HI-ACT

Hydrogen Integration for Accelerated Energy Transitions

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HI-ACT: Briefing Paper on Whole Energy Systems with a Focus on Hydrogen Integration

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1. Definition of Whole Energy Systems

A whole energy systems approach examines the interactions between energy systems (e.g. electricity, gas, heat and transport) to assess interdependencies in order to better manage and optimise energy resources across various sectors (see Figure 1). Traditionally, energy sectors operated in isolation with oil, for example, dominating the transport sector, gas primarily used for heating and electricity generation, while electricity provided energy for lighting and industry[i]. Whole energy systems thinking recognises that due to the interrelationships between energy systems, addressing complex challenges such as meeting net zero targets requires consideration of the entire energy landscape, rather than focusing on isolated systems, in order to devise lasting solutions[ii]. Adopting a whole energy systems approach will help in understanding how changes in one energy system will have implications across other systems. This will lead to the creation of a more efficient, robust and sustainable energy system that can better integrate emerging technologies in the future.

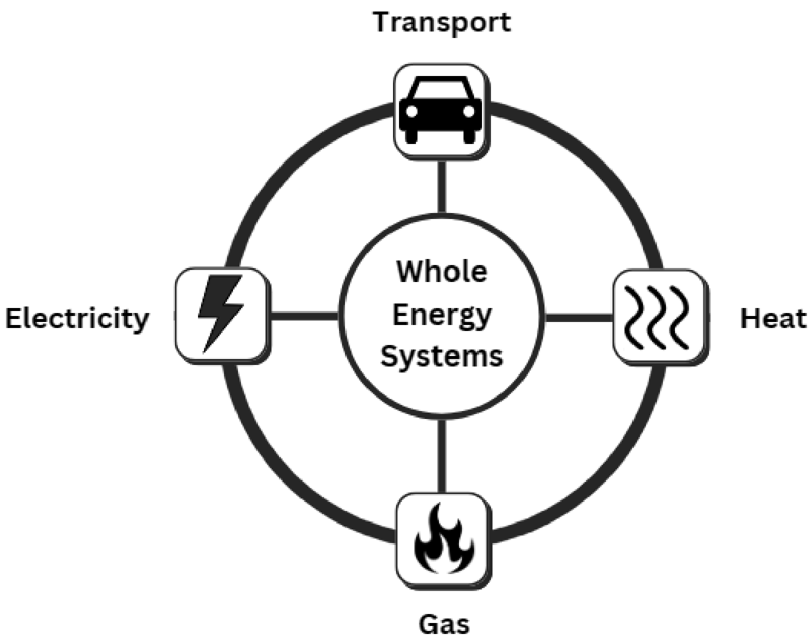

Figure 1: Whole Systems Approach to Energy

2. Methods used in Whole Energy Systems Studies

Whole Energy System studies employ various techniques, depending on the specific objectives of the study, which could incorporate technical, economic, environmental, and social dimensions. Some of the key methods used in Whole Energy Systems studies include[iii iv v vi]:

- **Modelling:** This is an essential tool which utilises computers to generate models in order to simulate and analyse the complex interactions within the whole energy system. Optimisation models are often employed in energy system studies, primarily to determine the most efficient configuration for whole energy systems which satisfy pre-defined objectives.
- **Techno-Economic Assessment** This technique evaluates the technical and economic feasibility of integrating energy technologies by analysing both technical and financial data.
- **Life Cycle Assessment (LCA):** This is an environmental impact assessment tool for energy systems throughout all stages of their life cycle, from the extraction of raw material to recycling or final disposal.
- **Scenario Analysis**: This technique involves creating various future scenarios to assess the impact of changes (e.g. implementation of new policies or adoption of new technologies) on whole energy systems and determine how they may respond to various conditions.

- **Integrated Assessment Models (IAM):** Combine knowledge from socio-economic, technological, and environmental domains to analyse the complexities and consequences of integrating different energy systems.

3. Barriers and enablers of Whole Energy Systems Optimisation

Whole Energy System (WES) optimisation refers to the comprehensive and coordinated operation of diverse energy vectors to achieve maximum efficiency, sustainability, and resilience across the entire energy spectrum. It involves strategic decision-making and collaborative efforts to optimise the energy generation, energy import, energy conversion, distribution, storage, and consumption of multiple energy vectors within a unified and interconnected system. While striving for the efficient, sustainable, and resilient operation of diverse energy vectors, various barriers must be acknowledged, such as adaptation of existing infrastructure, financial constraints, and data security and privacy[vii viii ix]:

On the other side, the realisation of WES optimisation is supported by a spectrum of enabling factors. These enablers include technology advancement, policy support, pilot and demonstrator projects, and flexible business models, for example[x xi]:

WES optimisation represents a transformative approach to energy management, but its success is contingent on effectively addressing barriers and leveraging enablers. A comprehensive strategy that embraces technological innovation, policy support, collaboration, and public engagement is essential for overcoming challenges and realising the full potential of integrated energy systems.

4. Including hydrogen in Whole Energy Systems modelling

There is a widespread consensus on the substantial potential of hydrogen in addressing climate change. However, uncertainties persist regarding its scale, production methods, and competitive applications. Hydrogen can be produced through diverse pathways involving electricity, natural gas, and biomass, with applications spanning energy, transportation, and industry. To comprehensively understand hydrogen's role in the whole energy system, a thorough exploration of challenges and opportunities is essential. Consequently, model-based investigations are necessary to assess hydrogen's holistic value, identify near-term actions, and devise long-term strategies for transitioning to low-carbon energy systems.

Various modelling strategies can examine hydrogen's incorporation into whole energy systems (see Figure 2). These methods include delineating operational features of hydrogen technologies, employing models considering interactions across temporal and spatial scales, and utilising techniques for infrastructure expansion plans, investment decision-making, and assessing hydrogen's role within the whole energy system.

The first modelling method involves employing bottom-up optimisation models, considering the operational details of the hydrogen value chain. This includes detailed modelling of hydrogen technologies, such as energy supply and consumption, storage, transportation features, capacity limits, and other operational characteristics. The modelled technologies encompass hydrogen production[xii xiii], storage[xiv], transportation networks[xv], and consumption[xvi] in turbines, fuel cells, vehicles, and heat generators.

The second modelling approach explores how hydrogen evolves in coordination with other vectors, evaluating economic and environmental benefits[xvii]. It utilises models assessing the role of hydrogen in both short and long terms, often formulated as long-term optimisation problems with yearly cost or revenue objectives[xviii]. Some models operate at an hourly resolution, capturing short-term operational characteristics. To assess hydrogen's contribution to regional or national energy transitioning, models of large-scale hydrogen infrastructure deployment in regional or national energy systems[xix] are employed.

The third modelling approach encompasses various models informing hydrogen development strategy, including expansion planning, investment decision-making, stakeholder interactions, and evaluating technology contributions in the whole energy system. Cost-oriented expansion planning models minimise costs and maximize profits, considering investment, operation, maintenance costs, and energy trade revenue[xx]. Game-theory models simulate decision-making by different stakeholders with varying economic goals, providing insights into investment decisions and profitability[xxi].

As we navigate the intricate landscape of energy transition, these modelling strategies serve as invaluable tools. They not only elucidate the technical and economic aspects of integrating hydrogen into the energy system but also pave the way for a sustainable and resilient energy future. The holistic understanding gained from these modelling approaches is paramount in realising the transformative potential of hydrogen within the whole energy ecosystem. Through these endeavours, the groundwork is laid for a more secure, efficient, and environmentally conscious energy paradigm.

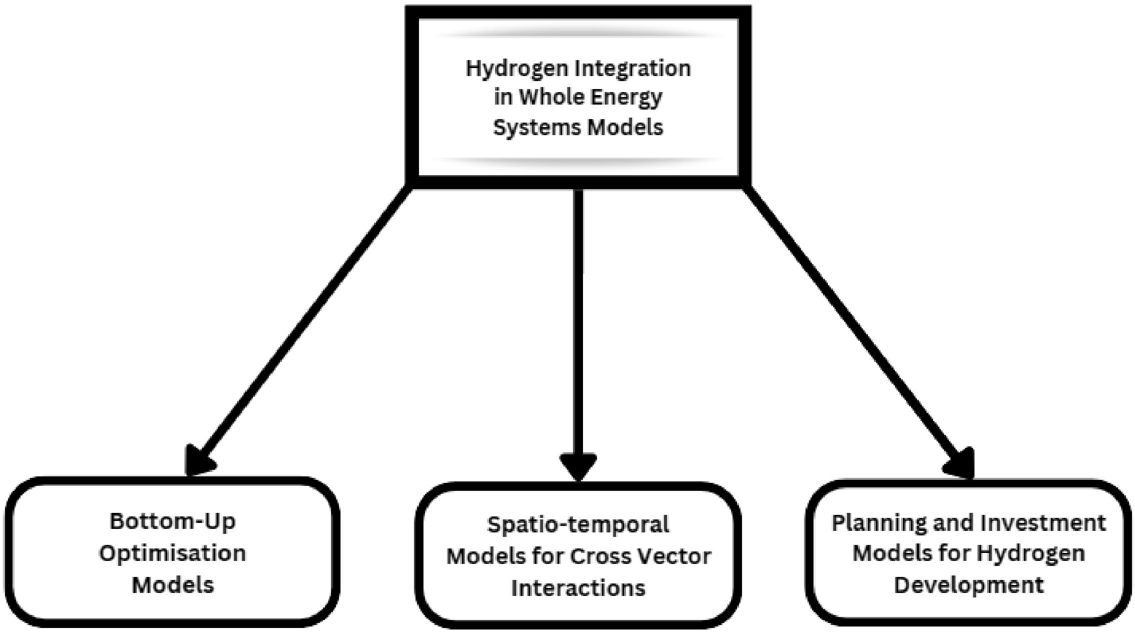

Figure 2: Summary of Approaches to Hydrogen Integration in Whole Energy Systems Models

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[i] National Grid. "Our Whole System approach." https://www.nationalgrid.com/electricity-transmission/pathway-to-net-zero/our-whole-system-approach (accessed 19/12/2023).

[ii] Council for Science and Technology, "A Systems Approach to Delivering Net Zero: Recommendations from the Prime Minister's Council for Science and Technology," 19 August 2020. Accessed: 18/12/2023. [Online]. Available: Https://Assets.Publishing.Service.Gov.Uk/Media/5f3d315e8fa8f51747a88083/Cst-Net-Zero-Report-30-January-2020.Pdf

[iii] Fattahi, A., Sijm, J. and Faaij, A., 2020. A systemic approach to analyze integrated energy system modeling tools: A review of national models. Renewable and Sustainable Energy Reviews, 133, p.110195.

[iv] Volkart, K., Mutel, C.L. and Panos, E., 2018. Integrating life cycle assessment and energy system modelling: Methodology and application to the world energy scenarios. Sustainable production and consumption, 16, pp.121-133.

[v] Edmonds, J.A., Calvin, K.V., Clarke, L.E., Janetos, A.C., Kim, S.H., Wise, M.A. and McJeon, H.C., 2012. Integrated assessment modeling. In Climate Change Modeling Methodology: Selected Entries from the Encyclopedia of Sustainability Science and Technology (pp. 169-209). New York, NY: Springer New York.

[vi] Mahmud, R., Moni, S.M., High, K. and Carbajales-Dale, M., 2021. Integration of techno-economic analysis and life cycle assessment for sustainable process design–A review. Journal of Cleaner Production, 317, p.128247.

[7] Berjawi, A.E.H., Walker, S.L., Patsios, C. and Hosseini, S.H.R., 2021. An evaluation framework for future integrated energy systems: A whole energy systems approach. Renewable and Sustainable Energy Reviews, 145, p.111163.

[8] Laes, E., Valkering, P. and De Weerdt, Y., 2019. Diagnosing barriers and enablers for the flemish energy transition. Sustainability, 11(20), p.5558.

[9] Hosseini, S.H.R., Allahham, A., Walker, S.L. and Taylor, P., 2020. Optimal planning and operation of multi-vector energy networks: A systematic review. Renewable and Sustainable Energy Reviews, 133, p.110216.

[10] Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L.D.S.N.S. and Fasihi, M., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy, 227, p.120467.

[11] Kovač, A., Paranos, M. and Marciuš, D., 2021. Hydrogen in energy transition: A review. International Journal of Hydrogen Energy, 46(16), pp.10016-10035.

[12] Berger, M., Radu, D., Fonteneau, R., Deschuyteneer, T., Detienne, G. and Ernst, D., 2020. The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies. Electric Power Systems Research, 180, p.106039.

[13] Wei, X., Zhang, X., Sun, Y. and Qiu, J., 2021. Carbon emission flow oriented tri-level planning of integrated electricity–hydrogen–gas system with hydrogen vehicles. IEEE Transactions on Industry Applications, 58(2), pp.2607-2618.

[14] Ge, P., Hu, Q., Wu, Q., Dou, X., Wu, Z. and Ding, Y., 2020. Increasing operational flexibility of integrated energy systems by introducing power to hydrogen. IET Renewable Power Generation, 14(3), pp.372-380.

[15] Zhou, J., Li, S., Zhou, X., Li, C., Xiong, Z., Zhao, Y. and Liang, G., 2022. Operation optimization for gas-electric integrated energy system with hydrogen storage module. International Journal of Hydrogen Energy, 47(86), pp.36622-36639.

[16] Qiu, Y., Zhou, S., Wang, J., Chou, J., Fang, Y., Pan, G. and Gu, W., 2020. Feasibility analysis of utilising underground hydrogen storage facilities in integrated energy system: case studies in China. Applied energy, 269, p.115140.

[17] Song, X., Qu, Z., Kou, J., Wang, Y. and Georgievitch, P.M., 2022. Environmental Economical Dispatching of Electric–Gas Integrated Energy System Considering Hydrogen Compressed-Natural Gas. Processes, 10(12), p.2642.

[18] He, G., Mallapragada, D.S., Bose, A., Heuberger-Austin, C.F. and Gençer, E., 2021. Sector coupling via hydrogen to lower the cost of energy system decarbonization. Energy & Environmental Science, 14(9), pp.4635-4646.

[19] Gils, H.C., Gardian, H. and Schmugge, J., 2021. Interaction of hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in Germany. Renewable Energy, 180, pp.140-156.

[20] McDowall, W., 2014. Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling. Futures, 63, pp.1-14.

[21] Tuofu, H., Changhao, H., Qingyun, H., Dongxiao, Y., Tian, H. and Yi, F., 2022. A coordination analysis of stakeholder interests on the new subsidy policy of hydrogen fuel cell vehicles in China: From the perspective of the evolutionary game theory. International Journal of Hydrogen Energy, 47(58), pp.24493-24510.