERC, Washington DC. Re Docket No. AD14-14-000.
- Niu, L., Zhao, Z., Tan, J., Liang, T., Zhang, F., Xiao, N., He, Y., Xie, S., Jing, R., Lin, J., Wang, F., and Zhao, Y. (2025). 'A dynamic reliability assessment framework for integrated energy systems: A new methodology to address cascading failures', *Advances in Applied Energy*, 17, 100203.
- Peng, D., and Poudineh, R. (2016). 'A holistic framework for the study of interdependence between electricity and gas sectors', *Energy Strategy Reviews*, 13, 32-52.
- Pliousis, A., Andriosopoulos, K., Doumpos, M., and Galaritis, E. (2019). 'A multicriteria assessment approach to the energy trilemma', *The Energy Journal*, 40(1_suppl), 143-166.
- Pollitt, M. G. (2012). 'Lessons from the history of independent system operators in the energy sector', *Energy Policy*, 47, 32-48.
- Posner, R. A. (1978). 'Natural monopoly and its regulation', *The Journal of Reprints for Antitrust Law and Economics*, 9, 767.
- Raheli, E., Wu, Q., Zhang, M., and Wen, C. (2021). 'Optimal coordinated operation of integrated natural gas and electric power systems: A review of modeling and solution methods', *Renewable and Sustainable Energy Reviews*, 145, 111134.
- Rious, V., Glachant, J. M., Perez, Y., and Dessante, (2008). 'The diversity of design of TSOs', *Energy Policy*, 36(9), 3323-3332.
- Rotger, J. A., and Felder, F. A. (2001). 'Reconciling market-based transmission and transmission planning', *The Electricity Journal*, 14(9), 31-43.
- Saad, D. M., Sodwatana, M., Sherwin, E. D., and Brandt, A. R. (2025). 'Energy storage in combined gas-electric energy transitions models: The case of California', *Applied Energy*, vol. 385, 125480.
- Schwele, A., Arrigo, A., Vervaeren, C., Kazempour, J. and Vallée, F. (2020). 'Coordination of electricity, heat, and natural gas systems accounting for network flexibility', *Electric Power Systems Research*, 189, 106776.



Simeone, C. E. and Rose, A. (2024). 'Barriers and Opportunities To Realize the System Value of Interregional Transmission', NREL/TP-6A40-89363, National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Spees, K., and Lave, L. B. (2007). 'Demand response and electricity market efficiency', *The Electricity Journal*, 20(3), 69-85.

Strbac, G., Pollitt, M., Konstantinidis, C. V., Konstantelos, I., Moreno, R., Newbery, D., and Green, R. (2014). 'Electricity transmission arrangements in Great Britain: Time for change?', *Energy Policy*, 73, 298-311.

Tagliapietra, S., Zachmann, G., Edenhofer, O., Glachant, J. M., Linares, , and Loeschel, A. (2019). 'The European Union energy transition: Key priorities for the next five years', *Energy Policy*, 132, 950-954.

United Kingdom Department for Energy Security and Net Zero. (2024). 'New publicly owned National Energy System Operator to pave the way to a clean energy future', 13 September.

United States (U.S.) Department of Energy (2023). 'National Transmission Needs Study', October, <https://www.gov.uk/government/news/new-publicly-owned-national-energy-system-operator-to-pave-the-way-to-a-clean-energy-future>.

United States (U.S.) Department of Energy (2024a). 'TSO-DSO-Aggregator Market and Operational Coordination Requirements', April, https://www.energy.gov/sites/default/files/2024-07/47990_DOE_OE_TDC_Project_Coordination_Platform_v9_RELEASE_508.pdf.

United States Department of Energy. (2024b). 'Sourcing Distributed Energy Resources for Distribution Grid Services', December, <https://www.energy.gov/sites/default/files/2024-12/Sourcing%20DER%20for%20Dist%20Services%20final%2012.17.24.pdf>.

United States (U.S.) Federal Energy Regulatory Commission (2020). 'Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators', 17 September.

Von Wald, G., Sundar, K., Sherwin, E., Zlotnik, A., and Brandt, A. (2022). 'Optimal gas-electric energy system decarbonization planning', *Advances in Applied Energy*, 6, 100086.

Webb, D., and Ayyub, B. M. (2017). 'Sustainability quantification and valuation. I: Definitions, metrics, and valuations for decision making', *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 3(3), E4016001.

Zarnikau, J., Zhu, S., Woo, C. K., and Tsai, C. H. (2020). 'Texas's operating reserve demand curve's generation investment incentive', *Energy Policy*, 137, 111143.

Zhao, B., Conejo, A. J., and Sioshansi, R. (2017). 'Coordinated expansion planning of natural gas and electric power systems', *IEEE Transactions on Power Systems*, 33(3), 3064-3075.

Zheng, T., and Litvinov, E. (2010). 'On ex post pricing in the real-time electricity market', *IEEE Transactions on Power Systems*, 26(1), 153-164.