Contribution ID: **25** Type: **Session Talk**

Large-scale implementation of sector coupling in Europe - key concepts, barriers, and solution space

Friday, April 4, 2025 2:55 PM (25 minutes)

Overview
Sector coupling could be a cost-efficient supplement in addressing the European challenge of increasing electricity grid expansion costs. Its large-scale implementation could unlock significant electricity flexibility, storage and cross-sector synergy potential, thereby saving costs and increasing sustainability. Previous research in sector coupling concentrated on energy systems modelling and techno-economic assessments. Studies have proven the potential benefits of sector coupling, theoretically in system modelling and practically in pilot studies. However, in practice, it has not yet found large-scale implementation with studies citing different barriers. Recent literature reviews have focused on technologies and models or specific barrier categories but have not yet displayed a full picture of barriers. Therefore, this paper aims to provide a multi-perspective understanding of why sector coupling has been falling short of its potential with a focus on large-scale implementation barriers in the EU.

Methods
Using a systematic literature review methodology, an integrated and interdisciplinary understanding was gained applying a 3-step logic. 1) A 3-string search was used, consisting of "sector coupling"and used synonyms, a focus on business and economics perspective and a geographical focus on the EU. The resulting 70 search string combinations were used in the databases EBSCO host, Science Direct, Web of Science. 2) Papers were manually reviewed based on title and abstract. 3) Additions were made based on cross citations and further research. The final literature set included 150 publications The analysis consisted of a discussion of key concepts towards a clear definition of sector coupling, a collection and aggregation of implementation barriers into 6 categories and the synthesis of these towards 11 solution spaces to unlock the potential of sector coupling.

Results
Key concepts in sector coupling include power-to-mobility, power-to-heat/cooling and power-to-gas/liquid, and some authors also include power-to-power and power-to-negative emissions concepts. Definitions for sector coupling range from one-way energy conversion in specified end uses to a holistic cross-carrier energy system optimization. Relevant literature can be found within the terms sector coupling, smart energy, power-to-X, multi-energy systems, energy systems integration, and integrated energy systems. To capture the full body of research but also clearly delimitate the scope, a necessity for a clear definition emerges. This paper outlines a holistic definition of sector coupling to capture its full benefits.

The systematic literature review identified a total of 63 *barriers* for large-scale implementation of sector coupling in Europe, which were aggregated under 6 barrier categories:

1. Technical (203 mentions), e.g., technology development risks (top example, 28 mentions)
2. Regulatory (171), e.g., insufficient regulatory and policy frameworks (37)
3. Economic (157), e.g., high upfront investments for infrastructure and technology (43)
4. Market (149), e.g., unclear value chain and market design (28)
5. Social & environmental (106), e.g., consumer engagement and consumer behaviour (30)
6. Institutional & managerial (75), e.g., lack of coordination/ challenges in cross-company/ sector planning and operation (35).

These barriers across categories were further analysed and clustered based on similar root problems while accounting for dependencies between them. The result of this synthesis lead to the emergence of 11 *solution spaces* that provide a fertile ground for overcoming the large-scale implementation barriers of sector coupling:

1. Adapting to the frame conditions, referring to mentioned barriers that cannot be changed
2. Achieving technological progress to reduce technical constraints, risks, and eventually costs
3. Accelerating infrastructure expansion, e.g., grid expansion, charging points, heat pumps, or smart meters
4. Refining the political strategy, i.e., national implementation and detailing
5. Designing sector coupling markets, i.e., distribution of costs and benefits, and connection to energy markets
6. Standardizing and integrating regulation, from international, cross-sectoral, and cross-subsidy perspective
7. Unlocking financial investments, i.e., through targeted ramp up support and regulatory stability
8. Managing technical complexity, e.g., in modelling, technical coupling, operating, and cyber-security
9. Integrating people to ensure social acceptance and steer consumer behaviour
10. Unlocking business innovation, i.e., through cross-stakeholder collaboration and business model creation
11. Prevailing against competition, i.e., increase competitiveness against fossil fuels and renewable alternatives.

Conclusions

This paper has looked at the state of research in sector coupling, summarizing the barriers that inhibit its large-scale implementation in the EU within 6 categories and suggesting 11 solution spaces to overcome them. While barriers from multiple sides hinder the implementation, the most severe barriers seem to be non-technological, thereby indicating it is not only technical but i.e. also regulatory, market, and social barriers hindering the implementation. Furthermore, it becomes evident how the development of sector coupling is dependent on technology adoption, e.g., the rollout of smart meters and heat pumps. Therefore, the large-scale implementation will have to be orchestrated with the overall energy system development. This also means, the potential of sector coupling to achieve immediate relief on energy transition costs seems rather limited. For the implementation, this suggests working within the solution spaces while accounting for interrelations, not only for the pace of the energy transition, but also between sectors, nations, energy carriers, and the barriers itself.

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Session Classification: Challenges of technological advances I