Research project

Title: Development of a decision-making support method applied to railway projects to support the energy transition of regions through the search for synergies.

Key words: energy transition, mobility, territory, transport economics, energy economics, decarbonisation, industrial and territorial ecology, decision support.

Context

Between February 2023 and January 2024, the global temperature was 1.52°C higher than in the period 1850-1900 (Copernicus, 2025), exceeding the most ambitious target of the Paris Agreement to limit warming to less than 1.5°C (United Nations, 2015). Although years of data are still needed to declare formal defeat, it seems more relevant than ever to arm ourselves with tools to promote the transitions necessary for our survival.

Energy and transportation are the two largest greenhouse gas-emitting sectors worldwide (IPCC, 2023). The transportation sector accounts for approximately 15% of global emissions, largely because it is one of the world's primary energy consumers, still heavily reliant on fossil fuels (IEA, 2023). More broadly, the energy transition represents one of today's defining global challenges, shaping economic strategies, industrial policies, and public investment priorities.

Governmental strategies aimed at reducing transportation's emissions often rely on rail to achieve modal shift objectives. However, they usually do not clearly specify how this transition should be implemented, lacking clear methodologies and decision-making tools.

These essential transformations in the energy and transport sectors are directly linked to the United Nations (UN) Sustainable Development Goals (SDGs), in particular SDG 13, which calls for 'urgent action to combat climate change and its impacts', SDG 7 to 'ensure access to affordable, reliable, sustainable and modern energy services for all' and SDG 11, which promotes 'more sustainable and inclusive cities and infrastructure' (UN, 2022). According to the UN, the SDGs are 'a global call to action to end poverty, protect the planet and ensure that all human beings enjoy peace and prosperity by 2030'. The latest IPCC report is unequivocal: an unequal society is much more vulnerable to the impacts of climate change. Furthermore, investments in networked infrastructure play a decisive role in reducing social inequalities (Hooper et al., 2017). Therefore, major infrastructure projects could be one of the most relevant ways to build a more resilient and equitable future.

Because environmental challenges are multiple and interconnected, our vision of ecological transition cannot be limited to reducing carbon emissions alone. The ecological crisis also encompasses the collapse of biodiversity, the depletion of natural resources, air, water and soil pollution, and the resulting social inequalities. Sustainable transformation therefore requires a holistic approach that rethinks our modes of production, consumption and collective organisation, taking into account planetary limits and human needs. To build a new model of society, it will not be enough to find a single technical solution. We will need to draw on all the tools at our disposal – economic, technical and political – and use them intelligently to devise a clear and coherent strategy. What should the infrastructure of tomorrow look like in order to meet ecological and social imperatives? What model of development do we want to move towards? While the paths to avoid have been clearly identified, we still need to define those that will ensure a sustainable and inclusive transition.

The IPCC also warns of the urgent need for a profound transformation of transport infrastructure. Such transformation is essential if we are to achieve the goal of limiting global warming to 1.5°C. However, the planning and implementation of such infrastructure is a long-term process, involving a multitude of stakeholders, including workers, engineers, urban planners, economists, policy makers and many others. From design to operational phases, several decades may pass, with major socio-economic implications at local and national level. These projects are also particularly capital-intensive, often involving heavy and largely irreversible investments, whose structural effects will continue over the long term. So how can this process be properly thought out, organised and planned? How can we ensure that the projects designed today will best meet the challenges of tomorrow?

Introduction

Any major mobility infrastructure project brings about significant changes to the local area. This phenomenon is well documented in the field of urban planning through LUTI (Land Use and Transport Interaction) models, which study the interactions between land use and transport networks. However, these models rarely include energy aspects in their analyses, leaving a gap in the overall assessment of the territorial impacts of infrastructure.

However, the transport sector accounts for a major share of energy consumption in most countries: it is a sector that is structurally dependent on available energy. Indeed, unlike other uses, mobility cannot exist without energy consumption. In order to guarantee energy availability for each specific use, each consumption market is considered individually. This is leading to an oversized production system which is problematic in contexts where the energy mix relies on intermittent or uncontrollable sources. According to RTE (France's transmission system operator), in 2025, negative price episodes led to the abandonment of approximately 3 TWh of solar and wind power generation (RTE, 2025). On average, this magnitude meets a third of the annual consumption of the railway company SNCF[1] (SNCF, 2024). Rethinking and coordinating the organisation of electricity production and consumption upstream, appears to be a clear course for improving the overall efficiency of the energy system. It seems fundamental to integrate actual uses and needs into the planning stage.

Any discussion about the future of transport must necessarily include the issue of energy, not only from an environmental perspective, but also as a key factor in economic efficiency, sovereignty and regional resilience. Bringing together the various aspects of energy production, consumption and storage is particularly useful in addressing the instability of renewable energy production. Furthermore, the transport sector, particularly rail, and renewable energy are characterised by long-term infrastructure commitments. Given that making a heavy investment commitment entails risks in view of the uncertainties inherent in long-term prospects (demand, cost structure), it seems necessary to work on energy demand at the same time as on supply. In the case of use of alternative energy carriers, the creation of ecosystems surroundings the heavy railway infrastructure may encourage other players to enter the market and thus trigger the energy transition of an entire region.

This research will seek to establish a link between distinct fields such as transport economics, railway infrastructure engineering and energy economics. Today, these areas are still too often addressed in isolation, each using its own indicators and analytical approaches. This fragmentation limits the scope of public policies, which struggle to integrate the essential interconnections between these sectors. To build a sustainable future, it is necessary to develop an integrated approach that takes these

[1] Of which are 82% for train traction.

interdependencies into account and strikes a balance between their respective constraints. With this in mind, we will analyse the interactions and respective influences between transport and energy, both economically and technically. The aim will be to mobilise several economic principles in order to model situations offering opportunities for industrial synergies, thereby contributing to the design of more sustainable infrastructure and the development of a methodology applicable to all major projects.

Research motivation

This research will build upon a concrete case study: the completion of a feasibility study conducted in Montevideo (Uruguay) on the possible reintroduction of a passenger rail service as part of an energy transition and urban mobility transformation strategy.

In Uruguay, the transport sector plays a central role in energy issues: it accounts for around 26% of the country's total energy consumption (as is the case in most places in the world) and is by far the largest consumer of fossil fuels, accounting for nearly 70% of national consumption. In a context where electricity production is largely decarbonised thanks to renewable energies, the decarbonisation of the transport sector thus appears to be a strategic and priority lever for continuing the country's energy transition.

The study conducted by Setec brought a systemic approach at the regional level, integrating technical, economic, territorial and political dimensions.

This experience has led to several observations. On the one hand, it highlights the potential for transition in a region that can be brought about by a reorganisation of mobility systems. However, this requires an interdisciplinary analysis that goes beyond traditional approaches. This experience has therefore revealed that today's analytical tools do not allow for an assessment of the real relevance of these projects, considering their overall impact. Railway projects are assessed solely on their transport impacts. However, and because they are publicly funded, consideration could be given to maximising the benefits of these investments by building infrastructure that supports the energy transition of the rest of the region.

In this context, this research aims to continue and further develop this initial approach by designing a rigorous, integrated and reproducible method for evaluating, comparing and supporting mobility projects with a view to the energy transition of territories. This research will analyse the benefits of developing modes of transport that are compatible with energy transition objectives, while exploring possible synergies with the use of renewable energies. The aim is to develop this method using a sound scientific approach, combining transport economics, energy economics and technical engineering solutions, with an aim to assist public actors in their decision-making.

Research questions

The aim of this PhD thesis will be to answer the following question:

- How can technical and economic dimensions be coordinated to promote synergy between mobility strategies and energy policies, and what information should be provided to decision-makers to ensure informed decisions tailored to regional issues?

This question will be broken down into several questions that will structure the thesis:

- How are energy transition projects currently designed, and how can their effectiveness and territorial relevance be enhanced?
- To what extent can interactions between the rail sector and renewable energies reduce uncertainties associated with long-term investments and promote sustainable joint growth?
- How can we break down the barriers between analyses conducted within the disciplines of transport economics and energy economics?
- What tools and analytical elements should be made available to decision-makers to ensure informed decision-making and guide them towards the optimal solution in the case study?

Literature review

As this thesis lies at the intersection of several disciplines, it will need to draw on a literature review covering a variety of fields, ranging from transport and energy economics to decision-making approaches in contexts of uncertainty, as well as methodologies derived from industrial ecology, industrial symbiosis and urban metabolism. The aim is to construct a solid theoretical and methodological framework for analysing the interactions between transport infrastructure and regional energy transition.

Energy carriers, their particular use in railway and the energy transition

The literature review will initially include an exploration of methodologies developed in the fields of industrial and territorial ecology (Erkman 1997; Gibbs 2008), industrial symbiosis (Diemer 2016), and urban metabolism (Zhang 2013; Kennedy et al. 2011). It will also cover modelling work such as that developed at CIRED with the IMACLIM model (Sassi 2008; Sánchez 2021). These approaches will make it possible to identify situations offering opportunities for industrial synergies and contribute to the design of more sustainable infrastructure. Following this same logic, a literature review will be conducted to map the various existing energy carriers according to their nature, uses and suitability for the different types of territories and needs identified (Seto et al. 2014; IEA 2025). This step will be essential in determining the carriers best suited to promoting the energy transition of territories.

Decision support

Because the method for identifying synergy opportunities is intended to be a decision-making tool, the literature review will also include a study of various decision-making methods identified in the literature. Several approaches will be explored, such as real options analysis (Dixit and Pindyck 1994), scenario testing (Schoemaker 1995), the regret minimisation method , the stochastic approach (Shapiro et al. 2009) and robust optimisation (Ben-Tal et al. 2009).

Given that existing methodologies for decision-making in contexts of uncertainty are based on models that require variable levels of input data, rely on different degrees of uncertainty, or depend on the number of actors involved, it will be necessary to analyse each of these approaches, compare them and identify the one that appears most suitable for modelling the situation under study. Depending on the results of this exploratory phase, it may be possible to combine certain elements from different approaches and possibly add resources from other fields of study in order to construct a model that is as representative as possible of the situation under study and consistent with the data actually available.

Because the rail transport and renewable energy sectors are characterised by long-term investments, we will focus on the interactions that may emerge, enabling the transport sector to reduce energy uncertainties and the renewable energy sector to secure long-term demand. Public-private partnerships, for example, could complement elements of the method developed (Eshun et al. 2020; Medda 2007). We will therefore analyse the dynamics of the two sectors (transport and renewable energy) to assess the best paths for joint growth, avoiding competition for access to engineering companies and financial markets.

Finally, other markets will be studied in order to seek analogies that could provide food for thought, such as the electricity market (Lund et al. 2017; Ventosa et al. 2005) or the organisation of charging for individual electric vehicles (Noel *et al.* 2019).

Case study

The thesis will be based on analyses of real case studies. The main case study will be an assessment of the opportunity and feasibility of re-implementing a passenger service between Montevideo (Uruguay) and its northern suburbs (60 km).

The study was conducted by Setec Ferroviaire and Setec International between February 2024 and April 2025. It consisted of three main phases:

1. Phase 1: Mobility analysis

   The first step consists of a detailed assessment of mobility in the Montevideo metropolitan area, particularly along one of Uruguay's main roads, Corridor 5, which is the focus of the study. The aim is to understand transport supply and demand in this region. To do this, modelling tools are used to accurately map the different areas around the railway line and analyse passenger flows. This analysis, based on origin-destination surveys and an analysis of the current transport supply, makes it possible to accurately define the potential demand for mobility and the specific challenges of the territory.

2. Phase 2: Mobility system design

   Based on the results of the assessment, mobility system scenarios are developed to meet the identified needs. The approach taken is systemic, taking into account not only the rail network, but also its connection with other existing modes of transport. The aim is to optimise the integration of this new infrastructure into the overall transport network in order to improve the user experience and offer a coherent and efficient service designed to compete with single-occupant car use (and provide an alternative to the need for motorisation among non-urban households). This involves collaboration with various local stakeholders to ensure a sustainable mobility offering that is tailored to the specific characteristics of the region.

3. Phase 3: Energy scenario study

   This phase consists of analysing different energy scenarios for powering this transport system. More than eight energy scenarios were studied in order to determine which ones were technically feasible: diesel, catenary electrification, partial electrification batteries, spot and battery swap batteries, hydrogen fuel cells, and two dual-mode versions. Of these eight scenarios, four were deemed feasible and were therefore studied in greater detail. They were subjected to an economic analysis and a multi-criteria analysis including numerous technical, economic, political and environmental criteria, which made it possible to determine the optimal energy scenario.

The study provided Uruguayan leaders with the information they needed to make an informed decision. If they decide to proceed with the project, they will have the following information at their disposal:

- The expected level of demand based on the pricing structure they decide to implement.
- The number of trains per hour and per direction that will be needed to meet this demand.
- A 50-year economic assessment comparing the different energy sources available to power the service.
- A summary of the advantages and disadvantages of each of the energy sources considered in relation to their situation.
- An exploration of opportunities for synergies between local stakeholders who could benefit from the deployment of energy facilities.

Bibliography

Ben-Tal, Aharon, Laurent El Ghaoui, and Arkadi Nemirovski. 2009. *Robust Optimization:* Princeton University Press. https://doi.org/10.1515/9781400831050.

Copernicus. 2025. *Global Climate Highlights 2024*. https://climate.copernicus.eu/sites/default/files/custom-uploads/GCH-2024/GCH2024-PDF-1.pdf.

Diemer, Arnaud. 2016. 'Les symbioses industrielles : un nouveau champ d'analyse pour l'économie industrielle'. Gestion. *Innovations* 50 (2): 65–94. https://doi.org/10.3917/inno.050.0065.

Dixit, Avinash K., and Robert S. Pindyck. 1994. *Investment Under Uncertainty*. Princeton University Press.

Erkman, S. 1997. 'Industrial Ecology: An Historical View'. *Journal of Cleaner Production* 5 (1–2): 1–10. https://doi.org/10.1016/S0959-6526(97)00003-6.

Eshun, Bridget Tawiah Badu, Albert P. C. Chan, and Robert Osei-Kyei. 2020. 'Conceptualizing a Win–Win Scenario in Public–Private Partnerships: Evidence from a Systematic Literature Review'. *Engineering, Construction and Architectural Management* 28 (9): 2712–35. https://doi.org/10.1108/ECAM-07-2020-0533.

Gibbs, David. 2008. 'Industrial Symbiosis and Eco-Industrial Development: An Introduction'. *Geography Compass* 2 (4): 1138–54. https://doi.org/10.1111/j.1749-8198.2008.00123.x.

'Global Energy Review 2025'. 2025. *IEA Publications*.

Groupe SNCF. 2024. 'Notre engagement pour la sobriété énergétique'. March 18. https://www.groupe-sncf.com/fr/engagements/developpement-durable/sobriete-energetique.

Hooper, Emma, Sanjay Peters, and Patrick Pintus. 2017. 'To What Extent Can Long-Term Investment in Infrastructure Reduce Inequality?' *SSRN Electronic Journal*, ahead of print. https://doi.org/10.2139/ssrn.2952365.

IEA. 2023. 'Rail'. July 11. https://www.iea.org/energy-system/transport/rail.

Intergovernmental Panel On Climate Change (Ipcc), ed. 2023. 'Emissions Trends and Drivers'. In *Climate Change 2022 - Mitigation of Climate Change*, 1st edn. Cambridge University Press. https://doi.org/10.1017/9781009157926.004.

Kennedy, C., S. Pincetl, and P. Bunje. 2011. 'The Study of Urban Metabolism and Its Applications to Urban Planning and Design'. *Environmental Pollution* 159 (8–9): 1965–73. https://doi.org/10.1016/j.envpol.2010.10.022.

Lund, Henrik, Poul Alberg Østergaard, David Connolly, and Brian Vad Mathiesen. 2017. 'Smart Energy and Smart Energy Systems'. *Energy* 137: 556–65. https://doi.org/10.1016/j.energy.2017.05.123.

Medda, Francesca. 2007. 'A Game Theory Approach for the Allocation of Risks in Transport Public Private Partnerships'. *International Journal of Project Management* 25 (3): 213–18. https://doi.org/10.1016/j.ijproman.2006.06.003.

Nations Unies. 2015. 'Accord de Paris'.

Nations Unies. 2022. *Rapport Sur Les Objectifs de Développement Durable*. https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022_French.pdf.

Noel, Lance, Gerardo Zarazua de Rubens, Johannes Kester, and Benjamin K. Sovacool. n.d. *Vehicle-to-Grid*. Palgrave Macmillan. Energy, Climate and the Environment. https://link.springer.com/series/14966.

RTE. 2025. 'Bilan Électrique 2025 - Rapport Complet'. https://assets.rte-france.com/analyse-et-donnees/2026-03/BE2025%20-%20Rapport%20Complet.pdf.

Sánchez, Arancha. 2021. 'IMACLIM R-Monde'. *CIRED*, September 6. https://www.centre-cired.fr/en/imaclim-r-monde/.

Sassi, Olivier. 2008. *L'impact du changement technique endogène sur les politiques climatiques*.

Savage, Leonard J. 1954. *The Foundations of Statistics*. 2nd rev. ed. Dover publ.

Schoemaker, Paul. 1995. 'Scenario Planning: A Tool for Strategic Thnikingh'. *Sloan Management Review*, January.

Seto, Karen C., Shobhakar Dhakal, Anthony Bigio, et al. 2014. 'Human Settlements, Infrastructure, and Spatial Planning'. *IPCC* AR5 Synthesis Report: Climate Change 2014.

Shapiro, Alexander, Darinka Dentcheva, and Andrzej P. Ruszczyński. 2009. *Lectures on Stochastic Programming: Modeling and Theory*. With Society for Industrial and Applied Mathematics. MPS-SIAM Series on Optimization 9. SIAM. https://doi.org/10.1137/1.9780898718751.

Ventosa, Mariano, Álvaro Baíllo, Andrés Ramos, and Michel Rivier. 2005. 'Electricity Market Modeling Trends'. *Energy Policy* 33 (7): 897–913. https://doi.org/10.1016/j.enpol.2003.10.013.

Zhang, Yan. 2013. 'Urban Metabolism: A Review of Research Methodologies'. *Environmental Pollution* 178 (July): 463–73. https://doi.org/10.1016/j.envpol.2013.03.052.