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The 35-35 energy equation: understanding Switzerland's goal of 35 TWh renewable energy in 2035 through the lens of cumulative energy demand

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Abstract. In 2023, Switzerland set a goal of producing 35 TWh per year from renewable sources by 2035 and developed three deployment scenarios to reach it through specific technology mixes of renewable energy production. However, current models do not consider the impact of the cumulative energy demand (CED) of those technologies, accounting for production, transport, installation, performance, maintenance, and disposal. This study integrates CED and its related uncertainty using a 90% confidence interval (CI) to compare net energy across three future energy scenarios. The diverse renewable sources scenario yields a median net production of 29.1 TWh (90% CI: [27.7, 30.2]) and requires 6.24 GW of additional capacity to meet the 35 TWh target. The solar PV-focused scenario, with the highest embodied energy due to battery storage demands, has the lowest net output at 25.2 TWh (90% CI: [23.7, 26.5]), necessitating an extra 11.35 GW. The productivity-maximization scenario achieves the highest net production at 30.8 TWh (90% CI: [29.5, 31.7]), requiring 3.68 GW more capacity. In all energy scenarios, increasing gross renewable targets is essential to reach the net 35 TWh/year goal. Optimizing renewable deployment by prioritizing low CED technologies, such as wind, can maximize net energy production. Policymakers should incorporate embodied energy metrics into planning to ensure sustainable and realistic energy transition strategies.

1. Introduction

The transition to low-carbon energy solutions is a current challenge for society at the global and local levels. Multiple countries worldwide have put renewable energy strategies in place to address it. A deep and rapid transformation of the Swiss electricity supply is a prerequisite to achieving Switzerland's Energy Strategy 2050 goals [1]. Zero-carbon electricity supply forms the backbone of Switzerland's net-zero emissions strategy, underpinning substantial electrification in the transportation and heating sectors [1]. With a planned nuclear phase-out and limited carbon capture and storage options, Switzerland must significantly scale up renewable energy production to reach net-zero carbon emissions by mid-century. The Federal Act on a Secure Electricity Supply from Renewable Energy Sources (*the Mantelerlass*), mandates this expansion, targeting renewable energy production of 35 TWh annually by 2035 from hydropower, solar photovoltaic (PV), wind, and biomass. Studies suggest solar PV alone could potentially generate up to 25 TWh annually, underscoring its central role due to rapid technological advancements and scalability [2, 3]. However, existing renewable energy targets largely overlook the total energy required throughout the lifecycle of renewable technologies, including production, transportation, maintenance, and disposal. This oversight can underestimate environmental impacts, resulting in a misleading perception of sustainability [4] and the net environmental benefit of supposedly clean renewable energy technologies [5].

2. Background

2.1 EU and Swiss renewable energy targets

Switzerland's renewable energy targets align closely with broader European Union (EU) policy frameworks, notably the EU's *"Fit for 55"* legislative package and the overarching European Green Deal, which aims for a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels [6]. The EU aims for a renewable energy share of approximately 40% of gross final energy consumption by 2030, effectively doubling the renewable proportion from the 2019 baseline of 19.7% [7].

Despite differences in scale and specificity, both Switzerland and the EU face strategic challenges such as enhancing grid infrastructure, energy storage, and cross-border energy trade, essential for reliable renewable electricity integration [8]. In addition, many renewable energy targets focus primarily on operational energy use, while the required energy, which accounts for the entire lifecycle of energy systems, including production, operation, and disposal, remains underemphasized. This oversight introduces uncertainties, as existing techno-economic models and geographical boundaries typically fail to integrate these metrics into typical policy frameworks.

2.2 Current policy integration of embodied energy

While renewable energy policies in Switzerland and the EU emphasize decarbonization and operational efficiency, they often overlook the energy required for the deployment of renewable technologies across an energy system's entire lifecycle, leading to an incomplete sustainability assessment.

A primary gap in existing policies is their limited application of embodied energy considerations, mostly confined to the building sector. Embodied energy refers to the total energy consumed in producing and transporting materials, components, and infrastructure [9]. Chen et al. (2019) [4] highlight that embodied energy analysis *"provides a more integrated perspective on energy consumption and demand"* and offers a scientific basis for policy-making to enhance energy security and sustainability. Still, the concept remains inadequately integrated into current Swiss and EU policies. Switzerland's SIA Efficiency Path 2040 [10] and the EU's Energy Performance of Buildings Directive [7]) offer some degree of lifecycle energy accounting but only address embodied energy in building standards and assessments.

A second gap arises from how embodied energy is typically measured. While this concept provides valuable insights into the initial energy required for constructing energy infrastructure, it falls short in capturing the full lifecycle energy demand over time. To bridge this gap, Cumulative Energy Demand (CED) offers a complementary metric. Unlike embodied energy, which primarily focuses on upfront energy accounting, CED accounts for all energy inputs throughout a system's entire lifecycle, including production, transport, maintenance, and end-of-life energy implications. This is particularly relevant when assessing net energy scenarios and developing energy policies that aim for long-term sustainability. Therefore, CED and the uncertainties linked to lifecycle energy demand should be considered in net energy scenarios for future renewable energy deployment.

2.3 Three deployment scenarios for 35 TWh of renewables in 2035

The SWEET EDGE project, as detailed in the Renewable Energy Outlook [3], has developed three future deployment scenarios to achieve Switzerland's renewable energy targets, each with distinct implications for embodied energy:

Diverse Scenario (University of Geneva): Utilizing the EXPANSE model, this scenario explores near-optimal energy transition pathways by evaluating energy capacity expansion and transmission at high spatial resolution, incorporating both national and international energy exchanges. Therefore, it focuses on technological diversity, integrating various renewable sources (wind, solar, biomass, etc.) to ensure supply security, with wind deployment in the Jura mountains [3].

Solar PV-Focused Scenario (ETH Zurich): The Nexus-e platform integrates centralized and distributed energy perspectives, optimizing energy generation, transmission, and investment strategies, with a focus on consumer-driven investments such as rooftop solar and battery storage. Therefore, it focuses on solar PV with batteries while also relying on pumped hydropower and electricity imports [3].

Productivity-Maximization Scenario (EPFL): The OREES model determines efficient investment strategies for solar and wind energy while ensuring grid stability, integrating hydropower infrastructure dynamics, seasonal storage, and interconnection constraints to enhance national energy autonomy. Therefore, it focuses on maximizing productivity by concentrating solar and wind installations in optimal geographical locations to maximize energy output [3].

3. Methodological Approach

This study places the focus on *net energy* when developing energy policies and modeling target energy scenarios. For that, we use Cumulative Energy Demand (CED), which includes energy consumed across the entire lifecycle, and we consider different levels of uncertainty in the scenarios deployed. Thus, our methodology proceeds in two main steps: first, we establish a stochastic Cumulative Energy Demand (CED) assessment for each technology, and then we apply the resulting distributions to scenario-based analyses of net energy production. Finally, we examine whether each scenario can reliably meet or exceed a 35 TWh net energy target under uncertainty, computing any additional capacity expansions needed to achieve that threshold with a 90% confidence interval.

3.1. Cumulative energy demand assessment

We considered epistemic uncertainty due to the limited knowledge in the real installations of Switzerland, which are addressed with values derived from literature. While some parameters (e.g., global horizontal irradiation and capacity factor) do have inherent natural variability (aleatory uncertainty), the way these parameters' ranges are defined is intended to capture the uncertainty due to the lack of knowledge of current and future installations.

For each technology, we identified key parameters that significantly influence the CED. Mean CED values reported in the literature (see Table 1) serve as reference points. To compute the CED, we used technology-specific equations that relate input parameter values to the overall energy output over the system's operational life. This enabled us to integrate life cycle stages and derive a final CED value in MJ/kWh, reflecting the energy expended per unit of electricity generated (or stored).

We assumed a Beta-PERT distribution for each uncertain parameter because it requires only three intuitive inputs (minimum, mode, maximum), while maintaining flexibility in how the distribution curves toward the most likely value. To propagate parameter uncertainties into our final CED estimates, we employed Monte Carlo sampling, drawing thousands of samples (e.g., 50,000) from each Beta-PERT distribution. For each iteration, a random draw for each uncertain parameter is used to calculate a single CED outcome per technology. Repeating this many times yields a probability distribution of potential CED values, allowing us to analyse median results, quantiles, and overall variation.

Table 1. Uncertainties Description per Technology

Technology	Uncertainty	Range [Min, Median, Max]	Mean CED per technology (MJ/kWh)	Reference
Photovoltaic Panels	Global Horizontal Irradiation (kWh/m2/year)	[800, 1100, 1500]	1.05	Asdrubali et al. (2015) [11]
	Lifetime (years)	[20, 25, 30]		
	Performance Ratio (%)	[75, 85, 90]		
Wind	Lifetime (years)	[15, 20, 25]	0.19	Asdrubali et al. (2015) [11]
	Capacity Factor (%)	[10, 25, 35]		
Biomass	Annual Plant Efficiency (%)	[50, 80, 100]	2	Nussbaumer & Oser (2004) [12]
	Transport distance of fuel* (km)	[5, 50, 5000]		
Battery (Li-Ion)	Specific Energy Density (kWh/kg)	[0.05, 0.16, 0.30]	0.97	Peters et al. (2017) [13]

*fuel is considered here as wood, eco-pellet, pellet and wood chips.

3.2. Scenario analysis and comparison of net energy

We employed the three deployment scenarios proposed by the SWEET EDGE project, which define different installed capacities for each technology as follows: The diverse renewable sources scenario has 22,300 MW of solar, 900 MW of biomass, and 1,800 MW of wind; the solar PV-focused scenario has 24,100 MW of solar, 500 MW of biomass, 100 MW of wind, and 200 MW of batteries; and the productivity-maximization scenario has 18,900 MW of solar, no biomass, and 2,200 MW of wind. To estimate the annual energy output for each technology, we applied historically based production figures from the Energiereporter database [14] corresponding to 758.1 MWh/MW for photovoltaic (PV) systems, 647.7 MWh/MW for biomass, and 9,924.7 MWh/MW for wind energy. For batteries, we assumed their role in bridging the gap between combined renewable generation and the 35 TWh target.

We then integrated the Monte Carlo outputs from our CED distributions, generated with Beta-PERT sampling, by subtracting the fraction of total life cycle energy (CED) from each technology's deterministic electricity output. Repeating this procedure for 50,000 iterations furnished a robust picture of each scenario's net energy range, allowing us to compare median production levels, standard deviations, and confidence intervals. Lastly, to find out how much technology should be deployed per scenario to achieve 35 TWh of Net Energy at the 90% confidence interval, we computed an additional scaling factor to increase installed capacities as needed, considering the same technology mix.

4. Results

4.1 Cumulative energy demand estimates for each scenario

Analysis of cumulative energy demand (CED) distributions reveals substantial variability across renewable technologies (Figure 1). Wind energy shows the lowest CED at 0.19 MJ/kWh, with minimal uncertainty, which reflects its efficiency and low lifecycle energy requirements. Solar photovoltaic (PV) has a moderate mean CED of 1.05 MJ/kWh, with a wider distribution than wind, indicating some variability due to the global horizontal irradiation and lifetime. Biomass exhibits the highest CED at approximately 2.0 MJ/kWh, with a broad uncertainty range, highlighting the energy-intensive nature of fuel harvesting, processing, and transportation distance. Battery storage, modeled separately for the solar PV-focused scenario, has a mean value of 0.97 MJ/kWh of CED with a variation due to the energy density that depends on the material capacity and inefficiencies in the discharge.

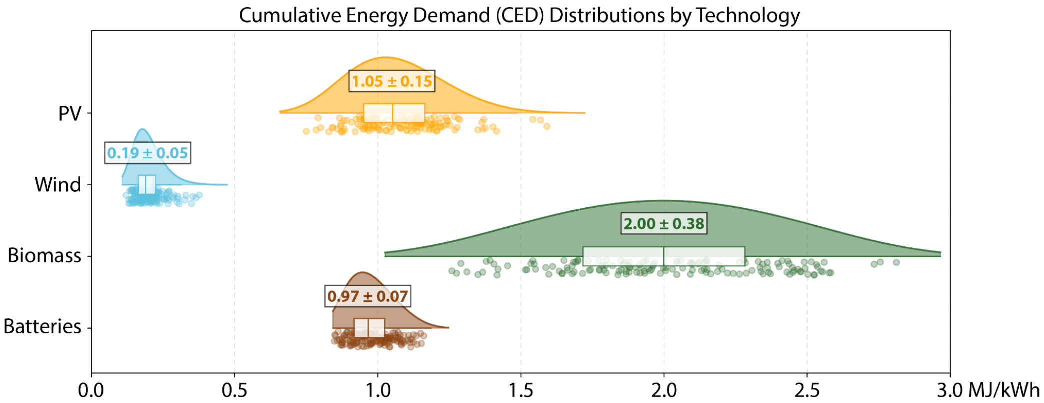

Figure 1. Sampling distributions of CED per technology

4.2 Net energy calculations after factoring in CED

Our analysis explicitly accounting for CED highlights variability in net renewable energy achievable by 2035 across the three deployment scenarios:

- **The diverse renewable sources scenario** (Figure 2, top) indicates a median net energy production of 29.1 TWh/year, with a 90% confidence interval suggesting that the net energy is likely between 27.7 and 30.2 TWh/year. Integrating solar PV, biomass, and wind, this scenario provides a balanced output. To meet the 35 TWh target with a 90% confidence, the deployment of approximately 6.23 GW extra new technologies is required.
- **The solar PV-focused scenario** (Figure 2, middle) exhibits the lowest median net energy production at 25.2 TWh/year with a 90% confidence interval between 23.7 to 26.5 TWh/year, primarily due to the high embodied energy of biomass required to balance solar PV intermittency. To reach the 35 TWh goal with a 90% confidence interval, an increaseof 11.33 GW on the installed power is necessary.
- **The productivity-maximization scenario** (Figure 2, bottom) achieves the highest initial net energy production of 30.8 median TWh/year with a 90% confidence interval between 29.5 to 31.7 TWh/year, benefiting from optimized wind and solar PV placement that minimizes embodied energy impacts. 3.67 GW extra installed power would be needed to meet the 35 TWh goal with a 90% confidence interval.

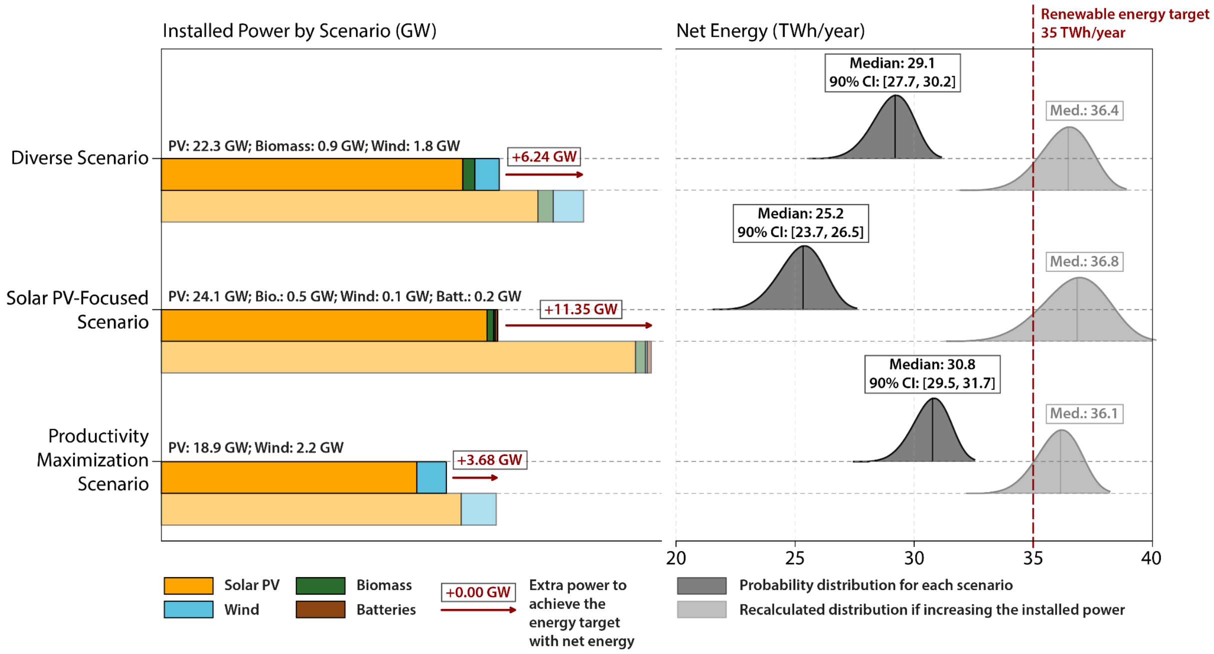

Figure 2. Installed power per technology and net energy distributions per scenario

5. Discussion

The results highlight how some/specific energy technologies offer higher certainty than others when dealing with the uncertain future of the desired energy transition. That is, variability both in uncertainty and demand is observed across the studied renewable technologies. Solar PV, for instance, shows a wider uncertainty range compared to wind energy, making the latter a more predictable option in future modeling. Conversely, biomass requires the highest energy demand due to energy-intensive processes like fuel harvesting and transportation. Thus, regardless of technological uncertainty, biomass remains a high-energy, energy-intensive option in any scenario.

The comparison of the three deployment scenarios gives us insights into the *"right"* energy mix to achieve the target goals. An optimized mix of wind and solar PV, as seen in the productivity-maximization scenario, indeed yields the highest net energy production. The diverse renewables scenario, which incorporates biomass, provides a balanced mix but requires additional capacity adjustments to meet the 35 TWh target. The solar PV-focused scenario suffers from higher CED due to battery storage requirements. It is important to note This analysis considers only domestically installed power in Switzerland, excluding imported energy from international exchanges. Based on these findings, we can extract several recommendations to increase the share of net energy when modeling future deployment strategies. Policymakers should integrate embodied energy metrics into renewable energy planning to avoid overestimating net energy potential and prioritize technologies with lower CED to meet long-term sustainability targets.

6. Conclusion

This analysis emphasizes that for future energy scenarios based on renewable energy production, it is crucial to account for cumulative energy demand (CED). Without considering CED, the true environmental and sustainability impacts of renewable technologies may be overlooked. By incorporating CED into energy planning, policymakers and scientists can more accurately evaluate the long-term viability of renewable energy solutions and ensure more effective and informed energy policies.

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