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EXECUTIVE SUMMARY OF THE THESIS

The European power sector toward 'Net Zero by 2050': OSeMOSYS optimization vs IEA Scenarios

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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1. Introduction

This thesis examines the evolution of the Continental European power sector toward 2050 using OSeMOSYS, a simplified linear optimization model. Moving from a retrospective assessment of World Energy Outlook (WEO) projections, which demonstrates the critical sensitivity of energy pathways to structural modeling choices, the research implements OSeMOSYS within a systematic model taxonomy to test whether an aggregated framework can reproduce WEO 2024 trends under harmonized inputs.

The work constitutes an original research contribution through four key innovations:

(i) A novel comparison against WEO 2024 to validate the consistency of simplified open-source models with institutional projections,

(ii) The first documented application of the MUIO interface for OSeMOSYS to the Continental European power sector up to 2050,

(iii) The construction and calibration of a new European power dataset to 2050 specifically tailored to the MUIO-OSeMOSYS framework,

(iv) An original assessment of end-of-horizon effect and salvage value distortions within the OSeMOSYS environment.

The study concludes by synthesizing long-term sectoral evolution patterns, discussing the inherent limitations of deterministic optimization, and outlining methodological refinements for future research.

2. Background and motivation

Europe's pathway to climate neutrality by 2050 requires a profound reconfiguration of the power sector, with a shift from fossil-based generation toward systems dominated by variable intermittent renewable energy (VRE) and flexibility resources. Long-term planning is therefore increasingly model-driven. At the same time, many authoritative scenario exercises rely on highly complex, partly proprietary frameworks that can behave as "black boxes," making it difficult to interpret how assumptions, constraints, and modelling choices shape the final trajectories.

To build the analytical sensitivity needed for a robust modelling exercise, this thesis begins with a retrospective comparison between the IEA's World Energy Outlook (WEO) 2010 global projections, historical time series (1990–2024), and the updated pathways in WEO 2024, focusing on total primary energy demand, electricity generation by source, and CO_2 emissions. This step is designed to evaluate the accuracy and the consistency of past trajectories against historical evidence and to analyze how these projections have been subsequently redefined over time. To ensure comparability over time, historical CO_2 values retrieved from older WEO editions are harmonized to the WEO 2024 accounting methodology: WEO editions are grouped into seven methodology-consistent clusters, each characterized by a uniform CO_2 emissions accounting methodology, correction factors are computed to translate earlier-edition emissions series into the WEO 2024 framework, and adjustments are performed using the IPCC Time Series Consistency approach.

The analysis identifies the systematic underestimation of wind and especially solar PV deployment (Figure 1) alongside marked fossil fuel persistence in the 2010 edition; a downward revision of total energy demand projections coupled with an upward revision of total electricity production in the 2024 edition relative to the earlier outlook; and a drastic downward revision of CO_2 emission trajectories in the 2024 edition relative to 2010 levels.

This methodological step highlights that model outcomes depend more on its structure, input data, and policy framing than on computational complexity alone [1] [2]. Given that increased complexity does not guarantee accuracy when based on outdated or conservative assumptions, this observation establishes the premise for Research Question 1 and defines the overarching objective of this research.

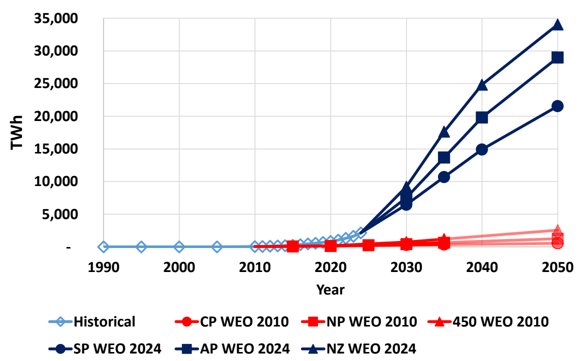

Figure 1: Solar PV Electricity Production

3. Research objective and research questions

The core objective of this thesis is to assess whether a simplified, aggregated model can reproduce the key trends and insights of a major international benchmark (IEA WEO 2024) for the Continental European power sector up to 2050. This is tested across multiple scenarios of increasing climate ambition, including a Net Zero Emissions (NZE) pathway. Specifically, the thesis addresses two research questions:

1. *RQ1*: Can a simplified, aggregated linear optimization model, focused solely on cost minimization, produce trends and outputs consistent with those of the IEA WEO 2024 Europe scenarios given a consistent set of input parameters?
2. *RQ2*: Building on the modeling framework established for the benchmarking in RQ1, identify the long-term systemic implications and structural shifts arising from the Continental European power sector's evolution across the three modeled scenarios.

To ensure methodological stability in a long horizon to 2050, the analysis adopts Continental Europe (the IEA geographic definition) rather than EU political boundaries, avoiding distortions that could arise from future enlargements or administrative changes.

4. Methodological pathway and modelling approach

The thesis adopts a step-by-step methodology to select and implement the most suitable modelling framework for the research questions. First, it reviews the main energy-model classification schemes to map the key macro-features of energy models (e.g., simulation vs. optimization, spatial and temporal resolution, bottom-up vs top-down). Second, it translates these insights into a set of explicit model requirements, namely a bottom-up capacity-expansion and dispatch model with intertemporal linear optimization, a total system cost–minimization objective function, limited complexity, and extensive use in the energy-modelling literature and applied studies. Third, using a published database that reports the main characteristics of 75 energy system models [3], it screens potential candidates and performs a focused comparison of oemof, Balmorel, Calliope, and OSeMOSYS. Based on these requirements, OSeMOSYS was selected as the modelling framework and implements the model through the MUIO interface, building an aggregated linear programming formulation for European capacity expansion and energy delivery from 2024 to 2050. Prior to implementation, the study examines the core logic of OSeMOSYS, its key inputs and outputs and the structure of its equations, to ensure full consistency between model formulation, data preparation, and scenario design. In its standard formulation, OSeMOSYS computes the energy supply mix (in terms of generation capacity and energy delivery) that meets energy demands in each year and time step of the system under study, while minimizing total discounted system costs. In mathematical terms, it is a deterministic, bottom-up linear optimization, long-term modelling framework. The model then identifies least-cost investment and operation trajectories that satisfy increasing electricity demand while respecting scenario-specific assumptions and constraints.

A deliberate simplification is adopted: the model is implemented as a single-node and single-region representation (i.e., an idealized transmission system without internal bottlenecks) so that the analysis focuses on aggregate system dynamics and long-term investment outcomes, rather than on intra-regional network constraints. This choice is consistent with the goal of testing whether an aggregated, cost-optimal model can still replicate benchmark trends.

5. Model design, scenario architecture, and key assumptions

The model is configured to mirror the WEO 2024 scenario logic and is run under three pathways aligned with WEO 2024 narratives: Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and a Net Zero Emissions (NZE) pathway. Scenario differentiation is implemented primarily through demand trajectories, evolving technology costs, fuel prices, carbon pricing, and (in the normative pathway) explicit emission constraints. The technologies available from the start of the simulation include Single Cycle Gas Turbine (SCGT), Combined Cycle Gas Turbine (CCGT), oil (OIL), coal (COAL), biomass (BIO), geothermal (GEO) and nuclear (NUC) power plants, as well as Solar PV, Wind Onshore (WINDON) and Wind Offshore (WINDOFF) turbines, and hydropower technologies, Hydro Reservoir (RESERVOIR) and Hydro Run-of-River (ROR). Starting from 2025, the model is additionally allowed to invest in technologies equipped with Carbon Capture and Storage as Gas (GASCCS) and Coal (COALCCS) power plant. Storage technologies include batteries (BATT) and pumped hydro energy storage (PHES).

Across scenarios, the set of available technologies is kept constant; what changes are the deployment constraints, including annual maximum installation/investment limits and bounds on year-to-year changes in electricity production.

The thesis emphasizes that a cost-minimization framework alone does not automatically reproduce the policy-driven constraints embedded in institutional scenarios. To partly address this gap, scenario-specific constraints are implemented as maximum annual investment levels and limits on the annual rate of change in electricity production (maximum increase/decrease in percentage terms). These assumed bounds are derived from the policy context and deployment pace based on the WEO 2024 scenarios.

6. 2024 baseline reconstruction and model calibration

Table 1: Total Net Electricity Production 2024: RES vs Model

Tot Net Elec. Production 2024 [TWh]	RES	MODEL
BIO	191.9	23.7
COAL	434.0	210.3
GEO	24.2	24.4
RESERVOIR	374.0	681.4
ROR	293.2	293.2
CCGT	654.4	859.4
SCGT	34.4	10.9
NUC	742.0	741.4
OIL	102.4	2.5
PV	384.9	384.9
WIND OFF	99.9	99.9
WIND ON	519.2	519.2

The thesis includes a 2024 baseline calibration step to ensure consistency between the model's starting point and the subsequent long-run scenarios. The calibration begins by constructing a representative Reference Energy System (RES) for Continental Europe in 2024, consistent with the aggregated technology set used in OSeMOSYS. Installed capacities and net production levels of technologies are reconstructed to provide an empirical benchmark against which the model's endogenous 2024 dispatch can be assessed.

The calibration then proceeds in two steps. First, a base-year-only simulation is run to reveal mismatches between model output and the reconstructed RES benchmark, as in Table 1. The thesis identifies several drivers of misalignment, including limited data granularity, structural simplifications (e.g., lack of heat sector and CHP), and operational abstractions. For example, the absence of the thermal sector can penalize biomass dispatch because the model cannot capture cogeneration value streams that matter in real-world operations.

Second, the model is calibrated by imposing activity constraints to synchronize dispatchable generation with the validated 2024 reference mix. In particular, the calibration acts on Total Technology Annual Activity Lower/Upper Limit constraints: hydro reservoir production is capped to reflect resource limits, while dispatchable technologies (e.g., coal, gas, oil, biomass) are constrained to reproduce the reconstructed 2024 output levels. This ensures that the 2025–2050 optimization evolves from a technically grounded and historically coherent starting point rather than from a purely mathematical least-cost configuration.

Complementary calibration steps include estimating transmission and distribution losses and defining efficiency coefficients so that projected electricity demand inputs are correctly translated into generation requirements. This is crucial for scenario comparability and for later benchmarking to WEO-based demand definitions.

7 Benchmarking OSeMOSYS vs WEO 2024 (RQ1)

Table 2: STEPS Scenario Electricity Production (TWh): Weo 2024 vs OSeMOSYS

STEPS	WEO	OSeMOSYS	WEO	OSeMOSYS	WEO	OSeMOSYS
Year	2030	2030	2035	2035	2050	2050
Total	4,719	4,579	5,508	5,073	6,893	6,617
Coal	281	54	201	4	167	-
Gas	495	938	331	794	206	600
Nuclear	779	907	765	649	834	588
Fossil	1,555	1,908	1,297	1,448	1,207	1,188
Renewable	3,118	2,671	4,178	3,624	5,673	5,428
Wind	1,209	1,016	1,844	1,559	2,687	2,395
PV	871	829	1,226	1,247	1,638	2,294

Table 3: APS Scenario Electricity Production (TWh): Weo 2024 vs OSeMOSYS

APS	WEO	OSeMOSYS	WEO	OSeMOSYS	WEO	OSeMOSYS
Year	2030	2030	2035	2035	2050	2050
Total	5,027	4,878	6,059	5,638	8,174	7,948
Coal	180	54	97	5	56	31
Gas	476	780	251	608	73	315
Nuclear	795	889	802	664	1,172	906
Fossil	1,451	1,732	1,150	1,313	1,301	1,251
Renewable	3,540	3,146	4,888	4,325	6,846	6,697
Wind	1,441	1,229	2,297	1,931	3,540	3,273
PV	1,021	1,063	1,438	1,577	1,863	2,685

To answer *RQ1*, the thesis performs a focused benchmarking exercise comparing OSeMOSYS outputs with IEA WEO 2024 results for Continental Europe, as reported in Table 2 and Table 3. Owing to data-availability constraints, the comparison is limited to STEPS and APS Scenarios (European annex detail is not available for WEO 2024 NZE), and it concentrates on indicators where a direct alignment is feasible, most notably total electricity production by sources, while excluding a direct CO_2 benchmarking because WEO regional emissions are not reported exclusively for the power sector. Before comparison, datasets are harmonized by converting OSeMOSYS outputs from net to gross electricity (accounting for own use/auxiliary loads), enabling a like-for-like comparison with WEO reporting conventions.

Overall, the benchmarking shows that, despite its simplified structure, OSeMOSYS captures the aggregate 2050 outcome for Continental Europe with high robustness, especially once results are grouped into macro-categories. At the same time, the model exhibits non-negligible divergences along intermediate trajectories and at the level of single technologies, reflecting the fundamental difference between a deterministic, perfect-foresight least-cost optimizer (OSeMOSYS) and a policy-driven scenario framework (GEC Model of WEO 2024).

In STEPS (Table 2), OSeMOSYS underestimates total electricity generation relative to WEO 2024 by roughly 3% in 2030, 8% in 2035, and 4% in 2050; however, by 2050 it reproduces the broad macro-division with high accuracy, underestimating fossil-based generation by only ~1.5% and total renewable (plus other zero-carbon) generation by ~4% versus WEO, as in Table 2.

In APS (Table 3), the model similarly underestimates total generation by approximately 3% in 2030, 7% in 2035, and 3% in 2050, a divergence primarily attributable to different assumptions on electricity demand evolution and technology performances, in particular, a linear demand growth profile in OSeMOSYS versus a more non-linear pathway embedded in WEO. Yet, when aggregated into Fossil vs. Renewable/Zero-carbon macro-categories, alignment improves markedly: by 2050, OSeMOSYS underestimates fossil generation by ~3.8% and renewable/zero-carbon generation by ~2%, confirming that the simplified optimization logic is broadly consistent with the benchmark at the system-wide level even when technology-specific paths differ.

It is therefore essential to underscore that while OSeMOSYS accurately replicates the 2050 macro-level electricity production split for Continental Europe, it exhibits noticeable divergences in intermediate milestones and specific technology trajectories. These discrepancies are primarily attributable to the drivers analyzed in Section 7.1.

7.1 Main drivers of discrepancies: OSeMOSYS vs WEO 2024

- Optimization vs. policy-driven scenario logic: OSeMOSYS identifies a mathematical least-cost solution, whereas WEO pathways reflect policy design, feasibility constraints, and institutional inertia and political preferences.
- Perfect foresight vs. recursive dynamics: OSeMOSYS internalizes all future costs/constraints up to 2050 at once, enabling "just-in-time" investments and faster turnover than the more incremental, year-anchored evolution typical of WEO modelling.
- Cost-centric objective function: the OSeMOSYS optimizer does not natively value qualitative objectives (e.g., energy security, geopolitical risk, diversification), which are often central to the policy-driven scenarios modeled by the IEA.
- Policy representation: without explicitly encoding detailed policy instruments (targets, subsidies, phase-out agreements), OSeMOSYS follows the most cost-efficient path, often accelerating coal phase-out relative to WEO.
- Technology allocation mechanism: linear programming tends toward corner solutions (technology polarization), while WEO uses adoption/market-share formulations, such as Logit and Weibull functions, that yield smoother and more diversified mixes.
- Geographic aggregation: a single-region Continental Europe representation cannot fully capture country-level heterogeneity, localized resource constraints, and national targets reflected in WEO results.
- Operational detail: simplified operational constraints (no ramping, start-up, minimum stable output, etc.) reduce "system friction," allowing more abrupt shifts than in WEO.
- Data and forecasting depth: The WEO draws on extensive high-quality primary data and proprietary forecasting tools, whereas this OSeMOSYS study relies on publicly available datasets; this can introduce additional uncertainty and reduce the level of market granularity, limiting full alignment with IEA projections.

8 Results across scenarios (RQ2)

Across scenarios, the model produces an increasingly deep decarbonization of the generation mix as climate ambition rises, with a growing dominance of renewables and an evolving role for firm capacity. The total discounted system cost (objective value) increases with ambition: STEPS is the least costly at 3,754.8 billion USD, APS rises to 4,501.1 billion USD (+19.9% vs STEPS), and NZE reaches 5,179.8 billion USD (+37.9% vs STEPS), reflecting the scale of investment required to achieve near-zero or zero emissions by mid-century.

A major driver of these cost differences is the assumed electrification intensity and therefore electricity demand growth. The model uses trajectories that scale from a 2024 baseline of 3,481 TWh to 5,950 TWh in STEPS, 7,088 TWh in APS, and 7,671 TWh in NZE by 2050, requiring proportionally higher capacity additions and infrastructure buildout under more ambitious pathways.

In emissions terms, the scenarios exhibit distinct end-states by 2050. The thesis reports that STEPS maintains high residual emissions (around 140 Mt CO_2 in 2050), APS reduces emissions to a low residual level (around 35 Mt CO_2 in 2050), while NZE achieves full carbon neutrality by 2049–2050 under the imposed zero-emission requirement.

Within the NZE pathway, the thesis highlights a non-linear decarbonization profile: although a linear emission trajectory is imposed as a constraint, the model endogenously generates an almost exponential decline due to interacting drivers, rising carbon tax, declining renewable CAPEX, retirement of the existing fleet, and investment constraints on fossil fuel technologies, pushing decarbonization earlier than the minimum required profile.

A recurring insight across scenarios is that economic signals alone are insufficient to deliver the full transition on the required timeline. Even with falling renewable costs and increasing carbon prices, the model indicates that deep decarbonization requires complementary policy frameworks and feasibility mechanisms that prescribe and accelerate fossil phase-out and support less immediately competitive technologies.

Finally, as renewables dominate the mix, the role of conventional technologies structurally shifts from bulk energy provision to peaking and firm capacity, primarily to cover demand peaks and provide adequacy and flexibility rather than base generation, with a corresponding decline in their capacity factors as they are dispatched less frequently and for shorter periods. The results suggest that completing the fossil phase-out increasingly depends on additional system flexibility, especially demand-side flexibility and long-duration energy storage (LDES), shifting electricity from periods of surplus renewable output (visible as curtailment) to periods of low renewable availability and higher demand.

9 Horizon effect

An additional chapter explicitly investigates a classic optimization artefact: the horizon effect and the role of salvage value in distorting end-of-period investments. The thesis focuses on the APS scenario, where the 2050-limited run exhibits concentrated late investments (e.g., onshore wind, biomass, run-of-river) that appear opportunistic rather than structurally motivated. To isolate the effect, the model is re-run with an extended horizon to 2070, holding parameter values constant beyond 2050, and results up to 2050 are compared between the two horizons. The longer horizon also reshapes technology competition. For CCS, the 2050 run tends to favour Gas CCS due to lower upfront costs, whereas the 2070 run allows high-CAPEX options to amortize and therefore shifts toward Coal CCS, which has markedly lower variable costs (driven mainly by lower coal fuel costs), making it more competitive over a longer timeframe. The extended horizon strengthens investments in high-CAPEX, near-zero marginal cost technologies and complements, most notably the solar PV-battery pairing and nuclear, because their cumulative savings become more valuable when evaluated over multiple decades. As a result, the 2050 production mix changes significantly under the 2070 horizon: Coal CCS increases (reported +37.5%), solar PV rises (+7.1%), while both onshore and offshore wind decline (about −6% to −7%). The PV-dominant mix increases flexibility needs, which the model meets through higher use of peaking generation and storage, including increased output from SCGT (+47.5%), CCGT (+13%), and greater dispatch of batteries and pumped hydro (about +6%). Overall, the 2070 horizon delivers a more "structural" least-cost architecture by 2050, built around a firm CCS baseload plus high PV shares supported by flexibility resources, rather than relying on end-of-horizon renewable additions boosted by salvage value.

In emissions terms, the horizon effect produces a trade-off: with extended foresight, the model decarbonizes faster in the early-to-mid term (up to −9.6% emissions by 2043 relative to the 2050 run), but it ends with higher residual emissions in 2050 (43.45 Mt vs 35.85 Mt) because the longer-horizon solution selects more firm capacity (notably higher Coal CCS and SCGT) to support system adequacy under higher PV penetration.

10 Limitations and future work

This section examines the limitations of the 2050 European power system optimization, arising from the simplified modeling required for the RQ1 benchmarking. Key constraints include a single-region representation, simplified operations (e.g., no ramping), low temporal resolution, asset aggregation and electricity-only scope. The current focus on the power sector alone significantly limits the comprehensiveness of the findings within the analysis. Expanding the scope to total primary energy consumption represents the most critical future development. Future work will address these gaps by integrating higher temporal resolution, stringent flexibility constraints, long-duration storage, and sector-coupling extensions.

11 References

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