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Développement d'une méthode d'évaluation intégrée pour concevoir des stratégies en matière d'énergie, climat et qualité de l'air

Development of an Integrated Method for Formulating Strategies Concerning Energy, Climate, and Air Quality

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Résumé

Depuis le début du XIXe siècle, la consommation mondiale d'énergie a connu une augmentation fulgurante, principalement alimentée par les énergies fossiles. Cette dépendance soulève deux défis majeurs : d'une part, elle expose les économies à une forte volatilité, comme en témoignent les chocs pétroliers historiques et les crises énergétiques, tandis que l'épuisement progressif des réserves et l'augmentation des coûts d'extraction contribuent à l'instabilité des prix et à l'incertitude économique. D'autre part, la combustion des énergies fossiles libère des gaz à effet de serre (GES) et des polluants atmosphériques, accélérant ainsi le changement climatique.

Les projections indiquent une hausse de la température mondiale de 1,5 °C à 4,5 °C d'ici 2100, entraînant une augmentation de la fréquence et de l'intensité des événements météorologiques extrêmes, des perturbations des cycles hydrologiques, une dégradation des écosystèmes, une baisse des rendements agricoles et des déplacements de populations depuis des régions de plus en plus inhabitables. Ces impacts soulignent l'urgence de mettre en place des stratégies globales combinant adaptation et atténuation pour faire face aux conséquences étendues du changement climatique.

Les stratégies d'adaptation visent à réduire la vulnérabilité des sociétés et des écosystèmes face aux impacts climatiques, notamment par le développement de systèmes d'alerte précoce, d'infrastructures résilientes, de relocalisation des communautés et de pratiques agricoles durables pour sécuriser les ressources alimentaires et hydriques. Cependant, l'adaptation seule pourrait s'avérer insuffisante si les seuils climatiques critiques sont dépassés, rendant indispensables les efforts d'atténuation pour réduire les émissions de gaz à effet de serre à la source. Bien que des solutions de géo-ingénierie, telles que la gestion du rayonnement solaire ou l'élimination du dioxyde de carbone, aient été proposées, elles restent controversées en raison de leurs effets imprévisibles sur les systèmes atmosphériques complexes et de leur incapacité à traiter la cause profonde des émissions. Une transition énergétique durable nécessite une approche holistique, évaluant et intégrant des options technologiques viables tout en tenant compte des facteurs économiques, sociaux et environnementaux pour garantir une stabilité et une résilience à long terme.

Pour ces raisons, il est essentiel de concevoir et d'évaluer des stratégies énergétiques axées sur le remplacement des sources d'énergie fossiles par des alternatives durables, afin de réduire efficacement l'impact environnemental.

Les sources d'énergie peuvent être classées selon différents critères. Une distinction fondamentale repose sur leur caractère renouvelable et leur capacité à se renouveler, les divisant en sources d'énergie non renouvelables (EnRn) et en sources d'énergie renouvelables (EnR). Une autre classification clé concerne leur capacité à ajuster la production d'énergie en réponse aux fluctuations horaires de la demande. Les sources contrôlables, qui incluent à la fois les EnR (comme l'hydroélectricité, la géothermie et la biomasse) et les EnRn (comme le nucléaire et les centrales thermoélectriques), peuvent adapter leur production pour répondre aux variations de la demande. En revanche, les sources intermittentes, comme l'énergie solaire et éolienne, dépendent de la disponibilité de leurs ressources primaires (ensoleillement ou vent) et ne peuvent pas aligner leur production sur les fluctuations de la demande en temps réel. Cette variabilité intrinsèque pose des défis uniques pour la stabilité du réseau et la planification des systèmes énergétiques.

L'énergie solaire et éolienne joue un rôle crucial dans la transition énergétique, car ce sont des EnR qui génèrent très peu de GES et dont les coûts ont régulièrement diminué au cours des dernières décennies. Cependant, ces sources ne peuvent pas répondre à toutes les fluctuations horaires de la demande et doivent donc être combinées avec d'autres sources adaptées. Ce problème d'intermittence devient plus critique à mesure que la part des énergies solaire et éolienne augmente dans le mix énergétique, car l'introduction de sources intermittentes modifie les caractéristiques de toutes les sources contrôlables du système, c'est-à-dire la production d'énergie et la capacité installée.

La conception de stratégies énergétiques présente plusieurs difficultés, notamment l'existence d'un nombre infini de combinaisons technologiques possibles pour répondre à la demande énergétique, ainsi que la complexité de comparer ces combinaisons à l'aide de plusieurs indicateurs (ou critères de décision).

Les méthodes existantes pour concevoir et évaluer les stratégies énergétiques se divisent en deux catégories : i) les méthodes d'optimisation qui considèrent de nombreux scénarios mais un seul indicateur (généralement les coûts économiques), ou ii) la comparaison de scénarios sélectionnés par des experts, qui peuvent utiliser plusieurs indicateurs mais ne considèrent que quelques scénarios. Une approche alternative étend la méthode d'optimisation pour générer plusieurs solutions, formant une courbe de Pareto, qui illustre les compromis entre les caractéristiques (par exemple, les émissions de GES et les coûts), permettant une représentation graphique des scénarios et simplifiant la sélection du compromis optimal.

Dans cette thèse, une méthode est développée en s'inspirant de certains éléments des méthodes typiques de conception et d'évaluation des stratégies énergétiques. Cependant, cette méthode intègre plusieurs aspects innovants : i) elle distingue deux types de sources en fonction de leur capacité à adapter leur production d'énergie aux fluctuations horaires de la demande : les sources contrôlables et les sources intermittentes ; ii) elle peut évaluer plusieurs indicateurs d'intérêt pour les décideurs et est conçue pour intégrer facilement de nouveaux indicateurs locaux ; iii) les tendances des caractéristiques du système et des indicateurs sont évaluées à travers de nombreux scénarios conçus autour de l'introduction d'énergies intermittentes dans le mix ; iv) le mix de technologies de production d'énergie dans les scénarios est défini sur la base de l'optimisation des coûts ; v) elle peut considérer des scénarios avec différentes valeurs de demande projetée ; vi) elle permet une représentation graphique simultanée des tendances pour tous les indicateurs et caractéristiques des scénarios (par exemple, la production d'énergie, la capacité installée et les coûts annuels totaux) ; et vii) elle permet une analyse de sensibilité de l'adaptation temporelle de la demande à la production d'énergie dans les scénarios optimisés. De plus, les effets du stockage d'énergie sur les scénarios optimisés ont été étudiés.

Un aspect novateur intégré à la méthode est la capacité de réaliser une analyse de sensibilité pour évaluer l'adaptation des fluctuations temporelles de la demande à la production d'énergie à différentes échelles de temps, telles que quotidienne ou saisonnière. Cependant, la mise en œuvre de l'adaptation de la demande est techniquement complexe et coûteuse en raison des aspects sociaux, politiques et technologiques. Compte tenu de l'urgence d'accélérer la transition énergétique, les politiques devraient privilégier la réduction globale de la demande énergétique plutôt que son adaptation aux profils temporels variables, car cette approche est susceptible de produire des résultats plus rapides et plus concrets.

La méthodologie a été testée à l'aide de deux études de cas : i) la région Grand Est en France et ii) Cuba. Ces deux cas présentent des caractéristiques complémentaires pour les raisons suivantes : premièrement, Cuba, située dans la zone intertropicale, dispose d'un potentiel solaire significativement plus élevé que les latitudes moyennes où se trouve la région Grand Est. Deuxièmement, la localisation des deux régions entraîne des variations saisonnières différentes de la demande et de la production d'énergie intermittente (solaire et éolienne), Cuba présentant des variations saisonnières beaucoup plus faibles que la région Grand Est. Troisièmement, le scénario officiel des autorités cubaines anticipe une augmentation de la demande énergétique dans les décennies à venir, reflétant la trajectoire de développement économique typique d'une nation en développement, tandis que la demande énergétique dans la région Grand Est a diminué depuis les années 2000 malgré la croissance du Produit Intérieur Brut (PIB) de la région, et les autorités locales projettent que cette tendance de découplage entre la demande énergétique et la croissance économique se poursuivra à l'avenir. Les indicateurs utilisés incluent les coûts, les émissions de GES, l'utilisation de sources non renouvelables et de ressources locales.

L'analyse de la région Grand Est utilise 2021 comme année de référence, choisie pour éviter les distorsions de la demande énergétique causées par la pandémie de COVID-19 en 2020. En 2021, la consommation totale d'énergie de la région a atteint 176 TWh/an, dont 44 TWh/an consommés sous forme d'électricité et 133 TWh/an sous forme de combustibles fossiles. La consommation primaire d'énergie pour la production s'est élevée à 291 TWh/an, incluant 102 TWh/an d'énergie importée (combustibles fossiles et uranium enrichi pour le nucléaire). La production d'électricité dans la région a atteint 100 TWh/an, provenant du nucléaire (61,3 TWh/an), de la biomasse (1,1 TWh/an), du biogaz (5 TWh/an), de l'hydroélectricité (9,8 TWh/an), du solaire (5,8 TWh/an) et de l'éolien (18 TWh/an). Malgré l'exportation de 56 TWh/an d'électricité, la région est restée importatrice nette d'énergie en tenant compte des importations d'énergie primaire et des importations occasionnelles d'électricité (~5 TWh/an) lors des pics de demande.

La stratégie énergétique à long terme de la région, décrite dans le plan SRADDET (2030–2050), vise une dénuclearisation progressive, une autonomie électrique totale et une décarbonation profonde. D'ici 2050, la demande totale d'énergie devrait être réduite de moitié à 89,6 TWh/an, tandis que la part de l'électricité dans le mix énergétique passera de 25 % à 44 %. Les changements sectoriels de la demande incluent des réductions marquées dans les secteurs résidentiel (-93 %) et tertiaire (-58 %), ainsi qu'une croissance dans l'industrie (+58 %) et les transports (+203 %). Pour répondre à la demande, le plan s'appuie sur une maximisation de l'hydroélectricité et de la biomasse, ainsi que sur une expansion du solaire (+2,5 TWh/an), de l'éolien (+12 TWh/an) et du biogaz (+11,6 TWh/an). Cependant, le potentiel du biogaz pourrait être surestimé : des évaluations réalistes suggèrent que seulement 6,8 TWh/an sont réalisables, nécessitant l'importation de 4,8 TWh/an de biogaz. En utilisant le scénario SRADDET comme référence, la méthode de cette étude évalue les impacts d'une augmentation de la production solaire et éolienne sur les coûts, les émissions de GES, la dépendance aux EnRn et les importations, estimant des coûts de production de 2,77 milliards de dollars/an, des émissions de 6 117 tCO_2/an, une utilisation nulle d'EnRn et des importations de 4,8 TWh/an de biogaz dans les conditions de référence.

Pour la région Grand Est, la tendance de la demande est un facteur critique dans la détermination de la stratégie énergétique optimale. Si la demande d'électricité est faible et en déclin, la région pourrait facilement répondre à ses besoins entièrement par des EnR, avec une part intermittente couvrant 60 % à 90 % de la demande sans coûts excessifs ou utilisation importante des terres. En revanche, si la demande est élevée et en croissance, les décideurs sont confrontés à un compromis : opter pour les EnR (économiques mais gourmandes en espace) ou intégrer l'énergie nucléaire (moins gourmande en espace mais plus coûteuse).

L'année 2015 a été choisie comme point de référence pour analyser le système énergétique cubain, car elle offre des données complètes et accessibles, et représente une période stable non affectée par les perturbations ultérieures, telles que la pandémie de COVID-19. En 2015, la consommation totale d'énergie de Cuba a atteint 46 TWh/an, dont 20,3 TWh/an sous forme d'électricité. Pour répondre à cette demande, le pays a utilisé 103,3 TWh/an de ressources énergétiques primaires, dont 74,5 TWh/an dédiés à la production d'électricité.

La production d'électricité à Cuba en 2015 était dominée par les combustibles fossiles, en particulier le pétrole et ses dérivés. Les centrales thermoélectriques (à base de pétrole) ont généré 11,94 TWh/an, tandis que les groupes électrogènes alimentés au pétrole ont contribué

à hauteur de 4,40 TWh/an, représentant ensemble 80 % de la production totale d'électricité. Les turbines à gaz naturel ont ajouté 2,95 TWh/an, tandis que les sources renouvelables ont joué un rôle mineur : bagasse (0,90 TWh/an), hydroélectricité (0,05 TWh/an), éolien (0,04 TWh/an) et solaire (0,02 TWh/an).

Pour le scénario de référence 2030, le gouvernement cubain vise à atteindre une plus grande autosuffisance énergétique en : i) renforçant l'utilisation des combustibles locaux (pétrole brut et gaz naturel) ; ii) améliorant l'efficacité de la génération, de la distribution et de la consommation grâce à des mesures d'économie d'énergie ; iii) développant l'intégration des énergies renouvelables. Cette stratégie est détaillée dans le document « Cartera de oportunidades Cuba – 2017 », reflétant un virage vers un système énergétique plus durable et résilient.

Pour Cuba, l'autosuffisance énergétique (zéro importation) peut être atteinte en optimisant le scénario de référence, où 7 % de la demande est couverte par des sources intermittentes. En augmentant cette part à 100 %-140 %, les décideurs pourraient atteindre une plage où les coûts de production sont les plus bas, avec une forte part d'EnR et de faibles émissions de GES. Au-delà de 140 %, la situation évolue peu, car atteindre 100 % d'EnR et zéro émission de GES reste impossible.

Les scénarios sans stockage d'énergie nécessitent de maintenir une capacité installée suffisante de sources contrôlables pour répondre à la demande pendant les périodes où l'énergie intermittente n'est pas produite. La mise en œuvre du stockage d'énergie pourrait éliminer le besoin de sources contrôlables dans les scénarios où l'énergie intermittente génère une quantité d'énergie équivalente ou supérieure à la demande. Cependant, ces scénarios sont économiquement irréalisables en raison des coûts élevés associés au stockage d'énergie.

Certaines technologies sont économiquement compétitives en l'absence d'énergie intermittente dans le mix énergétique, mais deviennent non viables à mesure que le solaire et l'éolien sont introduits.

Mots clés : transition énergétique ; évaluation des scénarios ; intermittence ; changement climatique ; LCOE ; stockage de l'énergie

Abstract

Since the early 19th century, global energy consumption has surged, driven overwhelmingly by fossil fuels. This dependence presents two critical challenges: first, it exposes economies to volatility, as demonstrated by historical oil shocks and energy crises, while the gradual depletion of reserves and rising extraction costs contribute to price instability and economic uncertainty. Second, the combustion of fossil fuels releases greenhouse gases (GHG) and atmospheric pollutants, accelerating climate change.

Projections suggest a global temperature rise of 1.5°C to 4.5°C by 2100, leading to more frequent and severe extreme weather events, disruptions in water cycles, ecological degradation, reduced agricultural yields, and the displacement of populations from increasingly uninhabitable regions. These impacts highlight the urgent need for comprehensive strategies that combine adaptation and mitigation to address the far-reaching consequences of climate change.

Adaptation strategies aim to reduce the vulnerability of societies and ecosystems to climate impacts, including the development of early warning systems, climate-resilient infrastructure, community relocation, and sustainable agricultural practices to secure food and water resources. However, adaptation alone may be insufficient if critical climate thresholds are surpassed, making mitigation efforts essential to reduce greenhouse gas emissions at their source. While geoengineering solutions, such as solar radiation management or carbon dioxide removal, have been proposed, they remain controversial due to their unpredictable effects on complex atmospheric systems and their failure to tackle the root cause of emissions. A sustainable energy transition requires a holistic approach, evaluating and integrating viable technological options while considering economic, social, and environmental factors to ensure long-term stability and resilience.

For these reasons, it is essential to design and evaluate energy strategies focusing on replacing energy sources derived from fossil fuels with sustainable alternatives, to effectively reduce the environmental impact.

Energy sources can be categorized using different criteria. One fundamental distinction is based on their renewability and capacity for self-replenishment, dividing them into non-renewable energy sources (non-RES) and renewable energy sources (RES).

Another key classification focuses on their ability to adjust energy production in response to hourly fluctuations in demand. Controllable sources—which include both RES (such as hydropower, geothermal, and biomass) and non-RES (such as nuclear and thermoelectric plants)—can adapt their output to meet demand variations. In contrast, intermittent sources, like solar and wind energy, depend on the availability of their primary resources (sunlight or wind) and cannot align their production with real-time demand fluctuations. This inherent variability poses unique challenges for grid stability and energy system planning.

Solar and wind energy play a crucial role in the energy transition as they constitute RES that generate very few GHG and whose costs have been decreasing consistently during the last decades.

However, solar and wind sources cannot respond to all the hourly fluctuations of demand and must therefore be combined with other suitable sources. This intermittency problem becomes more critical as solar and wind sources share increases in the mixes, since the introduction of intermittent sources modifies the characteristics of all controllable sources in the system, i.e., energy production and installed power capacity.

The design of energy strategies presents several difficulties, notably the existence of an infinite number of possible technology combinations to meet energy demand, as well as the complexity of comparing these combinations using several indicators (or decision criteria).

Existing methods for designing and evaluating energy strategies are divided into two categories: i) optimization methods that consider many scenarios but only one indicator (typically economic costs), or ii) the comparison of expert-selected scenarios, which can use multiple indicators but only consider a few scenarios. An alternative approach expands the optimization method to generate multiple solutions, forming a Pareto curve, which illustrates the trade-offs between characteristics (e.g., GHG emissions and costs), enabling graphical representation of scenarios and simplifying the selection of the optimal compromise.

In this thesis, a method is developed by drawing inspiration from certain elements of typical energy strategy design and evaluation methods. However, this method includes several innovative aspects: i) It distinguishes two types of sources based on their ability to adapt their energy production to hourly demand fluctuations: controllable sources and intermittent sources; ii) It can evaluate multiple indicators of interest to decision-makers and is designed to easily integrate new local indicators; iii) Trends in system characteristics and indicators are evaluated across numerous scenarios designed around the introduction of intermittent energy into the mix; iv) The mix of energy production technologies in the scenarios is defined based on cost optimization; v) It can consider scenarios with different projected demand values; vi) It allows for graphical representation of trends for all indicators and scenario characteristics (e.g., energy production, installed capacity and total annual costs) simultaneously; and vii) It enables sensitivity analysis of the temporal adaptation of demand to energy production in optimized scenarios. Additionally, the effects of energy storage on optimized scenarios were studied.

One novel aspect integrated into the method was the capability of performing a sensitivity analysis to evaluate the adaptation of temporal fluctuations in demand to energy production across different time scales, such as daily or seasonal, etc. However, the demand adaptation implementation is technically challenging and costly due to social, political, and technological aspects. Given the urgency of accelerating the energy transition, policies should prioritize reducing overall energy demand rather than adapting it to time-varying patterns, as this approach is likely to yield faster and more concrete results.

The methodology has been tested using two cases of study: i) the Grand Est region of France and ii) Cuba. These two cases exhibit characteristics that make them complementary for the following reasons: Firstly, since Cuba is located in the intertropical zone, it has a significantly higher solar energy potential compared to the mid-latitudes where the Grand Est region is situated. Secondly, the location of both considered regions lead to different seasonal variation of the demand and the intermittent energy production (solar and wind), whereas Cuba exhibits much weaker seasonal variation than the Grand Est region. Thirdly, the official scenario of Cuban authorities anticipates rising energy demand in the coming decades, reflecting the economic development trajectory typical of a developing nation, in contrast, energy demand in the Grand Est region has declined since the 2000s despite the region's growing Gross Domestic Product (GDP), and local authorities project this trend of decoupling energy demand from economic growth to continue in the future. The indicators used include costs, GHG emissions, use of non-renewable sources and local resources.

This analysis of the Grand Est region uses 2021 as the base year, selected to avoid the distortions in energy demand caused by the COVID-19 pandemic in 2020. In 2021, the region's total energy consumption reached 176 TWh/year, with 44 TWh/year consumed as electricity and 133 TWh/year as fossil fuels. Primary energy consumption for production totaled 291 TWh/year, including 102 TWh/year of imported energy (fossil fuels and enriched uranium for nuclear power). Electricity generation in the region amounted to 100 TWh/year, sourced from nuclear (61.3 TWh/year), biomass (1.1 TWh/year), biogas (5 TWh/year), hydropower (9.8 TWh/year), solar (5.8 TWh/year), and wind (18 TWh/year). Despite exporting 56 TWh/year of electricity, the region remained a net energy importer when accounting for primary energy imports and occasional electricity imports (~5 TWh/year) during peak demand.

The region's long-term energy strategy, outlined in the SRADDET plan (2030–2050), aims for progressive denuclearization, full electricity autonomy, and deep decarbonization. By 2050, total energy demand is projected to halve to 89.6 TWh/year, while electricity's share in the energy mix rises from 25% to 44%. Sectoral demand shifts include sharp reductions in residential (-93%) and tertiary (-58%) consumption, alongside growth in industry (+58%) and transport (+203%). To meet demand, the plan relies on maximized hydropower and biomass, alongside expanded solar (+2.5 TWh/year), wind (+12 TWh/year), and biogas (+11.6 TWh/year). However, biogas potential may be overestimated—realistic assessments suggest only 6.8 TWh/year is feasible, requiring 4.8 TWh/year of biogas imports. Using the SRADDET scenario as a baseline, this study's method evaluates the impacts of increased solar and wind production on costs, GHG emissions, non-RES reliance, and imports, estimating \$2.77 billion/year in production costs, 6,117 tCO_2/year in emissions, zero non-RES use, and 4.8 TWh/year of biogas imports under the baseline conditions.

For the Grand Est region, the demand trend is a critical factor in determining the optimal energy strategy. If electricity demand is low and declining, the region could easily meet its needs entirely through renewable RES, with an intermittent share covering 60% to 90% of demand without excessive costs or significant land use. On the other hand, if demand is high and growing, decision-makers face a trade-off: opt for RES (economical but land-intensive) or integrate nuclear energy (less land-intensive but more costly).

The year 2015 was chosen as the reference point for analyzing Cuba's energy system, as it offers comprehensive, accessible data and represents a stable period unaffected by later

disruptions, such as the COVID-19 pandemic. In 2015, Cuba's total energy consumption reached 46 TWh/year, with electricity accounting for 20.3 TWh/year. To meet this demand, the country relied on 103.3 TWh/year of primary energy resources, including 74.5 TWh/year dedicated to electricity generation.

Cuba's electricity production in 2015 was dominated by fossil fuels, particularly oil and its derivatives. Thermoelectric power plants (oil-based) generated 11.94 TWh/year, while oil-fueled generator sets contributed 4.40 TWh/year, together accounting for 80% of total electricity production. Natural gas turbines added 2.95 TWh/year, while renewable sources played a minor role: bagasse (0.90 TWh/year), hydropower (0.05 TWh/year), wind (0.04 TWh/year), and solar (0.02 TWh/year).

For the 2030 baseline scenario, Cuba's government aims to achieve greater energy self-sufficiency by: i) enhancing local fuel utilization (crude oil and natural gas); ii) improving efficiency in generation, distribution, and consumption through energy-saving measures; iii) expanding renewable energy integration.

This strategy is detailed in the "Cartera de oportunidades Cuba – 2017" document, reflecting a shift toward a more sustainable and resilient energy system.

For Cuba, energy self-sufficiency (zero imports) can be achieved by optimizing the baseline scenario, where 7% of demand is met by intermittent sources. By increasing this share to 100%-140%, decision-makers could reach a range where production costs are lowest, with a high share of RES and low GHG emissions. Beyond 140%, the situation changes little, as achieving 100% RES and zero GHG emissions remains impossible.

Scenarios without energy storage require maintaining sufficient installed capacity of controllable sources to meet demand during periods when intermittent energy is not produced.

The implementation of energy storage can eliminate the need for controllable sources in scenarios where intermittent energy generates an amount of energy equivalent to or greater than demand. However, these scenarios are economically unfeasible due to the high costs associated with energy storage.

Some technologies are economically competitive in the absence of intermittent energy in the energy mix but become unviable as solar and wind are introduced.

Keywords: energy transition; evaluation of scenarios; intermittency; climate change; LCOE; energy storage

If I have seen further than others, it is by standing upon the shoulders of giants

Isaac Newton

Dedico este trabajo de investigación a las generaciones futuras, les deseo fortaleza y coraje que necesitamos todos para enfrentar los desafíos que vendrán con el cambio climático

I dedicate this research work to future generations. I wish you strength and courage, which we all need to face the challenges that will come with climate change

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Thesis introduction

1. Addressing fossil fuel world dependency and climate change

The world's energy consumption has been strongly increasing since the early 19th century. The major part of the resources to supply this increasing demand are currently fossil fuels (Figure 1)(BP, 2024; Energy" & Smil "Energy Transitions: Global and National Perspectives," 2024). This dependency on fossil fuels has two main drawbacks: i) Modern economies have faced three major oil shocks (1973, 1979, and 2008) and an energy crisis (2021-2022), highlighting their vulnerability to fluctuations in the oil market. Although new fossil fuel reserves are regularly discovered, they are being gradually depleted, and their extraction is becoming more challenging leading to higher production costs (Arbib & Seba, 2017; Jacobson, 2020; Madrazo Bacallao, 2018; Seba, 2014). This depletion creates uncertainties that reduce our ability to meet the growing energy demand, leading to fluctuations in energy prices amplified by speculation, which destabilizes world economies; ii) Fossil fuels burning main product is energy, however, their combustion also generates byproducts such as greenhouse gases (GHG) and substances harmful to human health (i.e., atmospheric pollutants).

Latest projections show that GHG emissions will cause a rise in global temperature from 1.5°C to 4.5°C on average in 2100(Intergovernmental Panel on Climate Change (IPCC), 2023). As a consequence of this climate change, different effects are attended(Holme & Rocha, 2023; Kotz et al., 2024), e.g., more frequent and extreme climatic events like heat waves in many regions will result in an intensification of human mortality and morbidity. Climate change is also altering the water cycle resulting in more frequent and severe floods and landslides, longer droughts and wildfires, ecological losses such as reduction and extinction of animal and vegetal species, lower agricultural yields, and food security issues. The consequence of these disruptions is an ever-increasing migration of populations located in the most vulnerable regions becoming inhabitable. Considering this situation, it is imperative to implement simultaneous adaptation and mitigation strategies.

Adaptation strategies aim to reduce the vulnerability of societal and biological systems to climate change. Examples of adaptation strategies to more frequent and extreme climate events could include expanding early warning systems and emergency response plans for heatwaves, floods, and wildfires to protect lives and health. Building climate-resilient infrastructure, such as water storage and flood control systems, may help to manage altered water cycles, reduce landslide risks, and ensure stable water supplies during droughts. Supporting the relocation of communities from highly vulnerable areas and promoting sustainable agricultural practices can help secure food resources, while protecting and restoring natural ecosystems may prevent biodiversity loss.

As climate change progresses, it may reach critical tipping points beyond which it will be strongly amplified making adaptation impossible. Implementing mitigation strategies to reduce climate change is therefore necessary(Intergovernmental Panel on Climate Change (IPCC), 2023). These strategies fall into two categories: i) the reduction of anthropogenic sources of GHG and ii) the development of geoengineering methods to remove GHG emissions from the atmosphere or to compensate for their effects on the greenhouse. Geoengineering can involve solar radiation management (SRM), such as injecting sulfur into the stratosphere or cloud seeding above the ocean, to enhance the reflectivity (albedo) of the atmosphere and counteract the greenhouse effect. However such radiative compensation methods are debated since the atmosphere is a complex nonlinear system whose reaction to change is difficult to predict and can ultimately become impossible to control(Hepburn et al., 2019; Hubert et al., 2016; Keith, 2001; Ricke et al., 2023; Vandeginste et al., 2024). Another category of geoengineering is less controversial as it consists of creating or amplifying greenhouse gas sinks such as carbon dioxide removal (CDR). Nevertheless, all geoengineering strategies can be counterproductive because they do not address the root of the problem, this is, the GHG emitted by human activity, which must be reduced anyway. A crucial aspect of anthropic GHG abatement planning is to consider all the future energy strategies that can be implemented by combining technologies that are currently or will be very soon available. The choice between all technologically feasible options must consider many factors that go far beyond the simple reduction of GHG.

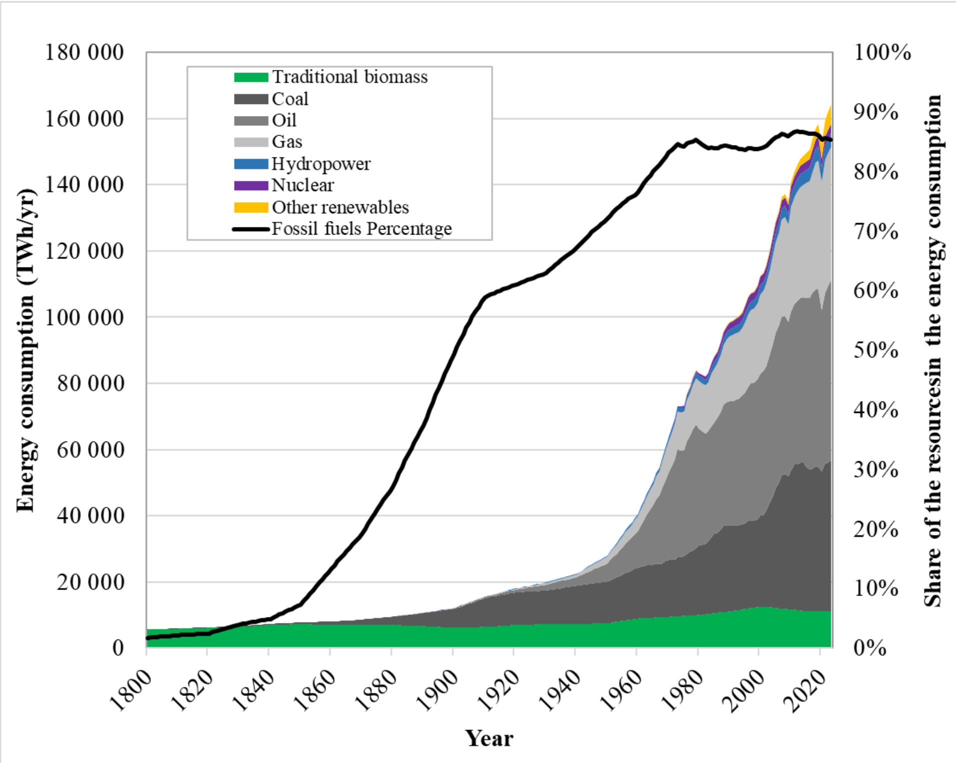


Figure 1 World total energy consumption of primary resources from 1800 to 2023, the solid line corresponds to the percentage of fossil fuels resources. The category of fossil fuels includes coal, oil, and gas, and the category of other renewables includes biofuels, geothermal, wind, and solar.

Throughout their history, human societies have been marked by struggles and conflicts motivated by the desire to control and ensure the resources they need. As energy is certainly one of the most essential resources, energy strategies are deeply interconnected with geopolitics. Two kinds of interactions between geopolitics and resources of energy are possible: i) direct interactions, based on the pursuit of energy exploitation and control have historically contributed to significant geopolitical tensions. Among many other examples is the U.S. invasion of Iraq in 2003, a military intervention driven by strategic interests in the control of oil resources; and ii) indirect interactions, when geopolitical events cause the increase of oil price and perturbations in the global oil market. Some notable examples are the first and second oil shocks of 1973 the event known as the Kippoour War and 1979 the oil shock triggered by the rise of Ayatollah Khomeini to power in Iran, which disrupted global oil supplies and caused market instability, and the energy crisis of 2021-2022 a worldwide energy shortage, caused by the strong global economic recovery following the recession linked to the Covid-19 pandemic from 2020, then amplified from March 2022 by Russia's invasion of Ukraine, as a consequence (Figure 2).

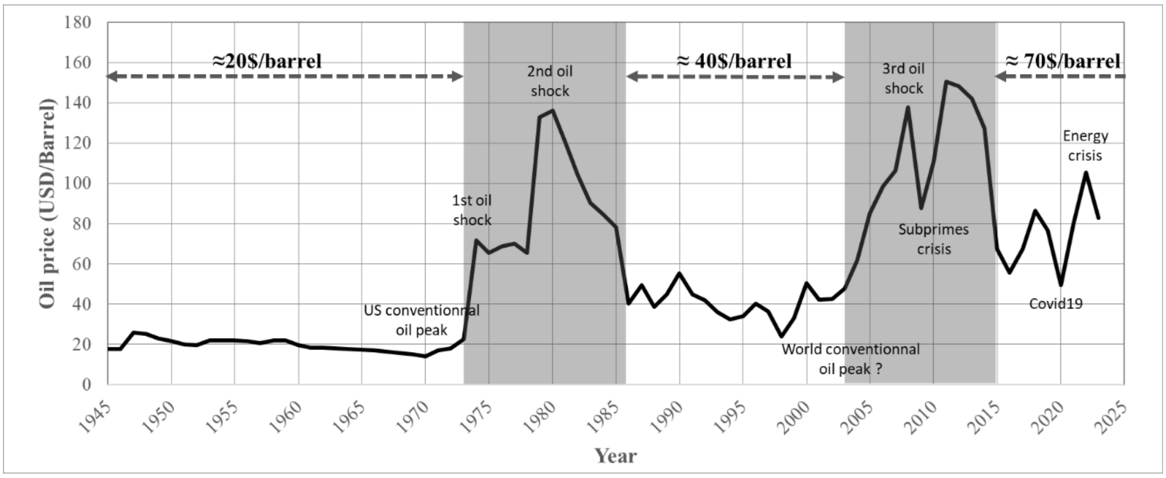


Figure 2 Oil price trend from 1950 to 2023 (constant USD of 2023). In the shadowed periods, the plot shows several peaks: the first and second oil shocks of 1973 and 1979, the oil shock of 2008 and the economic crisis of 2010, and the rise of the demand after the Covid-19 pandemia. The general trend indicates that before 1973, a price of $20 per barrel was sufficient to pay for the extraction of conventional oil resources. Following the first and second oil shocks (1985-2005), the oil price rose to $40 per barrel, driven by the need to finance the extraction of non-conventional oil, e.g., Alaskan/Siberia fields and offshore. Subsequent oil shocks have pushed the oil prices further, reaching $70 per barrel to enable the economic viability of shale oil extraction after 2014(BP, 2024).

The example of oil illustrates that the price of energy depends on the accessibility of resources, which directly impacts production costs (Figure 2). However, when accessibility is not a limiting factor, the production costs are primarily determined by technological advancements used in the extraction, transformation, and transport of energy resources. Generally, technologies evolve to become more competitive thanks to the scale effects of mass production and the shortening the energy and raw materials supply chain(IRENA, 2020, 2022b; Lazard, 2024). This is why the production costs of solar and wind energy have dropped exponentially over the past years (Figure 3). It is important to note that these energy sources also have limiting factors that have not yet been reached, such as the land surface required, and the components needed for their production (like rare earth elements and low-abundance metals).

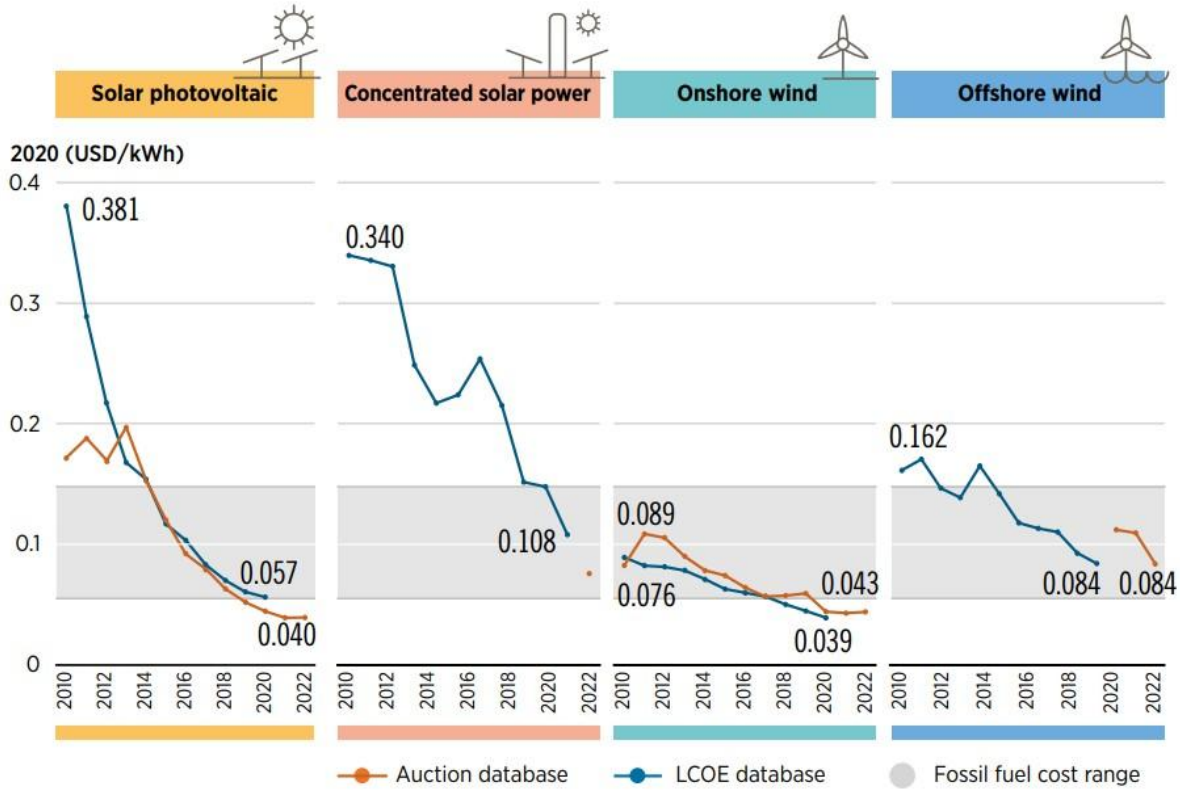


Figure 3 The global weighted-average The cost of producing one unit of energy by a particular energy-producing system over its entire lifetime, known as Levelized Cost of Electricity (LCOE), and auction prices for solar photovoltaics (PV), concentrated solar power (CSP), onshore wind and offshore wind, 2010–2023. The grey band represents the fossil fuel-fired power generation cost range. Original figure taken from: "World Energy Transitions Outlook 2022"(IRENA, 2020, 2022b).

Unlike resource accessibility and technological constraints, the costs associated with environmental impact are generally poorly accounted in the energy prices. Every stage in the life cycle of an energy-producing technology (its production, use, and disposal) requires energy and material resources but also generates waste and emissions (such as CO2) which have an impact on the environment. Legislation is then needed to introduce indirect environmental constraints on the prices, through taxes, subsidies, or the use of mandatory standards. However, there is an exception when environmental risks are so high that they directly impact production costs, as is the case with nuclear energy production. Accounting for these risks has two consequences: i) the implementation of nuclear technologies is complex and requires significant investments to ensure a minimal risk of incidents, which primarily drives production costs; and ii) since risks are partially unpredictable, they have to be regularly reassessed, they require continuous technological improvement leading to a gradual increase in production costs. Nuclear does not benefit from the scale effect as the other technologies(Flyvbjerg, 2021; Grubler, 2010). It has been reported that, as more reactors are built new environmental and safety issues continue to emerge, consequently, additional countermeasures, including the implementation of advanced control systems and stricter safety protocols, are required, these measures contribute to a significant rise in the construction costs of new nuclear power plants (Figure 4)(Lazard, 2024).

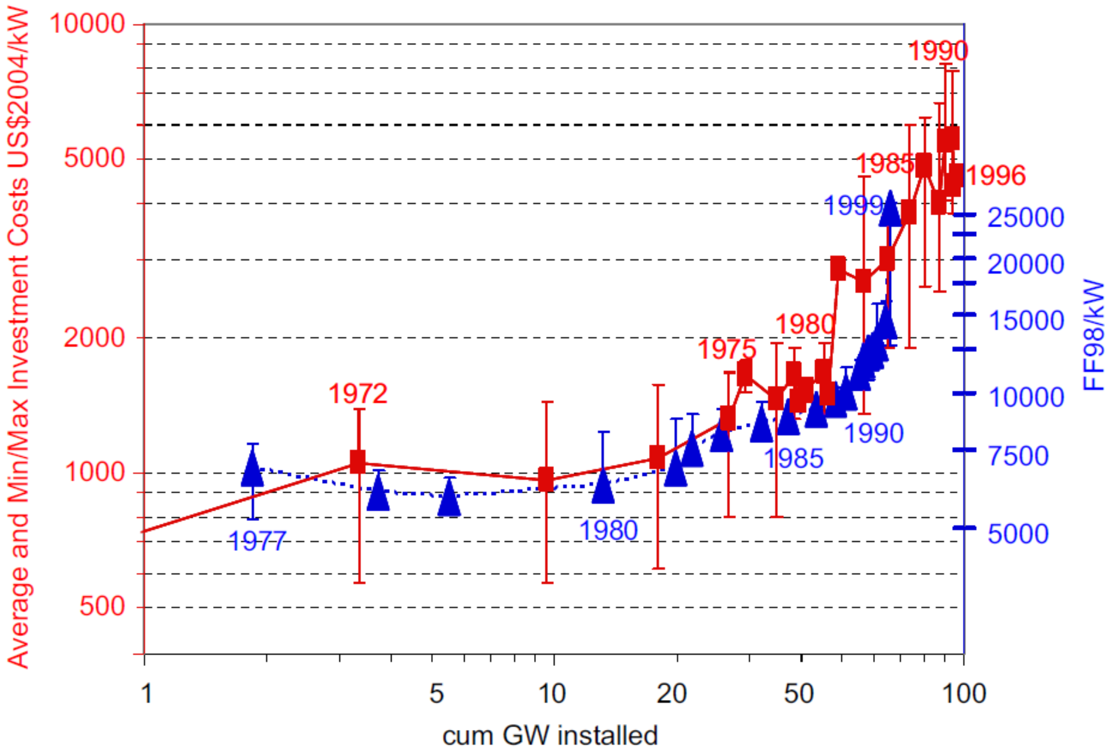


Figure 4 Negative learning by doing in nuclear energy. Red squares denote costs of nuclear powerplants in the United States and blue triangles denote costs estimated in France before the release of reactor-specific costs from the French Cour des Comptes in 2012, Average reactor construction costs per year of completion date versus cumulative capacity completed(Flyvbjerg, 2021; Grubler, 2010; Lovering et al., 2016).

To outperform an older technology on the market, new technology must offer advantages, either by providing the same service at a lower cost, or by providing a better or more extensive service, even if its costs are higher. In past decades, the appeal of new technologies was little influenced by environmental protection. Nowadays, environmental issues must be considered in the attractiveness of technologies, even if they require compromise on factors that were previously prioritized, such as cost or time saving. For this reason, the constraints introduced by environmental issues are not always well received by the public. One of the challenges in promoting clean technologies is motivating the public to give the environment the same level of importance, or more than the factors that have guided their choices so far. This requires the acceptance of substantial lifestyle changes.

On the other hand, overemphasizing the environment and hoping to find non impacting technologies will lead to a dead end. It is important to accept that the use of any technology will have some impact on the environment and that making a choice involves finding a compromise. None of the available technologies can satisfy all the above aspects (GHG emissions, cost, security of supply, and acceptance), so the choice of energy strategy to be followed must be made by comparing the pros and cons of the assembly of technologies in the energy mix.

2. Energy sources review

Energy sources can be classified according to various criteria. One first classification can be made based on their renewable nature and self-replenishing capacity as *non-renewable* energy sources (non-RES) and *renewable* energy sources (RES)(IRENA, 2015a). Another classification of sources is based on their capacity to adapt their energy production to the hourly fluctuations of energy demand over time. The sources that are capable of this adaptation are referred to as *controllable sources*. These can be classified as either RES (e.g., hydropower, geothermal, and biomass) or non-RES (e.g., nuclear and thermoelectric). In contrast, sources such as solar and wind provide energy depending on the availability of the primary resources and are unable to follow the hourly fluctuations of the energy demand. They are referred to as *intermittent sources*.

Energy sources are used for electricity production through generating technologies (e.g., thermoelectric powerplants, gas turbines, nuclear central powerplants, photovoltaic panels, etc.), or directly used by the consuming sectors (e.g., industry, agriculture, residential, etc.). How these sources and technologies are mixed determines the characteristics, advantages, and disadvantages of the energy strategies because each type of energy source has characteristics that affect various aspects of the energy strategies, e.g., each type of system has a different lifespan, variable, and fixed costs, GHG emissions, etc.

2.1. Fossil sources

2.1.1. General description

Fossil fuels as a source of energy (e.g., coal, petroleum oil, and natural gas) are largely used. The history of fossil fuels began with coal, which became the cornerstone of the Industrial Revolution in the 18th century. The widespread availability and energy density of coal-powered steam engines, factories, and later, electric power plants, fundamentally transformed industrial processes and transportation. By the 19th century, coal mining had expanded globally, underpinning the economic growth of many nations and setting the stage for modern industrial society.

One advantage of the steam engines is that they could be placed anywhere. The use of waterpower was a successful method for the operation of early mills; however, the advent of the steam engine enabled the establishment of factories in locations that were not necessarily in proximity to a water source. The availability of waterpower was subject to seasonal fluctuations, which posed a challenge for its consistent utilization.

The 20th century witnessed the rise of petroleum, it replaced coal as the most consumed primary energy source due to its superior energy content and versatility. However, the coal consumption continued to increase just slower than the oil. The discovery of vast oil fields and the development of internal combustion engines revolutionized transportation and industry. Petroleum became integral to not only fueling automobiles, airplanes, and ships but also as a raw material for a multitude of chemical products, including plastics and pharmaceuticals. The geopolitical landscape was heavily influenced by oil, leading to the establishment of major oil companies and the strategic importance of oil-rich regions(Etminan et al., 2016; Shindell et al., 2009).

Later, in the mid-20th century, natural gas emerged as a significant energy source, prized for its efficiency and lower GHG emissions emitted during its combustion compared to coal and oil. However, the total GHG emissions are greater than those of coal and oil due to the losses during extraction and transportation processes.

Advances in pipeline technology and liquefied natural gas (LNG) shipping facilitated its global distribution. The European Union has declared natural gas as one strategic source for the energy transition of the region(DW, 2022).

In recent decades, the advent of hydraulic fracturing (fracking) has marked the latest disruption in the fossil fuel sector. Fracking, which involves injecting high-pressure fluid into subterranean rock formations to release oil and natural gas, has dramatically increased the accessibility of these resources. This technological innovation has reshaped the energy market and altered the geopolitical dynamics of energy production and consumption, e.g., in 2010 thanks to fracking the United States became the largest oil producer worldwide. This has affected the global economy and geopolitics. One of the consequences was the drop in the oil prices. States whose economies depended mostly on fossil sources were highly impacted, e.g., Venezuela, Russia, Colombia, Mexico, etc. This shows that relying on fossil fuels exports as the main source of currency is not a sustainable strategy, it can put the country in a risky situation in terms of economics and energy security.

2.1.2. Advantages

Fossil fuels offer several advantages, including high energy density, reliable and stable energy supply, and well-established infrastructure. Their high energy density ensures efficient energy production and transportation, supporting large-scale industrial processes and electricity generation.

Fossil fuels provide a consistent and dependable energy source, a helpful characteristic for keeping the grid stable and meeting peaks of demand when needed.

The extensive existing infrastructure for extraction, refinement, and distribution enables continued economic feasibility and rapid deployment.

2.1.3. Disadvantages

The fluctuation in the costs of fossil sources represents a major drawback for many countries depending on their prices since their public finances depend on sales of coal, oil, and gas. Also, in developed countries fossil fuel prices directly affect society in terms of purchasing power and inflation.

The combustion of fossil fuels is a major source of GHG emissions, contributing to climate change and air pollution, which have severe public health, societal, and ecological consequences.

Additionally, the extraction and transportation of fossil fuels can lead to habitat destruction, oil spills, and other environmental hazards whose costs are difficult to estimate.

The finite supply of fossil fuels also raises concerns about long-term energy security and price volatility. Especially in regions with no fossil source reserves or without the infrastructure necessary to exploit them.

These drawbacks highlight the urgent need for transitioning into more sustainable and environmentally coherent energy sources.

2.2. Nuclear

2.2.1. General description

The use of nuclear energy for energy production is derived from the fission of heavy atomic nuclei such as uranium-235 and plutonium-239. In a nuclear reactor, controlled chain reactions release vast amounts of energy, which is used to produce steam that drives turbines connected to electricity generators.

The history of nuclear energy began in the early 20th century with the discovery of radioactivity and the realization of the immense energy potential within the atomic nucleus. Key scientific advancements by figures like Marie Curie, Ernest Rutherford, and Enrico Fermi laid the groundwork, culminating in the Manhattan Project during World War II, which demonstrated the power of nuclear fission. Post-war, attention turned to peaceful applications of nuclear energy, leading to the first civilian nuclear power plant in Obninsk, Union of Soviet Socialist Republics (USSR), in 1954. The rapid development and construction of nuclear reactors took place globally during the 1950s and 1960s. However, the Three Mile Island accident in 1979 and the Chernobyl disaster in 1986 among other numerous nuclear incidents worldwide raised safety concerns, resulting in heightened regulation and a slowdown in new reactor construction. In recent decades, nuclear energy has experienced a resurgence due to the urgent need to address climate change and reduce GHG emissions. Advances in reactor design, focusing on safety, efficiency, and waste management, have led to the development of Generation III+ and IV reactors.

Nuclear energy is critical in military applications, powering nuclear submarines and aircraft carriers, and serving as the foundation for nuclear weapons. Additionally, nuclear energy has diverse applications across multiple sectors. In medicine, it is essential for cancer treatment through radiotherapy and advanced diagnostics like medical imaging. Industrial uses include material testing and sterilization. In agriculture, nuclear technologies such as food irradiation and plant mutation breeding enhance food safety and crop yields. Regarding energy production, based on the low direct GHG emissions of this technology, Nuclear (and natural gas) was named a green and strategic energy source for the energy transition in Europe(DW, 2022; Le Monde, 2022; Schneider & Froggatt, 2021).

2.2.2. Advantages

This process results in a high energy output with minimal direct GHG emissions, positioning nuclear power as a strategic resource in efforts to reduce carbon footprints and face climate change(Pomponi & Hart, 2021; Weisser, 2007). For this, the European Union has declared nuclear energy as one strategic source for the energy transition of the region(DW, 2022).

A small amount of nuclear fuel can produce a large amount of energy. This efficiency translates into a reduced physical footprint compared to other energy sources, allowing for significant energy production without extensive land use.

The energy densities (lower heating value per kilogram of material) illustrate the enormous advantage of fissile materials like uranium compared to fossil fuels. Uranium, when used in nuclear reactors, has an energy density of approximately 500 000 MJ/kg, whereas fossil fuels such as coal, oil, and natural gas have significantly lower energy densities: coal ranges from 24-30 MJ/kg, oil around 42 MJ/kg, and natural gas about 53 MJ/kg(Haas & Lutz Mez, 2019).

2.2.3. Disadvantages

Despite the effectiveness of nuclear energy in reducing direct GHG emissions, great issues arise from nuclear technologies for electricity production.

Nuclear energy technologies raise questions due to the significant risk associated with nuclear disasters because of the severity of the consequences., as evidenced by historical incidents such as Fukushima, Chernobyl, and Three Mile Island. These events show that there is a real risk of a major nuclear accident. This can happen because of human error, design flaws, or natural disasters. Leading to widespread radioactive contamination(Yanovskiy et al., 2020). The environmental impacts are extensive, including long-term soil, water, and ecosystem contamination, with Fukushima alone resulting in an estimated $200 billion in cleanup costs. The Chernobyl disaster has had an estimated economic impact of over $235 billion, factoring in cleanup, health care, and loss of productivity(Hindmarsh, 2013; Marino & Nunziata, 2018). Public health concerns are equally significant, Chernobyl is linked to around 4,000 cases of thyroid cancer and an estimated 9,000 to 16,000 excess cancer deaths across Europe. Fukushima has raised concerns about increased thyroid cancer, particularly among children. Psychological impacts, including mental health disorders, have also been significant(Haas & Lutz Mez, 2019; Okano et al., 2022).

In countries without local production and refining of fissile material, enriched nuclear fuels are an imported resource, an important issue for local energy security. This is a risky situation in case of an interruption in the supply of enriched nuclear fuels. This dependency can be reduced by replacing nuclear with other locally available controllable or intermittent sources. An example of this is the French dependence on Nigerian uranium and Russian nuclear products for its nuclear powerplants, this corresponds to a great risk for the energy security of France given the current policy of nuclear capacity expansion of the French government(Euractiv France, 2023; Le Monde, 2023; Pécout, 2023).

All these risks explain why nuclear costs (construction and production) are consistently rising(Grubler, 2010; Lovering et al., 2016). As a result of this, higher prices have to be paid by the user, and greater subventions are needed to keep the energy production based on nuclear technologies.

Also, the costs of technologies such as nuclear are highly uncertain and have increased over time during the last decades, and they will keep increasing in the future (Haas & Lutz Mez, 2019; IRENA, 2020). An example of this is the case of the nuclear power plant of Flamanville in France, a project based on the European pressurized reactor (EPR) technology with great costs of more than 10 billion € and overdue of more than 10 years in its implementation(World Nuclear News, 2022). Although this is a critical case, given that it is a recent one, future nuclear projects may exhibit similar financial performance during implementation.

Another alternative for future nuclear projects is the installation of Small Modular Reactors (SMRs). These are being designed with greater flexibility in mind. SMRs may offer better load-following capabilities and could potentially mitigate some of the challenges faced by traditional large nuclear reactors. However, the market for SMRs is still emerging, and there is great uncertainty about the level of demand and the willingness of utilities and investors to commit to this new technology, SMRs like other models of nuclear reactors generate radioactive waste that require careful management and long-term storage solutions. While the volume of waste might be smaller, the challenge of safe disposal remains significant. Uncertainty about the costs and risks of nuclear waste management, dismantling of old nuclear facilities, and incidents are important sources of concern worldwide.

Moreover, the construction and decommissioning of nuclear power plants involve substantial financial investments and time, often making nuclear projects economically burdensome.

Regarding the intermittency nuclear energy production can not follow the hourly variations of the demand. Nuclear reactors are designed to operate continuously at a steady output level. Rapid changes in power output can stress the reactor components, potentially reducing their lifespan and increasing maintenance costs. Nuclear reactors have a limited ramp rate, meaning they cannot increase or decrease their power output quickly. This slow ramp rate makes it challenging to respond to rapid fluctuations in electricity demand(Haas & Lutz Mez, 2019).

2.3. Biomass

2.3.1. General description

The history of biomass as an energy source dates to the earliest human civilizations, where it was the primary means of obtaining heat and light. Ancient humans used wood and other organic materials for cooking, heating, and eventually for metallurgical processes. This reliance on biomass continued for millennia, with wood remaining a dominant fuel source until the advent of coal during the Industrial Revolution. The development of agriculture further expanded the use of biomass, as crop residues and animal waste became additional energy sources. By the 19th century, the discovery and exploitation of fossil fuels began to overshadow biomass, but it remained a critical energy source in rural and developing areas.

There are two main types of biomass energy pathways: dry processes and wet processes. Dry processes include methods like combustion, carbonization, and gasification, which directly convert dry biomass into energy or energy carriers. On the other hand, wet processes, such as anaerobic digestion (methanization) and fermentation, involve the breakdown of organic matter in the presence of water.

Advances in technology enabled more efficient conversion of dry biomass into electricity, heat, and biofuels. Additionally, from the heat production facilities based on biomass, the cogeneration facilities allow to profit from the fatal heat to produce electricity.

Techniques based on wet biomass, such as anaerobic digestion, pyrolysis, and gasification allowed the production of biogas, biochar, and syngas, expanding the versatility of biomass. Additionally, the development of liquid biofuels like ethanol and biodiesel provide sustainable alternatives to petroleum-based fuels. Today, biomass is recognized for its potential to reduce greenhouse gas emissions and enhance energy security, playing a crucial role in the transition towards a more sustainable energy system.

The energy capacities of wet processes are generally lower compared to dry methods, as a portion of the organic matter is preserved and not fully converted into energy. This makes dry processes more efficient in terms of energy yield, while wet processes are often valued for their ability to handle wet waste materials and produce byproducts like biogas or biofuels.

2.3.2. Advantages

Biomass energy offers three key advantages: (i) the creation of value and jobs, benefiting rural areas and populations, as it often involves local resource utilization and labor-intensive processes; (ii) the valorization of inevitable residues generated by more noble uses of biomass, such as food production, fibers, or chemical components, turning waste into a valuable energy source; and (iii) the significant potential for improving productivity yields.

Natural biomass yields are typically low (less than 1%), but dedicated energy crops can achieve much higher efficiencies, with yields reaching up to 3%. This highlights the opportunity to enhance biomass energy's contribution to sustainable energy systems while supporting rural economies and reducing waste.

Biogas production contributes to waste management and energy production simultaneously, supporting circular economy principles. When managed properly, the carbon dioxide released during the combustion of biomass is offset by the carbon dioxide absorbed during the growth of the source plants, achieving a near-zero net carbon impact.

The decentralization potential of biomass and biogas systems can also enhance energy security and provide economic opportunities in rural areas.

2.3.3. Disadvantages

One significant concern is the potential for land use competition, where the cultivation of energy crops may encroach on land needed for food production, leading to food security issues. Also, land use for biomass production is linked to social issues in some countries. In some cases, deforestation problems are linked to biomass production.

The combustion of biomass can produce air pollutants such as particulate matter, which pose health risks.

Biogas production relies on organic waste, which can lead to increased consumption and waste generation. As a result, its effectiveness in reducing overall energy consumption compared to other renewables such as solar and wind energy is diminished. To overcome this challenge, it is essential to diversify energy sources and expand their shares of solar and wind energy. While balancing waste reduction with biogas production is feasible, more research is needed to optimize these systems.

2.4. Hydropower

2.4.1. General description

Hydropower is a renewable energy source harnessed from the kinetic energy of flowing or falling water, typically using dams or river systems to drive turbines connected to electricity generators. It is one of the oldest and most widely used forms of renewable energy, providing a substantial part of global electricity. This energy source is integral to many energy strategies due to its capacity for reliable, consistent, and flexible power generation.

The history of hydropower dates to ancient civilizations, where it was first harnessed for mechanical tasks, such as grinding grains and irrigating crops. The Greeks and Romans built water wheels to utilize the kinetic energy of flowing water, setting the stage for more advanced hydraulic technologies. During the Industrial Revolution, hydropower played a pivotal role in powering mills and factories, providing a renewable and reliable energy source before the widespread adoption of steam engines fueled by coal. By the late 19th century, the advent of electrical generation transformed hydropower's role, with the construction of the first hydroelectric power plants, such as the one at Niagara Falls in 1881, marking the beginning of its integration into modern energy systems.

Throughout the 20th century, hydropower expanded significantly as technological advancements allowed for the construction of larger and more efficient dams and turbines. Major projects like the Hoover Dam in the United States and the Itaipu Dam on the Brazil-Paraguay border showcased hydropower's capacity to generate vast amounts of electricity while providing flood control and water management. Today, hydropower is the largest source of renewable energy worldwide, accounting for a significant portion of global electricity production. It is valued for its ability to provide consistent baseload power and support grid stability.

Specifically, Run-of-river hydroelectric plants generate electricity through the diversion of water from flowing rivers, without large dam structures. The history of run-of-river hydroelectricity is as old as several hundred years, but modern development has been an activity of the recent decades or so. Conceptually simple, run-of-river hydroelectric systems have been employed in small-scale operations for centuries but only in the 20th century did technology receive significant attention as a cleaner alternative to large dam-based hydroelectric plants(International Energy Agency, 2024).

2.4.2. Advantages

Many countries possess substantial hydropower potential. Hydropower plants produce minimal direct greenhouse gas emissions, contributing to climate change mitigation efforts. It ensures a continuous supply of energy, contingent on water availability, without depleting natural resources(Gemechu & Kumar, 2022; Gómez-Gener et al., 2023).

Dams can be adapted for energy storage using Pumped-storage Hydroelectricity (PSH) technology, offering a viable alternative in regions with extensive hydropower systems. Hydropower provides excellent grid stability and energy storage capabilities through pumped-storage systems, which can balance supply and demand fluctuations.

The infrastructure of hydropower projects can also offer auxiliary benefits, such as flood control, irrigation, and water supply for communities, enhancing their overall utility and value.

2.4.5. Disadvantages

The global exploitation of water resources for electricity generation is widespread, significantly impacting landscapes, and ecosystems, and contributing to GHG emissions(Cuadros Tejeda et al., 2019; Gemechu & Kumar, 2022). The construction of large dams and reservoirs can have profound ecological and social impacts, including habitat destruction, alteration of river ecosystems, and displacement of local communities. Hydropower projects can disrupt local biodiversity and lead to the loss of fish populations and other aquatic life.

Hydropower's dependence on consistent water flow makes it vulnerable to climate change, as altered precipitation patterns and prolonged droughts can reduce water availability and energy output. This situation will become more critical since climate change will lead to stronger and longer dry seasons, which will harm the water resources and dam levels. As has recently happened in South America due to ENSO in 2016 and 2023(M. A. Guevara-Luna et al., 2023; Kim et al., 2022; Singh et al., 2022).

2.5. Solar

2.5.1. General description

Solar energy is one of the most rapidly expanding RES due to its fast decrease in costs during the last decades. Solar energy captures the sun's radiation using photovoltaic cells or concentrated solar power systems to produce heat and electricity. Therefore, solar energy sources vary hourly depending on the availability of the primary resource, i.e., solar radiation.

The history of solar energy can be traced back to the 19th century when the French physicist Alexandre-Edmond Becquerel studied the photovoltaic effect for the first time in 1839, i.e., whereby light is converted into electrical energy. In 1954, researchers at Bell Labs developed the first silicon solar. In the early stages of development, solar technology was employed in space exploration, with satellites and space missions being the primary applications. The 1970s oil crises led to an increasing interest in solar energy, resulting in the establishment of government-funded research and development programs(Marques Lameirinhas et al., 2022).

The use of solar energy has increased dramatically in the early 21st century, driven by several factors, e.g., technological advancements, declining costs, and supportive government policies. The efficiency and cost-effectiveness of solar photovoltaic (PV) modules have increased. The integration of these technologies into the grid has been facilitated by advances in energy storage and smart grid technologies(Guney & Tepe, 2017; Lund et al., 2014; Mlilo et al., 2021).

The accelerated decline in costs of solar energy has rendered these energy sources competitive with, and frequently more economical than, fossil fuels, prompting a shift in investment and infrastructure development. It is anticipated that the introduction of these sources will result in a notable reduction in GHG emissions and an enhancement of many other aspects such as energy security and greater energy democratization, enabling localized energy production and reducing the necessity for extensive transmission networks(IRENA, 2016, 2020).

Agrivoltaics is an innovation that is rapidly gaining traction and reshaping the relationship between the energy and agriculture/livestock sectors. This approach involves the dual use of land for both agricultural activities and solar energy production, where solar panels are installed above crops or grazing areas. By optimizing land use, agrivoltaics not only generates renewable energy but also enhances agricultural productivity through microclimate regulation, reduced water evaporation, and improved crop resilience. This innovative synergy between energy and agriculture is transforming traditional practices, offering sustainable solutions for food and energy production while addressing land-use challenges(IRENA, 2022b).

2.5.2. Advantages

Solar sources are abundant and inexhaustible, providing a reliable and sustainable supply of energy. Solar energy has interesting advantages, it is present in many locations worldwide, and its costs have been decreasing during the last two decades and this trend may continue in the future. Technological advancements and economies of scale have led to decreasing costs, making this source increasingly competitive with traditional fossil fuels(IRENA, 2023). From 2010 to 2019 there have been sustained decreases in the costs of solar energy (85%), technologies of energy storage such as ion-lithium batteries (85%), and large increases in their deployment(IRENA, 2016, 2017, 2020; Power Engineering International, 2017).

Solar energy does not emit GHG or air pollutants during its operation. One great advantage of solar is that it can be deployed at various scales, from small residential setups to large utility-scale projects, offering flexibility and accessibility with different impacts on local communities and the environment.

Photovoltaic (PV) energy offers three additional advantages that underscore its growing adoption worldwide. First, its extreme modularity allows it to be deployed at scales ranging from a few watts for small, off-grid applications to terawatt-level installations for large power plants. Second, solar energy is globally available, as sunlight can be harnessed virtually anywhere, making it a universally accessible and versatile energy source. Third, the rapid implementation of PV power plants stands out, with projects often completed in just 1 to 2 years, far quicker than many other energy infrastructure developments. These benefits, modularity, global availability, and fast deployment, make PV a highly adaptable and efficient solution for meeting diverse energy needs(IRENA, 2022a, 2022b; Lund et al., 2016; Tian et al., 2019).

2.5.3. Disadvantages

Solar energy production is limited by daylight hours and weather conditions. Consequently, the intermittent and variable nature of this source poses challenges to grid stability and reliability.

The manufacturing, deployment, and decommissioning of solar panels involve material and energy inputs, which can have environmental and economic implications, e.g., GHG indirect emissions in the fabrication and installation stages.

2.6. Wind

2.6.1. General description

Wind energy is one of the fastest-growing renewable energy sources (RES), driven by a recent decrease in costs. It operates by converting the kinetic energy of wind streams into mechanical power using turbines. Like solar energy, wind energy production fluctuates hourly, depending on the availability of the primary resource, i.e., wind speed. This variability makes wind energy an intermittent source, requiring complementary solutions to ensure a stable energy supply.

In contrast, the history of wind energy is more extensive, with evidence of its use dating back to ancient civilizations. The first uses of wind energy included the windmills for mechanical tasks such as grinding grain and pumping water. But it has not been until more recently during the 19th century that the first wind turbine for electricity production was developed in Scotland in 1887 by Professor James Blyth. Nevertheless, it was not until the late 20th century that wind energy began to be considered as an alternative for electricity production. As for solar energy, the 1970s energy crisis raised interest in wind energy. For this, the last 50 years have had great technological advancements such as the development of more efficient and larger turbines(Kaldellis & Zafirakis, 2011).

Recent innovations in wind turbine design have significantly improved both capacity and reliability, making wind energy a more viable and efficient option. These advancements have facilitated the implementation of major wind energy projects, further accelerating the adoption of this renewable energy source on a large scale(Agudelo et al., 2021).

Offshore wind energy is a rapidly growing sector worldwide, offering important power capacity and higher capacity factors compared to onshore wind. By harnessing stronger and more consistent winds at sea, offshore wind farms can generate more electricity more reliably. This technology is experiencing strong global growth, driven by advancements in turbine design, floating platforms, and grid integration. Countries with extensive coastlines, such as those in Europe, Asia, and the United States, are increasingly investing in offshore wind as a key component of their renewable energy strategies, making it a cornerstone of the transition to cleaner and more sustainable energy systems.

2.6.2. Advantages

Wind energy is abundant in many regions globally, and its costs have steadily decreased over the past two decades, a trend likely to continue in the future. Large-scale implementation of wind power worldwide will further integrate this resource into the global energy mix, driving down costs and advancing both onshore and offshore wind turbine technologies. Between 2010 and 2019, there was a sustained reduction in wind energy costs, reflecting the growing competitiveness of this renewable source(IRENA, 2016, 2017, 2020; Power Engineering International, 2017). As solar, wind sources do not emit GHG or air pollutants during their operation(IRENA, 2022a, 2022b).

2.6.3. Disadvantages

Wind energy depends on wind patterns, which can be unpredictable and vary widely. The large land areas required for wind farms and the potential for habitat disruption and noise pollution are environmental concerns. Additionally, the manufacturing, deployment, and decommissioning of wind turbines raise questions regarding their defenses of energy, need for adequate infrastructure, and costs.

2.7. Other intermittent sources of energy

2.7.1. General description

There are other sources, different than solar and wind, that do not provide a continuous or predictable supply of power, as their output depends on environmental conditions. Besides solar and wind, other variable-energy sources include tidal energy, and wave energy. Tidal energy harnesses the motion of the water that is induced by the gravitational forces of the moon and the sun, while wave energy uses the energy transported by surface waves on oceans and seas. The history of tidal and wave is as old as several hundred years, but modern development has been an activity of the recent decades or so.

It finds its background in early mill systems where tidal mills were used to grind grain as far back as the Middle Ages. The first great stride in harnessing tidal energy was the first large-scale tidal power plant, that being the Rance Tidal Power Station in France back in the 1960s. However, there are few places where this technology can be deployed. Wave energy research began in earnest in the 1970s following the oil crises, driving interest in alternative energy sources. Despite early prototypes, technical and economic barriers have restrained their large-scale commercial deployment up to this date. Ongoing technological developments and increasing demand for renewable energy sources continue to outline the pace of their development, with growing investments in research and pilot projects targeted at improving the viability of such sources.

2.7.2. Advantages

Intermittent energy sources are hitherto endowed with many comparative advantages that make them allure in the future for renewable energy. In the first place, they are environmentally benign, since during operation they emit almost negligible quantities of GHGs. Particularly, tidal and wave energy is based on the regular and predictable movement of water, which means that their energy output can be forecast relatively accurately well in advance. Besides, run-of-river hydroelectric systems generally have a much lower environmental impact than the more usual hydroelectric projects based on dams, since no great changes in the riverine ecosystem are necessary. These technologies could also help further diversify energy resources and reduce dependence on fossil fuels, thereby contributing to energy security. Taken together, global growth in intermittent sources, plus technology advances, may further bring down the cost and encourage innovations in energy storage and grid integration solutions.

2.7.3. Disadvantages

There are formidable barriers to deploying intermittent energy sources at a large scale, despite the great promise. First, there is the basic issue of intermittency and unpredictability in their natural availability, which raises complications concerning grid management and continuous power supply. In this respect, tidal and wave energy depend on the natural cycles of the ocean, which may also receive seasonal or extreme weather variations. Their wide utilization is also restricted by the geographical limitations of these resources, viable only in locations that provide appropriate site conditions. For instance, tidal and wave energy are found in coastal areas. Besides, high capital costs in the development and deployment of these technologies, in particular, marine-based energy infrastructures, have barred them from commercial competitiveness. In addition, other environmental issues, which include the potential impacts on marine life and any life in the water, are also development barriers for these intermittent energy sources.

Although intermittent energy sources other than solar and wind represent a very important diversification and environmental benefit, improvements in technology and infrastructure will be very crucial in addressing the challenges that face their advancement, particularly those with variability, cost, and environmental impact.

There is however strategies to compensate for intermittent energy sources: first, the use of controllable energy sources (e.g., hydropower, gas, or nuclear), which can adapt to demand fluctuations but must now handle more frequent and intense peaks due to the variability of RES; second, importing electricity from other regions to balance supply and demand, though this carries risks like potential blackouts, especially if those regions also rely heavily on intermittent sources; and third, deploying energy storage systems (e.g., batteries or pumped hydro) to store excess energy and release it when needed. Nevertheless, storage alone cannot fully address intermittency if intermittent sources cover less than 100% of average demand.

3. Design and evaluation of energy strategies

3.1. Methods to design and evaluate energy strategies

As highlighted previously, it is necessary to implement energy strategies aiming to radically reduce the use of fossil fuels. However, the design and evaluation of these energy strategies present two major challenges: i) there is a wide range of energy production and storage technologies, which can be combined in an infinite number of possible options, and ii) the evaluation and comparison of different options are not limited to technical feasibility, as decision-makers will be guided by a wide range of criteria, e.g., economic, environmental, geopolitical, etc.

Most of the methods currently used to design and evaluate energy strategies can be classified into two main types of approaches: i) optimization methods to automatically generate scenarios encompassing the whole range of possibilities and select the best scenario by minimizing a specific criterion, usually the economic cost, and ii) selecting a few expert-designed strategies and comparing them based on a set of relevant criteria.

The optimization method has the advantage of generating scenarios systematically until it finds the optimum scenarios based on a defined criterion, usually the economic costs of the strategy. However, it has two drawbacks: i) not being able to consider enough characteristics to select the most appropriate scenario for decision-makers, i.e., the search for minimum costs is perhaps not the only important criterion for a decision-maker, who must also consider many other aspects like social, political, and/or geopolitical issues; and ii) since it converges in one single scenario, it omits other possible alternatives that can be also interesting regarding the ensemble of criteria(T. Li et al., 2020; Potrč et al., 2021; Zhao & You, 2020).

The evaluation of expert-designed scenarios, which are usually chosen arbitrarily based on the specific experience and interest of the authors, has the advantage of comparing the designed scenarios using several indicators. But it has one important drawback, it can only manage a limited number of scenarios that have not been systematically generated, so there is a risk of missing scenarios that could be of interest to a decision-maker(Bompard et al., 2020; Connolly et al., 2016; De Rosa & Castro, 2020; Hansen et al., 2019; Luo et al., 2021; Vaccaro & Rocco, 2021).

An alternative approach involves expanding the optimization method to converge on multiple solutions rather than a single one, resulting in a Pareto curve (Figure 5). This curve illustrates the characteristics of various optimized scenarios (e.g., GHG emissions) along an axis (e.g., Costs of changing the plotted characteristic). This method enables the graphical representation of multiple scenarios, simplifying the selection of the optimal compromise among various alternatives.

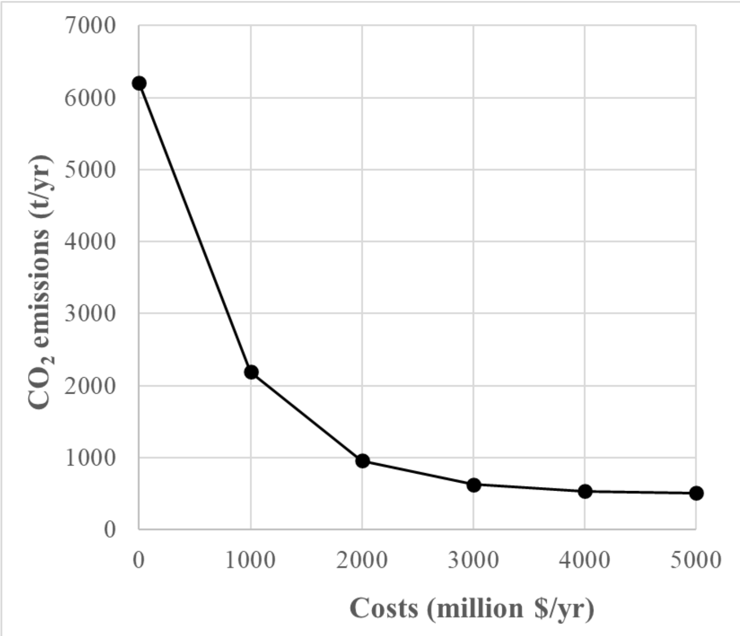


Figure 5 Pareto curve for the costs of scenarios reducing CO_2 emissions. In this example the more expensive a scenario, the less CO_2 it emits. The decision-maker must choose the compromise between cost and CO_2 emissions that seems best.

3.2. A new method for evaluation of energy strategies based on optimized tendencies of an increasing amount of intermittent sources

The energy transition must integrate renewable sources to replace fossil fuels. Solar and wind energy are crucial due to their declining costs and the absence of direct GHG emissions associated with their operation. However, these energy sources do not function like conventional ones, as they only generate power when sunlight and wind are available. Consequently, they cannot adjust to hourly fluctuations in demand.

The method developed in this work distinguishes between intermittent sources (solar and wind) and controllable sources. In the absence of intermittent sources, controllable sources produce all the energy needed to meet all demand, and their installed capacity must be sufficient to handle the peaks of demand (Figure 6-a). When intermittent energy is introduced in the mix, the controllable sources should supply only the residual energy defined as the difference between the demand and the intermittent energy production (Figure 6-b). This introduction of intermittent sources has a number of consequences: i) On the one hand, the contribution of the intermittent energy sources reduces in proportion the amount of energy to be produced by controllable sources. On the other hand, it has little impact on the installed capacity of the controllable sources, as they must continue to ensure energy supply during periods when solar and wind sources are not producing enough. The ratio between the energy produced and the install capacity of the controllable sources (i.e. capacity factor) is changing with the amount of intermittent sources introduced in the mix; ii) Intermittent sources overproduce energy at certain times. This excess energy can be stored and used to replace controllable sources by supplying peak demand when intermittent sources production is too few. However, the storage process is influenced by the alternating periods of energy surplus and deficit, which are driven by the amount of energy generated by intermittent sources. As a consequence, the characteristics of the energy system always change depending on the proportion of energy produced by intermittent sources. This is why the method developed in this study relies on the *percentage of intermittent energy in the mix calculated relative to total demand, to represent the trends of different relevant criteria for* *decision-makers.*

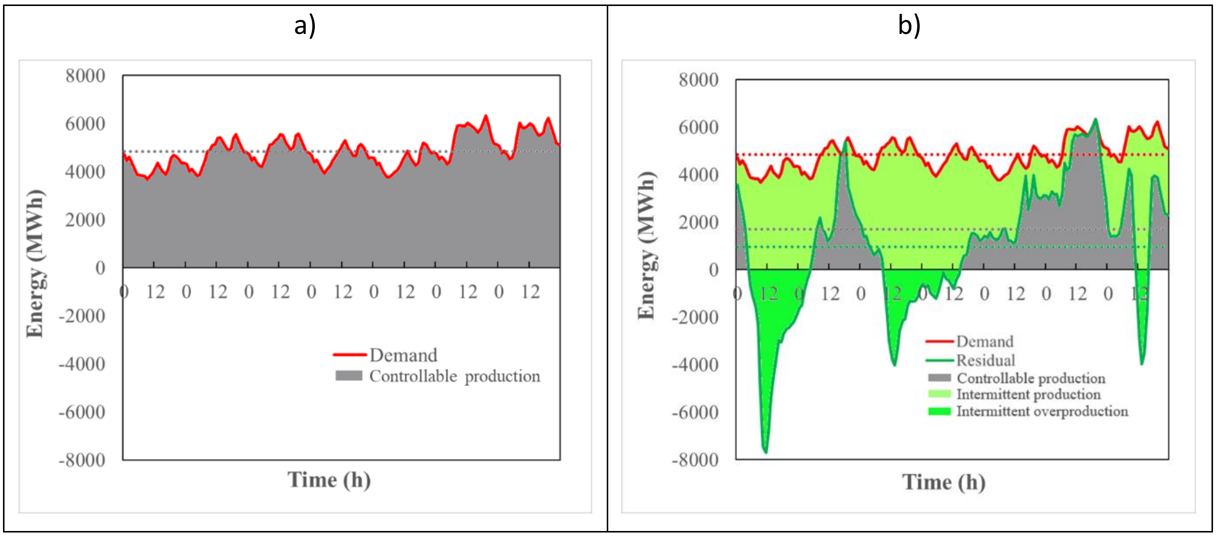


Figure 6 Illustration of hourly energy demand and sources. The grey area corresponds to the energy to be produced by the controllable sources; a) in the absence of intermittent sources; b) when intermittent energy production is introduced into the mix (represented by the green areas). Residual energy is equal to the demand minus the intermittent source and is represented by the green line. The dashed lines correspond to the mean demand and mean residual energy.

The method considers a baseline scenario which corresponds to a projection into the future for a given year. This baseline can be estimated as the result of applying a specific policy until the target year or simply as a "business as usual" evolution. The method aims to develop a series of scenarios in which the share of intermittent energies is gradually increased compared to the baseline. For each share of intermittent energy, it minimizes the costs for the wind/solar fraction, the combination of technologies for controllable sources and energy storage. The method estimates the benefits or losses of each optimized scenario compared to the baseline by calculating various indicators based on costs, GHG emissions, autonomy, etc., as a ratio between scenarios and baseline. Analysis of the trends in the various indicators does not lead to a single option but prompts decision-makers to choose what they consider to be the best compromise between various criteria. Figure 7 shows that the lowest-cost scenario is achieved by generating 60% of demand from intermittent sources, but still requires importing energy from outside the region under consideration. The costs of the 90% scenario are higher, but GHG emissions would be lower and imports no longer necessary. It's up to decision-makers to define their priorities and make the choice that makes the most sense to them.

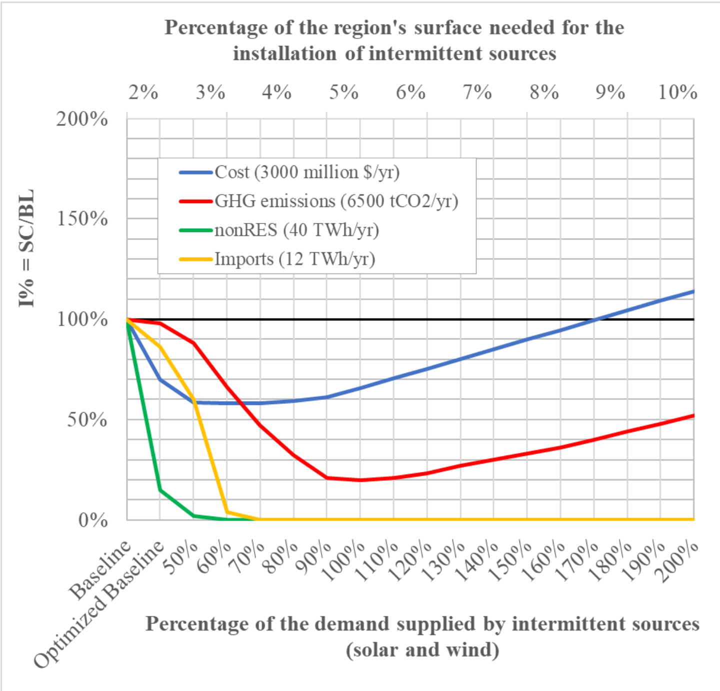


Figure 7 The introduction of intermittent sources changes the characteristics of the system, and as a result the criteria of interest for the decision makers also change. These changes can be plotted as indicators (I% = SC/BL), they correspond to the comparison of these criteria between the optimized scenarios and the baseline scenario. Values in parentheses shown in the legend of the plot correspond to the characteristics of the baseline scenario.

3.3. Criteria for the evaluation of energy strategies

To compare the types of resources that are part of energy strategies, criteria such as emissions, costs, surface requirements for their deployment, and their availability in terms of reserves can be used (Table 1). The data about the costs correspond to: reserves for non-RES(worldometer.info, 2023). GHG emissions are taken from already published studies(Engineering ToolBox, 2009; Fragkos et al., 2021; Solé et al., 2020). Regarding the surface need for the different types of energy sources, the data was retrieved from many sources(Cheng & Hammond, 2017; Hydrocoop, 2013; IRENA, 2015b; jancovici.com, 2003).

Table 1 Summary of the criteria for the different types of energy sources: fossils, nuclear, biomass, hydropower, solar, and wind. The values in the table are reference values for comparison purposes, they can change according to specific applications and particular conditions.

Criteria	Fossil	Nuclear	Biomass	Hydropower	Solar	Wind
GHG emissions (t-CO2eq/TWh)	Coal: $1.3\text{x}10^6$ Oil: 900 000 Gas: 496 040	~0	~0	19.85	41	11
Costs ($/MWh)	50 –180	290	66	47	Solar PV: 68 Solar CSP: 182	Wind onshore: 115 Wind offshore: 50
Surface (km²/TWh/yr)	Coal: 4 Oil: 0.5 Gas: 0.1	0.5	400-2200	86	12-27	25-83

Criteria	Fossil	Nuclear	Biomass	Hydropower	Solar	Wind
Reserves (years left) *	Coal: 133 Oil: 47 Gas: 52	30	*	*	*	*

*RES do not have a practical limit in terms of reserves.
Costs correspond to the Levelized Cost of Energy (LCOE), adjusted to 2023 as the reference year.
*With data for 2023 as the reference year.

4. Outline

The method was applied to two different cases of study: i) the Grand Est region of France in central Europe, a region with seasonal variation of the demand and intermittent energy production, and ii) Cuba a tropical country in the Caribbean region with great RES potentials and with lower seasonal variation of the energy demand and intermittent energy production. Also, these two cases of study have different technologies and resources currently in their energy systems.

This thesis document is distributed in 5 chapters. The first one (this section) corresponds to the introduction and background.

In the second chapter, the case of Cuba's energy strategies up to 2030 is aborded. This chapter corresponds to an already published article(M. Guevara-Luna et al., 2024). Cuba is an interesting first case of study due to 3 reasons: i) Energy demand in Cuba is already minimal and will not increase due to its geopolitical situation of “embargo”, ii) since it is an island there is no exchange of electricity with the neighboring regions or countries, and iii) for its location it has a great solar and wind energy potentials. A review of the current energy situation on the island and the resources potentials are included. Alternative scenarios were compared with the official plan of the Cuban government considering greater intermittent energy introduction. This leads to important improvements for the indicators even if the energy mix of the controllable is not optimized.

The third chapter shows the formalization and generalization of the developed method of “optimized tendencies” for the design and evaluation of scenarios without energy storage. This method is designed to evaluate the changes of the energy system when intermittent energy is introduced into the mix. The number of scenarios is reduced, and at the same time the mix of controllable technologies is defined by implementing cost optimization. Then, the resulting characteristics of the technologies in the strategies and the costs, are used to evaluate different indicators of interest for the decision makers.

The fourth chapter includes the evaluation of scenarios including energy storage for the management of the energy overproduced due to the intermittency of the system when the solar and wind sources are introduced. Scenarios with limited storage capacity and without limited storage capacity are compared. Also, the chapter includes the analysis of the adaptation of the demand to follow the variation of the energy production along the scenarios, and the storage time (or residence time) distribution on the utilization of the storage capacities of the scenarios.

The fifth chapter corresponds to the conclusions and perspectives arising from this research.

Chapter 1: Strategies toward an effective and sustainable energy transition for Cuba

Abstract

This study evaluated the possibilities of energy transition in Cuba 2030. Cuba is currently in a vulnerable energy situation since it strongly depends on the importation of fossil energy. Strategies based on intermittent RES (solar and wind) can reduce this vulnerability, but the introduction of this type of source impacts the energy system's characteristics and aspects at a country/regional scale. Most of the studies about energy transition strategies focus on the evaluation of a few specific arbitrary scenarios or the classic economic optimization approach. This research relies on existing methods to evaluate energy scenarios. However, some aspects of our approach are original: differently to the comparison of arbitrary scenarios we evaluate a fairly large number of scenarios, and differently to the classic optimization we consider many different indicators (e.g., energy security, carbon footprint, air quality, and economic). This allows the description of the trends of the changes in the energy system and the evaluation of the benefits linked to a progressive introduction of intermittent sources. Scenarios for Cuba correspond to a progressive introduction of intermittent sources to reduce fossil fuel importation. These scenarios were compared with the official projection of the Cuban government for 2030 showing that the introduction of solar and wind improve the situation of the island by reducing CO_2 emissions, improving air quality, and generating economic benefits. Monetizing the CO_2 emissions results in greater economic benefits through carbon compensation. Furthermore, replacing Internal Combustion Vehicles (ICVs) with Electric Vehicles (EVs) could offer additional benefits across all these aspects.

Keywords

Energy scenarios; decision-making; energy policy; renewable energy sources; carbon compensation

Highlights

- Design of a set of indicators to analyze different energy transition scenarios.
- Carbon footprint, air quality, and economic indicators are improved through the introduction of solar and wind sources and carbon compensation.
- To improve energy security, the consumption of fuels must be reduced by introducing RES.
- The shift of demand from fuels to electricity in transport and industry is necessary to enhance energy security.

1. Introduction

Human activities in our modern society require more and more energy which is mainly supplied by fossil fuels (~80%). This type of energy source is responsible for the acceleration of global warming and premature mortality due to poor air quality worldwide(EIA, 2016; Franco et al., 2015; IPCC, 2021; Technical University of Denmark (DTU), 2021). To face these problems, it is urgent to substitute fossil fuels with other energy sources. There are several possible options for implementing this substitution. The choice of the best option depends on the availability of technologies and the energy resources they require. But this choice is not only dictated by technological constraints but also by economic, social, and political considerations so it must be adapted to the different local situations(Jacobson, Delucchi, Bauer, et al., 2017).

A large number of studies are regularly published to analyze energy supply systems as a whole (from production to energy demand) in order to help choose the best options(Mazzeo et al., 2021). Some of these studies simply assess the current state of an energy system(Jorge Morales Pedraza, 2019), but the majority are concerned with developing scenarios for the future(Bompard et al., 2020; Connolly et al., 2016; De Rosa & Castro, 2020; Hansen et al., 2019; Luo et al., 2021; Miguel et al., 2016; Niu et al., 2021; Proskuryakova & Ermolenko, 2019; Soler-Castillo et al., 2021; Vaccaro & Rocco, 2021). Since a very large number of options can be considered, the methods used for these studies must be able to handle many different scenarios.

Some methods are based on optimization algorithms that automatically generate a very large number of scenarios and select a single one by minimizing a very few characteristics (usually economic costs) (T. Li et al., 2020; Potrč et al., 2021; Zhao & You, 2020). This approach has the advantage of generating scenarios systematically but suffers from the disadvantage of not being able to consider enough characteristics to select the most appropriate scenario for decision-makers. Indeed, the search for minimum costs is perhaps not the only important criterion for a decision-maker, who must also consider many other characteristics linked to social, political, or even geopolitical issues.

Other methods consist of choosing arbitrary scenarios based on the expertise of the study's authors(Bompard et al., 2020; Connolly et al., 2016; De Rosa & Castro, 2020; Hansen et al., 2019; Luo et al., 2021; Vaccaro & Rocco, 2021). Compared with optimization-based methods, it can use a larger number of diverse criteria to compare the different scenarios. In general, such methods do not result in the choice of a single scenario but seek to describe as best as possible the many characteristics of the scenarios evaluated. Their weakness is that they can only handle a limited number of scenarios that have not been systematically generated, so there is a risk of missing scenarios that could be of interest to a decision-maker. Improvements can be achieved by using statistical classification methods, which can help to describe a larger number of scenarios by grouping them into clusters(Miguel et al., 2016; Niu et al., 2021). Designing scenarios based on progressive trends in their characteristics (such as an increasing percentage of wind power in the energy mix) is also a way of describing a larger number of scenarios more easily(Cabrera et al., 2018; Proskuryakova & Ermolenko, 2019; Soler-Castillo et al., 2021).

In this work, we decided to rely on the existing methods mentioned previously to generate and compare different scenarios. However, some aspects of our approach are original: Primary energy sources are divided between intermittent and controllable sources. Intermittent sources (solar and wind) can only provide energy when available in nature while controllable sources can potentially produce energy at any time. The scenarios to be analyzed are designed by gradually increasing the percentage of energy produced by intermittent sources. The remaining energy to be supplied by controllable sources is then hourly evaluated to meet the energy demand. For each percentage of intermittent energy considered, an optimization calculation is carried out to find the least expensive repartition between solar and wind for the intermittent production. A series of indicators (such as economic costs, climate and health benefits and/or necessary energy imports, etc.) are estimated for each scenario. This method aims to compare a fairly large number of scenarios using a fairly large number of criteria easily chosen according to the local context.

The local context chosen for this study is the case of Cuba since this country is in a very critical energy situation that requires rapid change. The country is both under embargo and is highly dependent on imports of fossil fuel resources(Madrazo Bacallao, 2018). Moreover, the Cuban energy transition is especially interesting to investigate due to several characteristics of the country: i) because of the embargo the Cuban population is already showing great sobriety to reduce its energy consumption, therefore, there is no need to consider scenarios dedicated to the energy demand reduction scenarios,

ii) the country is an island whose interest is to move towards energy autonomy by limiting its exchanges with neighboring countries/regions, which simplifies the analysis of possible scenarios, and iii) due to its location (tropical country) it has a large potential of renewable energy sources (RES), especially solar.

This research aims to analyze the Cuban energy system and a set of scenarios for a reliable energy transition. A base case that corresponds to the year 2015 is used to describe the current situation of the Cuban energy system in terms of resources, technologies, and services. 2015 has been selected as the reference year because data were easily available for this year. 2015 also has the advantage of being well representative of a situation where the country is not affected by the effects of the COVID-19 pandemic. The official projection of 2030 is chosen as the baseline scenario from which several alternative scenarios are derived by introducing solar and wind energy into the energy mix and electric vehicles for transportation. The different scenarios are analyzed and compared using indicators quantifying energy security (i.e. dependence on energy imports), carbon footprint (i.e. CO_2 emissions), air quality (i.e. concentration of harmful air pollutants), and economic cost (i.e. total annualized costs -TAC- and carbon compensation).

2. The energy system of Cuba

During the 1990s, after the collapse of the Soviet Union, energy dependency on foreign resources led to a major setback for the Cuban economy. The state was forced to slash its energy imports which affected its energy security. The government responded by implementing reforms that led to a change in society concerning energy use. Such reforms included: increasing the production of domestic crude oil and associated gas, reduction of energy demand, reduction of electricity losses, and improving energy infrastructure. Between 1992 and 2003, domestic oil production grew annually by 7%(Suárez et al., 2012), but this fuel showed to be far from optimal due to its high sulfur content. This condition caused damage to the power plants in terms of corrosion, as a consequence, many power plants had to shut down. This situation triggered a crisis in 2005, the government replied with the policy called the “Energy Revolution”. This decision instituted measures to reduce electricity demand and increase energy efficiency with investments in distributed electricity generation systems. Around 2000 small diesel generators were scattered around the island, covering 70% of the municipalities(Belt, 2010). The energy system continued to be highly dependent on imported resources.

During the 2000s preferential trading agreements with Venezuela allowed the importation of oil from this country. This dependency led to a new crisis that caused the Cuban energy sector to once again enter a period of uncertainty due to the political instability of the Venezuelan economy since 2010.

In July 2016, the Cuban government announced new goals to reduce electricity and fuel consumption by 6% and 28% respectively intending to reduce oil imports(Panfil, M., D. Whittle, 2017; Reuters, 2016). Currently, the country is still exploring ways of fostering energy efficiency: the necessity caused by the aforementioned economic crises enforced moving toward a less-demanding energy system, but it has been and still is heavily reliant on fossil fuels(ONE, 2016a). The country still largely uses fossil fuels and remains dependent on external sources compromising energy sustainability and security despite the large potential of RES available in Cuba.

2.1. Situation in 2015

2.1.1. Energy demand

Energy consumption is the consequence of human activities which are connected with all the aspects of daily life through the vast use of energy, from households to industries. In Cuba, industrial processes encompass major consumers (41%), followed by the residential sector (37%) and then transport (11%)(Table 2). The various other sectors (i.e., water supply, construction, and agriculture) use 12% of the total energy consumed. The demand of the island is fulfilled with two different branches of energy resources: Oil sub-product (63%) and electricity (37%).

Table 2 Energy demand of Cuba by demanding sectors in 2015(ONE, 2016a)

Macro Sector	Electricity (GWh/yr)	Oil Sub-products (GWh/yr)	Total (GWh/yr)
Residential	12 440	4 376	16 816
Industry	4 713	13 939	18 651
Transport	0	5 048	5 048
Other	0	5 459	5 459
Total	17 153	28 821	45 974

2.1.2. Electricity production

The largest part of electricity (59%) is produced by seven thermoelectric power plants that consume large amounts of crude oil as well as, in smaller quantities, fuel oil, and diesel (Pérez Sánchez, 2017). 22% of electricity is produced by a set of distributed generators (so-called “generator set”) reliant on fuel oil and diesel, 15% comes from natural gas by a combined-cycle gas turbine (CCGT) generating plants, 3.5% from biomass plants from bagasse (i.e. the dry pulp residue left over after sugar extraction from sugar cane), and around 0.5% from other renewables resources such as water, sunlight, and wind (Table 3).

Table 3 Electricity production of Cuba in 2015 sorted by technologies and resources, the energy consumption column corresponds to the primary resources needed to produce the amount of electricity in the column called electricity production with the current Cuban energy system.

Technologies	Resource	Electricity Production (GWh/yr)	Energy consumption (GWh/yr)
PV panels	Sun radiation	15	-
Wind turbines	Wind	35	-
Hydroelectric	Water	48	-
Sugar factory	Bagasse	898	22 450
CCGT	Natural Gas	2 950	7 375
Thermoelectric	Oil & Oil sub-product	11 943	33 175
Generator set	Oil sub-product	4 399	11 576
Total		20 288	74 576

Thermoelectric power plants have an installed capacity of 2.59 GW. Currently, the obsolescence of these technologies joined with the use of low-quality crude oil leads to high rates of failure and inefficiencies. Most of the power plants run at only 60-65% of their potential(Berg & Bäck, 2013).

Generator-sets account for 2.52 GW, this technology is a singular aspect of the Cuban grid, it offers benefits against centralized schemes since it helps when facing natural disasters, such as hurricanes, as each generator set contributes to a sector of the grid with its capacity(Feldmuller, 2017; Panfil, M., D. Whittle, 2017). Generator-sets also reduce electricity losses as they do not rely on transmission networks extensively and they can be brought back online faster than centralized generation plants(Momoh, J. A., S. Meliopoulos, 2012). One important disadvantage is that the generator sets require high-quality oil subproducts, which leads to a costly option to match daily load profiles(Benjamin-Alvarado & Benjamin, 2010). Previews studies show that they are not a viable solution in the long run and may only serve as a supplementary power source to the major thermoelectric power plants(Berg & Bäck, 2013).

The installed capacity of natural gas power plants is mostly of the type CCGT which currently accounts for 580 MW. This infrastructure is operated by the foreign company Energas (i.e. a joint venture between Canada's Sherritt and Cuba's Cupet and Unión Eléctrica). The largest facilities are located near the country's capital city (i.e. Havana)(Panfil, M., D. Whittle, 2017).

Biomass power plants account for 470 MW spread among 40 sugar factories. The sugar industry is the sector that uses most of the biomass to cogenerate heat and electricity. But currently, only small amounts of electricity are exported to the grid (i.e., 3.5% of the energy produced) (Jimenez Borges et al., 2017; Madrazo Bacallao, 2018; MINAS et al., 2016; Rodríguez-Machín, L., D. H. Bretón-Glean, R. Perez-bermudez et al., 2012; Sagastume et al., 2017). In addition, biomass-based energy is used only for 3600 h per year (~150 days).

The RES capacity is composed of 62.8 MW of hydropower, 11.7 MW of onshore wind turbines, 24.4 MW of utility-scale photovoltaic (PV) panels, and 0.66 MW of biomass-based power plants from the gasification of forest biomass. RES are currently not significantly exploited. They are mainly used in remote locations, inaccessible to the supply of conventional resources(Sagastume et al., 2017).

2.1.3. Fuel production

The country uses 106 TWh/yr of primary resources: 42% imported and 58% produced domestically. The domestics (45 TWh/yr) include 3 million tons of crude oil, 1200 million cubic meters of natural gas, and 1.2 million tons of sub-products from oil and gas.

Cuban crude oil is a heavy product (less than 10 °API) extracted from shallow waters just off the coasts with high-sulfur content(Käkönen et al., 2014). Crude natural gas corresponds to the associated light hydrocarbons of the crude oil reservoirs(Benjamin-Alvarado & Benjamin, 2010).

The primary energy imports (40 TWh/yr) account for 9 TWh/yr of crude oil and 31 TWh/yr of oil sub-products. Due to the low quality of the Cuban crude oil, refined light fuels such as diesel, fuel oil, and gasoline, are obtained from the refining of imported oil, or directly imported as oil subproducts. These imports are mainly from Algeria (which accounts for 80-85% of the total imports), Venezuela (8%-10%), the European Union (6%), Mexico (2%), and Russia (2%), such imports account for 25-30% of total domestic demand of refined products(Pérez Sánchez, 2017).

In terms of gross domestic product (GDP) the country spends more money on energy (mainly imports) than other nations; the total value of the energy consumed in Cuba is 14% of the GDP, whereas the world average is 10%(Panfil, M., D. Whittle, 2017).

2.1.4. Overview of the energy fluxes

Figure 8 shows the Cuban energy system in 2015 through a Sankey diagram (Bostock, 2014). Blocks correspond to production, transformation, or consumption processes. The links between blocks show the energy flow going from the left to the right of the diagram linking the production to the consumption through the transformation of different energy forms. The differences between the size of the left (input) and right (output) links in a block provide information about the losses associated with a transformation process.

Energy is mostly demanded by three macro sectors (right side of diagram Figure 8): residential, industry, and transport, the industry being the most demanding followed by residential. These three macro sectors need energy from electricity (17 TWh i.e. 37% of the demand) and oil subproducts (29 TWh i.e. 63% of the demand). The residential sector consumes mostly energy as electricity meanwhile the industry consumes mostly oil subproducts. The transport sector currently demands only oil subproducts.

Part of the oil subproducts is directly imported while another part is refined from imported or domestic crude oil. The losses which result from the refining process amount to 10% (Figure 8).

The electricity production generates more losses than the refining processes used to obtain the oil subproducts. The lost part of primary resources depends strongly on the way the electricity is produced. The losses of the production by generators are 62%, by thermoelectric power plants 64%, by CCGT 60%, and by sugar factories 96%. Solar, wind, and water resources are not comparable to the other primary resources such as fossil fuels or biomass, as they are used to produce electricity directly, without any transformation processes. This is why we have chosen not to associate losses with the production of electricity from solar, wind, and water. However, the power supply is affected in all cases by additional losses due to the transport of electricity through the grid. These losses are estimated at 15.5% in the Cuban situation (shown between electricity generation and electricity demand in Figure 8).

The energy supply can be affected by very different losses depending on the resources used, with different consequences:

- while electricity production consumes 55% of all primary resources: hydropower, solar, and wind included, it satisfies only 37% of energy demand,

- while the electricity is produced at 95% by fossil fuels and only 5% by biomass.

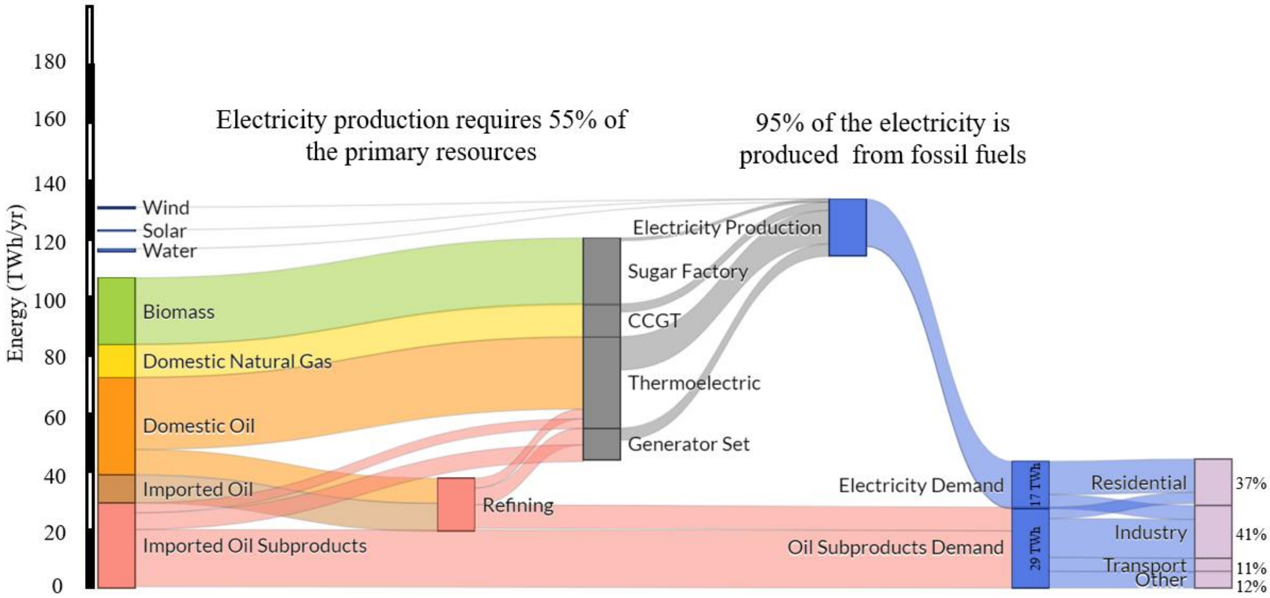


Figure 8 Sankey diagram of the Cuban energy flows for the year 2015. The energy flows go from the primary energy resources on the left of the diagram to the main sectors of human activity on the right of the diagram.

2.2. Official projection into 2030

2.2.1. Energy demand

The energy generation and consumption in Cuba have been relatively steady during the last decades(ONE, 2016a; Sagastume Gutiérrez et al., 2018). Figure 9 shows the energy demand trends in terms of electricity and fuels.

The electricity sector will play an increasingly important role in energy consumption, which prompted the Cuban government to implement several policies to improve the performance of the energy sector. A fundamental part of them was the replacement of household and state entities appliances with more efficient equipment. The policy also introduced a new electricity tariff with a reduction of government subsidies to encourage savings of electricity(Guevara-stone L. et al., 2009; Suárez et al., 2012). The industrial sector, although technologically outdated(Sagastume Gutiérrez et al., 2018), has also implemented policies to improve energy efficiency(Gonzales del Toro, 2016). Despite the measures taken by the government, the electricity consumption from 2002 to 2015 shows an average increase of 3.6% per year, with 4.8% from 2014 to 2015 alone (Figure 2). This trend can be explained by the increased demand from the residential sector (around 4.7% per year after 2010). According to (Reuters, 2016), the opening of the private segment of the economy during the 2000s (where Cubans were allowed to set up businesses in their homes and front porches) highly influenced this drift. For all other sectors, the increase is lower (less than 3% per year). Following this trend, Cuban electricity consumption is expected to have a small variation in the future(Käkönen et al., 2014). Official estimations foresee an increase of 3.28% per year reaching around 28 TWh in 2030(MINAS et al., 2016).

It is important to keep in mind that a significant increase in temperature is expected in the coming years due to climate change that will particularly affect the Caribbean region(Angeles et al., 2010, 2018). This should lead to an increase in the use of air conditioning throughout this region. Because of this, the rate of increase of 3.28% per year of the electric demand estimated by the Cuban authorities is optimistic and it is very likely to be higher than 4% per year(Madrazo Bacallao, 2018).

The direct consumption of oil sub-products, by services other than electricity, experienced a decreasing trend. At the risk of being too pessimistic about the planning horizon, such demand is assumed to remain constant at 29 TWh. Consequently, the total energy demand will increase from 46 TWh in 2015 to 57 TWh in 2030 with a share of 51% of oil sub-product and 49% of electricity.

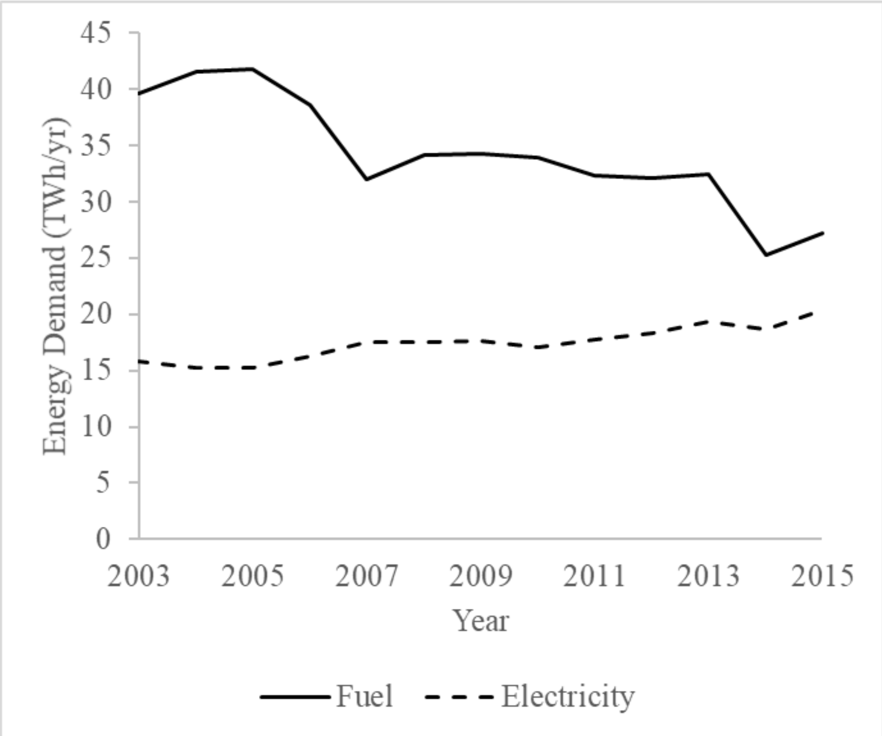


Figure 9 Trend of Cuban energy demand from 2002 to 2015

2.2.2. Electricity production

The Cuban government is aiming to match future energy needs with a more self-reliant supply. Its strategy consists of reducing the importation of energy by producing more domestic resources. Broadly, the 2030 strategy includes i) increasing technological capacity to use domestic fuels (i.e. crude oil and natural gas), ii) increasing efficiency of electricity production, distribution, and consumption with energy-saving measures, iii) and expanding the renewables share; (EFE & El Economista America.com, 2014), documented by "Cartera de oportunidades Cuba - 2017".

Thermoelectric capacity will increase by 800 MW in 2030 (an additional 13% of the current capacity), this new thermoelectric capacity will produce electricity by burning domestic oil allowing to initially reduce imported energy needs. CCGT will increase the installed capacity by 12% (Belt, 2010). The generator set installed capacity is maintained at the same level as in 2015.

Regarding the RES, 74 small hydroelectric plants (375 MW), 13 onshore wind farms (583 MW), and 19 utility-scale PV plants (263 MW) will be added. Most of the hydropower energy will remain produced in isolated areas. Onshore wind farms will be located on the northeast coast where wind speeds at 50m and 100m allow an average capacity factor greater than 30%. 720 MW of biomass burning-based powerplants will be added mainly by increasing the efficiency (between 5% and 10%) in nineteen of the existing sugar factories.

Table 4 summarizes the main energy technologies and resources projected for 2030.

Table 4 Electricity production of Cuba in 2030 sorted by technologies and resources

Technology	Resource	Electricity Production (GWh/yr)	Energy consumption (GWh/yr)
PV panels	Solar radiation	518	-
Wind turbines	Wind	1 535	-
Hydroelectric	Water	985	-
Biomass	Bagasse	5 152	34 347
CCGT	Natural Gas	4 481	11 203
Thermoelectric	Oil & Oil sub-product	15 855	44 042
Generator set	Oil sub-product	4 399	11 576
Total		32 925	101 167

2.2.3. Fuel production

To fulfill the projected demand in 2030 the country may manage around 120 TWh/yr of primary resources including crude oil and sub-products. Domestic crude oil production is expected to rise to 56 TWh/yr, and natural gas to 1 TWh/yr. The biomass may be set up to 34 TWh/yr. The importation of oil subproducts demanded by the generators sets, and the vehicles fleet will be needed due to the low quality of the domestic crude oil in Cuba. The needs of oil sub-products will be covered by Cuban facilities with refining capacities for 9 TWh/yr of imported oil and subproducts imports of 7 TWh/yr.

2.2.4. Overview of the energy fluxes

Figure 10 shows the Sankey diagram of the Cuban energy system for the year 2030. Final electricity demand reached 28 TWh/year, an increase of 11 TWh/year compared to 2015. The share of electricity generated from fossil fuels will decrease to 75% (from 95% in 2015) in the benefit of RES such as biomass, water, solar, and wind. However, the increase in the share of RES and the use of domestic fuels (to power thermoelectric and CCGT plants) is still insufficient to completely end dependence on imported sources (i.e., imported oil and oil subproducts).

Compared to 2015, the 2030 scenario (Figure 10) counts on an improvement in the efficiency of the different power generation processes, the loss rate is expected to reach 85% for the sugar factory. Even so, for the other technologies (CCGT, Thermoelectric, and Generator set) the loss rates are expected to be the same as in 2015.

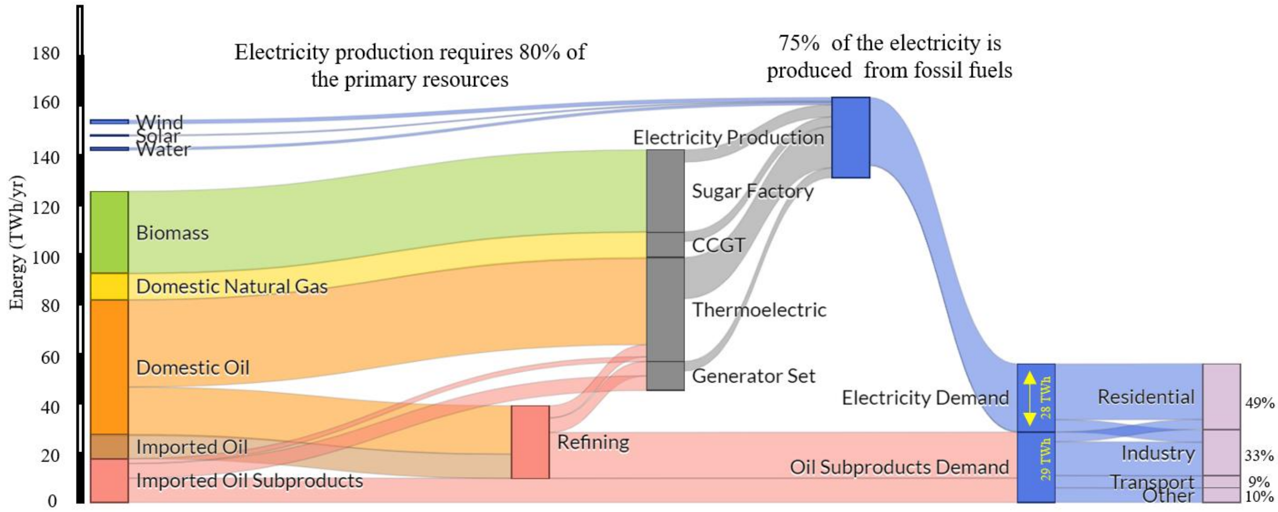


Figure 10 Energy flow Sankey diagram of Cuba for the year 2030

2.3. Environmental concerns

Since the energy system of Cuba is dependent on fossil fuels, greenhouse gas (GHG) emissions, and atmospheric pollution turn into important aspects(Wright et al., 2010). In addition, most of the power installations are close to urban areas which may have an impact on population health.

To represent the pollution on the island, and its variation with different emission scenarios, an air quality modeling (AQM) was performed. The AQM was developed using the Chemical Transport Model (CTM) called CHIMERE for the aforementioned scenarios of 2015 and 2030 (Mailler et al., 2017). The meteorology over Cuba needed for the AQM was simulated with the WRF (Weather Research and Forecasting) model (ARW, 2021; NCAR, 2019).

2.3.1. Emissions inventory (EI)

The emission inventory developed in a preview study for Cuba in 2015 was used to assess their projection into 2030 (Madrazo et al., 2018). Since this projection only acts on electric generation (i.e. other services held steady from 2015), only the emission parameters (i.e. emission factors, activity levels, and allocations) of power units are modified. The developed emissions inventory is based on eleven key macro sectors (MS) according to the SNAP sectors classification. A summary of the yearly emissions of the two baseline scenarios (2015 and 2030) is shown in Table 5 sorted by macro sector and pollutant.

Emissions from MS1 were calculated for each source location by using local activity levels and emission factors either measured (Abreu Elizundia et al., 2016; Meneses-Ruiz et al., 2018) or set based on "AP42, Compilation of Air Pollutant Emission Factors"(EPA, 2020). For the MS2, emissions were estimated according to fuel consumptions reported by the energy section of (ONE, 2016c) and emission factors from (EPA - U.S. Environmental Protection Agency -, 1998; GCE, 2006; Haneke & Johnson, 2001).

Emissions of MS7 were computed by using the EMISENS model(Bằng, 2014; Ho et al., 2014) according to the average activity levels of the Cuban vehicular fleet(ONE, 2016b), classified into five vehicle categories (gasoline and diesel passenger, heavy vehicles, buses, and motorcycles) and spared into five road categories (semi-urban, urban, locals, and neighborhood streets)(Madrazo et al., 2018, 2019; Madrazo & Clappier, 2018).

The road network lengths repartition used is based on OpenStreetMap®(Contributors, 2021). Emissions from MS3, MS4, MS6, MS9, and MS10 were compiled from the literature(ONE, 2016c).

The geographical location of stationary sources was taken from the Cuban State Registration of Companies and Budgeted Units in(ONE, 2010). For agriculture, the spatial distribution is based on the Global Land Cover Facility GLCF-Cropland database(Sexton et al. 2013), which supplies an extensive agricultural land classification from remotely sensed satellite data including built-up, water, snow, forest, savannas, and shrub, grass, and croplands(Emanuel et al., 2013; Friedl et al., 2010; Sexton et al., 2013).

CO_2 emissions have been computed using the emission factors in **Table 8**.

Changes in the pollutants' emissions are driven by the differences between the use of the primary energy sources. These differences are mainly characterized by the increase in biomass, domestic oil, and imported oil primary resources use in Cuba as explained in the sections above.

The differences in the emissions due to changes in the energy consumption between 2015 and 2030 are represented as changes in sector MS1. MS1 is taken as the key sector since it is the most energy-demanding one and it is directly related to the electricity production on the island, changes in the vehicles fleet are not considered between the scenarios 2015 and 2030.

The increase in the NO_x, SO_x, and VOC emissions is mainly linked to an augmentation of primary resources consumed by the thermoelectric power plants, CCGT; and oil subproducts production, storage, and transportation. While the increase in $PM_{2.5}$ and NH_3 emissions is due to the operation of new biomass-based power plants and the increase in biomass use as a primary resource.

As result by 2030, the emissions due to electricity generation will increase in comparison to 2015. The percentages of increase by pollutant are NO_x (19%), SO_x (36%), VOC (17%), $PM_{2.5}$ (330%), and NH_3 (94%).

The implementation of the official plan for the energy mix in 2030 will lead to an 18% increase in total CO_2 emissions. MS2 has an increase of 44% and MS1 has a small increase of 2% in the CO_2 emissions in 2030 with respect to 2015. The MS7 remained unchanged in terms of CO_2 emissions in 2030 compared to 2015.

Table 5 Emissions of Cuba (Ton/yr) for 2015 and 2030 baseline scenarios considering the sectors: Combustion in energy and transformation industries (MS1), Non-Industrial combustion plans and residential (MS2), Combustion in manufacturing industry (MS3), Production processes (MS4), Extraction and distribution of fossil fuels and geothermal energy (MS5), Solvent and other product use (MS6), Road transport (MS7), Other mobile sources and machinery (MS8), Waste treatment and disposal (MS9), Agriculture (MS10), and Other sources and sinks (MS11).

Sector	2015						2030					
	$PM_{2.5}$	NOx	SOx	VOC	NH_3	CO_2	$PM_{2.5}$	NOx	SOx	VOC	NH_3	CO_2
MS1	6 195	45 975	376 858	738	555	13 433 900	26 661	54 814	512 134	865	1 076	13 735 078
MS2	5 077	753 063	1 771	38 631	-	8 475 087	5 077	753 063	1 771	38 631	-	12 233 951
MS3	-	2	1 644	9 446	-	-	-	2	1 644	9 446	-	-
MS4	-	8	5 956	34 214	-	-	-	8	5 956	34 214	-	-
MS5	-	-	-	-	-	-	-	-	-	-	-	-
MS6	-	-	-	32 490	-	-	-	-	-	32 490	-	-
MS7	463	90 753	3 173	16 014	246	1 261 883	463	90 753	3 173	16 014	246	1 261 883
MS8	-	-	-	-	-	-	-	-	-	-	-	-
MS9	-	589	-	-	-	-	-	589	-	-	-	-

Sector	2015						2030					
	$PM_{2.5}$	NOx	SOx	VOC	NH_3	CO_2	$PM_{2.5}$	NOx	SOx	VOC	NH_3	CO_2
MS10	-	7 098	-	-	-	-	-	7 098	-	-	-	-
MS11	-	-	-	-	-	-	-	-	-	-	-	-
Total	11 735	897 488	389 402	131 533	801	23 170 870	32 201	906 327	524 678	131 660	1 322	27 230 911

2.3.2. Air quality modeling

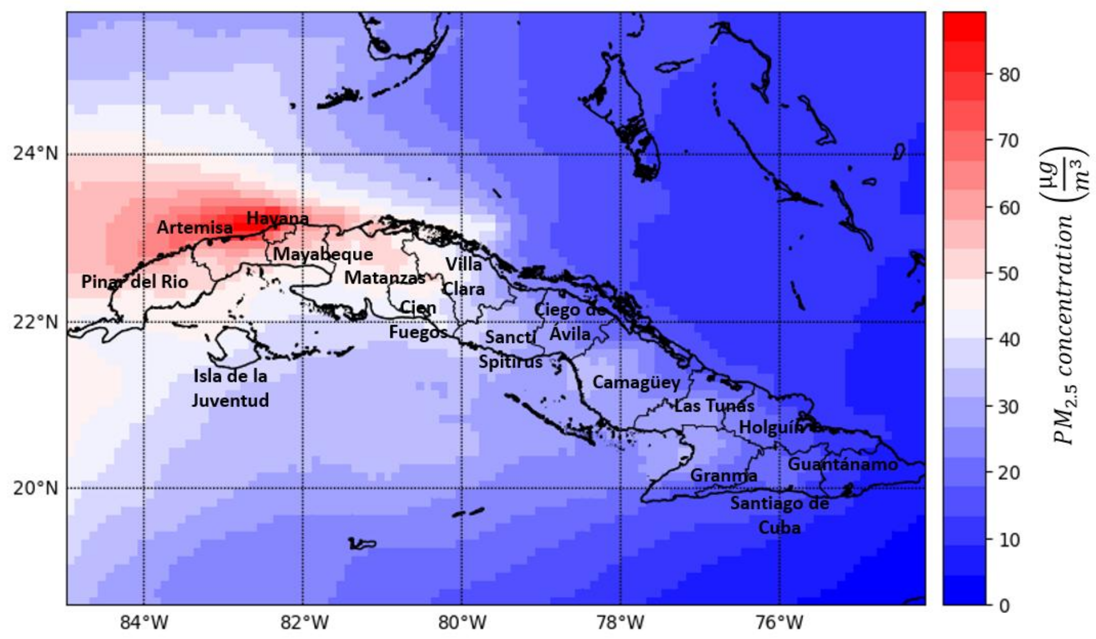
Figure 11 shows the AQM results regarding the $PM_{2.5}$ yearly average concentrations over Cuba for the current situation (2015), and the difference in the concentrations between 2030 and 2015.

Figure 11-a shows that the most polluted areas of Cuba are located in the northwest around Havana. Pollution is dispersed in the west of Havana, it is also evidenced in the north of Matanzas where the city of Matanzas and the touristic areas of Varadero are located.

Figure 11-b shows the difference between the pollution levels in 2030 and 2015, the color scale shows that the pollution in 2015 is relatively greater than the pollution levels in 2030 since an important number of cells are blue-colored on the map (i.e. the concentration of $PM_{2.5}$ is greater in 2015 than in 2030 for these cells).

The most important reductions are observed in the west of the island (i.e. the region of Pinar del Rio), and the east (i.e. region of Guantanamo). In the sea, the northern coasts have more reductions than the southern coasts except for the Guantanamo region near Santiago de Cuba. Two maritime areas present important reductions in the northwest of the simulation domain: one near Florida's coasts and the other on the west on the parallel 24°N and left of the meridian 84°W.

a)



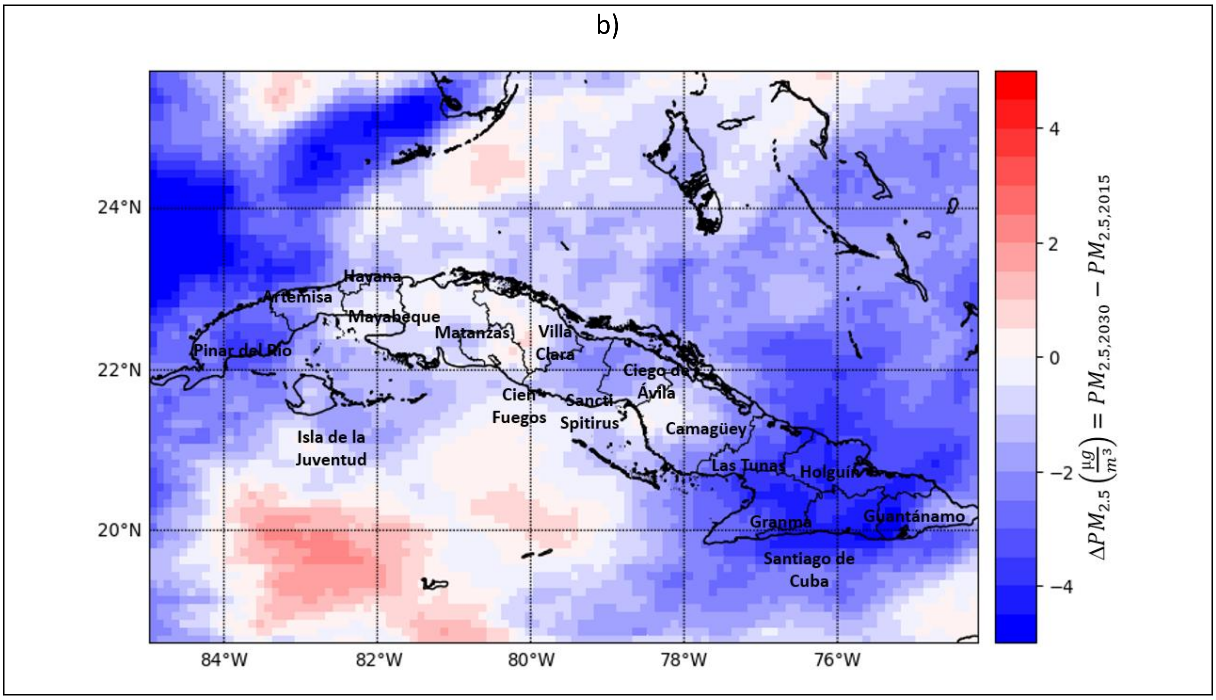


Figure 11 $PM_{2.5}$ yearly average concentration maps for Cuba: a) 2015, and b) difference of $PM_{2.5}$ concentrations between 2015 and 2030 $\left(PM_{2.5,2030} - PM_{2.5,2015}\right)$.

Air quality impact is evaluated based on the population exposure and is considered as a population-weighted mean level ($Ex_{PM2.5}$) of $PM_{2.5}$, it is calculated with equation 1 where $C_{PM2.5}$ is the annual average of $PM_{2.5}$ concentration at a region "*i*"; and Pop the population in the same region "*i*".

$Ex_{PM2.5} = \frac{\sum_i C_i^{PM2.5} \cdot Pop_i}{\sum_i Pop_i}$	(1)

2.4. Costs estimation

Evaluation and comparison of different energy transition strategies should consider the different components of the economical constraints. The first component is the total annualized cost (TAC) of the all energy system which is based on the investment and fixed costs as well as, the value of money over time, fuel costs, variable costs, and replacement linked to the use-life of the energy production infrastructure. The second component corresponds to the environmental gains, which are characterized as both local and global benefits. The local environmental benefits are linked to the reduction of the population's exposure to air pollutants, which is limited to the Cuban population and only affects the country's internal economy. Conversely, the reduction of GHG gas emissions provides global environmental benefits as it affects the entire world by helping to mitigate global warming. Local environmental benefits cannot be directly capitalized to obtain the foreign currency needed by the Cuban authorities to purchase equipment and fuel, while global environmental benefits can be used to raise funds through carbon compensation(Carbon Market Watch, 2010; CITMA, 2020; "Colectivo de autores coordinado por: Dr.C. Wenceslao Carrera Doral," 2020; Energy Information Administration [EIA], 2021; Obi et al., 2017; Sadiqa et al., 2018; Santoyo-Castelazo & Azapagic, 2014).

The economic indicators used in this study are based on the TAC and the carbon compensation. The carbon compensation uses the basecase 2015 as a reference to evaluate the reduction of GHG gas emissions in ton of CO_2 equivalent resulting from the introduction of solar and wind resources into the energy mix. It is then computed by taking a carbon price of 50 $/ton which is a projected price of CO_2

credits in 2030(Holder, 2021). The carbon compensation is added to the TAC to compute a carbon compensated total annual costs (CCTAC) of each scenario.

2.5. Cost calculation

2.5.1. Total annualized costs (TAC)

The total annualized costs of a technology “t” and scenario “SC” ($TAC_t^{(SC)}$) derives from two parts, the first part of the cost is variable and depends on the quantity of energy produced while the second part is fixed. For the scenario “SC” $TAC_t^{(SC)}$ is computed as the sum of a term proportional to the annual energy production in MWh/yr ($EP_t^{(SC)}$) and a term proportional to the installed capacity in MW ($IC_t^{(SC)}$). The $TAC_t^{(SC)}$ is calculated using the equation 2, where, FC_t is the annual fixed costs in \$/MW/yr, which corresponds to the costs of operating the system over a year and includes staff costs, insurance, taxes, repair, or spare parts. AC_t is the annualized capital cost in \$/MW/yr, it is calculated based on the overnight capital costs of the technology “t” (CC_t) in the energy mix in \$/MW, the lifetime (l) in years, and the discount rate (r) (equation 3). That is, AC_t is the value of the initial investment of the infrastructure amortized over its estimated lifetime. As a consequence, the AC_t has a value different from just dividing the capital investment costs by the lifetime in years due to the value of the money change in time according to r.

$$TAC_t^{(SC)} = IC_t^{(SC)} \times (AC_t + FC_t) + EP_t^{(SC)} \times \left(VC_t + \frac{FUC_t}{\eta_t}\right) \quad (2)$$

To consider the change of money value over time, the AC_t is calculated using a r value of 5.77% for the analysis of energy strategies based on the values reported in published studies(equation 3) (Aldersey-Williams et al., 2019; Jacobson et al., 2015; Jacobson, Delucchi, Cameron, et al., 2017; Murray et al., 2018; Obi et al., 2017).

$$AC_t = CC_t \times \frac{r \times (1+r)^l}{(1+r)^l - 1} \quad (3)$$

VC_t is the annual variable costs in \$/MWh/yr, which includes expenses related to the variation of the mean capacity factor of the system, e.g. contracted personnel, consumed materials, and costs for disposal of operational waste per year, excluding fuel costs. FUC_t is the cost of fuels consumed for electricity production in \$/MWh/yr, it is used with the fuel usage efficiency (η_t) to compute the ratio $\frac{FUC_t}{\eta_t}$ which corresponds to the cost of consumed fuel. With these parameters, and using equation 4 the $TAC_t^{(SC)}$ can be computed for the technology “t”. Then, adding all the technologies in scenario “SC” the $TAC^{(SC)}$ is calculated with equation 5.

$$TAC_t^{(SC)} = EP_t^{(SC)} \times \left(\frac{AC_t + FC_t}{Cf_t^*} + VC_t + \frac{FUC_t}{\eta_t}\right) \quad (4)$$

$$TAC^{(SC)} = \sum_t TAC_t^{(SC)} \quad (5)$$

The parameters used for the cost analysis of Cuba’s energy strategies in this research are presented in Table 6. These values are taken from the year of reference 2020 and are expressed as US dollars, assuming the currency value in 2020(Erichsen et al., 2019; Sadiqa et al., 2018; Santoyo-Castelazo & Azapagic, 2014). The fuel costs of reference are shown in Table 7 (Aguilera, 2014).

Table 6 Parameters for the calculation of costs for the case of Cuba's energy strategies.

Technology	Capital cost ($/MW)	Variable Cost ($/MWh)	Fixed cost ($/MW/yr)	lifetime (yr)	Efficiency
PV panels	1 500 000	0	20 000	25	-
Wind turbines	1 800 000	0	26 000	25	-
Hydroelectric	Not available estimation in Cuba	0	0	50	-
Biomass	2 050 000	10	74 000	30	0.15
Gas Turbine (CCGT)	850 000	7	20 000	25	0.4
Thermoelectric	1 500 000	10	74 000	25	0.36
Generation set	500 000	50	30 000	20	0.38

Table 7 Fuel costs estimated for Cuba.

Primary resource	Fuel Cost ($/MWh)
Coal	Not used in Cuba
Gas	31.9
Imported Oil	47.6
Domestic Oil	17.8
Biomass	Not data available for Cuba
Diesel	149.7
Fuel Oil	107.1
Refined motor gasoline, with local Oil	97.6
Refined motor gasoline, with imported Oil	98.9
Imported Gasoline	144.6

2.5.2. Carbon compensation and carbon compensated TAC (CCTAC)

The carbon compensation of any scenarios (BL2030, Int-a, or Int-b) is computed using the difference of carbon footprint between the scenario "SC" and the basecase scenario (BC) (equation 6).

$$CO_2C^{(SC)} = CAC \times max\left[0\,;\,\left(E_{CO2Eq}^{(BC)} - E_{CO2Eq}^{(SC)}\right)\right] \quad (6)$$

where CO_2C^{SC} is the carbon compensation of scenario "SC", CAC is the carbon cost. For the case of Cuba a carbon credit value is projected in 2030 (50 $/ton) (Holder, 2021).

E_{CO2Eq}^{BC} and E_{CO2Eq}^{SC} are the greenhouse gas (GHG) emissions of the BC and of the scenario "SC" in tons of CO_2 equivalent.

The carbon compensation and carbon compensated TAC (CCTAC) are calculated by equation 7.

$$CCTAC^{(SC)} = TAC^{(SC)} - CO_2C^{(SC)} \quad (7)$$

2.5.3. Cost difference between the scenarios

The difference between scenarios is denoted by Δ, e.g., the term $\Delta TAC_t^{(SC-BL)}$ denotes the difference of TAC between scenarios "SC" and BL, where "t" is one technology for electricity production (e.g., thermoelectric, solar, wind, etc…), and "SC" is the scenario (e.g., 30% of the demand meet by intermittents or 60%, etc.) (equation 8). The difference of TAC can be computed with equation 9.

$$\Delta CCTAC^{(SC-BL)} = \Delta TAC^{(SC-BL)} - \Delta CO_2C^{(SC-BL)} \quad (8)$$

$$\Delta TAC^{(SC-BL)} = \sum_{t} \left[\Delta IC^{(SC-BL)} \times (AC_t + FC_t) + \Delta EP^{(SC-BL)} \times \left(VC_t + \frac{FUC_t}{\eta_t} \right) \right] \quad (9)$$

For the scenarios Int-a and Int-b a large number of terms can be simplified since the installed capacity of the technologies that correspond to controllable sources keep their installed capacity "tc" and the variable and fuel cost of solar and wind are zero (equation 10).

$$\Delta TAC^{(SC-BL)} = \Delta IC_{solar}^{(SC-BL)} \times (AC_{solar} + FC_{solar}) + \Delta IC_{wind}^{(SC-BL)} \times (AC_{wind} + FC_{wind}) + \sum_{tc} \left[\Delta EP_{tc}^{(SC-BL)} \times \left(VC_{tc} + \frac{FUC_{tc}}{\eta_{tc}} \right) \right] \quad (10)$$

The difference of carbon compensation can be computed with equation 11.

$$\Delta CO_2C^{(SC-BL)} = CAC \times \left\{ max\left[0\ ;\ \left(E_{CO2Eq}^{(BC)} - E_{CO2Eq}^{(SC)}\right)\right] - max\left[0\ ;\ \left(E_{CO2Eq}^{(BC)} - E_{CO2Eq}^{(BL)}\right)\right] \right\} \quad (11)$$

The difference of carbon footprint (ΔCO_2C) for the BL2030 is negative so that its carbon compensation is zero then equation 11 can be written as equation 12.

$$\Delta CO_2C^{(SC-BL)} = CAC \times max\left[0\ ;\ \left(E_{CO2Eq}^{(BC)} - E_{CO2Eq}^{(SC)}\right)\right] \quad (12)$$

Then, the difference of GHG emissions results from differences of fuel consumption of the technologies that use controllable sources "tc" (see equation 13).

$$E_{CO2Eq}^{(BC)} - E_{CO2Eq}^{(SC)} = \sum_{tc} \left[\frac{\Delta EP_{tc}^{(BC-SC)}}{\eta_{tc}} e_{CO2}^{tc} \right] \quad (13)$$

where the factor $e_{CO2}^{tc}$are the CO_2 emission factors for the technology "tc"(Table 8)(Engineering ToolBox, 2009).

Table 8 Greenhouse gas (GHG) emission factors for the use of primary resources in the Cuban energy system.

Source/Technology	GHG (tCO_2/MWh primary resources consumed)
Solar	0
Wind	0
Biomass*	0
Gas turbine	0.18
Thermoelectric	0.31
Generation set	0.27
Fuel/gasoline	0.25

*The biomass is assumed to be a carbon-neutral primary energy source

2.6. Comparison between the scenarios

The historic dependency on imported fuels has made Cuba vulnerable to geopolitics and oil market variations, so that, energy security is a key issue in the economic development of the country. In addition, the availability of fossil fuels is finite, hence, the energy strategies based on fossil fuels are not a sustainable solution for the country's energy system and lead to the release CO_2 into the atmosphere. The current energy systems are using technologies based on combustion, the atmospheric emissions, and therefore, the concentrations of pollutant play an important role in the strategies to consider(Sagastume Gutiérrez et al., 2018; Vazquez et al., 2018).

Since the energy transition requires the introduction of RES-based technologies to produce energy there are costs associated with the investment and operation of the system of the old and new technologies. These costs change depending on the technologies characteristics, and energy mix (i.e. shares of different technologies within the system). These aspects make important to consider the financial aspects of the different assessed energy transition scenarios.

To evaluate the different possible energy strategies of Cuba a set of indicators was designed based on the country's specific interests: energy security, carbon footprint, air quality, and economic (CCTAC). These indicators may allow the comparison between the baseline scenario 2030 and other scenarios of the energy transition.

The indicators are expressed as ratios (equation 14) where the baseline scenario for 2030 (BL) is considered as a reference. In equation 14, I_s denotes the indicator value of scenario "s" for the different characteristics C used to compare the different scenarios. C can be the amount of imported fuels (energy security), the amount of emitted CO_2 (carbon footprint and global environmental benefit), the population exposure to air pollutants (local environmental benefit), or the economic cost of energy computed as the CCTAC. C_s , C_{BL} and C_0 are three values of the characteristic C: C_s is the value for scenario "s", C_{BL} is the value for the Baseline scenario "BL" and C_0 is the value for an ideal desired situation (i.e. zero fuel importations, zero CO_2 and other air pollutants emissions in Cuba, a TAC entirely compensated by the CO_2 compensation).

I_s can take different values relative to BL to compare the different scenarios. When I_s = 1 the scenario corresponds to a maximum possible improvement, i.e. it reaches the ideal desired situation, while it does not improve the BL situation when I_s takes a value greater or equal to 0.

$$I_s = \frac{C_{BL} - C_s}{C_{BL} - C_0} \qquad (14)$$

Table 9 Characteristics used for the calculation of the indicators of the scenarios of energy transition in Cuba

Indicator (I)	Characteristic (C)
Energy security	Energy imports (TWh/yr)
Carbon footprint	CO_2 emissions (Ton/yr)
Air quality	Population exposure to $PM_{2.5}$ concentrations (µg/m^3)
Economic	CCTAC of the energy system (million $/yr)

These indicators offer intuitive formulations that compare the needs of primary resources and the consequences on air quality of their use, using the 2030 official plan as a base. In short, when an indicator is equal to 1, there is no change in comparison to the baseline scenario for Cuba 2030. When the indicators are less than 1 there is an improvement over time, and likewise, when the indicators are larger than 1 there is deterioration over time. The ideal situation arises when these indicators have a value of zero.

3. Alternative Strategies for the energy mix: Introduction of additional solar and wind energy

The first set of alternative scenarios is designed to exploit more intensively the resources available in Cuba to supply the 28 TWh/yr of electricity demand anticipated in 2030 by the Cuban authorities.

3.1. Potential resources

3.1.1. Fossil fuels

The known quantity that would be extracted with the available Cuban technologies was estimated by the Cuba oil union (CUPE) as 98 million toe. Nevertheless, the recent discovery of crude oil and natural gas reserves in the so-called “Cuban economic exclusion zone (EEZ)” of the Gulf of Mexico is expected(Ministerio de Relaciones Exteriores de Cuba, 2017). The Cuban government has estimated that at least 2.7 billion tons can be found deep in the sea, while the United States Geological Survey's estimates a more modest 630 million tons, which is still a significant number (D. et al., 2004). Based on historical extraction rates for crude oil and gas (5 million tons), and considering hypothetically that all the reserves can be extracted, estimated onshore reserves will last approximately 22 years and offshore reserves approximately 155 years(IAEA, 2008).

3.1.2. Biomass

Sugar cane and marabu (marabu is a type of tree that has invaded vast swathes of agricultural land in Cuba) are expected to be the most important biomass sources in Cuba during the following years. The country has around 6.2 million ha of agricultural surface. During the last ten years, more than 0.4 million ha of sugar cane have been cultivated (Figure 12) for an average annual production of 14 610 million tons, with a harvest yield of 36 tons/ha.

In 2015, sugar cane was harvested across 436 600 ha (7% of the agricultural surface), with the total production increasing up to 19.3 million tons(Gómez et al., 2022; ONE, 2016c). One ton of sugar cane processed in a sugar factory yields on average around 240 kg of bagasse. Their cogeneration potential is documented in ranges of 20-25 kWh/ton-of-cane(Alonso-Pippo et al., 2008), 580 kWh/ton-of-bagasse(Sagastume Gutiérrez et al., 2018) or 35-40 kWh/ton-milled-sugarcane(Alonso-Pippo et al., 2008; Jimenez Borges et al., 2017; Sagastume Gutiérrez et al., 2018), based on different sugar factory generation pressures (18-23 bar) and efficiencies. Opportunities exist to increase the rates of production from bagasse, which include enhancements in harvest yields (90 ton/ha) and electricity production efficiency (140 kWh/ton-milled-sugarcane). Considering an average harvest of 47.5 million tons of sugarcane (i.e. following the trend 2010-2015 which increases production by 2 million ton/yr), the 2030 production of bagasse is estimated at 8.4 million tons. The potential cogeneration ranges between 1 700 and 6 500 GWh depending on current and optimal efficiencies.

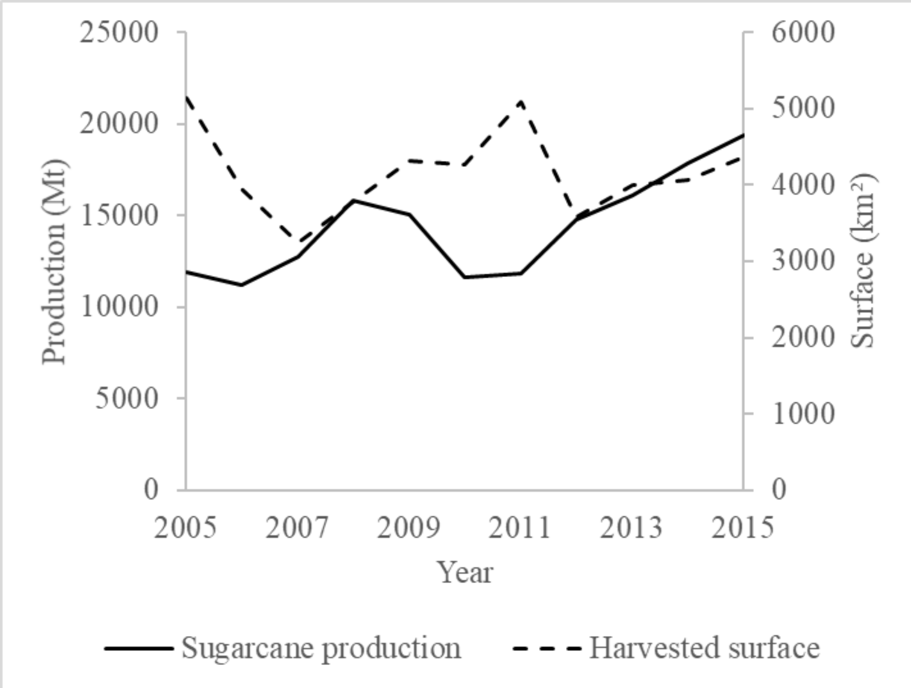


Figure 12 Trend of sugarcane production from 2005 to 2015 in Cuba.

The marabu covers over 1.7 million ha (i.e. 15% of the Cuban territory) (Käkönen et al., 2014; Rodríguez-Machín, L., D. H. Bretón-Glean, R. Perez-bermudez et al., 2012; Sagastume Gutiérrez et al., 2018). The shrub expands quickly at an average occupancy of 37 tons/ha and a natural renewability period of three years. Currently, about 63 million tons of marabu are available all over the country. This resource could either be progressively eradicated to release agricultural surface for other applications or be re-used. The heating value of this biomass is 120-1 268 kWh/ton(MINAS et al., 2016; Sagastume Gutiérrez et al., 2018). Considering the capability of harvesting 21 million tons (1/3 of availability) every year(Rodríguez-Machín, L., D. H. Bretón-Glean, R. Perez-bermudez et al., 2012), the potential electric generation ranges between 2 520 and 26 628 GWh/yr.

3.1.3. Water, wind, and solar

The average annual precipitation in Cuba is 1 400 mm. There are about 900 runoff water streams, though they are not extensive owing to the long and narrow shape of the country (with an average width of 97 km). The estimated hydropower potential is 1 300 GWh/yr(IAEA, 2008); however, it cannot be completely exploited because of environmental protection constraints. This research considers that the hydropower potential that can be effectively used is 985 GWh (75% of the official projection).

Estimations of the wind potential for the Caribbean derived a considerably large potential with good to exceptional power densities: 200–300 W/m^2(Chadee & Clarke, 2014) and 500-1 000 W/m^2(Maegaard, P., A. Krenz, 2013). However, investigations carried out with assistance from Cuban meteorological stations identified a limited number of twenty suitable sites with potential for around 2 GW (Käkönen et al., 2014) and a utilization factor of 23% (4.03 TWh/yr). Other Cuban estimations from climate modeling identified 448 km^2 of land with good wind conditions and merely 63 km^2 having excellent wind conditions for electricity generation; these led to an estimated potential of 2.55 GMW(Panfil, M., D. Whittle, 2017). The lowest values of the annual potential are around 1 200 MW (2.42 TWh) (IAEA, 2008) while the highest goes from 5 to 14 GW(Avila, 2009).

Due to its geographical location in the tropical latitude, the country is extremely well endowed with solar energy. Studies on climate conditions provide confirmatory evidence of around 2 800 sunshine hours (32% of utilization factor) annually. The daily average solar energy that reaches Cuban land throughout the year is 5 kWh/m^2(Panfil, M., D. Whittle, 2017). This value is relatively uniform across the country and shows little variation (0.5 kWh/m^2) from winter to summer seasons(MINAS et al., 2016). (Jacobson, Delucchi, Bauer, et al., 2017) estimated a possible PV panels' installed capacity of 8.73 TW, only considering suitable rural land areas (i.e. rural land areas receiving a minimum acceptable solar insolation and being appropriated for PV panel installation). This huge potential represents an amount of energy of around 24.4 TWh/yr.

Table 10 Potential of energy resources and oil and gas reserves of Cuba

Resources	**Potential (million tons/yr)**	**Potential (GWh/yr)**	**Reserves (yr)**
Solar energy	-	24 433 161	-
Wind energy	-	2 418-28 207	-
Marabu biomass	21	2 500-26 628	-
Crude oil and associated gas	5	15 110 -20 870	155
Bagasse biomass	4.8	1 700-6 500	-
Water energy	-	985	-

Table 10 shows the resource potentials estimated for Cuba. The reduction of energy dependence in Cuba entails more intensive exploitation of local renewable energy resources: biomass, wind, or solar radiation. However, the exploitation of these resources depends on the area that is dedicated to them, such that solar panels, wind turbines, and biomass crops must compete to occupy land surfaces across the country.

Figure 13 provides a comparison of the physical land surface needed for the use of each renewable resource assuming that it will provide 100% of the Cuban electricity demand by 2030. The physical land surface includes the spacing between devices avoiding, for example, the partial shadowing of the energy yield of PV systems or the interference due to the wake of a wind turbine with others downwind. Utility-scale PV has an installed spacing density of 100-300 MW/km^2, which is assumed based on estimations performed by (Al-Khazzar, 2017) for different types of PV modules with efficiencies of 0.12-0.20 and areas of 1.3-1.7 m^2.

For wind turbines, the range 7.1-13.6 MW/km^2 is used for the estimations(IRENA, 2015b; Jacobson, Delucchi, Bauer, et al., 2017). For biomass, the occupied surface area is based on the harvesting area needed to generate electricity during 150 days from bagasse and 225 days from marabu. This estimation also combines minimal and maximum expected generation rates in terms of harvesting yields, technological efficiencies, and biomass properties.

The comparison between the physical land surfaces needed by the different kinds of renewable energies shows that widespread use of solar or wind energy should account for 0.1-1.9% of Cuba's land, respectively. The estimation for biomass is between 14.6% and 128%.

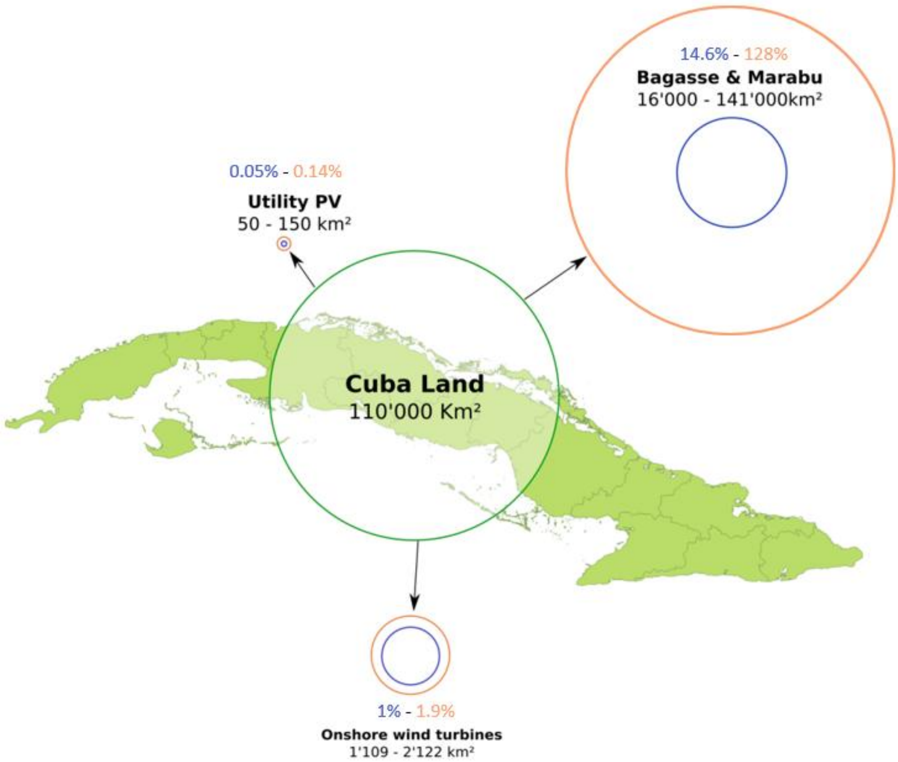


Figure 13 Land surface required to meet Cuban electricity demand from solar, wind, and biomass resources. The central green circle corresponds to the surface of the country. The other circles represent the surface required to install intermittent energy production infrastructure with the capacity to generate 100% of the country's electricity demand. The larger red circles correspond to the critical case in which the maximum surface is needed, and the smaller blue circles correspond to the cases of minimum surface required. The central green circle corresponds to the surface of the country.

3.2. Design of the scenarios

Since solar radiation and wind are intermittent energy sources, the energy produced by PV panels and wind turbines will depend on the local atmospheric conditions and their fluctuations over time. To consider how much of these intermittent sources of energy can be effectively introduced into the energy mix of the island an analysis of the solar and wind potential hourly fluctuations and the hourly electricity demand of Cuba was performed. The one-year-long hourly profiles of the intermittent potentials in terms of their capacity factors were obtained from climate simulations results from the weather research and forecasting (WRF) model ran over Cuba(ARW, 2021; NCAR, 2019; Skamarock et al., 2019). The hourly data of wind speed and solar radiation was used to estimate the average capacity factors profiles of typical utility-scale solar PV panels and wind turbines(IRENA, 2015b). The energy demand hourly profile was obtained from the model for analysis of energy demand (MAED) (IAE & International Atomic Energy Agency, 2006).

Hourly energy analysis was performed considering the following three components of the system: the electricity demand, the intermittent sources, and the controllable sources. The electricity demand of the country is hourly fulfilled by intermittent sources that cannot produce energy permanently (i.e., solar PV panels and wind turbines) and by controllable sources whose energy production can follow the variations of the demand and satisfy it every hour. Several calculations have been performed by introducing into the electricity mix different amounts of energy produced from intermittent sources (expressed as percentages of the electricity production ranging from 0% to 100%). In each of these calculations, the hourly electricity demand is first met by the intermittent sources, then the remaining electricity to be supplied is produced by controllable sources. Many technologies, such as gas power plants, can modulate their energy production to follow fluctuations in electricity demand, but cannot shut down completely. For these reasons, it was assumed that controllable energy sources could not fall below a minimum threshold equal to 20% of its maximum possible energy production(Bhatt, 2014).

The scenarios considered in this work do not involve electrical energy storage. Indeed, there are different storage technologies with different costs, which multiplies the possible options and makes the analysis of strategies more complicated. In the first step, it has been decided to publish only the analysis of the scenarios without electrical energy storage. The results obtained with storage will be the subject of a second publication.

For each percentage of intermittent sources introduced into the mix, the distribution between solar and wind sources is chosen to minimize the TAC.

The losses generated along the grid between the energy sources and the demand were considered as 15.5% assuming they will remain the same as in the current situation.

The results of this analysis are summarized in Figure 14. They show three important points: Controllable sources cannot be completely removed, and their full installed capacity must be maintained regardless of the amount of intermittent sources of energy introduced into the mix (Figure 14-a). The energy produced by the intermittent sources entirely substitutes the energy produced by the controllable sources as long as it does not exceed 40% of the electricity demand. Beyond 40%, the system is saturated, intermittent sources only partially replace controllable energy so solar and wind cannot satisfy the demand without the help of controllable sources and overproduce energy (Figure 14-b). The most economical share between solar and wind energy changes with the percentage of the electrical production it supplies. When this percentage is less than 20%, it is more cost-effective to use only solar and no wind. Beyond 20%, the best profitability is obtained by increasing progressively the percentages of wind compared to solar.

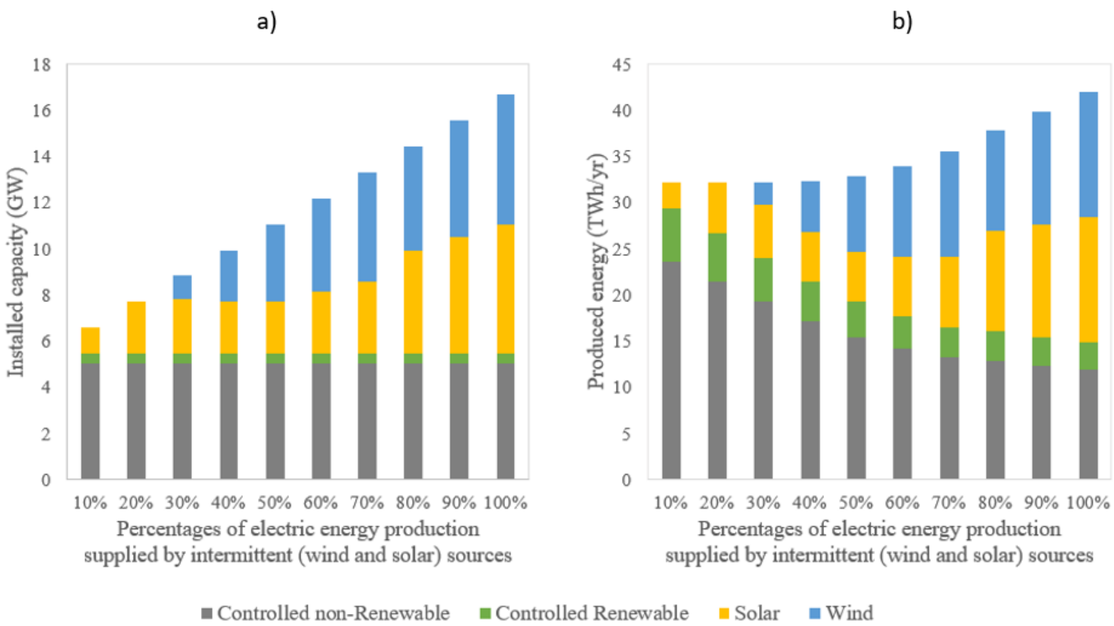
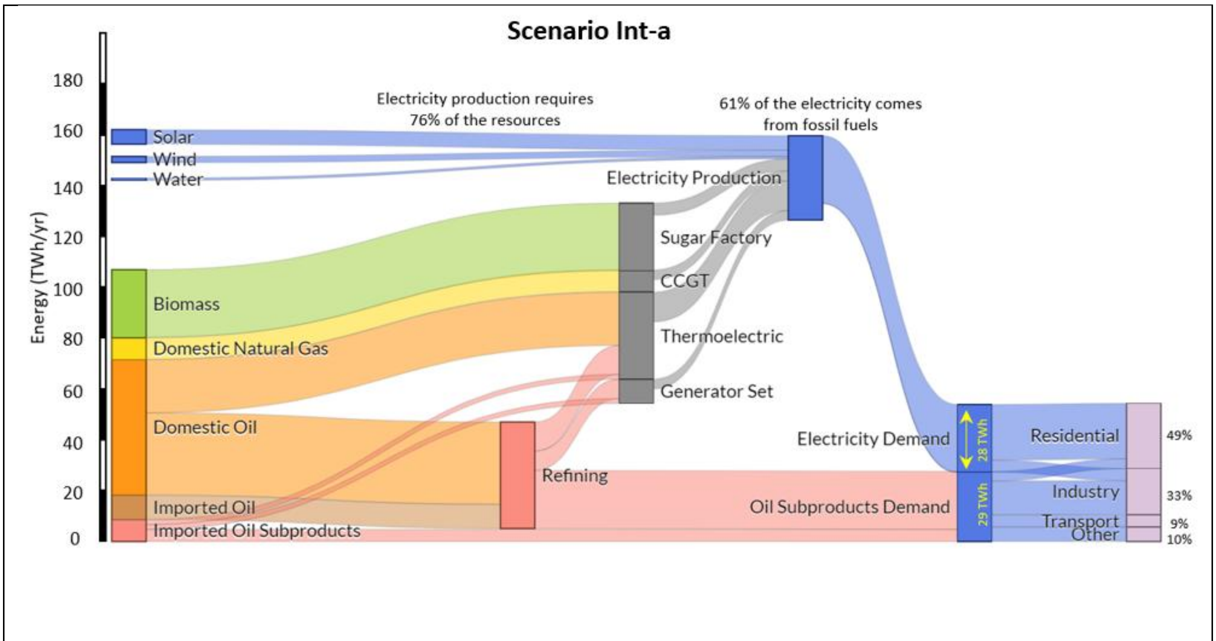


Figure 14 Installed capacity (a) and produced energy (b) for different percentages of the electricity production supplied by solar energy source without energy storage. The energy sources shown correspond to solar, wind, controllable renewable (hydropower and biomass), and controllable non-renewable (CCGT, thermoelectric, and generator set). The repartition between the solar and wind sources is chosen as the proportion that bring the greatest economic benefit.

Three specific scenarios have been analyzed. The baseline scenario (BL) is based on the official projection for 2030 and corresponds to 6% of the electricity supplied by wind and solar sources. Two scenarios (Int-a and Int-b) for which the intermittent sources reach respectively 30% and 60% of the electricity production. The scenario Int-a corresponds to the scenario in which GHG emissions are reduced to levels equal to those of the 2015 BC baseline scenario. The reduction in GHG emissions due to the introduction of solar and wind sources compensates the increase resulting from projected energy growth during 2015-2030. Therefore, carbon offsetting begins to have a net effect on the economic balance of the Cuban electricity generation system. The scenario Int-b corresponds to the maximum economic benefit (see Figure 18).

In the scenarios considered, the energy produced by controllable sources decreases as they are replaced by solar and wind energy. For each scenario, the reduction in energy from controllable sources was determined to affect each technology by the same percentage. This is to account for the constraints highlighted by our analysis based on hourly variations in resources and electricity demand: the capacity of controllable sources must be maintained despite the addition of solar and wind power (Figure 14), and controllable sources, such as gas or oil thermoelectric plants, cannot be completely shut down and must always produce a minimum amount of energy (20%).

The importation of primary energy sources (i.e. imported oil and imported oil subproducts) is progressively reduced with scenarios Int-a and Int-b (Figure 15). Even so, a small amount of imported primary resources is maintained. The main reason for this is the low quality of the Cuban oil since it can only be partially refined to obtain low-quality oil subproducts. Thus the importation of fully refined oil subproducts or crude oil of better quality remains necessary to supply the fuels demanded by the industry and transport macrosectors.



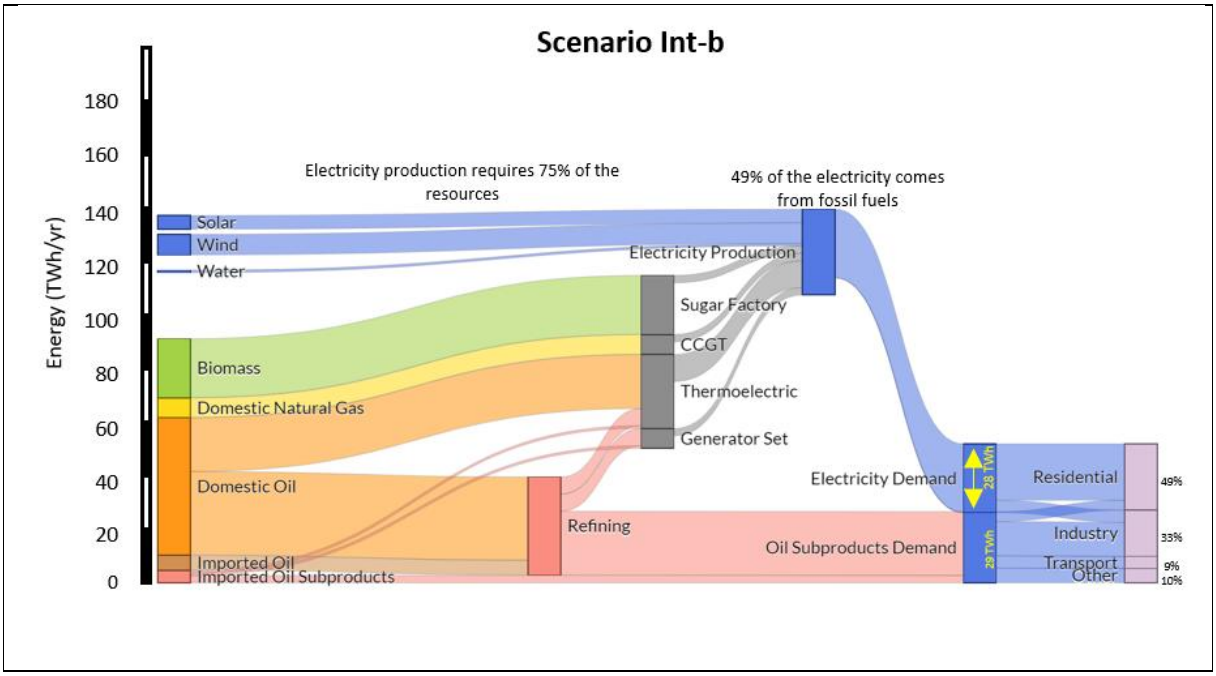


Figure 15 Sankey energy flow diagrams for Cuba's energy scenarios: Int-a (30% of intermittent) and Int-b (60% of intermittent).

3.3. Comparison of the different scenarios

Compared to the situation in 2015, the BL scenario for 2030 aims to use domestic primary resources and RES as much as possible. The BL scenario foresees that primary biomass resources increase strongly (from 6 to 34 TWh/yr) while solar, wind, and hydroelectric production increases too but remains low (from 0.02 TWh/yr to 0.52 TWh/yr for the solar, from 0.04 TWh/yr to 1.53 TWh/yr for the wind, and 0.05 TWh/yr to 0.99 TWh/yr for the hydroelectric). Domestic gas and oil production increases slightly (from 7 to 11 TWh/yr for gas and from 41 TWh/yr to 56 TWh/yr for oil). Oil importations (9 TWh/yr) are maintained constant while oil subproducts importations are reduced (from 31 TWh/yr to 18 TWh/yr). By reducing imports of oil subproducts, the country's energy security and resource sustainability are improved.

Figure 16 shows the primary resources used in scenarios BL, Int-a, and Int-b. The production of electricity by intermittent sources (solar and wind) is lower in the BL scenario (2 TWh/yr) than in the scenarios Int-a (8.5 TWh/yr) and Int-b (17 TWh/yr). The amount of biomass, water, domestic gas, domestic oil, imported oil, and imported oil sub products is progressively reduced with the introduction of solar and wind.

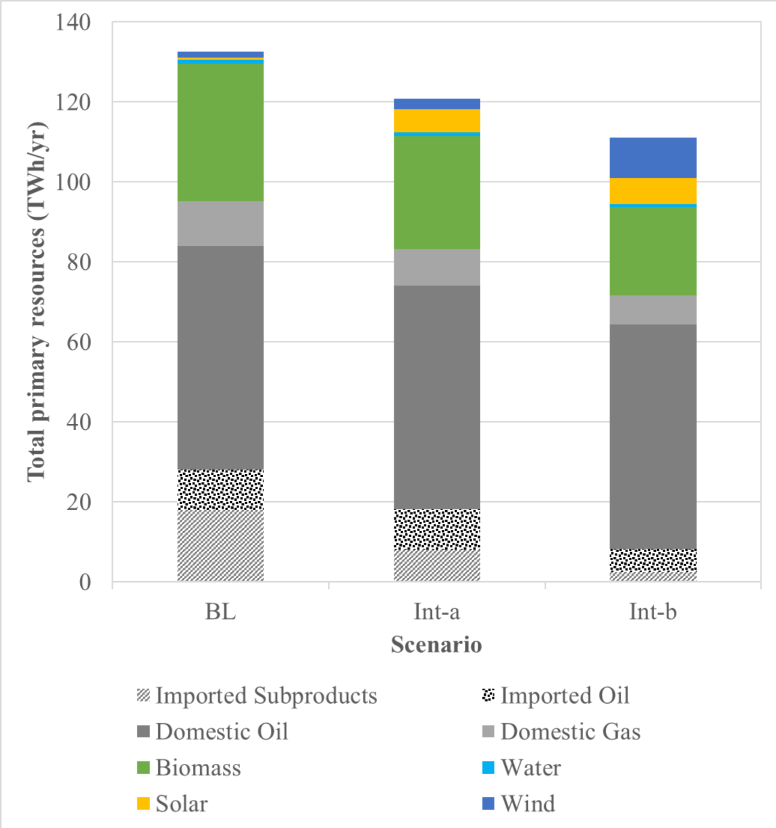


Figure 16 Primary resources estimated for the energy transition scenarios of Cuba: BL, Int-a, and Int-b.

Figure 17 shows the differences in CCTAC between the scenarios Int-a, Int-b, and the reference scenario BL (i.e. ΔCCTAC). It distinguishes the different economic consequences of implementing the scenarios Int-a and Int-b in terms of costs to be paid (negative part of the bars) and benefits from savings and carbon compensation (positive part of the bars). The ΔCCTAC without the carbon compensation is equal to the ΔTAC.

The necessary costs for the implementation of the scenarios are attributable to the investments and fixed costs related to the solar installation which do not require any variable or fuel costs. Since the installed capacity of the different powerplants and generator sets supplying the controllable sources must be preserved, savings are achieved only by reducing their variable and fuel costs.

Figure 17 shows that for scenarios Int-a and Int-b, the benefits exceed the costs. The Int-a scenario requires 377 million $/year of investment in solar panels and wind turbines to finance their operating costs (i.e., capital and fixed costs). On the other hand, this scenario can save 702 million $/year by reducing fuel and variable costs of the different powerplants and generator sets, and provides 4.2 million $/yr of carbon compensation, so the net benefit of the scenario can reach 329 million $/yr. The scenario Int-b shows a cost of 917 million $/year to fund the solar and wind farms and benefit shares between 1389 million $/year saved from fuel and variable costs due to the usage reduction in the controllable sources and 197 million $/year of carbon compensation which provides 669 million $/year of net benefit.

It is interesting to note that the cost (i.e. investment in solar and wind) of scenario Int-b is two times the cost of scenario Int-a. Similarly, the benefit (i.e. the fuel and variable costs savings, and the carbon compensation) of scenario Int-b is two times the benefit of scenario Int-a. As a result, the net benefit of scenario Int-b is twice the net benefit of scenario Int-a.

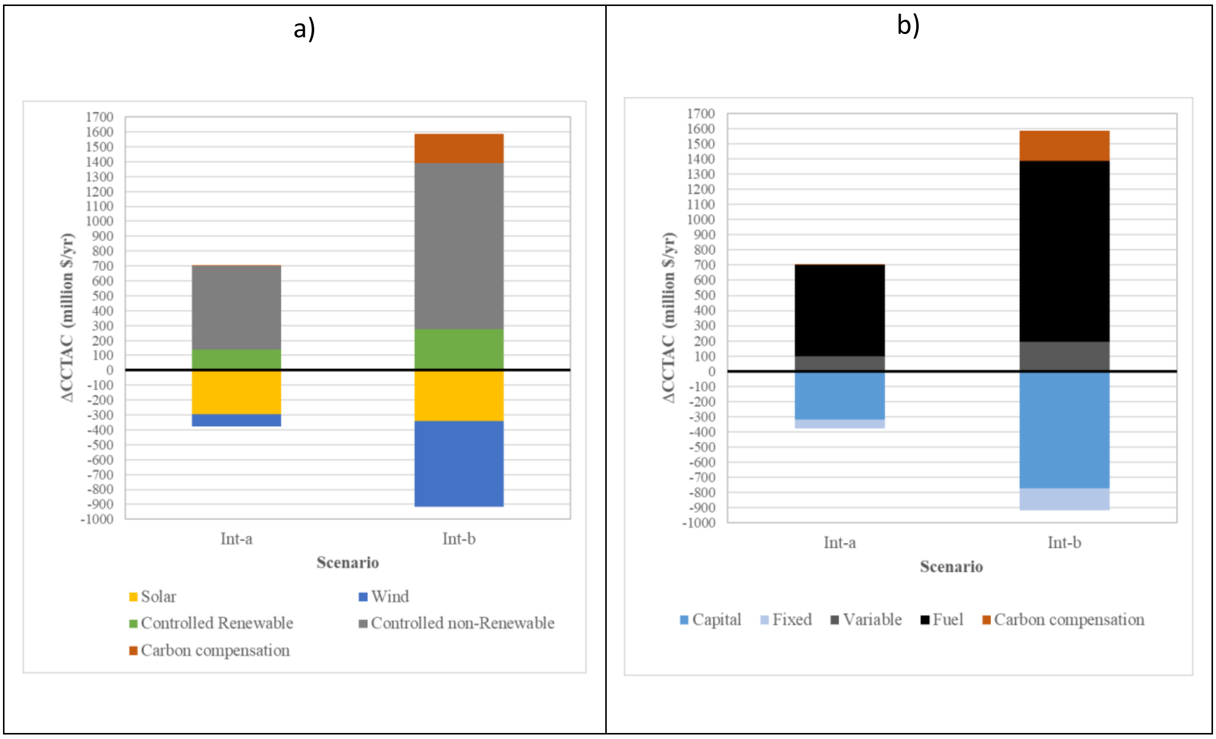


Figure 17 Components of the total annual costs difference between the scenarios Int-a and Int-b and the BL including carbon compensation (ΔCCTAC): a) energy production technologies (solar and thermoelectric, and b) types of costs components (capital, fixed, variable, and fuel). The carbon compensation is included in both parts of the figure (a and b).

Figure 18 shows the economic benefits evaluated for scenarios with percentages of intermittent between 0% and 100% of the electricity production of Cuba in 2030. These are plotted in terms of the difference in the total annual costs difference between the BL scenario and the scenarios Int-a and Int-b including the carbon compensation (ΔCCTAC) and without carbon compensation (ΔTAC).

The repartition between solar and wind shown in the boxes of Figure 18 corresponds to the one that gives the greatest benefit in terms of ΔTAC for each percentage of intermittent.

The maximum benefit is achieved in the scenario where 60% of electricity is generated from intermittent sources, and where the intermittence share is 40% for solar and 60% for wind. In this scenario the economic benefit without carbon compensation (ΔTAC) achieves nearly 500 million$/yr, and with carbon compensation (ΔCCTAC) nearly 700 million $/yr.

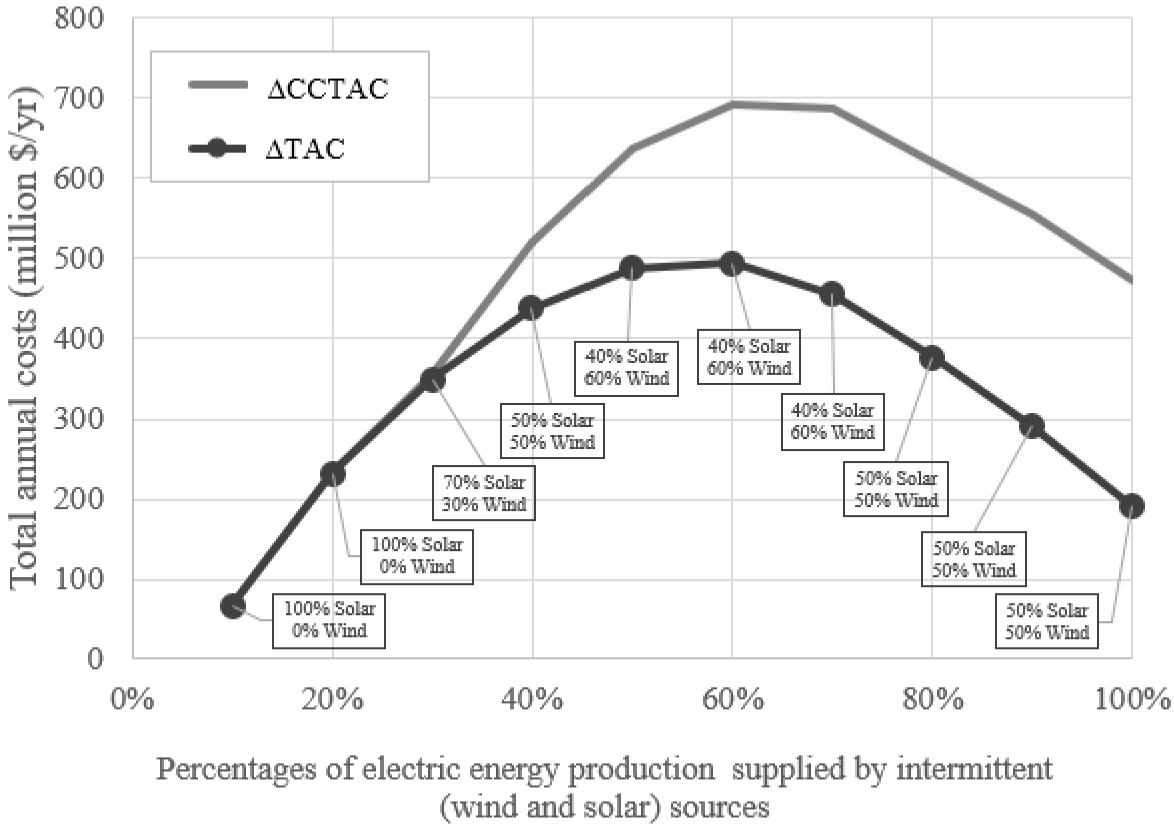


Figure 18 Total annual costs difference between the energy scenarios and the BL including carbon compensation (ΔCCTAC) and without carbon compensation (ΔTAC). The percentages in the boxes correspond to the repartition between solar and wind sources that makes the greatest benefit (maximum ΔCCTAC and maximum ΔTAC) for each scenario.

The different indicators mentioned in Table 9 are computed for scenarios Int-a and Int-b using Equation (2). The introduction of 30% and 60% of intermittent sources (solar and wind) in the energy system decreases oil consumption (Figure 16) which has a positive impact on the different indicators: energy security, carbon footprint, air quality, and economic savings (Figure 8). The reduction of fuel imports leads to improve the energy security indicator (35.4% for Int-a and 70.3 for Int-b) which is an important result considering the strategic goals of the Cuban government of reducing energy dependency from abroad. Replacing expensive imported fossil fuels with less expensive intermittent sources, such as solar and wind power, leads to an increase in economic indicator. Air quality indicator is also improved with the introduction of intermittent energy sources in the energy strategy of Cuba (Figure 19). Even so, this improvement is relatively small, it improves 5.6% and 7.5% in the Int-a and Int-b scenarios respectively. These differences are linked with the reduction of the primary energy needed by the non-renewable controllable sources.

The economic indicator (CCTAC) also shows an improvement with the introduction of intermittent energy sources. This indicator improves with respect to BL scenario by 8.2% and 16.6% for the scenarios Int-a and Int-b respectively (Figure 19).

The second largest improvement is related to the carbon footprint, 21.3% and 42.1% for the scenarios Int-a and Int-b respectively.

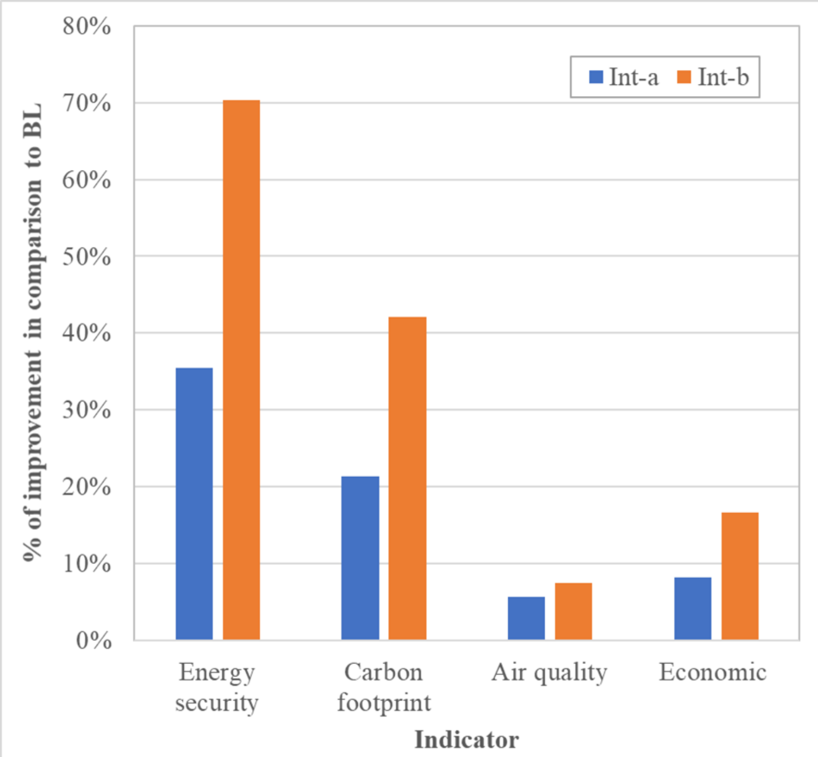


Figure 19 Percentage of improvement of scenarios Int-a and Int-b compared to the 2030 baseline scenario (BL) for the Cuban energy transition.

4. Alternative strategies for the energy demand: Introduction of electric vehicles

In the Int-a and Int-b scenarios, Cuba still needs to import refined fuels which are mainly required by the industrial and transport sectors. Therefore, energy security can be improved by reducing the oil subproducts demanded by these activity macro sectors (i.e. MS1 and MS7). Currently, the Cuban vehicle fleet is based only on internal combustion vehicles (ICVs), most of them being very old and using outdated technologies. Although there are relatively few vehicles in Cuba (38 cars per 1000 inhabitants), the 362 000 vehicles of the entire fleet still require around 336 400 tons of oil subproducts (diesel and gasoline) per year(Enoch et al., 2004). Consequently, the shift from ICVs to electric vehicles (EVs) may reduce the consumption of oil subproducts and improve simultaneously the energy security and carbon fingerprint indicators.

Calculations show that refined fuel consumption should decrease from 336 400 tons/year to 82 600 tons/year which reduces the energy security indicator to the value of 0.82 (i.e. an improvement of 18%). But if the consumption of refined fuel by the ICVs is reduced, the electricity demand will increase due to the new EVs. Thus, the total electricity consumption will increase by 8.5% to reach 30.2 TWh/yr. This increase is compensated by additional solar and wind electricity production which reaches 11 TWh/yr in scenario Int-a, and 28 TWh/yr in scenario Int-b.

To estimate the air quality impact of switching from ICVs to EVs, two additional scenarios (called Int-aEV and Int-bEV) were designed by replacing all ICVs with EVs in the Int-a and Int-b scenarios. The total emissions of different pollutants (NO_X, SO_X, $PM_{2.5}$, VOC, and CO_2) were evaluated for each of these scenarios. Figure 20 shows the normalized difference in the emissions (Δ) between the BL scenario and the scenarios Int-a, Int-b, Int-aEV, and Int-bEV for the pollutants NO_X, SO_X, $PM_{2.5}$, VOC, and CO_2. Only sectors of energy and transformation industries (MS1) and road transport (MS7) are presented since they are the only sectors with changes in the emissions associated to fleet replacement.

The emissions of the pollutants NO_X, SO_X, $PM_{2.5}$, VOC, and CO_2 vary by the introduction of intermittent energy sources in the Cuban mix, differently, the NH_3 is invariant since it is not linked to sectors MS1 or MS7, for this reason, this pollutant is not plotted.

$PM_{2.5}$ and SO_x emissions reductions are linked to MS1, meanwhile, NO_X and VOC are pollutants for which their emissions reductions are mainly related to MS7.

Reductions of NO_x and VOC emissions are considered for all the evaluated scenarios, being the scenarios with the introduction of EV (Int-aEV and Int-bEV) the ones with the largest emission reductions of these pollutants mainly driven by the electrification of the MS7 macrosector.

The reductions of CO_2 emissions are observed in all scenarios (Int-a, Int-b, Int-aEV, and Int-bEV).

For MS1, larger reductions of CO_2 are achieved with the current ICVs (scenarios Int-a and Int-b) than with the EVs (scenarios Int-aEV and Int-bEV). This is explained by how the electricity demanded by the EVs introduced is produced. In Cuba, this electricity is supplied mainly by thermoelectric plants that must use a greater amount of fuel to increase their production, which leads to higher CO_2 emissions.

Both scenarios, Int-aEV and Int-bEV, have the same CO_2 emission reductions associated with MS7, since the ICV base fleet is the same and is considered to be completely replaced by EV. That is, the amount of fuel used in the ICVs is no longer necessary when the EVs are introduced, which leads to a reduction of CO_2 in the same proportion in the Int-aEV and Int-bEV scenarios.

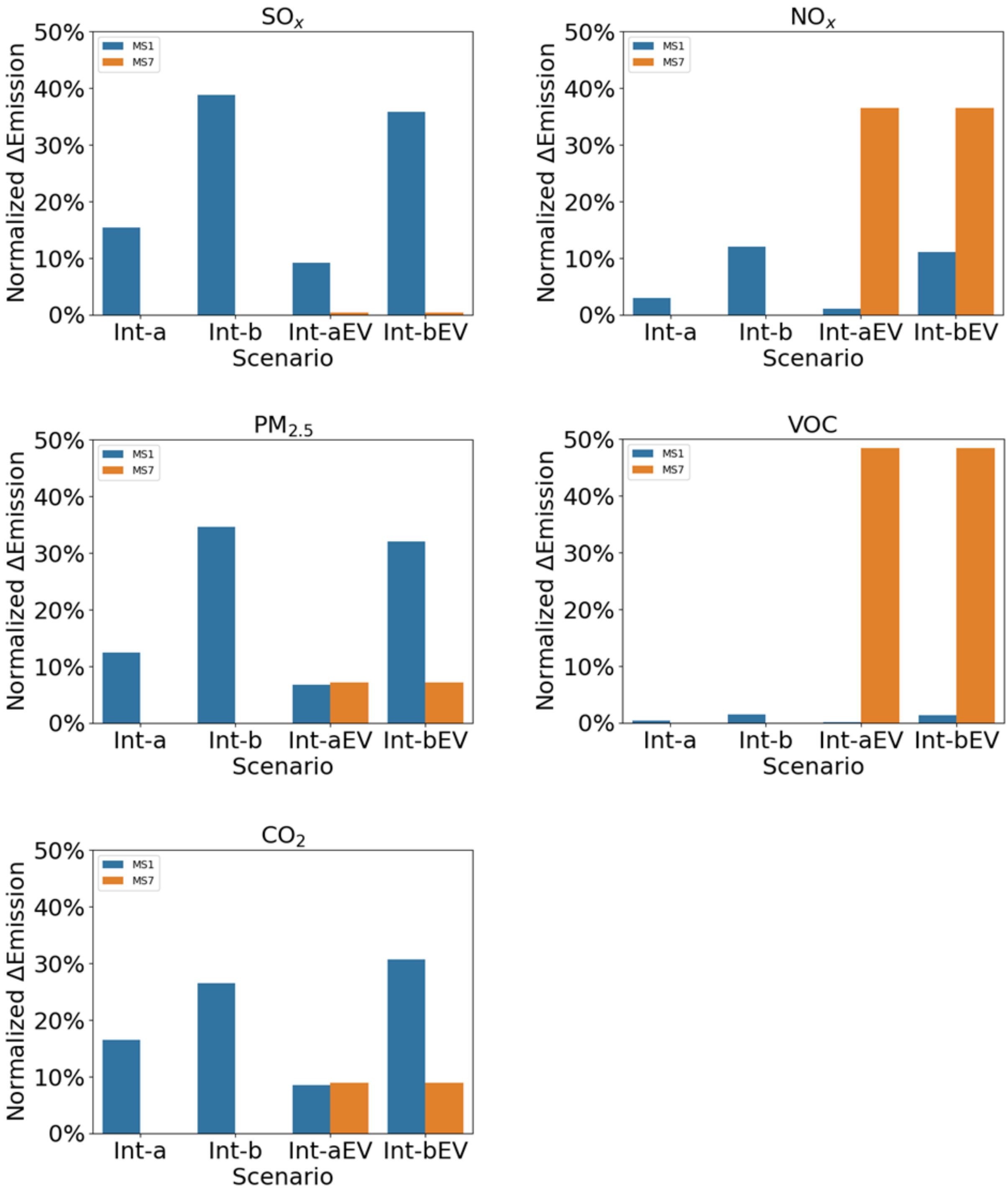


Figure 20 Normalized differences between the emissions in the baseline scenario for 2030 (BL), and Cuba's energy scenarios analyzed (Int-a, Int-b, Int-aEV, and Int-bEV) in 2030 for the pollutants: NOx, SOx, $PM_{2.5}$, VOC, and CO_2. The energy-demanding sectors in the plot are MS1 (combustion in energy and transformation industries) and MS7 (road transport).

5. Discussion

The discussion addresses the various uncertainties and limitations of the analysis developed in this article. As has already been mentioned, one of the limitations of this study is that it does not consider energy storage. The integration of storage solutions, which typically incur substantial expenses, is expected to elevate the overall costs associated with intermittent energy sources. On the other hand, storage should reduce the capacity of controllable sources by providing energy in their place during peak demand. This should only have a noticeable effect when the share of intermittent sources is high (> 60%). We have therefore planned a future study to address this subject.

Another limitation comes from the uncertainties in the parameters necessary for the estimation of the indicators characterizing the different scenarios. Some of these parameters, such as capacity factors of solar and wind resources, energy demand, and pollutant emissions, are likely to vary from one year to the next. However, the most important source of uncertainty comes from costs, in particular, the cost of fossil fuels and the investment costs of the various technologies used to generate electricity. In fact, almost all of the technologies used in Cuba are very old, especially those using fossil fuels to produce controllable energy, e.g., old thermoelectric power plants. These technologies have already been used well beyond their uselife time. Moreover, we are not supposed to know the intentions of the Cuban authorities regarding the renewal of this old infrastructure. It is therefore difficult to predict the depreciation of the capital cost of technologies used for controllable sources even in the near future. To overcome this difficulty our analysis is based on the calculation of the cost differences between the baseline scenario (official projection of the Cuben government for 2030) and the different alternative scenarios designed also for the year 2030. Using these differences, the scenario cost comparison depends only on the variable and fossil fuel costs of technologies used for controllable sources and of the capital costs of technologies used for intermittent sources (Figure 17). Uncertainties related to the investment costs of technologies used for intermittent sources (wind turbines and solar panels) are relatively easy to anticipate because these costs have continuously decreased over time during the past decades. We can expect this trend to continue until 2030 and probably beyond. In contrast, fossil fuel prices are difficult to predict because they vary erratically. However, despite the uncertainties surrounding the evolution of fossil fuel costs, we do not foresee a strong and long-lasting decline in these costs in the near future. It is therefore certain that the savings generated by reducing fossil fuel consumption will easily compensate for the investment costs of intermittent energies.

Other limitations are related to the geopolitical situation of Cuba. While wind and solar use free energy once installed, they require a significant and immediate investment. However, due to the embargo affecting the country, the Cuban authorities have difficulty accessing the banking system to borrow the money necessary for investments. The embargo also limits Cuba's access to international markets, making the purchase of solar panels, wind turbines, and electric vehicles limited.

6. Conclusions

The current situation of Cuban energy system is vulnerable since the country strongly depends of energy imports. This vulnerability is evidenced through the study of different aspects such as energy security, carbon footprint, air quality, and economic. The introduction of renewable intermittent sources (solar and wind) should improve all these aspects by reducing fossil fuel imports and CO_2 emissions, improving air quality, and generating economic benefits. These positive effects result from the replacement of fossil fuel consumption with solar and wind energy.

Despite Cuba's enormous solar energy potential, the best option is to use combined solar and wind energy. However, in the absence of energy storage, solar and wind resources cannot fully meet energy demand due to their intermittency, so the full capacity of controllable sources must be maintained.

The introduction of intermittent sources causes the reduction of fossil fuel consumption used for electricity production but does not lead to an important reduction of refined fuels which are used mainly in the transportation sector. The reduction in refined fuels can be achieved through the introduction of EVs to replace current ICVs, which will bring further positive benefits.

Because of its geopolitical situation, Cuba has more difficulty than other countries in accessing international markets, which could make the implementation of the energy transition in this country difficult. Nevertheless, the Cuban authorities can be advised to invest progressively in solar and wind energy. Every time solar and wind capacity is progressively increased, Cuban authorities will save on fuel costs and achieve environmental improvements and energy security. The money saved could be gradually reinvested in new solar and wind power installations. As long as intermittent sources provide less than 60% of the electricity demand, the economic benefits will be increasingly significant. Beyond 60% they will still be positive but will start to decrease.

At this stage, it will be time to refine the study already carried out to help Cuban authorities choose between investing in the renewal of obsolete technologies for the production of controllable energy or reducing the capacity of these sources by investing in storage technologies.

Chapter 2: Method based on optimized tendencies to evaluate the impact of the introduction of solar and wind energy sources in energy systems

Abstract

Fossil fuels represent most of the energy consumed worldwide. Their use is linked to vulnerability of the economy to fluctuations depending on their availability, difficulty exploiting them, geopolitics, and emitting GHG responsible for climate change. Introduction of solar and wind (intermittent) sources is an unavoidable alternative for decarbonization because their costs are dropping, and they can be exploited anywhere. However, this alternative has impacts on the characteristics of the energy system. This article presents the development of a method capable of accounting for this while managing many scenarios of increasing introduction of intermittent energy into the mix, and several indicators of interest for stakeholders are needed. The energy mix for each scenario is determined by minimizing energy production costs. Two study cases were used: Grand Est region of France and Cuba, because they have different potentials of solar and wind and demand fluctuations and evolution, using the costs, GHG emissions, use of non-RES, and local resources as indicators. In the Grand Est region, the optimal energy strategy depends on demand trends: low demand favors a high share (60–90%) of intermittent renewables at low cost and land use, while high demand requires a trade-off between cost-effective renewables needing more land and more expensive, land-efficient nuclear power. In Cuba, energy autonomy can be reached with just 7% intermittent sources, but the lowest production costs and emissions occur when their share increases to 100–140%. Beyond that, improvements plateau, and achieving full renewable supply with zero emissions remains unfeasible.

Keywords

Energy transition; evaluation of scenarios; intermittency; climate change; LCOE

Highlights

- We proposed an integrated methodology for the design and evaluation of scenarios and several indicators systematically.
- Additional indicators of interest for stakeholders can be easily implemented.
- The new method proposed a graphical analysis approach for visualizing several indicators simultaneously for each study case.
- Distinction between the controllable sources and intermittent sources facilitate the analysis of electricity production systems for future scenarios.
- Benefits on several indicators can be obtained by reducing energy production from controllable sources with the introduction of solar and wind sources into the mix.

1. Introduction

The world's energy consumption has been increasing since the early 20th century. The major part of the resources to supply this increasing demand are fossil fuels(BP, 2024; Charlez et al., 2021). This dependency on fossil fuels has two main drawbacks: i) Fossil fuels burning main product is energy, however, combustion also generates byproducts such as greenhouse gases (GHG) and atmospheric pollutants harmful to human health; and ii) Fossil fuels are finite resources, their increasing extraction entails greater difficulty in exploiting them thus increasingly higher costs. As a result, their availability will inevitably decrease, eventually leading to disruptions in the energy market(Arbib & Seba, 2017; Intergovernmental Panel on Climate Change (IPCC), 2023; Jacobson, 2020; Madrazo Bacallao, 2018; Seba, 2014). For this reason, the design and evaluation of energy strategies based on the replacement of fossil fuels by other types of energy sources is necessary.

The inventory of the different available energy sources indicates that they can be classified according to various criteria. One classification can be made based on their renewable nature and self-replenishing capacity as non-renewable energy sources (non-RES) and renewable energy sources (RES)(IRENA, 2015a). Another classification of sources is based on their capacity to adapt their energy production to the hourly fluctuations of energy demand over time. The sources that are capable of this adaptation are referred to as *controllable sources*. These can be classified as either RES (e.g., hydropower, geothermal, and biomass) or non-RES (e.g., nuclear and thermoelectric). In contrast, sources such as solar and wind provide energy depending on the availability of the primary resources and are unable to follow the hourly fluctuations of the energy demand. They are referred to as *intermittent sources*.

There is growing interest in deploying solar and wind energy sources due to their great potential in many regions and their significant cost reductions over the past two decades. This trend is likely to continue in the future making these RES interesting to be implemented in energy strategies worldwide(IRENA, 2022a; Power Engineering International, 2017). However, since wind and solar sources are unable to supply fluctuations in energy demand on an hourly basis they must be combined by other suitable sources. This problem of intermittency becomes more critical as solar and wind sources play an increasingly important part in the energy mixes. Thus, the introduction of intermittent sources (i.e., solar and wind) into the mix changes the characteristics of all the controllable sources in the system. For this, there is a need for a method for the design and evaluation of energy strategies by considering the effects of the introduction of intermittent sources on several aspects of the energy system.

The design of energy strategies has many difficulties, one is that there are an infinite number of possible combinations of technologies to supply energy demand, and another one consists of the difficulty of comparing all these combinations because a large number of criteria should be considered.

The methods found in the literature for designing energy strategies can be broadly categorized into two types: i) expert-design scenarios, these methods compare a few arbitrary scenarios (expert-designed scenarios). It allows to use a large number of indicators of interest such as costs or GHG emissions(Bompard et al., 2020; Connolly et al., 2016; De Rosa & Castro, 2020; Hansen et al., 2019; Lassonde, 2018; Luo et al., 2021; Vaccaro & Rocco, 2021)(Bompard et al., 2020; Connolly et al., 2016; De Rosa & Castro, 2020; Hansen et al., 2019; Luo et al., 2021; Miguel et al., 2016; Niu et al., 2021; Proskuryakova & Ermolenko, 2019; Soler-Castillo et al., 2021; Vaccaro & Rocco, 2021). However, these approaches may miss other interesting scenarios possibly underrated during the construction of scenarios; and ii) optimization methods which cover all possible scenarios using an automatic procedure and then generate an optimized solution based on the minimization of one or few criteria (most commonly the economic cost)(T. Li et al., 2020; Potrč et al., 2021; Zhao & You, 2020). These methods has some drawbacks, the first is to present at the end only one solution, and secondly, this approach only uses one single parameter for the comparison(Bist et al., 2018; De Rosa & Castro, 2020; Fragkos et al., 2021; Klevas et al., 2014; R. Li et al., 2022; T. Li et al., 2020; Mlilo et al., 2021; Santoyo-Castelazo & Azapagic, 2014; Solé et al., 2020; Stern et al., 2018; Vaccaro & Rocco, 2021; Weijermars et al., 2012). The use of optimization methods can be extended to the selection of several scenarios by calculating a trend curve (Pareto curve) by varying one criterion or very few and minimizing another, but it is still limited to one or very few criteria. These methods do not guarantee that the solution presented is the most convenient or interesting for decision makers who can be influenced by many indicators which can often be difficult to identify.

This study aims to develop a method for designing and evaluating future energy strategies (scenarios) by accounting for the consequences of introducing increasingly high shares of intermittent energy sources into the mix at regional or country level. The developed method in this study is inspired by the trend curve classic method (Pareto curve). However, this new method has several novel aspects: i) it is designed to generate trends followed by as many criteria as needed by decision makers (other than the typical economic costs). These criteria can be expressed as a set of decision-relevant scaled indicators, enabling their simultaneous analysis and comparison; and ii) it covers a wide range of scenarios, considering how the characteristics of energy systems evolve with the integration of varying amounts of intermittent energy sources. Then, for each of these scenarios, the method defines the best mix of production technologies that minimizes the costs.

This article first presents the basis and concept of the method developed in the study. It then presents the results obtained by applying the method to two different case studies cases with specific characteristics such as geopolitical context, temporal/seasonal variation of the demand and the energy production from RES, and RES potentials, e.g., Grand Est region of France and Cuba. A discussion of the method regarding its performance, uncertainty, and robustness together with the implication of the results on decision-making and policy is made in the last part.

2. Method

2.1. General concept of the method

The production of solar and wind energy depends on the availability of sunlight and wind, making it challenging to match supply with electrical demand. Consequently, there may be times when production is insufficient, while at other times, it may be excessive. Combining wind and solar energy ensures more regular production, as these resources generate energy at different times. Despite their complementary nature, solar and wind sources can experience periods of significantly low production (Figure 21-a), even when their installed capacity is substantial (Figure 21-b).

Solar and wind energy sources therefore require supplementation to meet demand during periods of low production. This can be achieved through controllable sources capable of supplying energy on demand. Another solution to supplement periods of low solar and wind production is to store electricity during periods of surplus of solar and wind energy production. This study focuses on the analysis of the scenarios without electrical energy storage. Indeed, there are different storage technologies with different costs, which multiplies the possible options and makes the analysis of strategies more complicated. The results obtained with storage will be the subject of future publications.

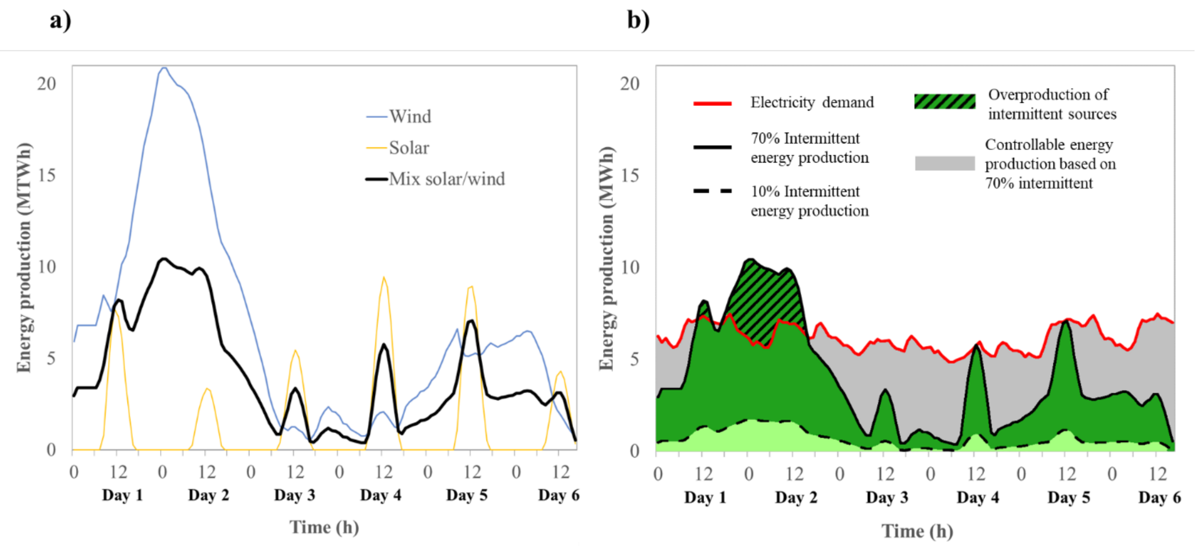


Figure 21 Representation of the hourly variation of the electric system: a) hourly variation of the intermittent energy production for different solar and wind repartition percentages: 0% solar (i.e. 100% wind), 100% solar, and 50% solar (50% wind) in the intermittent part; b) hourly variation of the electricity demand and intermittent energy production using a 50% solar and wind repartition, intermittent energy production to supply 10% and 70% of the demand, the difference between the intermittent energy production equal to 70% of the demand and the demand corresponds to the energy production from controllable sources.

Figure 22 illustrates the results of a calculation where it is assumed that hourly electricity demand is met by solar and wind power, supplemented by controllable sources as needed. This calculation demonstrates that as the share of solar and wind energy increases, these sources substitute more for controllable sources but can never entirely replace them. It also indicates that, despite the contributions of solar and wind energy, the installed capacity for controllable sources must still be maintained (Figure 22-b). Consequently, the ratio of controllable sources installed capacity to the energy production (RIE) increases as the share of solar and wind sources into the mix increases.

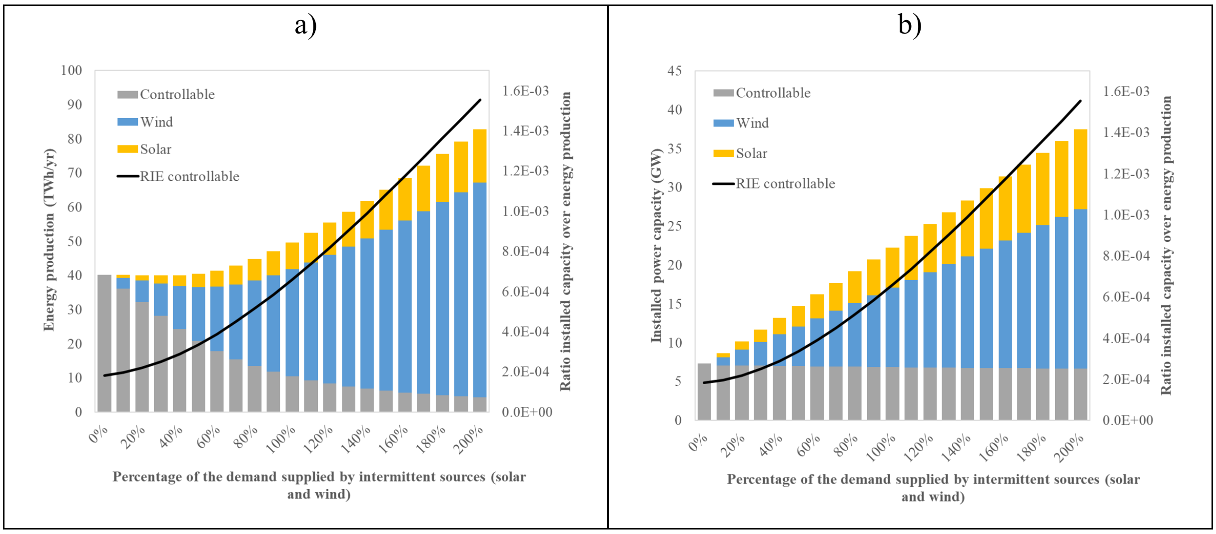


Figure 22 Energy production (a) and installed power capacity (b) of the intermittent (solar and wind) and controllable sources for the case of the Grand Est region of France (SRADDET demand for 2050). The global ratio of the installed capacity over the energy production for the controllable sources

(RIE) is plotted for the different percentages of intermittent. Solar/Wind repartition corresponds to the less costly combination.

Information on the installed capacity required for a technology to produce a specific quantity of energy is available in scientific literature in the practical form of capacity factors (Cf). Each of these capacity factors is defined as the ratio of average hourly energy production to the installed capacity of a technology. This metric offers the advantage of straightforward interpretation, where a theoretical maximum value of 1 would indicate continuous operation at full capacity, representing ideal use with constant production. However, achieving this perfect performance is impossible in practice for several reasons: i) all technologies require maintenance, which necessitates temporary interruptions in production; ii) production must meet an electrical demand that is never constant; and iii) electrical production relies on resources that are not always consistently available, such as solar radiation and wind power.

2.2. Cost calculation

The method is based on a reference scenario which corresponds to a future projection of the energy demand and mix (baseline). Then, the method generates scenarios based on a progressively increasing introduction of intermittent energy production into the energy mix with respect to the baseline and considers the consequences of this increasing intermittency on the characteristics of controllable sources.

The generated scenarios have different energy production of intermittent sources being denoted as a percentage of the demand. In each of these scenarios the repartition between solar and wind energy with solar panels and wind turbines technologies, and the mix of controllable technologies for energy production are defined by a minimization of energy production costs.

Both intermittent and controllable technologies have costs associated with their implementation and operation, these are represented by the total annual production costs (TAC). The TAC serves as a link between the characteristics of the energy system and the economics.

2.2.1. Total annual costs (TAC)

The costs of a specific scenario $\left(TAC^{(SC)}\right)$ results from the sum of all costs of the technologies into the energy mix "t" used to produce the energy $\left(TAC_t^{(SC)}\right)$ (equation 1).

$$TAC^{(SC)} = \sum_t TAC_t^{(SC)} \quad (1)$$

For each of these technologies "t" in the mix, the $TAC_t^{(SC)}$ depends on two terms as shown in equation 2. The first term is proportional to the energy produced $\left(EP_t^{(SC)}\right)$ in TWh and its unit cost (CEP_t), measured in millions of dollars per TWh while the second term is proportional to the installed capacity $\left(IC_t^{(SC)}\right)$ and its unit cost (CIC_t) in TW, measured in millions of dollars per TW. (CEP_t) depends on variable and fuel costs denoted by VC_t and FUC_t, and the efficiency in the use of the primary resources to produce the electricity (η_t). CIC_t depends on the fixed costs FC_{tc} and the annualized investment cost AC_t.

The annualized investment cost AC_t is estimated with an interest rate "r" and the lifetime "l" of the technology "t" (equation 3)(Aldersey-Williams et al., 2019; M. Guevara-Luna et al., 2024; Jacobson et al., 2015; Jacobson, Delucchi, Cameron, et al., 2017; Murray et al., 2018; Obi et al., 2017; Santoyo-Castelazo & Azapagic, 2014) (See supplementary material SP1).

$TAC_t^{(SC)} = EP_t^{(SC)} CEP_t + IC_t^{(SC)} CIC_t$	(2)

$CEP_t = VC_t + \frac{FUC_t}{\eta_t}$ and $CIC_t = AC_t + FC_t$ with $AC_t = CC_t \times \frac{r\times(1+r)^l}{(1+r)^l-1}$	(3)

The $TAC_t^{(SC)}$ for each technology in the mix can be calculated by introducing into equation (2) the levelized cost of electricity $\left(LCOE_t^{(SC)}\right)$, defined as the $TAC_t^{(SC)}$ per TWh of energy produced, and the $RIE_t^{(SC)}$ ratio, computed as the installed capacity divided by the energy produced.

$RIE_t^{(SC)} = \frac{IC_t^{(SC)}}{EP_t^{(SC)}}$ then $TAC_t^{(SC)} = EP_t^{(SC)} LCOE_t^{(SC)}$ with $LCOE_t^{(SC)} = CEP_t + RIE_t^{(SC)} CIC_t$	(4)

Since the method aims to distinguish between intermittent and controllable energy sources, the total cost of a scenario $\left(TAC^{(SC)}\right)$ can be computed as the sum of the costs of intermittent sources $\left(TAC_{int}^{(SC)}\right)$ and the costs of the controllable sources $\left(TAC_{cont}^{(SC)}\right)$ (equation 5).

$TAC^{(SC)} = TAC_{int}^{(SC)} + TAC_{cont}^{(SC)}$	(5)

2.2.2. TAC of intermittent sources

The ratios between installed capacity and energy production for the intermittent sources (solar and wind) depend primarily on the availability of the primary resources required (i.e., sunlight and wind). As a result, these ratios are independent of the number of solar panels and wind turbines installed and do not vary by scenario "SC". It can be computed with capacity factors Cf_{solar} for the solar and Cf_{wind} for wind technologies (equation 6).

$RIE_{solar} = \frac{1}{Cf_{solar}\times 24\times 365}$ and $RIE_{wind} = \frac{1}{Cf_{wind}\times 24\times 365}$	(6)

The levelized cost of electricity for the intermittent sources $\left(LCOE_{int}^{(SC)}\right)$, can be computed by introducing $\beta_{solar}^{(SC)}$ and $\beta_{wind}^{(SC)}$ which are the proportion of solar and wind energy produced with regards to the total energy produced by the intermittent sources $\left(EP_{int}^{(SC)}\right)$ (equation 7).

$\beta_{solar}^{(SC)} = \frac{EP_{solar}^{(SC)}}{EP_{int}^{(SC)}}$ and $\beta_{wind}^{(SC)} = \frac{EP_{wind}^{(SC)}}{EP_{int}^{(SC)}}$ then $LCOE_{int}^{(SC)} = \beta_{solar}^{(SC)} LCOE_{solar} + \beta_{wind}^{(SC)} LCOE_{wind}$ where $LCOE_{solar} = CEP_{solar} + \frac{CIC_{solar}}{Cf_{solar}\times 24\times 365}$ and $LCOE_{wind} = CEP_{wind} + \frac{CIC_{wind}}{Cf_{wind}\times 24\times 365}$	(7)

The total costs for the intermittent sources $\left(TAC_{int}^{(SC)}\right)$ are computed from the $LCOE_{int}^{(SC)}$ by introducing the percentage of intermittent energy with regards to the demand "D" $\left(\alpha^{(SC)}\right)$ (equation 8).

$\alpha^{(SC)} = \frac{EP_{int}^{(SC)}}{D}$ then $TAC_{int}^{(SC)} = \alpha^{(SC)} D \times LCOE_{int}^{(SC)}$	(8)

2.2.3. TAC of controllable sources

For the controllable technologies "tc" the ratio between the installed capacity and the energy production $\left(RIE_{tc}^{(SC)}\right)$ does not depend only on the maintenance but also of the hourly fluctuations of residual energy. The $RIE_{tc}^{(SC)}$can be shared between two terms: one term equal to the ratio when no intermittent energy is produced, and second term corresponding to an addition caused by the effects of the hourly fluctuation of energy production on the residual energy when intermittent energy is introduced into the mix. The capacity factors of the controllable technologies in the mix (Cf_{tc}) are reference values from the literature and do not vary with the changes in the $RIE_{tc}^{(SC)}$, i.e., it is the same value per controllable technology independently of the scenario "SC"(equation 9) (See supplementary material SP1).

$$RIE_{tc}^{(SC)} = \frac{IC_{tc}^{(SC)}}{EP_{tc}^{(SC)}} = \frac{IC_{tc}^{0}}{EP_{tc}^{(SC)}} + \frac{\delta IC_{tc}^{(SC)}}{EP_{tc}^{(SC)}} = \frac{1}{Cf_{tc} \times 24 \times 365} + \frac{\delta IC_{tc}^{(SC)}}{EP_{tc}^{(SC)}} \tag{9}$$

In this formulation for the costs of controllable energy in each scenario "SC" $\left(TAC_{cont}^{(SC)}\right)$, IC_{tc}^{0} corresponds to the installed capacity necessary to produce the total controllable energy production in the absence of intermittent energy $\left(EP_{tc}^{(SC)}\right)$, and $\delta IC_{tc}^{(SC)}$ corresponds to the additional installed capacity necessary to produce the energy when energy production from intermittent sources has been introduced into the system (equation 10).

$$TAC_{cont}^{(SC)} = \sum\nolimits_{tc} \left(EP_{tc}^{(SC)} LCOE_{tc}^{0} + \delta IC_{tc}^{(SC)} CIC_{tc}\right) \quad \text{with} \quad LCOE_{tc}^{0} = CEP_{tc} + \frac{CIC_{tc}}{Cf_{tc} \times 24 \times 365} \tag{10}$$

The $TAC_{cont}^{(SC)}$ can be expressed as the sum of two terms: the costs of controllable sources in the absence of intermittent energy production (TAC_{cont}^{0}) and the additional costs of controllable sources needed to complete the demand when intermittent sources in introduced $\left(\delta TAC_{cont}^{(SC)}\right)$. Also, the shares of the controllable technologies into the mix in terms of energy production $\left(\gamma_{tc}^{(SC)}\right)$, and in terms of installed capacity $\left(\varphi_{tc}^{(SC)}\right)$, can be introduced to the calculation of the total costs of controllable sources $\left(TAC_{cont}^{(SC)}\right)$(equation 11).

$$\begin{gathered} TAC_{cont}^{(SC)} = TAC_{cont}^{0} + \delta TAC_{cont}^{(SC)} \\ \text{where} \quad TAC_{cont}^{0} = EP_{cont}^{(SC)} \sum\nolimits_{tc} \gamma_{tc}^{(SC)} LCOE_{tc}^{0} \quad \text{and} \quad \delta TAC_{cont}^{(SC)} = IC_{cont}^{(SC)} \sum\nolimits_{tc} \varphi_{tc}^{(SC)} CIC_{tc} \\ \text{with} \quad \gamma_{tc}^{(SC)} = \frac{EP_{tc}^{(SC)}}{EP_{cont}^{(SC)}} \quad \text{and} \quad \varphi_{tc}^{(SC)} = \frac{\delta IC_{tc}^{(SC)}}{IC_{cont}^{(SC)}} = \frac{IC_{tc}^{(SC)}}{IC_{cont}^{(SC)}} - \frac{IC_{tc}^{0}}{IC_{cont}^{(SC)}} \end{gathered} \tag{11}$$

The levelized cost of controllable energy $\left(LCOE_{cont}^{(SC)}\right)$ can be computed based on the technological composition of controllable sources in the mix of the scenario "SC", i.e., $\gamma_{tc}^{(SC)}$ and $\varphi_{tc}^{(SC)}$ (equation 12).

$$\begin{gathered} LCOE_{cont}^{(SC)} = \sum\nolimits_{tc} \gamma_{tc}^{(SC)} LCOE_{tc}^{0} + RIE_{cont}^{(SC)} \sum\nolimits_{tc} \varphi_{tc}^{(SC)} CIC_{tc} \\ \text{where} \quad RIE_{cont}^{(SC)} = \frac{IC_{cont}^{(SC)}}{EP_{cont}^{(SC)}} \end{gathered} \tag{12}$$

2.2.4. Constraints and boundaries

The energy produced and installed capacity of intermittent and controllable sources in the mix should be always fulfilled. This condition expressed in terms of the shares of energy production shares of intermittent $\left(\beta_{wind}^{(SC)}\right)$ and controllable sources $\left(\gamma_{tc}^{(SC)}\right)$, and the installed capacity needed for the introduction of intermittent sources into the energy mix is shown in (equation 13).

$$\begin{gathered}\text{For the intermittent technologies:}\\ \beta_{wind}^{(SC)} + \beta_{solar}^{(SC)} = 1\\ \text{For controllable technologies:}\\ \sum\nolimits_{tc} \gamma_{tc}^{(SC)} = 1\\ \sum\nolimits_{tc} \varphi_{tc}^{(SC)} = 1 - \frac{1}{RIE_{cont}^{(SC)}} \sum\nolimits_{tc} \frac{\gamma_{tc}^{(SC)}}{Cf_{tc} \times 24 \times 365}\end{gathered} \tag{13}$$

Moreover, the energy production and the installed capacity of each technology in the mix should be limited by the available resources and the technical feasibility (boundaries) (equation 14), where EP_{tc}^{min} and IC_{tc}^{min} correspond to the minimum boundaries, and EP_{tc}^{max} and IC_{tc}^{max} correspond to the maximum boundaries for the energy production and installed capacity from controllable technologies.

$$\begin{gathered}0 \le \beta_{sol}^{(SC)} \le \frac{EP_{sol}^{max}}{\alpha D} \quad \text{and} \quad 0 \le \beta_{win}^{(SC)} \le \frac{EP_{win}^{max}}{\alpha D}\\ \frac{EP_{tc}^{min}}{EP_{cont}^{(SC)}} \le \gamma_{tc}^{(SC)} \le \frac{EP_{tc}^{max}}{EP_{cont}^{(SC)}}\\ \frac{IC_{tc}^{min}}{IC_{cont}^{(SC)}} - \frac{1}{RIE_{cont}^{(SC)}} \frac{\gamma_{tc}^{(SC)}}{Cf_{tc} \times 24 \times 365} \le \varphi_{tc}^{(SC)} \le \frac{IC_{tc}^{max}}{IC_{cont}^{(SC)}} - \frac{1}{RIE_{cont}^{(SC)}} \frac{\gamma_{tc}^{(SC)}}{Cf_{tc} \times 24 \times 365}\end{gathered} \tag{14}$$

2.3. Scenario generation and cost optimization

The method generates scenarios based on a progressively increasing introduction of solar and wind energy production as a percentage of the demand. In each of these scenarios the repartition between solar and wind, and the mix of controllable technologies is defined by optimizing the TAC.

To converge, the method is divided into two steps. The first step requires estimating the hourly electricity demand and the capacity factors of wind and solar sources (See supplementary material SP4). Then, the scenarios are generated by varying the percentage of intermittent sources, i.e., varying the α parameter from 0% (no intermittent sources in the mix) to 200% (twice the demand) and the shares of solar and wind ranging the $\beta_{solar} = 1 - \beta_{wind}$ parameter from 0% (only wind energy) to 100% (only solar energy). The hourly energy production from solar and wind is calculated using their respective capacity factors and the α, β_{solar}, and β_{wind} parameters, as defined in equations (7) and (8). It is assumed that a minimum of 30% of the hourly demand must always be met by controllable sources to ensure grid stability. The remaining 70% is supplied by intermittent sources when their production is sufficient; otherwise, controllable sources cover the shortfall. In the second step, the shares of various technologies capable of supplying the controllable energy needed for each scenario are computed by minimizing $TAC_{cont}^{(SC)}$. The minimum $TAC_{cont}^{(SC)}$ is achieved by first calculating $\gamma_{tc}^{(SC)}$ to minimize TAC_{cont}^{0} (equation 11) , while considering the constraints and boundaries on $\gamma_{tc}^{(SC)}$ (equation 14). The values of $\gamma_{tc}^{(SC)}$ are used to compute $\varphi_{tc}^{(SC)}$ by minimizing the $\delta TAC_{cont}^{(SC)}$ and considering the constraints and boundaries on $\varphi_{tc}^{(SC)}$(equation 14).

Optimization method used is the Sequential Least Squares Quadratic Programming (SLSQP) method.

The SLSQP method is particularly well-suited for nonlinear optimization problems with constraints and boundary conditions. This ensures convergence to a feasible solution while adhering to the specified technical limits(Weerasekara et al., 2023; Zahery et al., 2017).

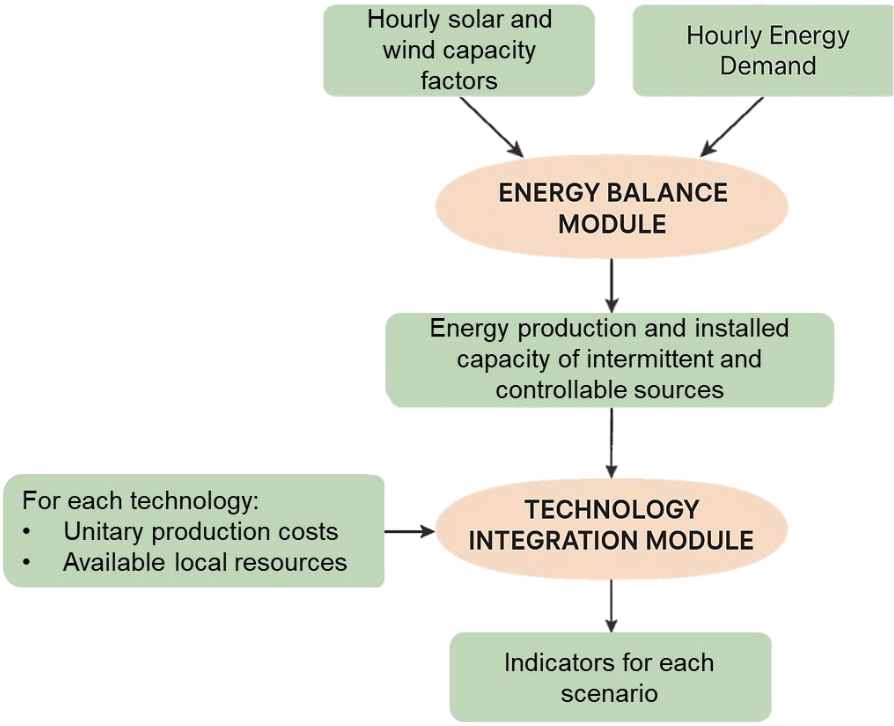


Figure 23 The computation is performed by two modules. The Energy Balance Module utilizes hourly solar and wind capacity factors, along with hourly electricity demand, to calculate the energy produced and the installed capacity required by controllable sources across various scenarios. In these scenarios, the contribution of the assembly of intermittent sources (solar and wind) to the mix increases from 0 to 200% of the demand. The Technology Integration Module determines, for each scenario, the share of the different controllable technologies by minimizing their Total Annual Costs (TAC) to meet the required energy production and installed capacity.

2.4. Indicators

Costs are frequently employed as indicators for evaluating energy strategies. However, it is crucial to consider other factors that may be of relevance to decision-makers in the local context. To this end, evaluation methods should be capable of incorporating as many indicators as needed, e.g., total annual costs (TAC), emissions, use of non-RES, and imports of energy.

The indicator $\left(I^{(SC)}\right)$ is calculated as the relationship between the characteristic value of the situation in the SC scenario $\left(C^{(SC)}\right)$ and the reference scenario or baseline scenario "BL" $\left(C^{(BL)}\right)$ (equation 15).

The emissions of GHG are estimated using reference values for the emission factors and characteristics of the technologies involved in the designed scenarios(Cuadros Tejeda et al., 2019; EMEP/EEA, 2019; United States Environmental Protection Agency (US EPA), 2014). The emissions factors used for the estimation of the emissions are reported in the supplementary material SP2.

$I^{(SC)}$ can take different percentages relative to BL to facilitate its interpretation by decision-makers. A value of 0% for any of the indicators corresponds to the best possible situation and a value of 100% means that the situation is the same as for the baseline scenario.

$I^{(SC)}(\%) = \frac{C^{(SC)}}{C^{(BL)}} * 100$	(15)

3. Results

The methodology has been tested using two cases of study: i) the Grand Est region of France and ii) Cuba. These two cases exhibit characteristics that make them complementary for the following reasons: Firstly, since Cuba is located in the intertropical zone, it has a significantly higher solar energy potential compared to the mid-latitudes where the Grand Est region is situated. Secondly, the location of both considered regions lead to different seasonal variation of the demand and the intermittent energy production (solar and wind), whereas Cuba exhibits much weaker seasonal variation than the Grand Est region. Thirdly, the official scenario of Cuban authorities anticipates rising energy demand in the coming decades, reflecting the economic development trajectory typical of a developing nation, in contrast, energy demand in the Grand Est region has declined since the 2000s despite the region's growing Gross Domestic Product (GDP), and local authorities project this trend of decoupling energy demand from economic growth to continue in the future.

3.1. Grand Est region of France

The base year selected for this analysis of the Grand Est region is 2021, marking the first year following the COVID-19 pandemic, chosen to avoid the distortions caused by the pandemic's abnormal impact, which significantly altered energy demand patterns in 2020.

In 2021, the total energy consumption in the region accounted for 176 TWh/year, 44 TWh/year in the form of electricity and 133 TWh/year in the form of fossil fuels. The consumption of primary resources to produce this energy (electricity and fossil fuels) is estimated at 291 TWh/year, of which 102 TWh/year is imported energy in the form of fossil fuels and enriched uranium for electricity generation in nuclear power plants.

The electricity production of the region accounted for around 100 TWh/year which have been produced by a mix of energy sources, including 61.3 TWh/year from nuclear power, 1.1 TWh/year from biomass, 5 TWh/year from biogas, 9.8 TWh/year from hydropower, 5.8 TWh/year from solar energy, and 18 TWh/year from wind energy. The region exhibited a surplus in electricity production, exporting approximately 56 TWh/year (100 – 44 TWh/year).

It is worth noting that while the region exports 56 TWh/year of electricity, a more comprehensive perspective should also account for the net energy balance with external countries. This includes the import of primary energy sources, which amounts to 102 TWh/year to support electricity production, as well as the occasional import of electricity (~5 TWh/year) to manage peak demand periods. The net balance favors finally importation over exports.

In 2018 the authorities of the region developed a plan for 2030 and 2050 called “Schéma régional d'aménagement, de développement durable et d'égalité des territoires” (SRADDET)(ATMO-Grand Est, 2021; Gavrilut et al., 2021; Grand-Est, 2021b, 2021a; SRADDET, 2019). The main characteristics of this plan are the progressive denuclearization to reach definitive closure of the regional nuclear power plants in 2050 while decarbonizing the production of energy as much as possible, the reaching of full autonomy of electricity production in the region through an increase in renewable sources and a decrease of demand.

The projected demand in 2050 is reduced from 176 TWh/year to 89.6 TWh/year for total energy, and from 44 TWh/year to 39.3 TWh/year for electricity. It is noteworthy that although overall energy demand decreases, the share of electricity demand rises significantly, increasing from 25% in 2021 to 44% by 2050.

The SRADDET scenario projects changes in electricity demand by sector between 2021 and 2050. It considers reductions of -12 987 TWh/year (93%) for residential, -5 950 TWh/year (58%) for tertiary, and -53 TWh/year (7%) for agriculture, while forecasting significant increases of 9 837 TWh/year (58%) for industry and 4 344 TWh/year (203%) for transport.

In this scenario, the electricity demand is fulfilled by the energy production of hydropower and biomass is maintained as both have already reached their maximum utilization potential in the region. It considers the projected increase in electricity production, including 2.5 TWh/year from solar energy, 12 TWh/year from wind energy, and 11.6 TWh/year from biogas.

Despite the SRADDET's goal of energy autonomy, the potential of the region for biogas is likely overestimated. According to other studies, only 6.8 TWh/year is realistically available (Paz, 2021), consequently necessitating the import of 4.8 TWh/year to meet demand.

The method developed in this work was assessed by exploring various scenarios based on the SRADDET plan for 2050 as a baseline. It evaluates the impacts of increasing the production of energy from solar and wind energy sources on several parameters of interest, e.g., costs of energy production, GHG emissions, non-RES production, and imports.

For the baseline used (SRADDET), the method estimated 2 772 million $/year of total electricity production cost, with GHG emissions of 6 117 tCO_2/year, zero non-RES, and energy imports of 4.8 TWh/year in the form of biogas.

Figure 24-a gives an overview of the trend of different indicators concerning electricity production cost, GHG emissions, use of non-RES, and imports vs the percentage of demand fulfilled by intermittent sources (i.e., solar and wind).

As the baseline is already using only RES, the non-RES indicator remains at zero for all scenarios. Imports decline and drop to zero after 60%. From 45% to 90% intermittent sources, the production costs are almost constant while GHG emissions are reduced progressively, then, both increase after 90% (Figure 24-a).

The most notable scenarios are those where intermittent energy production meets between 60% and 90% of demand. These scenarios achieve energy autonomy by eliminating the need for energy imports, significantly reducing GHG emissions, and maintaining comparable costs of energy production.

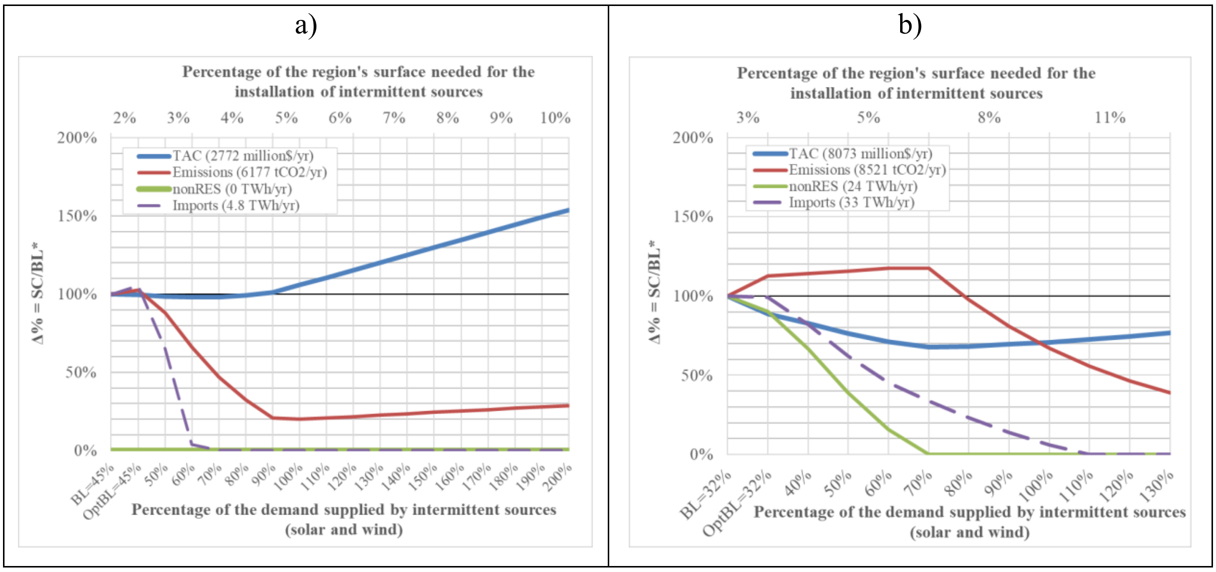


Figure 24 Tendencies of the indicators along the scenarios where intermittent sources (solar and wind) are introduced into the energy mix of the Grand Est region of France. The "OptBL" corresponds to the optimized baseline scenario: a) Minimum official projected demand, and b) the maximum projected demand. Indicators correspond to the total annual costs (TAC), emissions, use of non-RES, and imports. Values in parenthesis shown in the legend correspond to the characteristics of the scenarios used as reference (baseline). The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios. A value of 0% for any of the indicators corresponds to the best possible situation, a value of 100% means that the situation is the same as for the baseline scenario, and a value greater than 100% indicates a worse situation compared to the baseline scenario.

Figure 25 provides a detailed breakdown of the energy mix across different scenarios in terms of energy production (Figure 25-b), installed capacity (Figure 25-c), and production costs (Figure 25-a). Figure 25-a combines the results of Figure 25-b and Figure 25-c by multiplying energy and installed capacity by their respective costs parameters per technology.

Figure 25-b shows that when the amount of solar and wind energy increases it substitutes first for the biogas, which is the most expensive among controllable energy sources. When the percentage of intermittent in the mix is 60%, the reduction in biogas reaches 6.8 TWh/year and the region achieves energy autonomy.

Figure 25-a shows that from 60 to 90% of intermittent sources in the mix, the TAC remains almost constant, this is because the increase of costs associated with the investment for the introduction of solar and wind sources is compensated by the decrease in the cost of energy production based on biogas.

The parts of hydropower and biomass remain the same as in the baseline (i.e., same energy production, installed capacity and then, costs) (Figure 25). While the variable cost of biogas is reduced, its investment cost remains constant, as the installed capacity for biomass does not change (Figure 25-c).

A minimum amount of biogas is necessary to maintain sufficient installed capacity to address peak demand periods in the absence of sunlight and wind (Figure 25-c). For this, the reduction of biogas beyond the estimated biogas production of the region leads to a minimum limit of 1 TWh/year, a limit necessary to ensure the installed capacity of controllable sources to meet the peaks of demand (Figure 25-c).

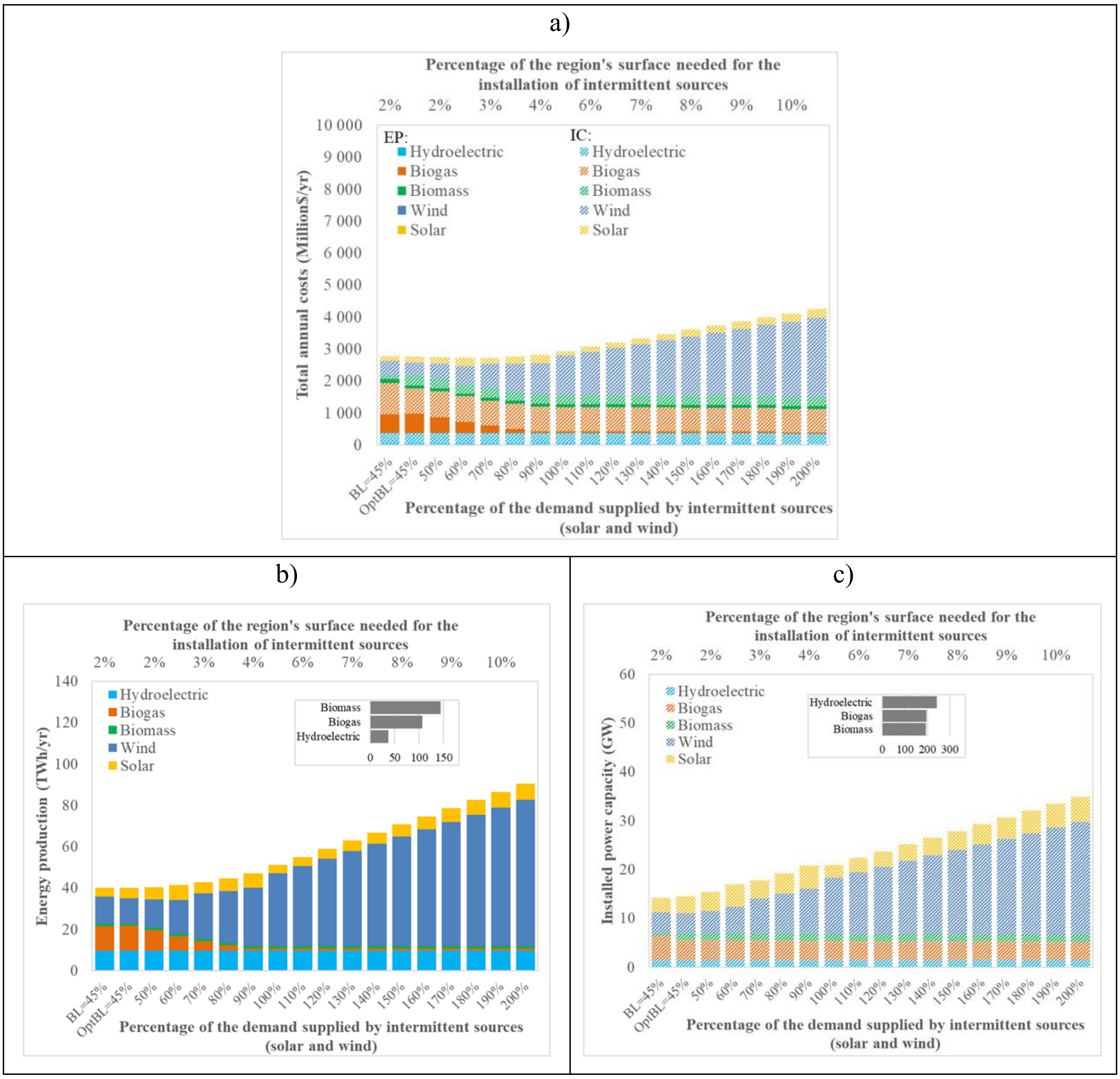


Figure 25 Energy scenarios for the Grand Est region of France in 2050. Electricity demand corresponds to the projected value in the SRADDET scenario(SRADDET, 2019). Technological composition corresponds to the minimal total annual costs (TAC): TAC (a), energy production (b), and installed capacity (c). The hatched color bars refer to installed capacity, which is an investment and fixed costs, and the continuous color bars to energy production, which is variable costs. The red box indicates the scenario in which the region's estimated biogas limit is met. The small bars subplots correspond to the costing parameters $CEP_{tc} + RIE_{tc} * CIC_{tc}$ (b) and CIC_{tc} (c) used for the definition of the technological mix though the optimization of costs. The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal axis corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios.

While electricity demand in the Grand Est region has been decreasing since the 2000s(ATMO-Grand

Est, 2021; RTE, 2022; Sankey-Diagrams, 2020), it remains uncertain whether the SRADDET's target of reducing electricity demand by 2050 will be easily attainable. Indeed, the implementation of the SRADDET, which was initially planned to begin in 2015, has been delayed, particularly in achieving targets for the residential sector. Furthermore, some national scenarios consider an increase of the electricity demand by 2050(RTE, 2021b, 2021c).

Based on the trend of a national-level forecasts by the Réseau de Transport d'Électricité (RTE), we have developed a scenario that deviates from the SRADDET projections. In this scenario, electricity demand rises by more than 30 TWh/year compared to actual levels, ultimately reaching 74 TWh/year.

This higher demand scenario considers changes in electricity demand by sector, comprising reductions of -1 987 TWh/year (14%) for residential, -1 237 TWh/year (12%) for tertiary, and -54 TWh/year (7%) for agriculture, while forecasting significant increases of 20 000 TWh/year (122%) for industry and 12 735 TWh/year (595%) for transport.

As a result, with this higher demand baseline, it becomes necessary to consider generating more electricity from both controllable and intermittent sources. Since the resources of the region, i.e., hydropower, biomass, and biogas reach their maximum local production capacity in the SRADDET estimation, this scenario required supplement them with other controllable energy sources to meet the region's electricity demand.

The decision to decommission the region's nuclear power plants has already been finalized, and the process is currently in progress, in line with SRADDET’s commitment to achieving denuclearization. This move underscores the region's shift toward alternative energy sources and its alignment with long-term sustainability goals. Nevertheless, French energy policy aims to encourage the development of its nuclear capacity developing the EPRs (Evolutionary Power Reactors) technologies with the goal of transitioning entirely to EPRs by 2050. We felt it important to include the use of nuclear energy (EPR) to meet the higher demand of the scenario.

Then, electricity production of the baseline is distributed as follows: solar contributes 5.8 TWh/year, wind 18 TWh/year, biomass 1.8 TWh/year, biogas 16 TWh/year, hydroelectric 9.8 TWh/year, and nuclear 24 TWh/year.

Figure 24-b shows the indicators for the scenarios with higher demand as intermittent energy is introduced in the mix. The baseline characteristics include a total annual cost (TAC) of 8 073 TWh/year, emissions of 8 521 tCO_2/year, non-renewable energy sources (non-RES) at 24 TWh/year, and imports of 33 TWh/year. These imports consist of primary resources for energy production, sourced from nuclear power plants (24 TWh/year) and biogas power plants (9 TWh/year).

With the introduction of intermittent energy sources, two notable scenarios emerge. A first scenario, when 70% of demand is produced by intermittent sources, the costs are minimum, it eliminates the use of non-RES and marks the beginning of a decline in emissions. For this scenario of 70% intermittent energy, the need for the surface for the installation of solar panels and wind turbines in the region is estimated as 6%. For the region, it is estimated that the available surface for the installation of solar photovoltaic panels and wind turbines is 6 893 km² (i.e., 12% of the total surface of the region)(Fernandez, 2020; IRENA, 2015b) (see Supplementary material SP3). And a second remarkable scenario when 110% of demand is produced by intermittent sources that results in zero imports. However, the 110% scenario has a great need for the surface for the installation of solar panels and wind turbines (i.e., 10% of the region’s surface).

Figure 26-a indicates that the minimum cost is achieved at 70% when nuclear energy is no longer utilized.

Figure 26-b shows that the zero-import condition is reached when an amount of energy equivalent to 110% of demand is produced by intermittent sources, thus the biogas used is sufficiently low (as in the low demand scenario) and no nuclear energy is needed.

The parts of hydropower and biomass remain the same as in the baseline (i.e., same energy production, installed capacity and then, costs). A minimum amount of biogas is necessary to maintain sufficient installed capacity to address peak demand periods in the absence of sunlight and wind. For this, the reduction of biogas beyond the estimated biogas production of the region leads to a minimum limit of 1 TWh/year, a limit necessary to ensure the installed capacity of controllable sources to meet the peaks of demand.

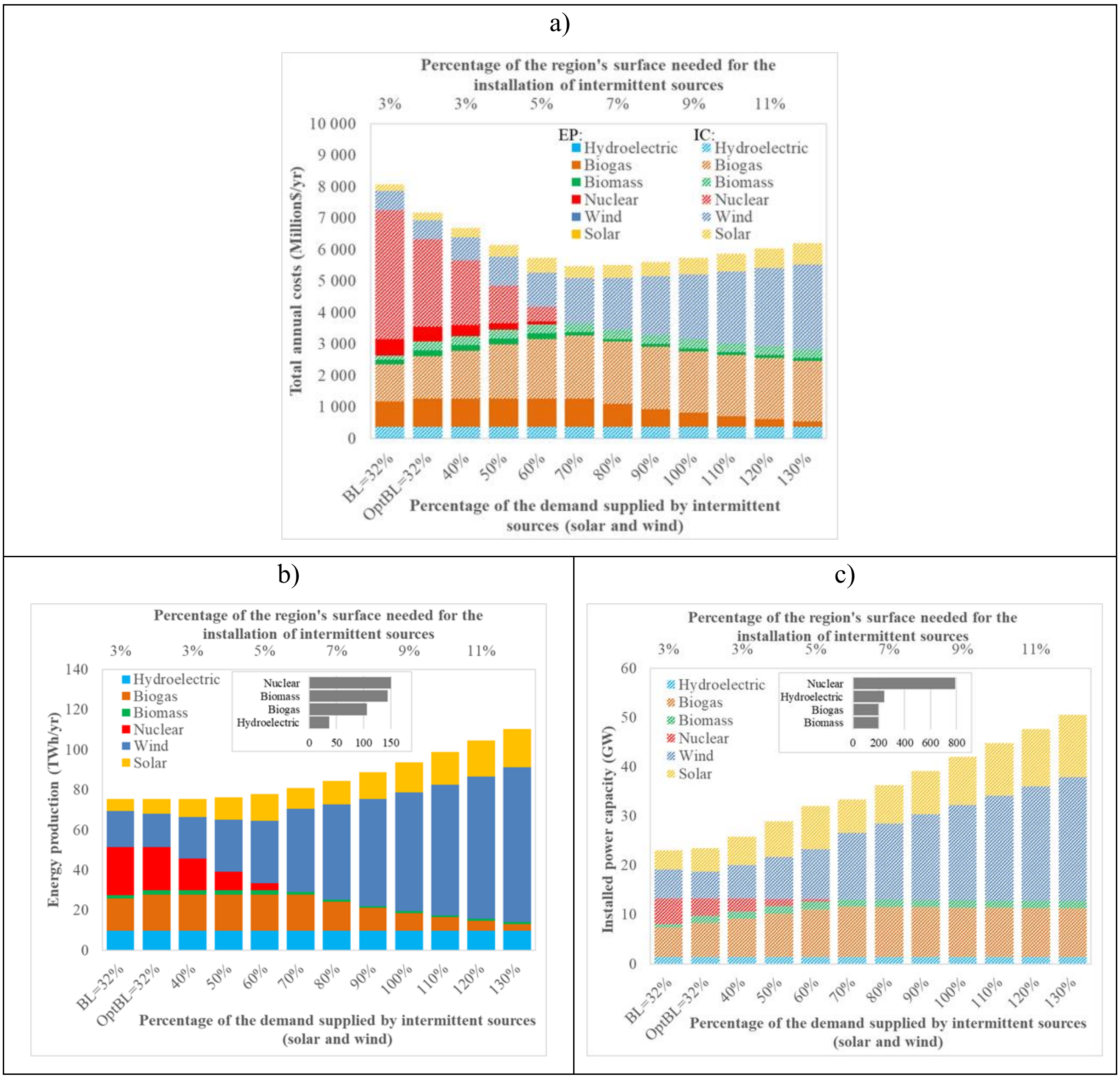


Figure 26 Energy scenarios for the Grand Est region of France considering the maximum demand projected to 2050. Technological composition corresponds to the minimal total annual costs (TAC): TAC (a), energy production (b), and installed capacity (c). The hatched color bars refer to installed

capacity, which is an investment and fixed costs, and the continuous color bars to energy production, which is variable costs. The red box indicates the scenario in which the region's estimated biogas limit is met. The small bars subplots correspond to the costing parameters $CEP_{tc} + RIE_{tc} * CIC_{tc}$ (b) and CIC_{tc} (c) used for the definition of the technological mix through the optimization of costs. The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal axis corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios.

3.2. Cuba

The year 2015 has been selected as the reference state for analyzing the Cuban energy system. This year is particularly suitable as the Cuban government provided easily accessible comprehensive data on its energy system during this period. Additionally, 2015 is representative of a stable energy scenario unaffected by the disruptions caused by the COVID-19 pandemic.

In 2015, Cuba's total energy consumption accounted for 46 TWh/year, with electricity consumption representing around 20.3 TWh/year. Overall, this total consumption required 103.3 TWh/year of primary resources, including 74.5 TWh/year for electricity production. Cuba's electricity production mix was heavily reliant on fossil fuels, with oil and oil sub-products dominating the energy system. Thermoelectric powerplants, fueled by oil and oil sub-products, generated 11.94 TWh/year, while generator sets, also using oil sub-products, contributed 4.40 TWh/year. Together, these sources accounted for approximately 80% of total electricity production. Natural gas turbines added 2.95 TWh/year, representing a smaller portion of the mix. Renewable energy sources played a modest role: bagasse from sugar factories produced 0.90 TWh/year, hydropower contributed 0.05 TWh/year, wind turbines generated 0.04 TWh/year, and solar panels 0.02 TWh/year.

The official projection of 2030 is selected as the baseline scenario designed by the Cuban government for 2030. It is projected to meet future energy demands through a more self-sufficient supply approach. The plan for 2030 includes: i) enhancing technological capabilities to utilize local fuels such as crude oil and natural gas, ii) improving the efficiency of electricity generation, distribution, and consumption through energy-saving initiatives, and iii) increasing the proportion of renewable energy sources. This strategy is outlined in the document "Cartera de oportunidades Cuba - 2017"(EFE & El Economista America.com, 2014).

The official projection calls for an increase of total energy from 46 TWh in 2015 to 57 TWh in 2030 with a share of 51% of oil sub-product and 49% of electricity. The baseline scenario considers that activities in the tertiary, agricultural, industrial and transport sectors are not likely to develop further but forecasts an increase in demand for electricity in the residential sector due to the growing use of air conditioning systems, i.e., 6 971 TWh/year (56%). This increase is due to the need to improve residential comfort, particularly in the tourist sector in a context of facing rising temperatures due to climate change(Angeles et al., 2010, 2018). Electricity production in 2030 is projected to total 32.9 TWh/year, sourced from a diversified mix of technologies. The largest contributor is thermoelectric plants, producing 16 TWh/year, followed by generator sets at 4.4 TWh/year, two technologies that depend on imported primary resources to operate. Natural gas turbines are categorized into two groups: old natural gas turbines, which are obsolete but planned to remain operational, producing 3.3 TWh/year, and new natural gas turbines, which are proposed for future installation to foster the utilization of natural gas (a locally available resource) with an expected production of 1.2 TWh/year. Regarding the RES, biomass energy contributes 5.2 TWh/year and hydropower at 1 TWh/year, while intermittent energy sources include wind at 1.5 TWh/year and solar at 0.5 TWh/year. Like in 2015, this energy production is still primarily driven by the reliance on fossil fuels, more specifically imported light oil and refined fuels. These imports are planned to be reduced thanks to the use of natural gas locally produced. For further details about the current situation and the base line, refer to our related article on Cuba(M. Guevara-Luna et al., 2024).

Figure 27 shows the trends of the indicators for the optimized scenarios of Cuba. For the baseline of Cuba 2030, the method estimated 4 452 million $/year, GHG emissions of 19 130 tCO_2/year, use of 25 TWh/year of non-RES, and 10 TWh/year of imports. Three interesting scenarios emerge: i) the optimization of the baseline scenario, where 7% of intermittent sources in the mix enables the achievement of the zero-imports condition while significantly reducing production costs and emissions; ii) the scenario with 100% of intermittent sources in the mix, where energy production costs reach their minimum; and iii) the scenario with 140% of intermittent sources in the mix, beyond which the non-RES and emissions indicators remain nearly constant.

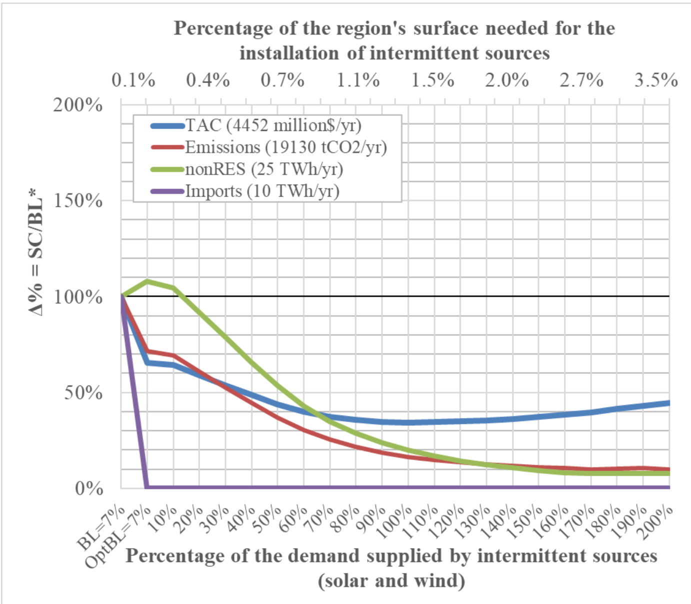


Figure 27 Tendencies of the indicators along the scenarios where intermittent sources (solar and wind) are introduced into the energy mix of Cuba. The indicators correspond to the total annual costs (TAC), emissions, use of non-RES, and imports. Values in parenthesis shown in the legend correspond to the characteristics of the scenarios used as reference (baseline). The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios. A value of 0% for any of the indicators corresponds to the best possible situation, a value of 100% means that the situation is the same as for the baseline scenario, and a value greater than 100% indicates a worse situation compared to the baseline scenario.

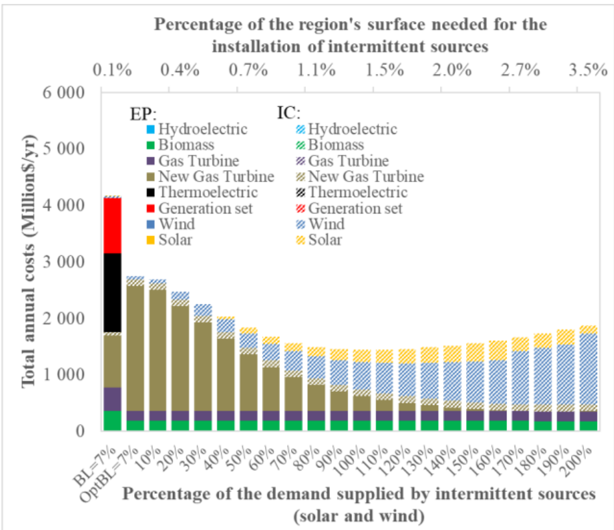
Figure 28-a shows the energy production costs per technology. The investment costs for the obsolete sources on the island (e.g., biomass, thermoelectric plants, and generator sets) are considered zero, since these have already been reimbursed. Even with the aging infrastructure, the Cuban government plans to maintain these systems operational, meaning that variable and fuel costs primarily drive the overall costs of the scenarios. Despite this, technologies with zero investment costs, such as thermoelectric plants and generator sets, rely on expensive fuels for their operation. Therefore, with the baseline optimization (the first of the remarkable scenarios) at 7% of the intermittent energy in the mix, they are immediately replaced by new gas turbines which use local and a less expensive resource.

Figure 28-a shows that from 7% to 100% of intermittent sources in the mix, the production costs decrease until they reach a minimum value and that as the share of solar and wind energy increases, if substitutes progressively the new gas turbines. For percentages of intermittent energy greater than 140%, total costs rise due to the overproduction of energy caused by increasing intermittency in the system.

Figure 28-b shows for percentages of intermittent sources greater than 10% the energy production from the new natural gas turbines is replaced by the energy produced from solar and wind sources. The energy production from old natural gas turbines, biomass powerplants, and hydropower remains the same as in the baseline. Figure 28-c shows that the installed capacity for controllable sources remains constant since the power capacity to supply energy during the peaks of demand, and in absence of solar and wind energy. Then, installed capacity of controllable demands investments that are the same for all scenarios, meanwhile the investment for wind turbines and solar panels increases as more intermittent energy is introduced in the mix.

Due to Cuba's high solar and wind energy potential, the land requirement for integrating intermittent renewable sources is minimal. At 100% introduction of intermittent sources, only 1.4% of the land surface is needed, increasing to 2% at 140% of intermittent sources introduction into the mix. Therefore, land availability is not a limiting factor for the deployment of solar and wind energy in the country.

a)



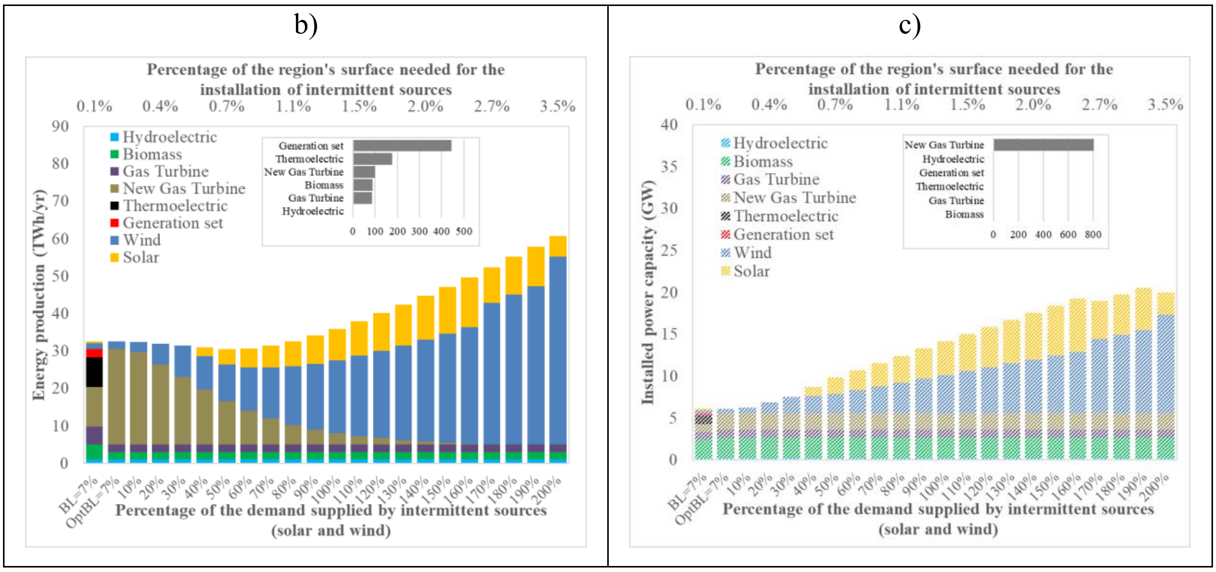


Figure 28 Energy scenarios for Cuba 2030. Technological composition corresponds to the minimal total annual costs (TAC): TAC (a), energy production (b), and installed capacity (c). The hatched color bars refer to installed capacity, which is an investment and fixed costs, and the continuous color bars to energy production, which is variable costs. The small bars subplots correspond to the costing parameters $CEP_{tc} + RIE_{tc} * CIC_{tc}$ (b) and CIC_{tc} (c) used for the definition of the technological mix through the optimization of costs. The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal axis corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios.

4. Discussion

4.1. Uncertainties of the developed method

The methodology used to design energy strategy scenarios is subject to uncertainties, arising mainly from variations in two types of input data, the inputs for the first module, and for the second module.

The input of the first module are the hourly electric demand and the hourly solar and wind capacity factors. The calculation relies on determining the residual energy, defined as the difference between the electricity demand and the energy production from intermittent sources derived from the solar and wind capacity factors. This residual energy is used to compute the required energy to be supplied by controllable sources to complement the intermittent sources and meet the demand. Consequently, the uncertainty of all inputs to the first module can be evaluated through a sensitivity analysis on the residual energy. This sensitivity analysis can be performed by independently varying the average of the residual energy and its temporal fluctuations, distinguishing between different scales (e.g., hourly, weekly, monthly, and seasonal). This assessment will be addressed as part of a future analysis.

The inputs for the second module are the unitary costs and emission factors associated with each energy production technology in the mix. These inputs are used to compute the total annual costs and the total GHG emissions of each scenario. The total annual costs are minimized by implementing the technologies in an optimum order starting from the cheapest to the most expensive up to their maximum limit. Emission factors are fairly well known and introduce relatively limited uncertainties into emissions compared with costs, which depend on unit costs that can vary significantly and are subject to greater uncertainty. Some unitary costs fluctuate frequently due to changes in fossil fuel prices, while others follow clear trends, such as solar and wind, which are steadily decreasing, and nuclear, which is steadily increasing. The total annual cost trends estimated by the developed method (Figure 24 and Figure 27) remain the same as long as the unitary costs of the different technologies in the mix stay in the same order. Thus, despite the uncertainties on the unitary costs, it is expected that the computed trends of the total annual cost of the scenarios over the percentages of introduction of intermittent energy remain robust, e.g., solar and wind energy should remain the cheapest technologies in the future while nuclear EPR is very likely to remain the most expensive one.

The method developed in this study considers the design and evaluation of strategies without the use of storage of electricity. The effects of this on the electricity mix will be included in future studies.

4.2. Trends of the controllable sources LCOE

The analysis has shown that the LCOE is changing with a growing share of intermittent sources into the mix. The LCOE for intermittent sources remains constant, while it increases for controllable sources due to the rise in their RIE_{tc} (equation 12 and Figure 29). Great investments and fixed costs of a technology leads to a more important increase of the LCOE with the introduction of solar and wind in the mix, e.g., the LCOE increase by 3.5 times for hydropower, 3.3 times for nuclear EPR, 2.9 times for conventional nuclear, 2 times for biogas, and 1.7 times for biomass when the percentage of demand supply by intermittent sources increase from 0 to 100%.

Thus, the increase of LCOE can change the order of the technologies. For example, nuclear conventional technology is less expensive than biogas and biomass when the percentage of intermittent energy in the mix is 0%, but it becomes most expensive among the three when the share of intermittent sources in the mix reaches 90%. Increasing the share of intermittent sources may amplify LCOE differences among controllable technologies, as the LCOE of technologies with high investment costs will rise more rapidly compared to those with low investment costs, e.g., EPR nuclear technology is 1.3 times greater than biomass with 0% intermittent energy in the mix, but it becomes 2.6 times greater than biomass with 100% intermittent energy in the mix.

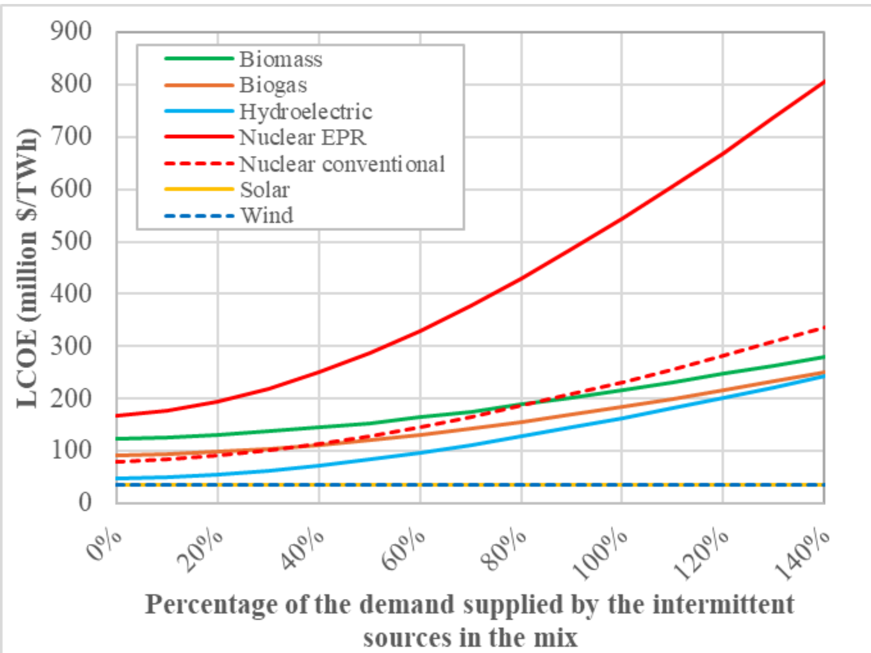


Figure 29 Levelized Cost of Electricity (LCOE) for the technologies in the mix of the scenarios of intermittent energy introduction in the Grand Est Region of France as percentage of the projected demand for 2050.

4.3. Policies alternatives

In the general situation if the demand is low enough it can be supplied by RES only. In such cases, solar and wind emerge as the most economically viable options, requiring only a modest land surface for installation. On the other hand, if the demand is high, all the RES sources are not able to produce enough energy to complete the demand, e.g., solar and wind energy would require a too important land surface, and biomass and biogas are also too limited local primary resources to produce electricity. This makes nuclear energy the only decarbonized option able to complete the mix, even if it is expensive and depends on imported primary resources. In this case, costs are higher compared to the use of local RES since nuclear is not the most economical solution for supplementing intermittent sources.

The demand is a critical factor in defining energy strategies. Two socio-economic policies are in opposition: i) Promoting energy efficiency and population sobriety, which can reduce demand to a level entirely met by RES; and ii) Asking for less sobriety efforts for the population and basing economic activity on growing energy consumption, which will exceed the capacity of RES alone and will require nuclear power as a complement. In terms of electricity pricing policies, electricity prices are expected to rise in both cases, in the first, to compensate for the decline of electricity sales to ensure the repayment of investments, and in the second, to finance the higher costs of nuclear power.

5. Conclusions

This study is based on the development of a method for analyzing the impacts of integrating intermittent sources (solar and wind) into an energy mix. This analysis led to the development of a methodology based on distinguishing between intermittent and controllable sources. It utilizes a reference scenario, typically derived from projections outlined in local energy policies, and generates a series of alternative scenarios, each characterized by an increasing share of intermittent energy in the mix. For each scenario, the method identifies the optimal combination of technologies that minimize energy production costs and calculates additional indicators, such as GHG emissions, energy imports, and non-renewable energy production. The methodology enables the graphical representation of trends for all indicators and other scenario characteristics, including energy production, installed capacity, and total annual costs.

The implementation of the methodology brings some general conclusions about the electric systems' characteristics when intermittent energy production is introduced into the mix. Intermittent sources cannot entirely substitute for controllable sources, as there are always periods when the sun and wind are insufficient to meet demand. Consequently, the integration of intermittent sources reduces the amount of energy that controllable sources must supply, but they are unable to reduce their installed capacity, which is still needed to cope with peaks in demand when sun and wind production are very low. Consequently, the LCOE from controllable sources increases with the rate of introduction of intermittent sources into the mix. The higher their investment and fixed costs, the greater this increase. As a result, some technologies may be economically competitive at low levels of intermittent energy but become too costly as the share of intermittent energy increases significantly.

The methodology has been applied to two case studies: The Grand Est region of France and Cuba. The case of the Grand Est region of France have been analyzed using two different projections of electric demand: a low-demand projection based on the official SRADDET scenario, and a high-demand projection based on the estimations of RTE for France at national level. In the case of low electric demand, renewable sources are sufficient to supply the system's demand in any scenario (i.e., non-RES indicators remain at zero), imports are not necessary when intermittent energy reaches 60% of the demand, and production costs stabilize between 45% and 90% intermittent energy while GHG emissions progressively decrease. In the case of the high-demand projection two notable scenarios emerge. At 70% intermittent energy, costs are minimized, non-RES use is eliminated, and emissions begin to decline. This scenario requires around 6% of the region's surface for solar and wind installations. At 110% intermittent energy, imports drop to zero, but the scenario requires around 10% of the region's surface for solar and wind installations.

For the Grand Est region, the demand trend is a critical factor in determining the optimal energy strategy. If electricity demand is low and declining, the region could easily meet its needs entirely through RES. Intermittent sources such as solar and wind power are particularly viable in this context, with their share covering 60% to 90% of demand without incurring excessive costs or requiring significant land use. Conversely, if demand is high and increasing, decision-makers face a trade-off. One option is to rely on renewable sources, which, while cost-effective, may require substantial land area. The alternative is to incorporate nuclear power, which occupies less land but comes with higher costs.

For the case of Cuba, the energy autonomy (i.e., zero imports) can be achieved optimizing the base line scenario which correspond to 7% of the demand supply by intermittent sources (solar and wind). By increasing this percentage to between 100% and 140%, decision makers could achieve the range where production costs are the lowest. This range also corresponds to situations where the share of RES is high and GHG emissions are low. Beyond 140%, the situation evolves little, as achieving 100% RES and zero GHG emissions remains unattainable.

Chapter 3: Integrated method for design and evaluation of energy strategies including energy storage and demand adaptation

Abstract

Global energy consumption, mainly driven by fossil fuels, is a major contributor to winter gas emissions (GHG). This exacerbates climate change and generates significant health risks. Therefore, decarbonization by reducing the dependence on fossil fuels is urgent. The introduction of solar and wind energy is an interesting alternative for decarbonization due to their declining costs and widespread availability, but the time fluctuation of energy production from these sources has effects on energy system characteristics. Also, the combinations of energy production technologies and resources are infinite, and the choice of one or the other may depend on several criteria. Thus, a robust method is required to assess many energy strategies (scenarios) of progressively increasing intermittent energy integration while several key stakeholder-relevant criteria. And integrating evaluation of storage time (residence time) and sensitivity analysis for the adaptation of the demand to the temporal variation of energy production. Two case studies were used to assess the method: the Grand Est region of France and Cuba. These cases were selected due to their differing energy demand, solar and wind production profiles, average values, and temporal fluctuations.

Keywords

energy transition; evaluation of scenarios; intermittency; energy storage; storage time; climate change; demand adaptation

Highlights

- Extends the method of "optimized tendencies" to evaluate energy strategies integrating intermittent sources (solar/wind) and storage, balancing multiple stakeholder criteria.
- Energy storage can eliminate the need for controllable sources when intermittent generation exceeds demand—but high costs currently limit feasibility unless costs of storage are reduced by ~20x.
- Demand adaptation does not significantly impact the evaluated indicators and is challenging; lowering the total demand is a more feasible and effective alternative.
- Prioritize local renewables (biomass/solar/wind) over non-RES to reduce costs, emissions, and avoid imports.

1. Introduction

The world's energy consumption has been increasing since the early 20th century. The major part of the resources to supply this increasing demand are fossil fuels (BP, 2024; Charlez et al., 2021). This extensive use of fossil fuels has driven climate change since their combustion emits greenhouse gases (GHG) and substances harmful to human health (i.e., atmospheric pollutants). The inevitable depletion of fossil fuels will lead to energy market disruptions, exacerbated by increasing conflicts due to resource scarcity (Arbib & Seba, 2017; Euractiv France, 2023; France24, 2024; IEA - International Energy Agency -, 2023; Intergovernmental Panel on Climate Change (IPCC), 2023; Jacobson, 2020; Madrazo Bacallao, 2018; Nakhle, 2023; Seba, 2014). Therefore, the design and evaluation of energy strategies based on the replacement of fossil fuels by renewable energy sources (RES) is necessary.

Solar and wind energy sources offer promising alternatives to fossil fuels. These RES have significant global potential and have seen substantial cost reductions over the past two decades, driven by increasing scales of production and improvements in the efficiency of solar panels and wind turbines, a trend expected to continue (IRENA, 2022a; Power Engineering International, 2017).

However, solar and wind energy sources are *intermittent*, relying on the availability of sunlight and wind. During periods of low resource availability, these sources may not meet hourly energy demand fluctuations. Therefore, they must be complemented by *controllable* sources that can adapt to demand variations. In line with this reasoning, the integration of significant solar and wind capacities can lead to periods of energy overproduction (M. Guevara-Luna et al., 2024). One alternative for the valorization of this excess of energy can be implementing energy storage. For these reasons, a robust method is needed to evaluate multiple energy strategies (scenarios) involving progressively higher integration of intermittent energy sources. This method should assess key criteria relevant to stakeholders, analyze the impacts of increasing intermittency on controllable sources, and demand adaptation.

Previous research was based on the development of a method to systematically design and evaluate energy strategies (scenarios) characterized by a progressive increase of the share of intermittent sources in the energy mix. For each scenario a cost minimization was implemented to set the energy mix with the shares of the technologies for electricity production in terms of energy production and installed capacity. This approach enabled the generation of “optimized tendencies” that can be used to analyze a great number of scenarios and to consider many criteria simultaneously in the form of comparable indicators (M. Guevara-Luna et al., 2024; Madrazo Bacallao, 2018). The method has the advantage of allowing the design and inclusion of additional indicators that may be of interest to decision-makers.

Obtained results with this method have shown that the introduction of intermittent sources into the mix has mostly positive impacts in all these indicators, especially regarding the reduction of costs, GHG emissions, and imports of energy. However, aspects such as the use of energy storage and adaptation of the temporal fluctuations of the demand in the designed scenarios have not been considered.

This study aims to complement the previously developed method of optimized tendencies by analyzing the effects of integrating intermittent energy sources into the energy system, alongside energy storage. It also includes an evaluation of storage time (residence time) and a sensitivity analysis of demand's adaptation in terms of temporal fluctuation.

This article will present firstly the concept of the developed method of optimized tendencies including energy storage, storage characteristics such as residence time, and demand adaptation. Then, the methods application in two different study cases is reported (Grand Est region of France (Central Europe) and Cuba). After, a discussion of the results and their implications and importance on decision-making and policy is made.

2. Method

In previous research, a method for the design and evaluation of energy scenarios was developed aiming to design and evaluate many scenarios using as many criteria as needed by decision makers, and distinguishing between *intermittent* and *controllable* sources, which allows considering the effects of introducing intermittent energy into an energy system. The previously developed method serves as a base for the developments reported in this study regarding the evaluation of energy storage and demand adaptation.

The developed method generates a series of alternative scenarios to form a trend curve (Pareto curve) defined by a progressively higher share of intermittent energy in the mix starting from a reference scenario (baseline). This baseline is based on official projections outlined in local energy policies. Energy is produced by different technologies that transform the primary energy sources into electricity. In the developed method, the mix of technologies for electricity production, in terms of their annual energy production and installed power capacity is defined by the minimization of costs in each scenario.

In this research, we examine the introduction of energy storage alongside intermittent sources and its impact on scenario characteristics. This is achieved by modeling features such as evaluating storage capacity, time of storage duration (residence time) across various time lengths, and conducting a sensitivity analysis of demand adaptation to energy production at different time scales (e.g., daily, seasonal).

2.1. Energy Model

Solar and wind energy are sources which energy production depend on the availability of sunlight and wind to produce electricity. The production of energy from these intermittent sources does not match with the fluctuations of the demand. Mixing the different capacities of solar and wind sources remains an intermittent resource, it can ensure more regular energy production. However, there are still times when even the assembly of both solar and wind is unable to produce energy at the right moment when it is demanded because neither sun nor wind is available, this situation can occur even with a significant installed capacity of solar and wind sources. Also, during periods of sunlight and wind, high installed capacities of these intermittent sources can lead to generate energy surpluses. To account for these effects, we have introduced the difference between the hourly energy produced from intermittent sources and the hourly demand, it corresponds to the "residual energy" denoted by R_h or simply R. It can be expressed without considering the losses by equation 1, where D_h is the demand and I_h is the intermittent energy production in the hour denoted by "h".

$$R_h = D_h - I_h \tag{1}$$

Grid stabilization is essential to maintain power balance, prevent voltage fluctuations, and ensure system reliability amid variable solar and wind energy production. In this case it is included as a fraction of D_h in the expression for the residual energy, it is denoted by θ (equation 2). A minimum amount of energy θD_h is supplied hourly from stable sources, i.e., controllable sources and/or energy storage. In this study a value of θ equal to 30% is used based on cited research (De Rosa & Castro, 2020; Luo et al., 2021).

$$R_h = \theta D_h - I_h + (1-\theta) D_h \tag{2}$$

Alternatively, the residual energy of equation 2 can be expressed as the sum of two terms, i.e., $R_h = R_h^D + R_h^{ID}$. The first part $\left(R_h^D\right)$ corresponds to the fraction of the demand supplied for grid stabilization each hour, and the second part $\left(R_h^{ID}\right)$ correspond to the effects of the intermittent sources.

For this R_h^{ID} is used as a criterion for the hourly configuration of the energy fluxes: i) when $R_h^{ID} \leq 0$ there is an overproduction of intermittent energy (Figure 30-a), the intermittent production supplies the hourly demand, and the excess of energy is used to charge the energy storage until the maximum storage capacity is attained. When the maximum storage is reached the excess of energy produced can be exported or just missed. The storage can be charged and discharged within the same hour to ensure grid stabilization; and ii) when $R_h^{ID} > 0$ the intermittent energy production is not enough to fill up the demand in the hour "h" (Figure 30-b), the demand is completed firstly by the energy stored and secondly by the controllable sources.

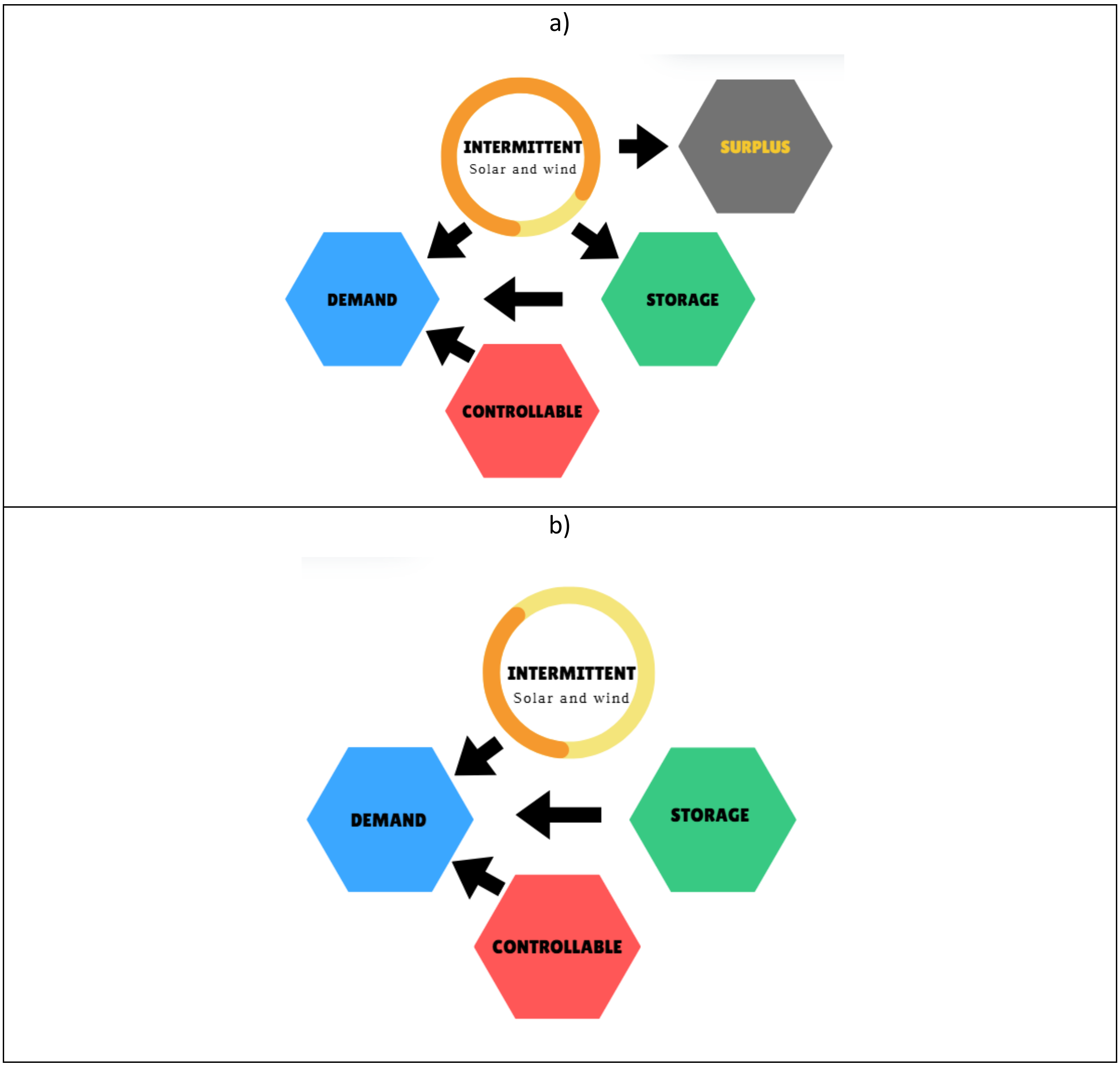


Figure 30 Hourly exchanges of energy between the intermittent sources (solar and wind), controllable sources, energy storage and demand. The sense of the arrows corresponds to the direction of the hourly energy flow, it is determined by the hourly value of the residual energy $(R_h^{ID} = D_h - I_h)$: a) $R_h^{ID} \leq 0$ (overproduction of intermittent energy) and b) $R_h^{ID} > 0$. The circle around the intermittent sources represents the combined hourly capacity factor of solar and wind sources. The energy flows, illustrated as arrows between the elements of the diagram, include losses that are considered in the method but not shown in the illustration.

To model energy storage, the overproduced energy, when R_h^{ID} takes values under zero, is stored until the energy storage capacity (S_{max}) is reached. The stored energy is then used to complement the intermittent sources and complete the demand as soon as energy is needed to fulfill the energy demand (i.e. as soon as R_h^{ID} becomes positive) (Figure 31). The energy stored is used until it runs out, then the controllable sources are used to complete the demand. The peaks are completed by controllable energy rather than by the stored energy. The hourly storage $\left(S_{h+\frac{1}{2}}\right)$ is calculated based on the change in the stored energy (S^*) and R_h (equation 3). An alternative method can be employed, which entails delaying the release of stored energy until a specific threshold value is reached, rather than discharging it as soon as R becomes negative. This strategy aids in peak reduction, and the impact of this method will be explored in future research.

$S^* = S_{h-1/2} + R_h$ $S_{h+1/2} = min[S_{max}; max(0; S^*)]$	(3)

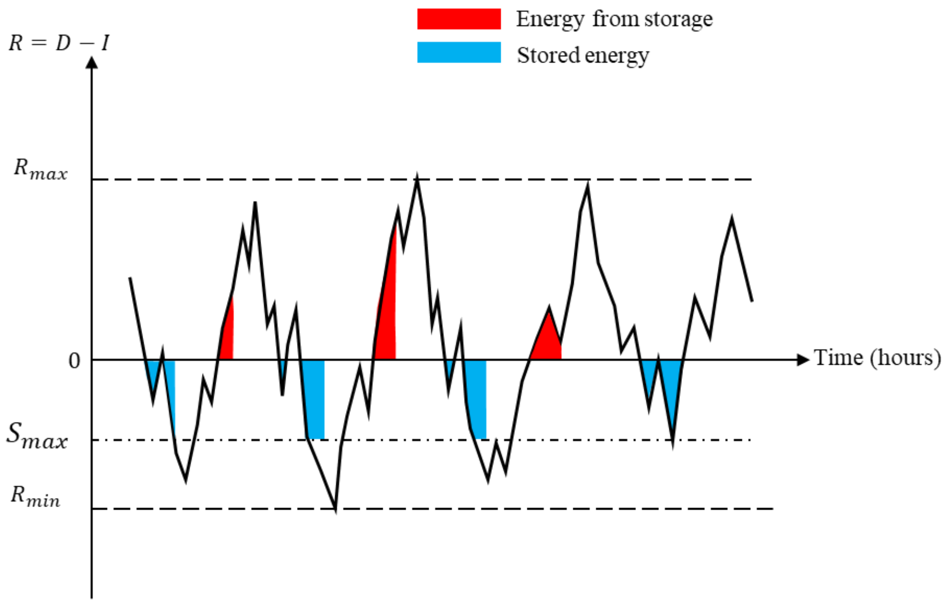


Figure 31 Residual energy (R=D-I) over time. It illustrates storage management with the Direct-Release method based on using the stored energy immediately when the intermittent sources are no longer sufficient to meet the demand.

2.2. Costs calculation

Both types of energy production technologies (intermittent and controllable) have costs associated with their implementation and operation, these are represented by the total annual production costs (TAC). The TAC serves as a link between the characteristics of the energy system and the economics. Additionally, the TAC connects many technical aspects of the alternative scenarios, such as installed capacity and energy production for the different technologies into the system, as well as the hourly capacity and energy input and discharge from the storage system.

The costs of a specific scenario $\left(TAC^{(SC)}\right)$ results from the sum of all costs of the technologies into the energy mix "t" used to produce and store the energy (equation 2). Where, "tc" is the subindex indicating controllable technologies and"ts" is the subindex indicating storage technology.

$TAC^{(SC)} = TAC_{int}^{(SC)} + TAC_{cont}^{(SC)} + TAC_{sto}^{(SC)}$ where, $TAC_{int}^{(SC)} = TAC_{solar}^{(SC)} + TAC_{wind}^{(SC)}$ $TAC_{cont}^{(SC)} = \sum_{tc} TAC_{tc}^{(SC)}$ $TAC_{sto}^{(SC)} = \sum_{ts} TAC_{ts}^{(SC)}$	(2)

Regarding only the TAC of energy production $\left(TAC_{EP}^{(SC)}\right)$ for the scenario "SC", a general form can be formulated (equation 3). Where, for each of the energy production technologies "t" in the mix, intermittent and controllable, the $TAC_t^{(SC)}$ depends on two terms as shown in equation 4. The first term is proportional to the energy produced $\left(EP_t^{(SC)}\right)$ and its unit cost (CEP_t), measured in millions of dollars per TWh while the second term is proportional to the installed capacity $\left(IC_t^{(SC)}\right)$ and its unit cost (CIC_t), measured in millions of dollars per TW. (CEP_t) depends on variable and fuel costs denoted by VC_t and FUC_t, and the efficiency in the use of the primary resources to produce the electricity (η_t). CIC_t depends on the fixed costs FC_{tc} and the annualized investment cost AC_t.

$TAC_{EP}^{(SC)} = \sum_{t} TAC_t^{(SC)}$	(3)

The annualized investment cost AC_t is estimated with an interest rate "r" and the lifetime "l" of the technology "t" (equation 5)(Aldersey-Williams et al., 2019; M. Guevara-Luna et al., 2024; Jacobson et al., 2015; Jacobson, Delucchi, Cameron, et al., 2017; Murray et al., 2018; Obi et al., 2017; Santoyo-Castelazo & Azapagic, 2014).

$TAC_t^{(SC)} = EP_t^{(SC)} CEP_t + IC_t^{(SC)} CIC_t$	(4)

$CEP_t = VC_t + \frac{FUC_t}{\eta_t}$ and $CIC_t = AC_t + FC_t$ with $AC_t = CC_t \times \frac{r \times (1+r)^l}{(1+r)^l - 1}$	(5)

This is valid for any energy production technology, intermittent or controllable. However, intermittent such as solar and wind lack variable and fuel costs, but their investment is important, this allows the omission of the second term of equation 4 for solar and wind technologies. Differently, controllable technologies can have diverse magnitudes of investment, fixed, fuel, and variable costs.

The energy mix (combination of the technologies in the electricity production system) of each of the scenarios is defined by the minimization of costs as described in the previous chapter.

In this case energy storage is included as part of the scenarios. It is modeled using one single technology of reference. In this study we have chosen the concrete tower storage systems since it is a technology that allows large scale energy storage and it can be deployed in both cases of study, it is the second cheapest technology of storage after batteries but capable of storing for periods longer than days or weeks (Balkan Green Energy News, 2019; Quartz, 2018).

TAC for a storage technology "ts" is composed of two parts: i) the variable costs which depend on the input energy flux, i.e., the energy that goes into the storage (charge); and ii) the fixed costs which depend on the storage capacity. Where the variables $SCA_{ts}^{(SC)}$ and $ES_{ts}^{(SC)}$ correspond to the storage capacity and the energy input into the storage by technology "ts" in the scenario "SC" (equation 6).

$TAC_{ts}^{(SC)} = ES_{ts}^{(SC)} * CEP_{ts} + SCA_{ts}^{(SC)} * CIC_{ts}$	(6)

CEP_{ts} and CIC_{ts} are the variable and fuel, and fixed and investment unitary costs parameters for the energy production technologies, similar to equation 5. The calculation for the annualized cost of the investment in energy storage technology "ts" (AC_{ts}) depends on the number of periods for the annualization calculation "np", and the interest rate "r" (equation 7). The storage energy units can be replaced once they reach their uselife, or when the number of cycles is attained. To account for this, the calculation of AC_{ts} can be adapted to consider the replacement time more precisely as shown in equation 7. Then, the number of periods is "np" corresponds to the minimum between the uselife of the storage technology and the replacement time due to its usage and the lifetime "l" of the reference technology (Aldersey-Williams et al., 2019; M. Guevara-Luna et al., 2024; Jacobson et al., 2015; Jacobson, Delucchi, Cameron, et al., 2017; Murray et al., 2018; Obi et al., 2017).

$AC_{ts} = CC_{ts} \times \frac{r \times (1+r)^{np}}{(1+r)^{np} - 1}$ with $np = min\left(l, \frac{simulated\ cycles}{uselife\ cycles}\right)$	(7)

2.3. Storage time or residence time

The storage time (residence time), which is the duration energy is stored before use, can be influenced by the amount of intermittent energy production introduced into the energy mix. We have developed a method to evaluate storage time by first discretizing the calculated storage of energy for the scenarios generated from the developed model, and then distributing the hourly charges and discharges across different storage levels called layers (Figure 32).

The principle of this method is to charge the layers sequentially, one after the other. When a discharge is required, the most recently charged layer is discharged first. In this way, for each layer, the largest time that it maintains its energy charge is calculated, e.g., in Figure 32, layer 1 will have a charge of 1 MWh that must be maintained during a storage time of 8 hours, and layer 2 has a storage time of 6 hours.

As a result, for each storage layer, there is a storage time. The longest storage times will correspond to the first layers of storage, meanwhile, the greatest storage times correspond to the greatest layers. In this study, 300 layers were used to evaluate the storage times of the modeled scenarios.

The resulting storage capacities and storage times can then be used to evaluate different technologies for storing energy within the scenarios.

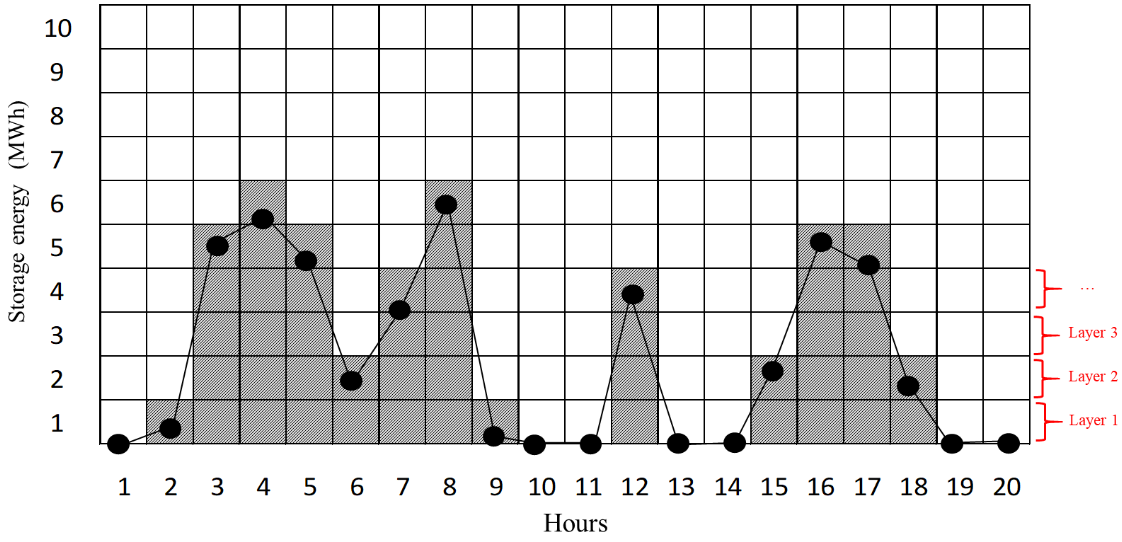


Figure 32 Storage time estimation method based on the discretization scheme of the storage energy into layers.

2.4. Demand adaptation sensitivity analysis

Modification, or adaptation, of demand can have effects on the energy system characteristics and therefore on indicators of the scenarios, e.g., costs, emissions, use of non-RES, etc. In this section, we address the question of what the potential effects are of adapting demand to energy production fluctuations when intermittent energy sources are introduced into the mix—specifically, within the scenarios generated by the developed method.

In this study, the adaptation of demand is based on adjusting the fluctuation of the hourly demand to the fluctuation of the hourly energy production at different time scales, e.g., hourly, daily, weekly, seasonal, etc. For this, the residual energy "R" is averaged at different time scales to obtain $\overline{R}^h$, $\overline{R}^d$, $\overline{R}^w$, $\overline{R}^s$, and $\overline{R}^y$ which correspond to its hourly daily, weekly, seasonal, and yearly averages respectively. '$-h$', '$-d$', '$-w$', '$-s$', and '$-y$' are operators computing the average of the R time series over the hourly, daily, weekly, seasonal, and yearly time scales respectively. The R values used as base for the calculation correspond to the hourly average, so we will refer now to R as $\overline{R}^h$, it can be decomposed into different contributions (temporal components), and the yearly average $\left(\overline{R}^y\right)$(equation 8).

$\overline{R}^h = \left(\overline{R}^h - \overline{R}^d\right) + \left(\overline{R}^d - \overline{R}^w\right) + \left(\overline{R}^w - \overline{R}^s\right) + \left(\overline{R}^s - \overline{R}^y\right) + \overline{R}^y$	(8)

$\overline{R}^y$ is a constant value equal to the yearly average to which the following temporal components are added: $\Delta R_{h-d} = \left(\overline{R}^h - \overline{R}^d\right)$, $\Delta R_{d-w} = \left(\overline{R}^d - \overline{R}^w\right)$, $\Delta R_{w-s} = \left(\overline{R}^w - \overline{R}^s\right)$, $\Delta R_{s-y} = \left(\overline{R}^s - \overline{R}^y\right)$ resulting in equation 9.

$\overline{R}^h = \overline{R}^y + \Delta R_{h-d} + \Delta R_{d-w} + \Delta R_{w-s} + \Delta R_{s-y}$	(9)

With this formulation, the terms $\widehat{R_h}$, $\widehat{R_d}$, $\widehat{R_w}$, and $\widehat{R_s}$ can be introduced, and they correspond to the hourly residual energy $\overline{R}^h$ without the hourly, daily, weekly, and seasonal temporal components respectively (equation 10). As example, $\widehat{R_h}$ is the hourly residual energy without the contribution of the daily component (ΔR_{h-d}), so for $\widehat{R_h}$ all the hourly averages over the day are equal. Similarly, for $\widehat{R_d}$ all the hourly averages are equal to the daily average, and so on.

$$\widehat{R_h} = \overline{R}^h - \Delta R_{h-d}$$
$$\widehat{R_d} = \overline{R}^h - \Delta R_{d-w}$$
$$\widehat{R_w} = \overline{R}^h - \Delta R_{w-s} \qquad (10)$$
$$\widehat{R_s} = \overline{R}^h - \Delta R_{s-y}$$

With this formulation we can evaluate the effect of adapting the demand to energy production at different timescales through a sensitivity analysis.

3. Results

3.1. Central Europe: Grand-Est region of France

3.1.1. Baseline for the Grand Est

The baseline scenario corresponds to a future situation projected by the official authorities of the studies region, or by an estimation based on data for the study case. The official projection of the demand used by the region's administration is the SRADDET strategy, which considers the denuclearization up to 2050 according to the sustainable development objectives of SRADDET (baseline) (SRADDET, 2019). According to the SRADDET projections, the total energy consumption of the region will decrease from 176 TWh in 2021 to 89.6 TWh in 2050. The electricity demand will decrease from 43.9 TWh in 2021 to 39.3 TWh in 2050.

The SRADDET projection considers the introduction of biomass and biogas to be an important development in the region. In particular, the use of biogas is estimated to be 27 TWh in 2050. However, there is a risk of not reaching this amount of biogas production, given that studies in the region have found that the local biogas potential from agricultural wastes is only 6.8 TWh/yr (Paz, 2021).

Future official estimates of SRADDET might be overly optimistic for two reasons: i) The expected decrease in demand may not be achieved; and ii) Local RES may be insufficient to meet local demand. These reasons suggest a significant risk of being unable to produce the necessary energy with the region's local resources by 2050, for example, if electricity demand increases or does not decrease as expected, and projected biogas production is not achieved.

Losses in the electric grid of the region are reported to be 2.28%.

3.1.2. Energy mix and costs

The model generates a great number of scenarios. The cost optimization implemented allows for the definition of the energy mix of production technologies for each scenario. The scenarios obtained start from a reference scenario, or official projection by local authorities of the region or country, called the baseline (BL). From this baseline scenario, alternative scenarios with increasing percentages of intermittent energy in the mix are generated until the intermittent energy production reaches twice the electricity demand (200% of the electricity demand), or until the estimated available surface area limit for installing solar panels and wind turbines in the region is reached.

The costs of energy storage can impact the different decision criteria evaluated. Therefore, investigating the effects of energy storage costs can provide insights into the conditions under which energy storage becomes feasible. For example, if the maximum storage capacity is limited, or if the unitary cost of implementing energy storage is reduced.

To evaluate this, two main types of results analyses were developed: i) Storage Capacity Limit (S_{max}): The storage capacity limit for each scenario is set as a percentage of the maximum calculated storage capacity without any limit (maximum storage capacity), several percentages of the maximum storage capacity of each scenario are evaluated; and ii) Reducing Unitary Costs: The unitary costs (or costing parameters) of energy storage are divided by a factor ranging from 10 to 1000, representing hypothetical conditions where storage costs are lower than the current reference costs in the optimized scenarios. For each scenario using these strategies the designed indicators are also analyzed following the formulation of indicators design and calculation of previous chapters, e.g., total annual costs, GHG emissions, imports, and use of non-RES.

3.1.2.1. Effects of energy storage: Limiting the maximum storage capacity

The results regarding the optimized scenarios of introducing solar and wind sources are shown in the Figure 33 for the demand of the projection in the official strategy of the Grand Est region (SRADDET)**.** The figure compares the indicators of the optimized scenarios without any limit on storage capacity (100% S_{max}) with the scenarios where energy storage is limited to 10% of the maximum calculated capacity (10% S_{max}).

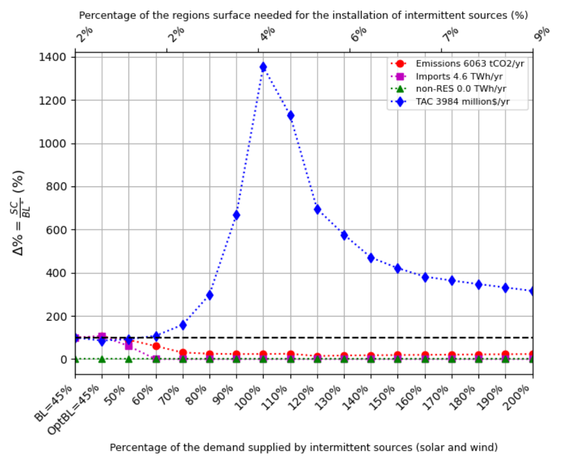
Figure 33 shows that the scenarios with energy storage are considerably expensive. While it may be hypothesized that reducing storage capacity could enhance the feasibility of storage solutions. However, the associated costs remain excessively high, even when the storage capacity is limited to a fraction of the scenario's peak requirement.

When the percentage of intermittent sources in the mix reaches 60%, the region's local biogas production potential in the region is sufficient to complement solar and wind energy, eliminating the need for further imports and reducing this indicator to zero.

Consequently, scenarios with percentages of intermittent energy greater than 60% leads to the reduction of GHG emissions and energy imports. The baseline scenario considers only RES, so the non-RES usage indicator remains at zero across all scenarios based on this low demand estimate.

The Grand Est region has approximately 6 893 km² available for the installation of solar panels and wind turbines (i.e., 12% of the total surface of the region) (Fernandez, 2020; IRENA, 2015b). In the optimized scenarios based on the official demand projection (SRADDET), this limit is not reached even when installing solar panels and wind turbines with the capacity to produce up to twice the demand (second horizontal axis in the plot).

100%Smax	10%Smax
a)	b)



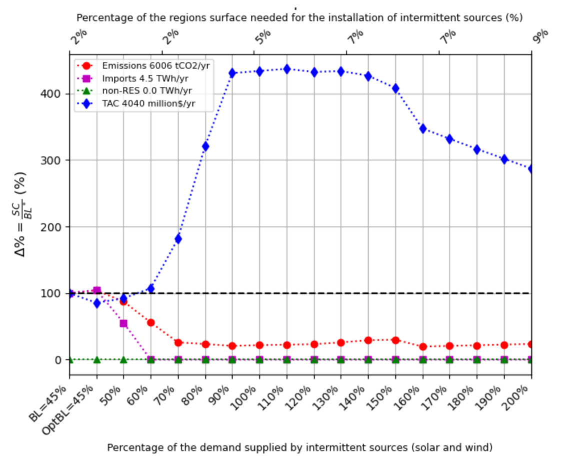


Figure 33 Tendencies of the indicators when intermittent sources (solar and wind) are introduced in the energy mix of the Grand Est region of France with the SRADDET projected demand for 2050; without limit on storage capacity (a) and with limit on storage capacity (b) (i.e., 10% of the maximum storage). The plotted indicators correspond to: Total annual costs (TAC), GHG emissions, energy imports, and use of non-RES. Values in parenthesis shown in the legend correspond to the characteristics of the scenarios used as reference (baseline). The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios. A value of 0% for any of the indicators corresponds to the best possible situation, a value of 100% means that the situation is the same as the baseline scenario, and a value greater than 100% indicates a worse situation compared to the baseline scenario.

While electricity demand in the Grand Est region has declined since the 2000s(ATMO-Grand Est, 2021; RTE, 2022; Sankey-Diagrams, 2020), achieving SRADDET's 2050 reduction target remains uncertain due to implementation delays, especially in the residential sector. Some national scenarios even project an increase in demand by 2050.

Based on trends from Réseau de Transport d'Électricité (RTE) forecasts, we developed a scenario where electricity demand rises by over 30 TWh/year, reaching 74 TWh/year. This scenario anticipates sector-specific changes: Residential: -1,987 TWh/year (14%); Tertiary: -1,237 TWh/year (12%); Agriculture: -54 TWh/year (7%); Industry: +20,000 TWh/year (122%); and Transport: +12,735 TWh/year (595%).

To meet this higher demand, both controllable and intermittent sources must be expanded. Local resources like hydropower, biomass, and biogas are already at maximum estimated capacity, necessitating additional sources. Although the region is decommissioning nuclear plants to achieve denuclearization, French policy supports developing nuclear capacity with EPR (Evolutionary Power Reactor) technology, aiming for a full transition by 2050. Thus, nuclear energy (EPR) is included in the scenario to meet higher demand.

The baseline electricity production is distributed as follows: Solar: 5.8 TWh/year; Wind: 18 TWh/year;

Biomass: 1.8 TWh/year; Biogas: 16 TWh/year; Hydroelectric: 9.8 TWh/year; and Nuclear: 24 TWh/year.

Figure 34 shows the indicators for the optimized scenarios with energy storage generated based on the maximum demand estimation, with and without storage capacity limitation.

As for the scenarios based on the minimum demand estimation, the TAC of scenarios with energy storage are considerably higher than those of the baseline scenario in cases with high intermittent energy production, i.e., when more than 60% of the demand is met by intermittent sources.

As previously noted, energy storage continues to be too expensive, even when the storage capacity is limited to a fraction of its maximum.

Since the energy mix in this case is supplemented with nuclear energy, a non-RES source, the indicator of use of non-RES is improved with the introduction of intermittent sources to replace nuclear energy. This indicator reaches its optimal value when nuclear energy use disappears, i.e., when more than 60% of the demand is met by intermittent sources.

The GHG emissions indicator increases as the intermittent energy production increases the energy mix. This is because reducing nuclear production requires increased use of other GHG-emitting controllable sources, such as biogas, to meet demand during periods of low intermittent production.

In the baseline scenario, importing 33 TWh/year is necessary because the region's biogas production potential of 6.8 TWh/year is insufficient to meet local biogas production needs (Paz, 2021). The energy import indicator drops to zero when imports of primary resources for nuclear or biogas production are no longer needed, i.e., in scenarios where intermittent production accounts for less than 80% of the demand.

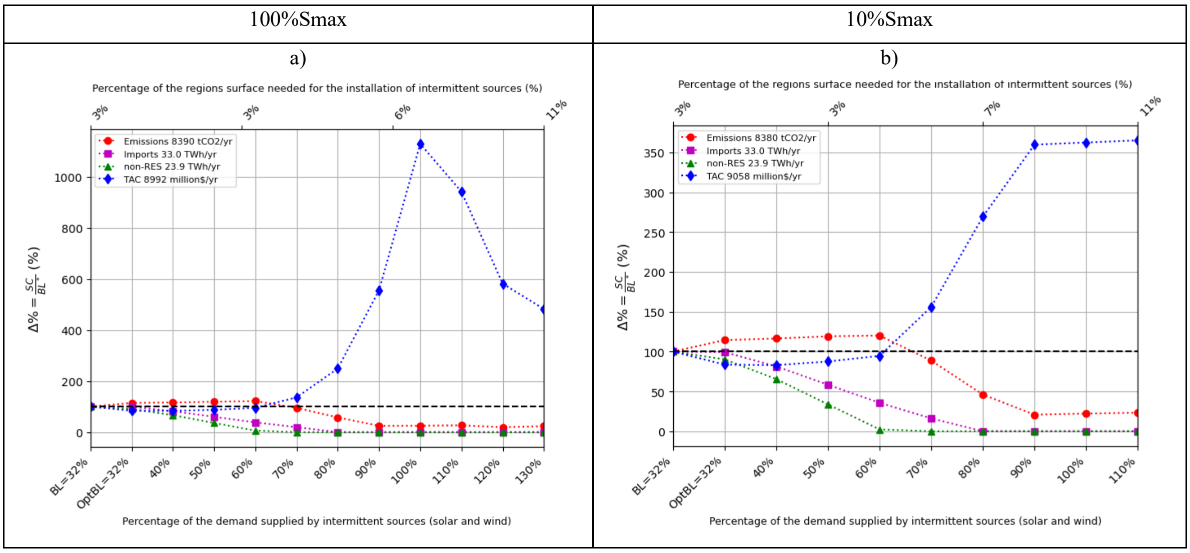


Figure 34 Tendencies of the indicators when intermittent sources (solar and wind) are introduced in the energy mix of the Grand Est region of France with the maximum estimated demand for 2050; without limit on storage capacity (a) and with limit on storage capacity (b) (i.e., 10% of the maximum storage). The plotted indicators correspond to: Total annual costs (TAC), GHG emissions, energy imports, and use of non-RES. Values in parenthesis shown in the legend correspond to the characteristics of the scenarios used as reference (baseline). The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top

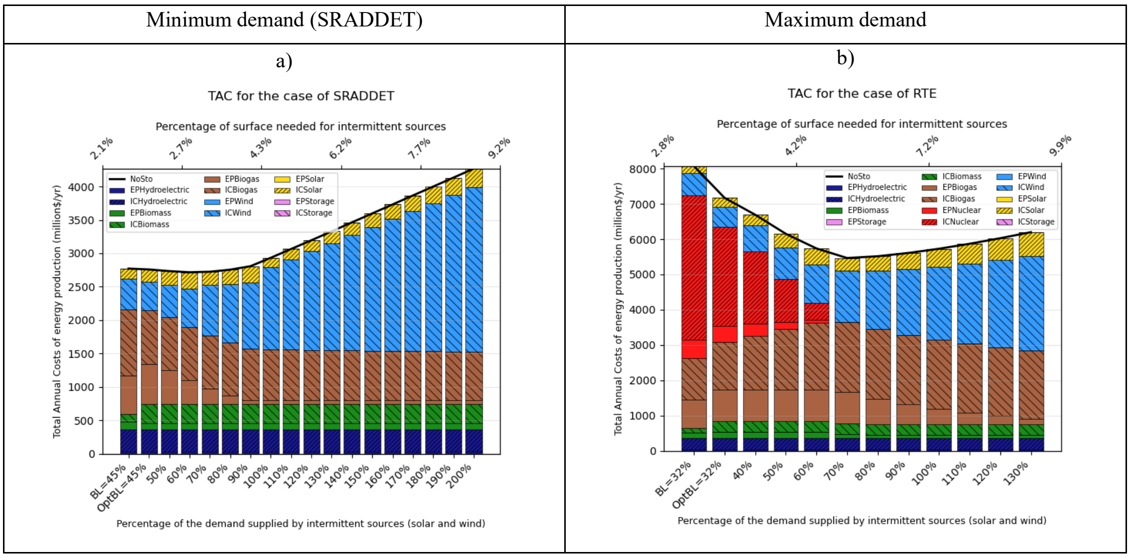
horizontal corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios. A value of 0% for any of the indicators corresponds to the best possible situation, a value of 100% means that the situation is the same as the baseline scenario, and a value greater than 100% indicates a worse situation compared to the baseline scenario.

3.1.2.2. Effects of unitary costs of storage

Energy storage significantly impacts the energy mix, especially in scenarios where intermittent energy production is substantial.

If the projected reference unit costs of energy storage are not reduced, the optimum scenarios are those without energy storage (Figure 35 parts a and b). This indicates that, given the reference energy storage costs, scenarios involving energy storage are not economically feasible.

Energy storage can become feasible with a reduction in unit costs, but it requires overproduction of energy, such as in scenarios where intermittent energy production exceeds demand (>100% intermittent in the mix). Figure 35 shows the TAC for the optimized scenarios with energy storage in the Grand Est region of France, with the minimum and maximum demand projections, considering a unitary cost for energy storage implementation divided by factor 50 (results with other factors of reduction are reported in the Supplementary material SP3). In each of these scenarios, the energy storage capacity limit is defined as the level that minimizes the TAC for each scenario. Additionally, these scenarios are compared with scenarios without energy storage (represented by the black line in the figures). This comparison allows evaluating the effect of energy storage at a competitive implementation cost compared to the costs of controllable sources.



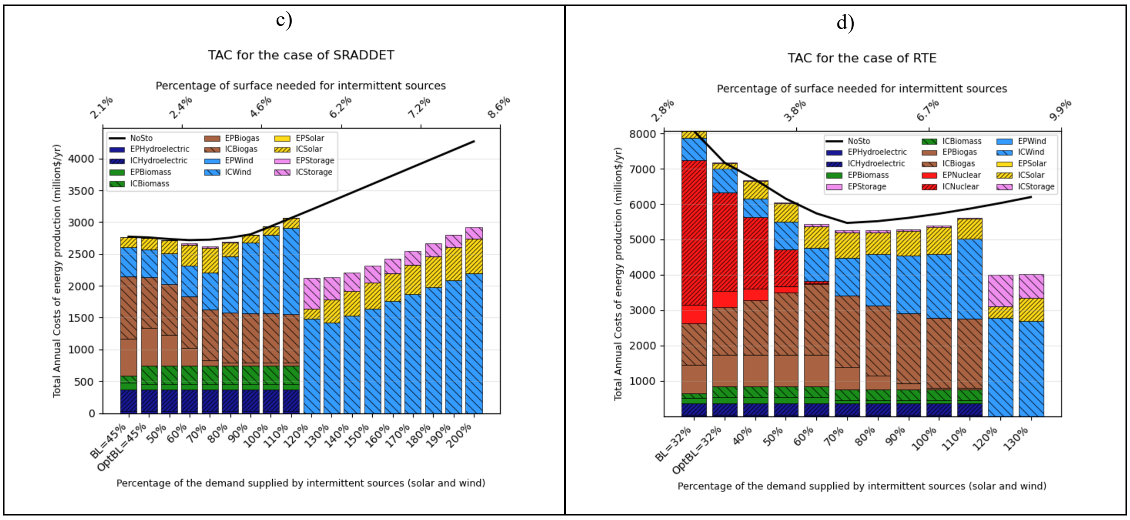


Figure 35 Total annual costs for the optimized scenarios with energy storage, with projected reference unitary costs (costing parameters value) (parts a and b), and reducing the unitary costs of energy storage by factor 50 (parts c and d), for the study case of the Grand-Est region of France. Results correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET) (parts a and c), scenarios designed based on a maximum demand estimation (parts b and d). The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

The reduction in energy storage unit costs primarily impacts TAC among the evaluated indicators (Figure 36). Since, in comparison to scenarios with unlimited energy storage (Figure 33), the costs are considerably lower.

For scenarios with the minimum demand projection, the reduction in energy storage unitary costs leads to additional improvements in the TAC and emissions indicators, especially when intermittent energy production exceeds 120% of the demand (Figure 36 part a). When energy is overproduced, the reduced costs of storage enable the complete elimination of controllable sources from the mix. However, for scenarios with lower intermittent energy production (<120%), controllable sources remain necessary and more feasible than storage to complement solar and wind sources.

For the indicators for the scenarios with maximum demand (Figure 36 part b), limiting the unitary storage costs leads to an improvement of the indicators scored except for the GHG emissions. Especially the TAC is reduced compared to the BL scenario with the introduction of solar and wind energy production.

GHG emissions are higher than in the BL scenario due to the expansion of biogas to its maximum limit to reduce the use of the expensive nuclear energy. When an amount of solar and wind energy exceeding 70% of demand is introduced into the mix, GHG emissions become lower than those in the BL scenario. With the introduction of solar and wind energy beyond 70%, the GHG indicator is further improved compared to the BL scenario.

The indicators of imports and use of non-renewable energy sources (non-RES) are consistently improved with the introduction of solar and wind energy into the mix. They reach their optimal condition (scored as zero) when 60% (for non-RES) and 80% (for imports) of the demand is produced by intermittent sources.

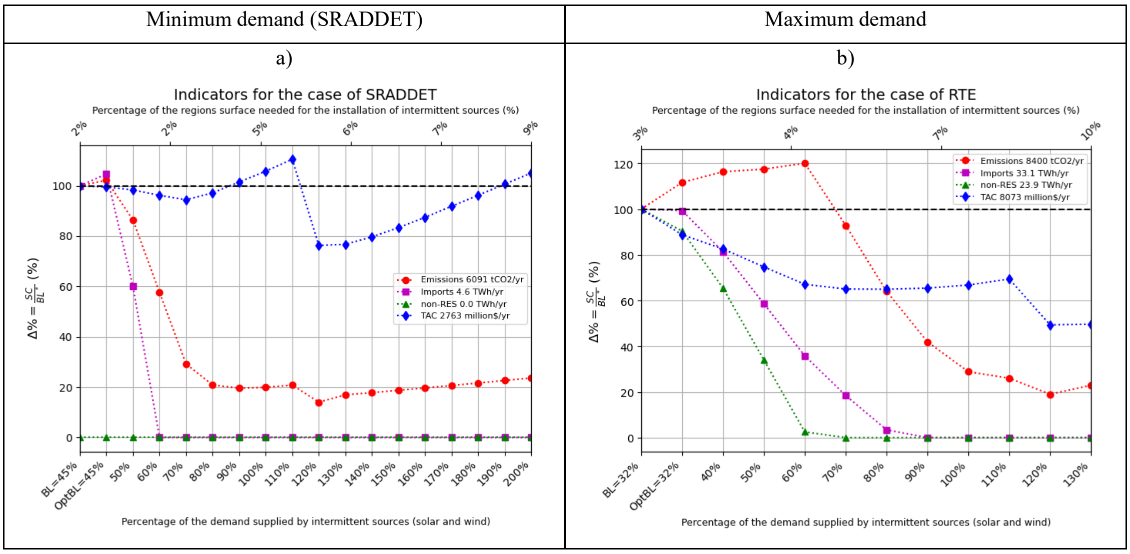


Figure 36 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 50, for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Parts a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

3.1.3. Demand adaptation

The adaptation of the demand to the energy production fluctuation over time was studied through a sensitivity analysis of the designed indicators. Figure 37 shows these indicators for the optimized scenarios of the Grand-Est's energy system obtained as a result from the modified residual energy (R) in the daily and seasonal time scales, i.e., $\widehat{R_h}$ and $\widehat{R_s}$, compared to the base case "BC or "$\overline{R}^h$". The results correspond to scenarios with and without energy storage, and to the storage capacity limit that minimizes the TAC for each scenario. The unitary costs for the implementation of energy storage in the scenarios are reduced by factor 50. Additional results of this sensitivity analysis are reported in the supplementary material SP4.

Costs are reduced thanks to energy storage, but only when intermittent energy production exceeds demand and storage implementation costs are low. For scenarios where intermittent energy production is less than demand, it is more cost-effective to implement scenarios without energy storage, using controllable sources to complement intermittent sources and meet demand during periods of low solar and wind production (Figure 37 parts a and e).

With me minimum projected demand, the minimum TAC scenario without energy storage occurs when intermittent sources produce 70% of the demand, and the demand aligns with the daily intermittent energy production. On the other hand, the scenario with the lowest TAC with energy storage occurs when intermittent sources produce 140% of the demand, and the demand adapts to the seasonal fluctuations in energy production.

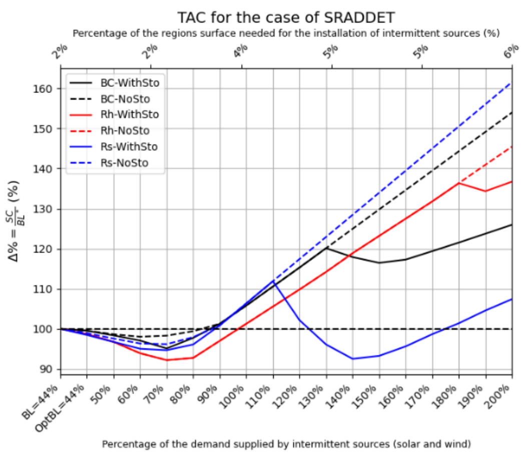
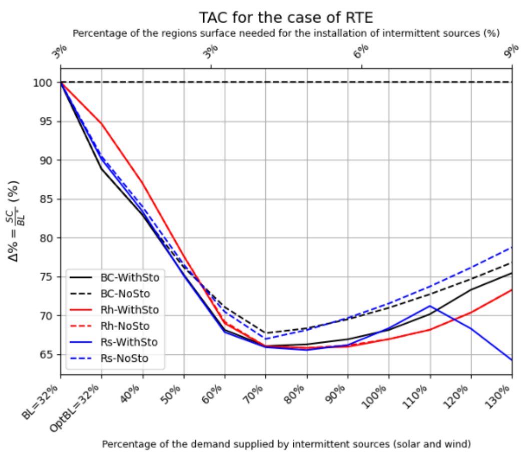
For scenarios with the maximum projected demand, the TAC indicator value does not change significantly with temporal demand adaptation when intermittent production is below 70% of the electricity demand. However, when intermittent production exceeds 70% of the demand, there is a more noticeable difference between scenarios with demand adapted to energy production.

In general, GHG emissions are reduced more significantly with the use of energy storage (Figure 37 parts b and f). In scenarios with the minimum energy demand, the GHG emissions indicator is reduced by 80% with the introduction of intermittent sources in the mix at a level of 80% of demand or higher. This reduction is slightly more pronounced when demand is not adapted.

With the maximum energy demand estimate, emissions increase by about 20% compared to the baseline with the introduction of low levels of intermittent energy production (<80% of demand). This is because biogas is more economical than nuclear energy, leading the optimization of the mix to extend the use of biogas to reduce the share of nuclear energy. The greatest benefit in GHG emission reduction with this high demand estimate is achieved with the use of energy storage and when demand adapts to the seasonal variation in energy production.

The imports indicator is not significantly impacted by the adaptation of the minimum projected demand. With the maximum demand projection, the imports indicator decreases as intermittent sources replace biogas and nuclear energy production in the mix. Scenarios with demand adaptation show a more significant reduction in imports when energy production is between 50% and 100% of the demand. With intermittent energy production exceeding the demand, imports are reduced to zero.

Adapting the demand does not have a significant impact on the indicator of use of non-RES.

	Minimum demand (SRADDET)	Maximum demand
Total annual costs	a) 	e) 

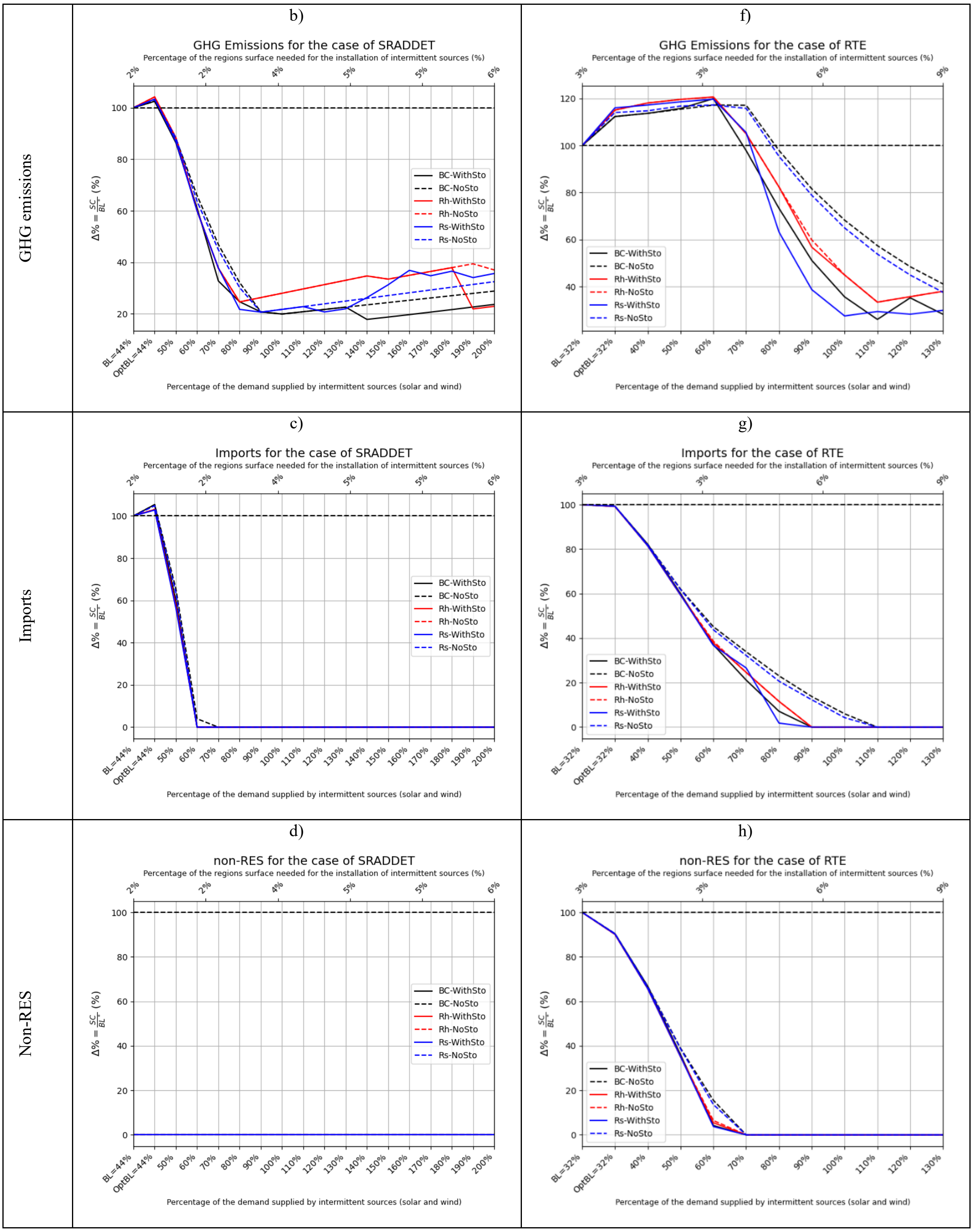


Figure 37 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a and e), GHG emissions (b and f), imports (c and g), and use of non-RES (d and h) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 50, for the study case of Grand-Est region of France. Parts a, b, c, and d correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts e, f, g and h correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted

as “BL” and “OptBL”. The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

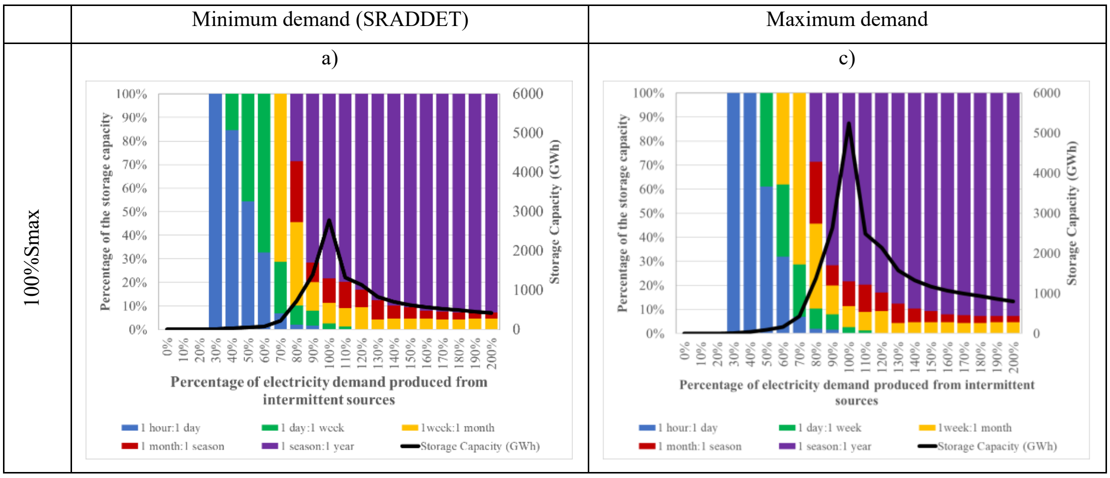
3.1.4. Storage time

Figure 38 shows the storage time ranges and capacity for the Grand Est region of France without limit on the storage capacity and with limit on the storage capacity for the minimum demand projected (SRADDET) and with the maximum demand projected respectively. A greater demand needs greater storage capacities but not necessarily longer storage times.

Limiting storage capacity leads to shorter storage times. As a result, the scenarios with a storage capacity limited to 20% of the maximum require storing the energy during periods shorter than 3 months for percentages of intermittent sources higher than 100%. In these cases, the fraction of storage capacity used to storage energy during more than 3 months ranges between 40% and 15%.

If storage demand is not limited, the scenarios with more than 90% intermittent sources in the mix uses most of the storage capacity (more than 70%) to storge energy during more than 3 months. And the fraction of the storage capacity used to store energy for longer than 1 month is 50% or more.

The effect of limiting the storage capacity of the scenarios is much more important in scenarios where demand is adapted to interseasonal variation in energy production ($\widehat{R_s}$), this demand adaptation reduces the fraction of storage used for long periods of time in all the scenarios. The daily adaptation of the demand ($\widehat{R_h}$) also helps to reduce the fraction of storage capacity used to store the energy during long periods, but the reduction of the storage times is lower compared to the seasonal adaptation of the demand to the energy production. The complete results regarding the storage time with the modified demand are reported in the Supplementary material SP5.



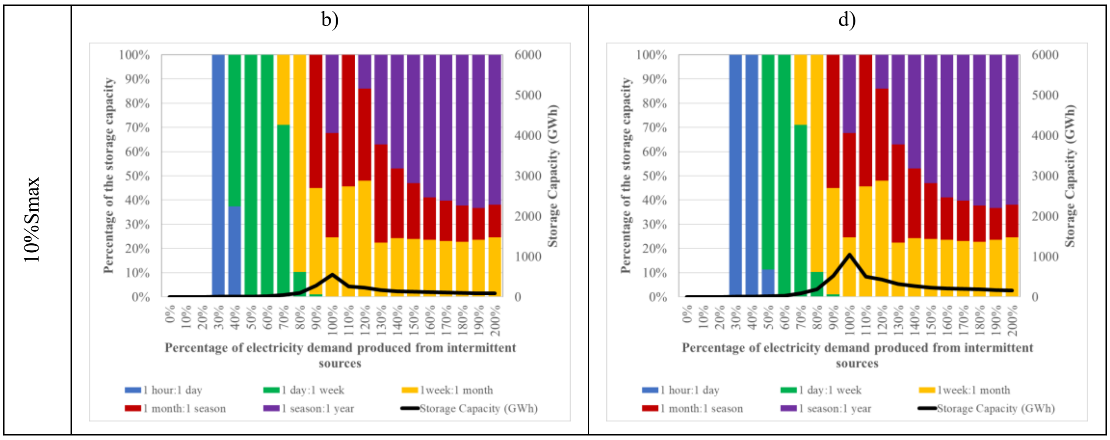


Figure 38 Storage time distribution and storage capacity for the Grand Est region of France, with the minimum projected demand (SRADDET) (a and c) and with the maximum projected demand(c and d), for the scenarios with maximum/unlimited storage capacity (a and b) and with limited storage capacity to the 10% of the maximum (b and d).

3.2. Cuba

3.2.1. Baseline for Cuba

In the case of Cuba, the baselines scenario is a projection for the 2030 based on the official plan of the Cuban government (M. Guevara-Luna et al., 2024). According to this plan, the energy production and consumption in Cuba have been relatively steady during the last decades (ONE, 2016a; Sagastume Gutiérrez et al., 2018). The electricity sector will play an increasingly important role in energy consumption, which prompted the Cuban government to implement several policies to improve the performance of the energy sector. A fundamental part of them was the replacement of household and state entities appliances with more efficient equipment. The policy also introduced a new electricity tariff with a reduction of government subsidies to encourage savings of electricity (Guevara-stone L. et al., 2009; Suárez et al., 2012). The industrial sector, although technologically outdated (Sagastume Gutiérrez et al., 2018), has also implemented policies to improve energy efficiency (Gonzales del Toro, 2016). Despite the measures taken by the government, the electricity consumption from 2002 to 2015 shows an average increase of 3.6% per year, with 4.8% from 2014 to 2015 alone (Figure 2). This trend can be explained by the increased demand from the residential sector (around 4.7% per year after 2010). According to (Reuters, 2016), the opening of the private segment of the economy during the 2000s (where Cubans were allowed to set up businesses in their homes and front porches) highly influenced this drift. For all other sectors, the increase is lower (less than 3% per year). Following this trend, Cuban electricity consumption is expected to have a small variation in the future (Käkönen et al., 2014). Official estimations foresee an increase of 3.28% per year reaching around 28 TWh in 2030 (MINAS et al., 2016).

A significant increase in temperature is expected in the coming years due to climate change that will particularly affect the Caribbean region (Angeles et al., 2010, 2018). This should lead to an increase in the use of air conditioning throughout this region. Because of this, the rate of increase of 3.28% per year of the electric demand estimated by the Cuban authorities is optimistic and it is very likely to be higher than 4% per year (Madrazo Bacallao, 2018).

The direct consumption of oil sub-products, by services other than electricity, experienced a decreasing trend. At the risk of being too pessimistic about the planning horizon, such demand is assumed to remain constant at 29 TWh. Consequently, the total energy demand will increase from 46

TWh in 2015 to 57 TWh in 2030 with a share of 51% of oil sub-product and 49% of electricity.

Losses in the grid of the island of Cuba is estimated as 15.5%.

3.2.2. Energy mix and costs

For the analysis of optimized scenarios for Cuba with energy storage, the same approach used for the Grand Est region is applied. This includes evaluating the storage capacity limit and the reduction in energy storage unitary costs. Additionally, the results related to demand adaptation to energy production across various temporal scales and storage duration are assessed. All the results from the analyses are reported in the Supplementary material.

3.2.2.1. Effects of energy storage: Limiting the maximum storage capacity

The results regarding the optimum technology mix that minimizes the TAC for the scenarios introducing solar and wind sources for the case of Cuba are evaluated by comparing the optimized scenarios without any limit on storage capacity (100% S_{max}) with the scenarios where energy storage is limited to 10% of the maximum calculated capacity (10% S_{max}).

Figure 39 shows the indicators for the optimized scenarios with energy storage generated for Cuba, with and without storage capacity limitation.

The TAC is significantly higher in scenarios without storage capacity limits when intermittent energy production exceeds 90% of demand, consistently demonstrating that storage is considerably expensive, and therefore not feasible as observed for the case for Grand Est region of France before. However, for the scenarios with percentages of intermittent energy introduction below 90%, all the indicators scored better than the BL scenario, and the TAC of the optimized scenarios with storage capacity limit is lower than the baseline for all the percentages of intermittent sources introduction.

With the introduction of intermittent energy sources in the mix, the indicators for GHG emissions, imports, and non-RES are improved compared to the baseline for all the percentages of intermittent sources into the mix, both with and without energy storage limits.

Regarding the surface needed to install the intermittent sources, Cuba does no need of large surface due to its great RES potentials.

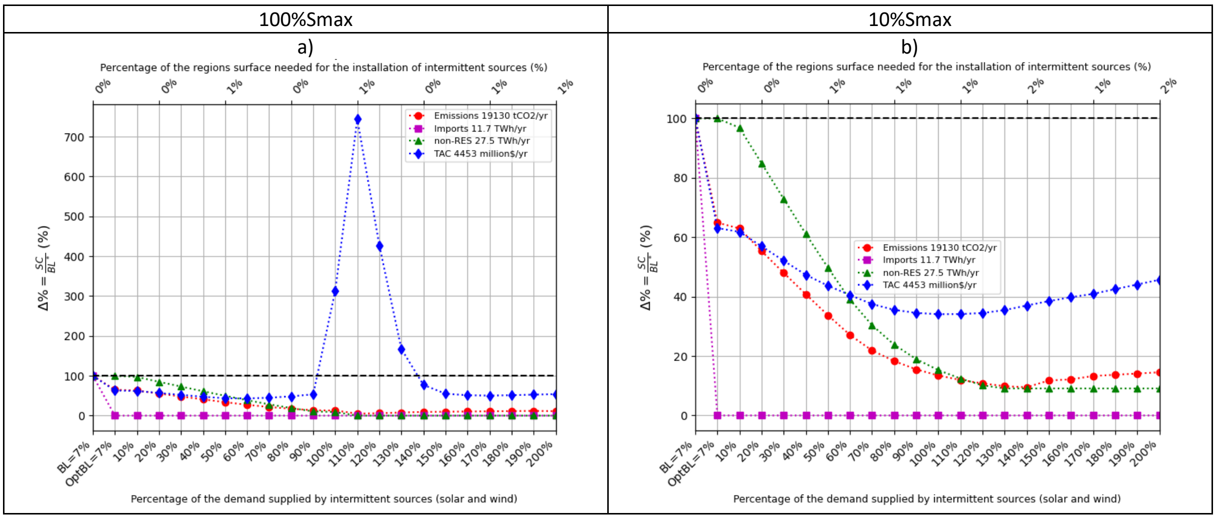


Figure 39 Tendencies of the indicators when intermittent sources (solar and wind) are introduced in

the energy mix Cuba; without limit on storage capacity (a) and with limit on storage capacity (b) (i.e., 10% of the maximum storage). The plotted indicators correspond to: Total annual costs (TAC), GHG emissions, energy imports, and use of non-RES. Values in parenthesis shown in the legend correspond to the characteristics of the scenarios used as reference (baseline). The bottom horizontal axis corresponds to the energy produced by intermittent sources expressed as a percentage of the demand, the top horizontal corresponds to the need of surface to install solar panels and wind turbines to produce the intermittent energy of the optimized scenarios. A value of 0% for any of the indicators corresponds to the best possible situation, a value of 100% means that the situation is the same as the baseline scenario, and a value greater than 100% indicates a worse situation compared to the baseline scenario.

3.2.2.1. Effects of unitary costs of storage

Energy storage significantly impacts the energy mix, an effect primarily observed through costs, especially in scenarios with substantial intermittent energy production.

The comparison between scenarios with energy storage and those without, using projected unreduced unitary costs of energy storage, shows that the more feasible strategies are those without energy storage (Figure 40 part a). Differently, Figure 40 part b shows the TAC for the optimized scenarios with energy storage for the case of Cuba considering a unitary cost for energy storage implementation divided by factor 50 (results with other factors of reduction are reported in the Supplementary material SP3). In each of these scenarios, the energy storage capacity limit is defined as the level that minimizes the TAC for each scenario. These scenarios are compared with scenarios without energy storage (represented by the black line in the figures).

With energy storage unitary costs are 50 times smaller, in scenarios with intermittent energy introduction below 100%, there are smaller costs in optimized scenarios with energy storage (bars in the plot) compared to the total cost of scenarios without energy storage (black line).

The energy produced by intermittent sources is sufficient to completely replace controllable sources in the energy mix when intermittent sources produce more than 120% of the electricity demand and the total energy production is reduced compared to the scenarios without energy storage. As consequence in these scenarios, the TAC is lower for scenarios with storage than for the scenarios without storage.

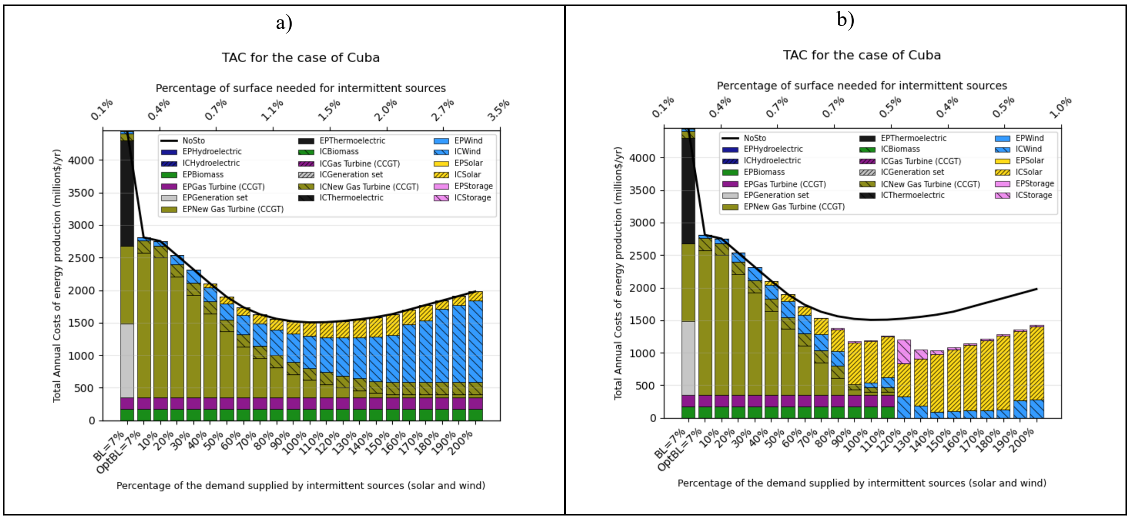


Figure 40 Total annual costs for the optimized scenarios with energy storage, with projected

reference unitary costs (costing parameters value) (a), and reducing the unitary costs of energy storage by factor 50 (b), for the study case of Cuba. Results correspond to scenarios designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

The reduction of unitary costs of storage leads to indicators that score better than the baseline for all the percentages of introduction of intermittent sources into the mix (Figure 41). This means the TAC of the energy scenarios are very sensitive to the storage costs also in tropical regions characterized by great RES potentials and small demand.

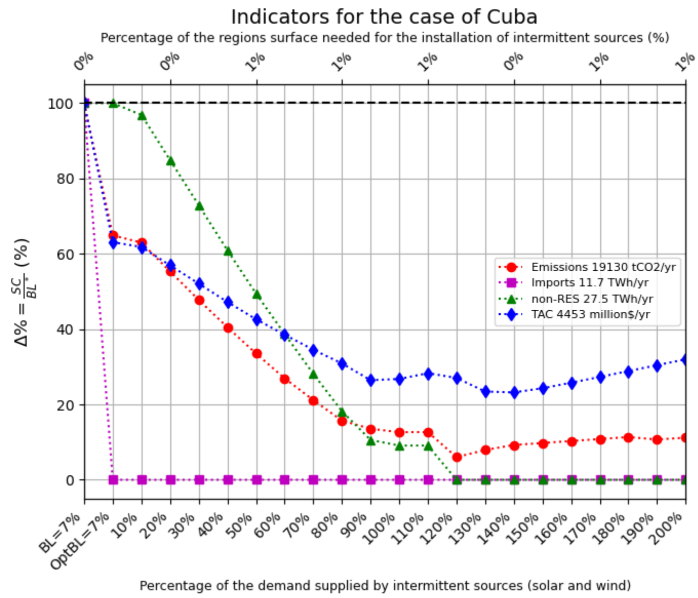


Figure 41 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 50, for the study case of Cuba. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

3.2.3. Demand adaptation

Similar to the analysis for the Grand Est scenarios, a sensitivity analysis was conducted for scenarios with and without energy storage in Cuba (Figure 42).

For scenarios where intermittent energy sources supply less than 100% of demand, those with demand adapted to inter-daily fluctuations incur higher costs compared to scenarios with demand adjusted to seasonal production or those with unadapted demand. Conversely, when intermittent sources exceed 100% of demand, scenarios with unadapted demand cost more than those where demand is aligned with interdaily or interseasonal variations in energy production. This cost difference arises because, in scenarios where energy production from intermittent sources exceeds 100% of demand, solar energy which predominantly exhibits interdaily variation plays a significant role in Cuba's energy mix. Consequently, aligning demand with interdaily variation reduces costs in these scenarios by needing less controllable energy and storage of energy.

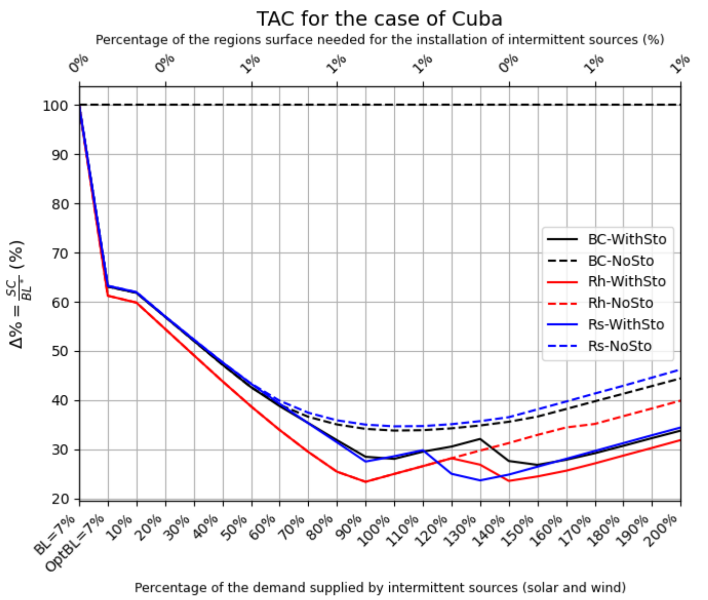
The most significant economic benefits compared to the baseline scenario are observed in scenarios where demand is adapted to interdaily variations in energy production.

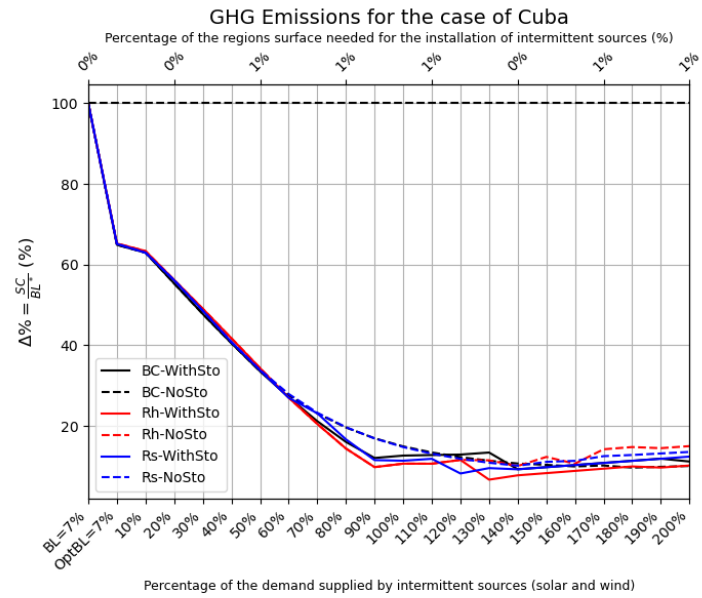
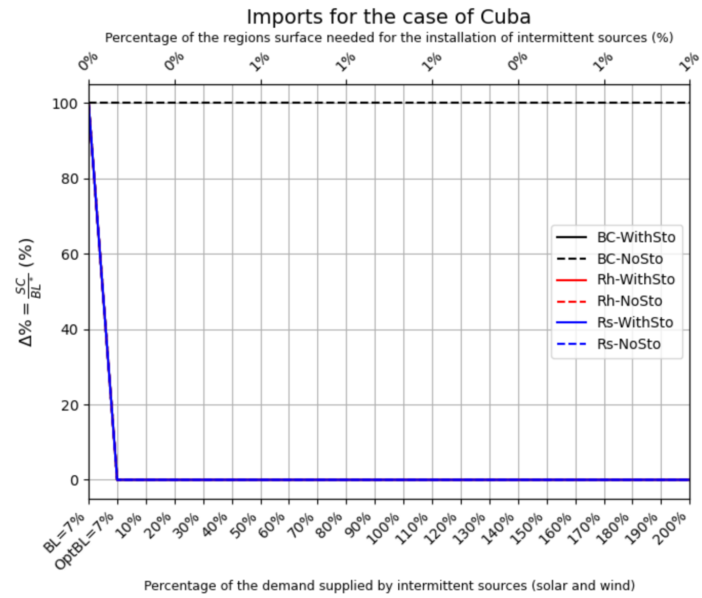
Regarding emissions, all evaluated scenarios show reductions compared to the baseline.

Demand adaptation has a minimal impact on emissions, imports, and use of non-RES indicators.

Since, the scenarios focus on utilizing local resources to reduce energy imports. This goal is achievable and economically viable with the optimized baseline scenario. Similarly, scenarios with higher penetration of intermittent sources (exceeding 7% of demand) can also achieve this ideal condition on the island. Demand adaptation does not significantly affect this indicator.

The results of the scenarios with demand adaptation are reported in the Supplementary material SP4.

	Cuba
Total annual costs	a) 

GHG emissions	b) 
Imports	c) 

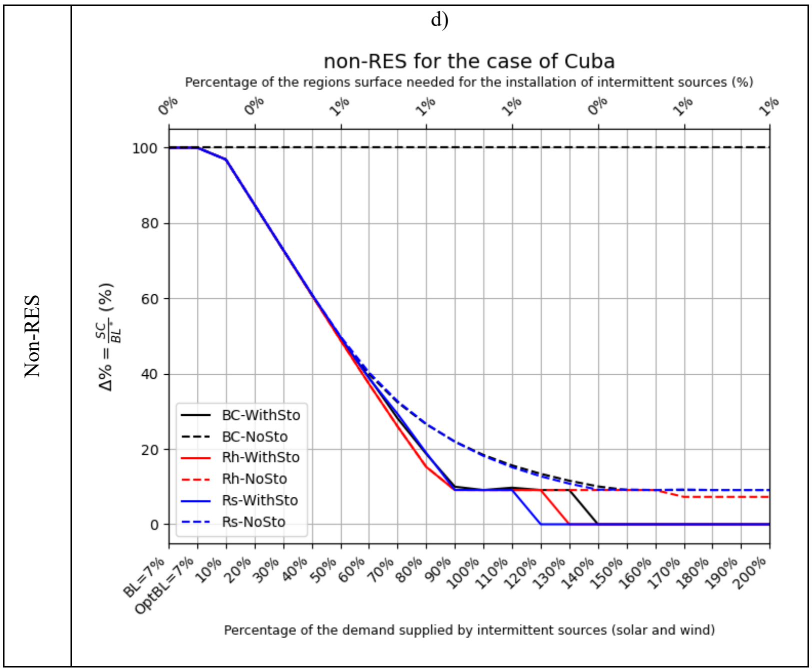


Figure 42 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a), GHG emissions (b), imports (c), and use of non-RES (d) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 50, for the study case of Cuba. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

3.2.4. Storage time

Figure 43 shows the storage time for the optimized scenarios with energy storage for Cuba.

The scenarios with limited storage capacity have shorter storage times than those without limited storage capacity.

Scenarios with intermittent energy production exceeding 130% of demand have storage times of less than one month. The scenarios with approximately 100% intermittent energy require longer-term energy storage. If the intermittent energy is less than 100%, the energy is stored predominantly for one day or a month as maximum. The results regarding the storage time with the modified demand are reported in the Supplementary material SP5.

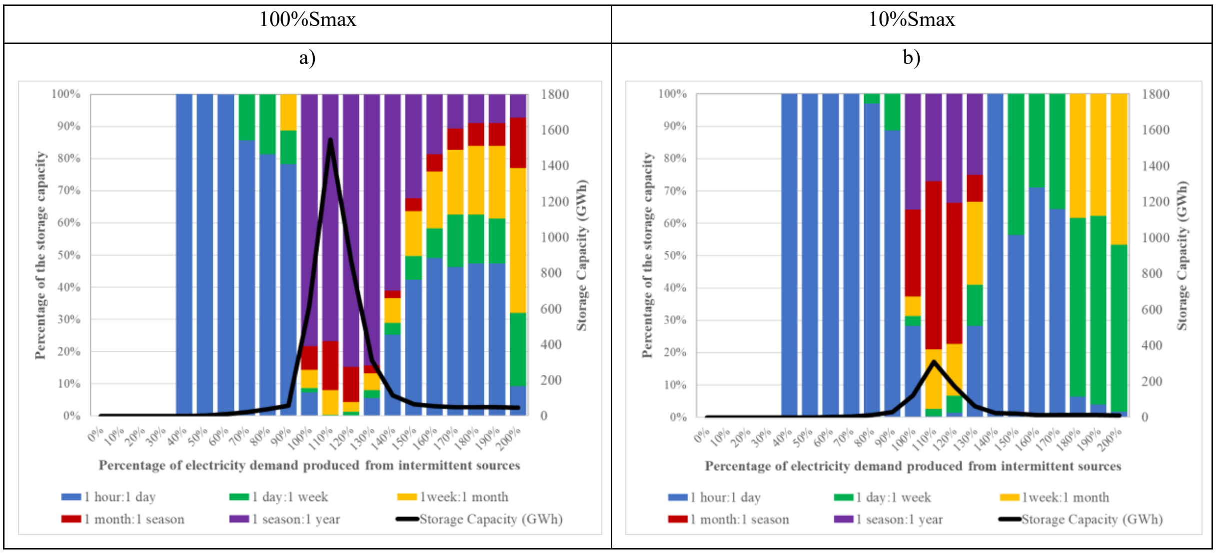


Figure 43 Storage time distribution and storage capacity for Cuba, for the scenarios with maximum/unlimited storage capacity (a) and with limited storage capacity to the 10% of the maximum (b).

4. Discussion

This study employs concrete towers as the reference storage technology, recognizing that while alternative technologies, such as batteries, may offer lower costs, they are not well-suited to the specific requirements of the Grand Est and Cuba case studies. Specifically, batteries are inefficient for energy storage durations extending beyond several weeks. Concrete towers, by contrast, represent one of the most cost-effective options available on the market, even if it still needs further development. Although combinations of multiple storage technologies could theoretically be considered, storage still is generally more expensive. Therefore, the study adopts the least costly yet viable storage technology.

The results regarding the mix of technologies indicate that the optimized baseline scenarios have a positive score for the TAC indicator, representing a reduction in costs compared to the baseline. This serves as a test of the robustness of the method, as the optimized baseline cannot have values of the TAC indicator greater to 100% because this would indicate that the optimized baseline scenario is more costly than the baseline.

There is evidence of competition between two possible decisions: i) maintaining the installed capacity of controllable sources necessary to complement intermittent sources during demand peaks and production valleys, without storage and independently of the percentage of introduction of intermittent sources into the mix; and ii) implementing the storage of overproduced energy during intermittent production peaks to be used during production valleys and demand peaks. This latter option is currently a less economically feasible option. It requires either limiting storage capacity (which means controllable sources cannot be eliminated from the mix) or reducing the unitary costs of energy storage (as storage technologies are still very expensive).

There is competition between two alternative types of energy strategies: maintaining controllable sources to complement intermittent sources during peaks of demand and production lows and storing excess energy from intermittent sources for later use. The latter option is currently less economically feasible, requiring either limited storage capacity or reduced storage costs due to the high costs of the storage technologies.

Regarding the demand adaptation method, the full variation R profile ($\overline{R_h}$) can be reconstructed from the temporal components calculated demonstrating the robustness of the formulation and evaluation of the demand to energy production at different timescales (Previous chapter).

The implementation of energy storage eliminates the need for controllable energy sources in scenarios characterized by a substantial integration of intermittent energy (exceeding 100% of demand). However, these scenarios are associated with significantly higher costs compared to the baseline scenario.

The introduction of intermittent energy sources also positively influences the indicators, including total annual costs (TAC), GHG emissions (Emissions), use of non-RES (non-RES), and importation of external sources (Imports).

The scenarios corresponding to the adaptation of demand to energy production at various time scales were studied, even if these are ideal demand adaptation situations, they show the maximum theoretical scope of strategies that consider demand modification.

In contrast to the scenarios without storage in which adapting demand to interdaily energy production brings the greatest benefits on the indicators (previous chapter), in this paper, the results obtained show that adapting demand to energy production on the interseasonal scale is the option that has the greatest positive impact on the indicators.

The interseasonal adaptation of demand to energy production can reduce the costs of the scenarios as it especially reduces the costs associated with energy storage capacity, one of the largest contributors to the total cost, and allows additional improvements in the other indicators evaluated.

When comparing scenarios with different total demand, but with the same potential for solar and wind energy production, i.e., scenarios with minimum demand (SRADDET) and maximum demand (RTE), we found that a lower total demand has better values of the evaluated indicators, e.g., lower costs, it is not necessary to use imported and non-RES resources (nuclear), and the use of limited resources such as biomass is reduced.

Demand flexibility is one of the strategies proposed in several studies to boost the introduction of intermittent energy sources. However, doing this is technically difficult and costly, due to social, political, and technological factors.

We are currently in a situation that requires rapid action to accelerate the energy transition. Therefore, policies related to adapting or modifying energy demand should focus on reducing total demand rather than adapting demand to time-varying patterns, this may result in faster and concrete outcomes.

Based on the results for the Grand Est region, regional energy policies should prioritize the deployment of intermittent energy sources as a complement to controllable local RES, e.g., biomass and biogas. This is essential to ensure energy supply under decreasing (SRADDET) or increasing demand projections in the region and minimizing reliance on imported non-renewable resources, e.g., nuclear energy. The region possesses enough surface area suitable for the installation of solar parks and wind farms, with the capacity to meet these conditions. This is possible in both in scenarios that incorporate energy storage (results in this article) and those that do not (Previous chapter), however, decision makers should consider that strategies with large storage capacity are not economically feasible.

The Cuba's optimized baseline scenario reveal that the replacement of imported energy sources has a profound impact on the evaluated indicators since all indicators show improvement in the optimized scenarios relative to the baseline. Consequently, Cuba's energy policy should prioritize the substitution of thermoelectric power plants and generator sets with solar and wind energy technologies, as the former are costly, non-renewable, and reliant on external resources.

Also, due to its geopolitical situation, the energy security of Cuba is at risk due to the island's dependence on external resources. Therefore, in Cuba it is specifically important to replace external energy sources with intermittent sources.

Scenarios with storage capacity limited to 10% of the maximum are more economically viable than those with no storage or limited storage capacity when the integration of intermittent energy production is around 100%. This increased viability arises from the shorter storage durations in these cases (less than one month), which significantly reduces the demand for large storage capacity.

Cuba's energy policy should focus on the introduction of energy production with intermittent sources in an amount greater than the 7% planned in the baseline scenario. However, for percentages of intermittent sources of more than 90% the scenarios without energy storage are economically more viable. Additionally, the introduction of intermittent sources positively impacts emissions, use of non-RES, and imports indicators in Cuba.

5. Conclusions

The optimized tendencies method offers a robust framework for assessing the impact of energy strategies that involve the introduction of intermittent energy sources and energy storage. This is achieved through key indicators of interest for decision makers tailored to the specific needs of each case study, such as total annual costs (TAC), GHG emissions, use of non-renewable energy sources (non-RES), and imports. Additionally, the methodology includes estimates of the surface area required to install solar panels and wind turbines for each scenario, reported alongside these indicators. The approach considers energy system characteristics in scenarios with storage, including storage duration and demand adaptation to temporal variations in energy production.

The results obtained with the proposed method make it possible to evaluate the energy transition strategies and identify the most interesting ones for the case studies according to the specific features of the study cases. The method was applied to two cases of study with different characteristics: the Grand Est region in Central Europe and Cuba.

Energy storage can eliminate the need for controllable energy sources in scenarios with the introduction of intermittent sources (solar and wind) to generate an amount of energy equivalent to or exceeding the demand. However, these scenarios are economically unfeasible due to the high costs associated with energy storage.

Scenarios with limited storage capacity are less expensive, but they still require the same installed capacity of controllable sources as the baseline scenario.

One way to make energy storage viable is to reduce its unitary costs, as electricity storage technologies are very expensive. However, even with reduced storage costs, the use of controllable sources remains necessary with modest shares of solar and wind in the mix. *The only way to eliminate the controllable sources from the energy mix is to overproduce energy by introducing intermittent sources at percentages exceeding 100% of demand plus distribution network losses alongside not restricted storage capacity.*

The adaptation of demand to energy production at various time scales were studied. The adaptation of the demand to the interseasonal variation of energy production can reduce the costs of the scenarios as it especially reduces the costs associated with energy storage capacity, one of the largest contributors to the total cost, and allows additional improvements in the other indicators evaluated.

Demand adaptation (flexibility) has been proposed as a strategy to enhance the integration of intermittent energy sources, but its implementation is technically challenging and costly due to social, political, and technological aspects. Given the urgency of accelerating the energy transition, policies should prioritize reducing overall energy demand rather than adapting it to time-varying patterns, as this approach is likely to yield faster and more concrete results.

In the case of the Grand Est region, a risk was identified that the official demand projection for 2050 may not be achieved (minimum demand condition or SRADDET), as it assumes a reduction that could be overestimated. Additionally, another risk was recognized concerning the supply of local controllable energy sources, e.g., biomass and biogas. To address these concerns, a supplementary situation was considered to represent a condition of increased demand (maximum demand condition or RTE). Given the limited availability of controllable energy sources within the region, nuclear energy was included to meet the demand, in alignment with the current policies of the French government and the European community, which enlist this technology as strategic for the energy transition.

For the Grand Est region, energy policies should prioritize the integration of intermittent sources alongside controllable local RES, such as biomass and biogas, to ensure a reliable energy supply under both decreasing (SRADDET) and increasing (RTE) demand projections. The region has sufficient area for solar and wind installations, meeting energy needs in scenarios with or without storage, but large storage capacities may be economically unfeasible.

The optimization of Cuba's baseline scenario demonstrates that replacing imported energy sources with local RES significantly improves the evaluated indicators, as these alternatives are less costly, renewable, and reduce reliance on external resources. Given Cuba's geopolitical vulnerability and dependence on external energy, the introduction of intermittent sources in the mix is crucial for ensuring the energy security of the island. Cuba must prioritize solar energy over fossil fuel-based sources to reduce imports and consequently energy dependency.

Thesis conclusions

The thesis is structured into 5 chapters aligned with the stages of developing a method for designing and evaluating energy strategies.

Chapter 1 constitutes the introductory section of the thesis, providing the context and background of the present research.

The goal of chapter 2 (Strategies toward an effective and sustainable energy transition for Cuba) is to develop a methodology for designing energy strategies using the case study of Cuba, a particularly simple case that allows the assessing of the method in this first stage of development. Cuba's energy transition presents a compelling case study for testing the developed method due to three key characteristics: i) its island geography helps to simplify the scenario analysis by avoiding the cross-border exchanges of electricity; ii) due to the embargo situation, Cuba is pursuing energy autonomy, aiming to reduce primary energy exchanges and increase energy sobriety; and iii) its tropical location offers exceptional renewable energy potential, particularly for solar energy.

The method developed for Cuba was inspired by pre-existing methods of design and evaluation of energy scenarios, which can be classified into two types: i) Expert designed scenarios methods: the generation of a few design scenarios by experts, which are compared against each other using numerous indicators; ii) Optimization methods: the selection of a single scenario, or few scenarios, from a very large number of automatically generated scenarios by minimizing one single indicator, usually economic costs. The use of optimization methods can be extended to the selection of several scenarios by calculating a trend curve (Pareto curve) by varying one indicator and minimizing another.

In this work, the developed method aims to consider many scenarios and evaluates them using as many indicators as needed. It is characterized by three key features: i) it distinguishes between intermittent and controllable energy sources; ii) it generates a series of alternative scenarios to form a trend curve (Pareto curve), defined by a progressively increasing share of intermittent energy, starting from a reference scenario based on projections from local energy policies; and iii) it includes the design and integration of multiple relevant indicators to support decision-making processes and makes possible to derive trends of predefined indicators, such as costs, greenhouse gas (GHG) emissions, air quality, and energy imports, for an increasingly high share of intermittent energy sources in the designed scenarios.

The use of the method over Cuba has shown the introduction of intermittent sources causes the reduction of fossil fuel consumption used for electricity production but does not lead to an important reduction of refined fuels which are used mainly in the transportation sector. However, regarding electricity production, shifting from fossil fuels to intermittent sources reduces fuel imports, cuts GHG emissions, improves air quality, and above all a significant economic benefit. Economic benefits peak when solar and wind sources supply 60% of the electricity demand.

The results of this study can be used to advise Cuban energy policy. Because of its geopolitical situation, Cuba has more difficulty than other countries in accessing international markets. The proposed solutions offer particularly relevant strategies for energy security. Nevertheless, the Cuban authorities can be advised to invest in solar and wind energy. Every time solar and wind capacity is progressively increased, Cuban authorities will save on fuel costs and achieve environmental improvements and energy security. Even if the mix keeps using the same technologies as nowadays. The money saved could be gradually reinvested in new solar and wind power installations to achieve further benefits on the evaluated indicators.

In the Chapter 3 (Method based on optimized tendencies to evaluate the impact of the introduction of solar and wind energy sources in energy systems), the method used to analyze the Cuban case in the Chapter 2 was generalized to be used in any study case (country or region) worldwide.

The generalization of the developed method to electrically isolated regions such as Cuba necessitates addressing the challenge of managing interactions with external regions whose energy policies remain uncertain. The analysis identifies that external dependence relies on two distinct energy forms: primary energy and electricity.

For primary energy, the evaluation of isolated regions has been already made by incorporating an indicator based on imported energy quantities, which further enables evaluation of both import costs and availability. Regarding electricity, assuming that neighboring regions can always compensate for local production variations—by purchasing surpluses or covering deficits— without knowledge of their energy policies, poses significant risks leading to misguided decisions. Consequently, two fundamental hypotheses are proposed: first, the region must maintain adequate capacity to address production deficits and prevent blackouts; second, the region will not depend on the marketing of surpluses to avoid exposure to market saturation scenarios characterized by low or negative electricity prices.

Chapter 3 has aimed also to enhance by including a new capacity of the method for the determination of optimal combination of technologies that minimizes production costs. As in the previews chapter for each scenario, the method identifies the optimal mix of technologies through a cost minimization and calculates a set of indicators for each optimum scenario, e.g., GHG emissions, energy imports, and non-renewable energy production.

The method reveals some general conclusions about the electric systems' characteristics when intermittent energy is introduced into the mix without storage of electricity. Intermittent sources cannot fully replace controllable sources, as there are always periods when solar radiation and wind speed are insufficient to meet demand. Consequently, the introduction of intermittent sources reduces the amount of energy that controllable sources must supply, but they are unable to reduce their installed capacity, which is still needed to cope with peaks in demand when sun and wind production are very low.

The Levelized costs of electricity (LCOE) of the controllable sources technologies increases with the introduction of intermittent sources into the mix. Some technologies may be economically competitive at low levels of intermittent energy but become progressively more costly as the share of intermittent energy increases significantly.

The methodology has been applied to two case studies: The Grand Est region of France and Cuba. The case of the Grand Est region of France has been analyzed using two different projections of electric demand: a low-demand projection based on the official "Schéma régional d'aménagement, de développement durable et d'égalité des territoires" (SRADDET) scenario, and a high-demand projection based on the estimations of RTE for France at national level. In the case of low electric demand, renewable sources are sufficient in any scenario (i.e., use of non-RES indicators is zero), imports are not necessary when intermittent energy reaches 60% of the demand, and production costs stabilize between 45% and 90% intermittent energy while GHG emissions progressively decrease. In the case of the high-demand projection two notable scenarios emerge. At 70% intermittent energy, costs are minimized, non-RES use is eliminated, and emissions begin to decline. This scenario requires around 6% of the region's surface for solar and wind installations. At 110% intermittent energy, imports drop to zero, but the scenario requires around 10% of the region's surface for solar and wind installations.

For the Grand Est region, the demand trend is crucial in determining the optimal energy strategy. With low and declining demand, the region can meet its needs entirely through renewable energy sources (RES). Solar and wind shares from 60% to 90% of demand are interesting because of low costs and land use (3.5%). However, with high and increasing demand, decision-makers face a trade-off: relying on RES (cost-effective but land-intensive) or incorporating nuclear power (less land use but higher costs).

Cuba's case differs from the case of the Grand Est region in that land surface is not a limiting factor. Due to its geopolitical situation, the major constraint is how to reduce imports as much as possible and reduce costs as much as possible, even if this means using fossil fuels produced locally. The implementation of the developed method for Cuba reveals that energy autonomy (defined as zero fuel imports) can be achieved through optimization of the baseline scenario, where intermittent renewable sources initially supply 7% of total demand. Increasing this share to 100%-140% minimizes production costs, maximizes RES use, and reduces GHG emissions. Beyond 140%, further improvements are limited, as achieving 100% RES and zero GHG emissions remain unattainable.

Chapter 4 entitled “Integrated method for design and evaluation of energy strategies including energy storage and demand adaptation” investigates the effects of energy storage on the characteristics of the electricity production systems when energy produced from intermittent sources is introduced.

The implementation of energy storage can eliminate the need for controllable energy sources in scenarios with the introduction of intermittent sources to generate an amount of energy exceeding the demand. Nevertheless, these scenarios with storage of energy are economically unfeasible due to the high costs associated with energy storage implementation. Reducing storage costs by 20 times can make scenarios with energy storage economically viable, particularly if energy production from intermittent sources exceeds demand.

In scenarios without energy storage or with energy storage but intermittent energy below 100%, sufficient installed capacity of controllable sources must be maintained to meet demand during periods without intermittent energy production.

One novel aspect integrated into the method was the capability of performing a sensitivity analysis conducted to evaluate the adaptation of temporal fluctuations in demand to energy production across different time scales, such as daily or seasonal, etc. However, the demand adaptation implementation is technically challenging and costly due to social, political, and technological aspects. Given the urgency of accelerating the energy transition, policies should prioritize reducing overall energy demand rather than adapting it to time-varying patterns, as this approach is likely to yield faster and more concrete results.

Perspectives

The selection of scenarios depends on multiple criteria, with the degree of dependency from external sources of energy being a critical factor for decision-makers in the current geopolitical context. From this research thesis, several aspects that could be the subject of future work were identified based on the hypotheses made about autonomy and surplus valorization.

One first aspect to consider for future investigation is the integration of electricity imports and exports with other neighboring regions. As previously mentioned, this study adopts two fundamental hypotheses: first, that all peak demand periods will be met through regional generation capacity, and second, that no energy surpluses will be commercialized externally. These assumptions may alternatively be considered probabilistically by incorporating a risk of needing electricity import from outer regions when local installed capacity is limited. This probabilistic framework would allow for: i) Partial fulfillment of the most critical peaks of demand through external sources; and ii) Controlled commercialization of surplus energy to neighboring regions experiencing coincidence energy deficits. This approach could help identify strategies that enhance the compatibility of a group of regions in the event of energy integration.

The autonomy of a region is intimately linked to the territorial distribution of densely populated and energy demanding areas (e.g., urban areas), and rural areas with high resource potential. Each territory will have an optimal size where there is a territorial equilibrium between resources and demand. A second aspect is related to the size of the region studied using the developed method. A very small region may electrify its demand quickly but will inevitably require electricity imports due to insufficient local primary resources, limited land area for installing solar panels or wind turbines, etc. For example, a city has a high demand density relative to its size, necessitating electricity production outside its boundaries and imports to supply energy to the consumption sectors, as well as fossil fuel imports for sectors like transportation. On the other hand, a large region has more resources, enabling energy autonomy as it can produce sufficient energy to meet its demand with local resources, e.g., enough land area for solar and wind installations. However, electricity transmission costs can be significant, as investments in transmission lines between areas with primary resources, electricity generation facilities, and high-demand zones can be substantial. This implies the existence of an "optimal size" for a region when designing and evaluating energy strategies. Alternatively, for a region with its politically defined borders, one possibility is to develop a way to assess whether it is too large or too small.

Producing the energy to meet the peaks of demand can be made through different ways: imports of electricity from outer regions, energy production from controllable sources, and/or use of energy storage. Energy storage systems are considered in the model, when a surplus occurs the energy is stored, then there are multiple management approaches of the stored energy. The surplus can be either: i) discharged instantaneously to meet demand as soon as there is not sufficient intermittent energy production to complete the demand (Direct-Release), or ii) deployed selectively when exceeding predetermined thresholds for peak load reduction (Peak-Shaving). This work implements the Direct-Release strategy, while subsequent research should examine alternative approaches of managing stored energy.

An additional critical consideration involves analyzing electricity pricing policies derived from the characteristics of scenarios optimized through the developed method. The phenomenon of renewable energy cannibalization manifests through progressively declining average prices for solar and wind power, but it is not like that for nuclear and fossil fuel-based technologies which became more costly as more solar and wind sources are introduced into the energy mixes. This makes the integration of solar and wind sources unavoidable in future energy strategies. Solar and wind sources generate surpluses during peak production periods while failing to meet demand during periods of low solar radiation and wind speed, necessitating complementary technologies (storage or controllable sources generation) for system reliability. However, market prices governed by supply-demand dynamics, where controllable generation and storage technologies command higher costs, make these essential components economically unviable. This imbalance is exacerbated during surplus production periods, when prices drop to near-zero or negative values. Consequently, a compensatory mechanism to redistribute revenues across all utilized technologies becomes necessary.

The model developed as the main tool for the optimized tendencies methodology is currently in the backend development stage. Some features can be developed and added to the model to enhance its capabilities and make it more user-friendly. This includes enabling a quick initial calculation by providing default data for rapid setup, allowing the generation of preliminary results even when limited information is available for a case study. Additionally, the design of a web-based graphical user interface (frontend) should be part of this future development phase, facilitating easy use and access worldwide.

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Annexes

Annex 1 Glossary

Energy Policy: A framework or set of principles and guidelines adopted by governments or organizations to manage energy resources, ensure energy security, and achieve sustainability goals.

Energy Strategy: A long-term plan designed to achieve specific energy objectives, such as reducing carbon emissions or increasing renewable energy adoption.

Intermittent energy sources: These are sources whose energy production depends on the availability of the primary resource. For example, solar panels produce energy depending on the intensity of solar radiation, and wind turbines depend on the presence of wind to generate electricity.

Controllable energy sources: These are energy sources capable of adapting their energy production to fluctuations in electricity demand, as long as sufficient primary resources are available. For example, thermoelectric plants, nuclear power plants, or hydroelectric plants.

Energy Programming: The process of developing and implementing specific projects or initiatives to meet energy policy goals.

Energy Planning: The systematic process of forecasting energy demand, assessing resources, and designing strategies to meet future energy needs efficiently and sustainably.

Energy Scenario: A plausible model or projection of future energy systems based on specific assumptions, used to explore potential outcomes and inform decision-making.

Energy Mix: The combination of different energy sources (e.g., fossil fuels, renewables, nuclear) used to meet a country's or region's energy needs.

Electricity Mix: The specific combination of energy sources (e.g., coal, natural gas, wind, solar) used to generate electricity in a given study area.

Electrically Interconnected Regions/Countries: Geographic areas or nations whose power grids are linked, allowing for the exchange of electricity across borders to enhance reliability, efficiency, and resource sharing.

Electrically Isolated Regions/Countries: Areas or nations that operate independently without connections to external power grids, often relying on local energy generation.

LCOE (Levelized costs of electricity): The average cost of generating one unit of electricity over the lifetime of a power plant.

Costs of Energy: The expenses associated with producing, distributing, and consuming energy.

TAC (total annual costs): The energy production costs for one year, considering the variable, fuel, fixed, and annualized investment costs.

Electricity Prices: The amount charged to consumers or paid in markets for electrical power.

Primary Energy Source: The raw form of energy (e.g., coal, wind, sunlight) used to generate electricity or other energy carriers.

Electricity Production Technologies: Methods or systems (e.g., solar panels, wind turbines) used to convert energy sources into electricity.

Capacity Factor: The ratio of actual energy output (energy production) to the maximum possible output of a power plant over an interval of time.

Indicator: A measurable variable used to track progress, performance, or trends in energy systems, it is defined based on the interests of stakeholder (e.g., decision makers).

Energy Imports: Energy resources or products brought into a country from external sources.

Energy Exports: Energy resources or products sent from one country to another for trade.

Value of Money Over Time: The concept that money available today is worth more than the same amount in the future due to its earning potential.

Annex 2 Supplementary material - Chapter 2

SP1. Cost parameters

The parameters used for the cost calculations of the possible energy strategies used in in this research are presented in Table 11 and Table 12 for Cuba and the Grand Est region of France respectively. These values are taken from the year of reference 2020 and are expressed as US dollars, assuming the currency value in 2020(Erichsen et al., 2019; Sadiqa et al., 2018; Santoyo-Castelazo & Azapagic, 2014). Electricity transmission losses in the Grand Est region have been reported as 2.28% in 2021(RTE, 2021a).

In the case of Cuba, the capacity factor of the biomass power plants is lower since the technology is old and therefore less efficient, and it will be maintained in the future. Also, in the case of Cuba, the investment costs and fixed costs are zero since the technologies have already overpassed their uselife. The transmission losses of Cuba are estimated as 15.5%(M. Guevara-Luna et al., 2024).

The nuclear energy costs are based on the updated costs of the new central at Flamanville-France up to 2022(World Nuclear News, 2022).

To consider the change of money value over time, the AC_{tc} is calculated using an interest rate (r) value of 5.77% for the analysis of energy strategies based on the values reported in published studies(Aldersey-Williams et al., 2019; M. Guevara-Luna et al., 2024; Jacobson et al., 2015; Jacobson, Delucchi, Cameron, et al., 2017; Murray et al., 2018; Obi et al., 2017).

Table 11 Cost parameters for the Grand Est region of France 2050.

Parameter (million$/TW)	Solar	Wind	Biomass	Biogas	Hydroelectric	Nuclear
AC_{tc}	42 522	77 957	186 530	191 282	239 056	733 299
FC_{tc}	10 404	28 971	7 461	4 568	3 108	58 664
VC_{tc}	0.0	0.0	1.1	3.1	2.70	5.00
FUC_{tc}	0.0	0.0	21.0	21.0	0.0	10.0
η_{tc}	1.0	1.0	0.2	0.4	1.0	0.6
Cf_{tc}	0.17	0.35	0.4	0.4	0.8	0.7

Table 12 Cost parameters for Cuba 2030.

Parameter (million$/TW)	Solar	Wind	Biomass	Gas Turbine (CCGT)	New Gas Turbine (CCGT)	Thermoelectric	Generation set	Hydroelectric
AC_{tc}	42 522	77 957	0.0	0.0	57 394	0.0	0.0	0.0
FC_{tc}	10 404	28 971	0.0	0.0	2 296	0.0	0.0	0.0
VC_{tc}	0.0	0.0	1.1	7	7	10	50	2.70
FUC_{tc}	0.0	0.0	21.0	32	32	60	150	0.0
η_{tc}	1.0	1.0	0.2	0.4	0.4	0.36	0.38	1.0
Cf_{tc}	0.24	0.49	0.20	0.6	0.6	0.4	0.4	0.8

SP2. Emission factors

The emission factors (EF) for the estimation of the greenhouse gas (GHG) emissions of the energy strategies are reported in Table 13.

The EFs for solar and wind sources consider the reference values for the fabrication and implementation of solar panels and wind turbines(IRENA, 2021, 2022b; Manwell et al., 2017; Pascaris et al., 2021).

Fossil fuel-based technologies use EFs for direct emissions, i.e., the emissions from fuel burning(Cuadros Tejeda et al., 2019; EMEP/EEA, 2019; United States Environmental Protection Agency (US EPA), 2014).

Biogas and biomass emission factor (EF) are calculated based on a configuration of 25% cogeneration and 75% direct generation for electricity production(Holmgren et al., 2015; Ozgen & Caserini, 2018; United States Environmental Protection Agency (US EPA), 1996, 2023; Verzat et al., 2015; Wu et al., 2022).

Table 13 Emission factors for the technologies in the energy strategies designed.

Technology	CO2eq (t/TWh produced)
Biomass	0.0
Biogas	487.00
Hydropower	19.85
Nuclear	0.0
Thermoelectric	1111.11
Generator set	710.53
Gas Turbine	450.00
Solar	41.00
Wind	11.00

SP3. Surface availability

We have estimated the land surface required to install the photovoltaic panels or wind turbines necessary to produce an amount of energy equivalent to the electricity demand of the Grand-Est region of France and Cuba for one year of reference 2018 and 2015 respectively. For this, we implemented the surface estimation method for RES by the International Renewable Energy Agency (IRENA)(IRENA, 2015b). This method considers the solar and wind potential of one region based on the local solar radiation and wind speed from global databases(JRC European Comission, 2017; Technical University of Denmark (DTU), 2021). This approach of land use assessment serves to define a boundary/limit for the designed strategies of solar and wind sources introduction. It has already been used to analyze the limits of energy transition scenarios in the Upper Rhine region of Central Europe(Gavrilut et al., 2021; RES-TMO, 2020).

Table 14 shows the percentage of the total surface needed to produce the electricity demand with solar and wind energy sources in the Grand Est (France) and Cuba.

Table 14 Emission factors for the energy storage technologies.

Case	Total Surface (km²)	Resource	Minimum need for surface (% of the total surface)	Maximum need for surface (% of the total surface)
Grand Est Region of France	6 893	Solar	1.3	2
		Wind	2	5.5
Cuba	110 000	Solar	0.05	0.14
		Wind	1	1.9

Figure 44 shows the results in terms of land area required to meet 100% of the energy demand with solar or wind energy. Between 1.3% and 2% of the surface of the region would need to be occupied by solar panels to meet 100% of the electricity demand while between 2% and 5.5% of the surface of the region would be needed for wind turbines. A similar analysis was published for the case of Cuba(M. Guevara-Luna et al., 2024).

Considering the land use and all the constraints that could oppose the installation of solar and wind energy production infrastructures previous study in the region shows that 12% of the total area of the region could be mobilized for the production of solar and wind energy in the Grand-Est region(Fernandez, 2020).

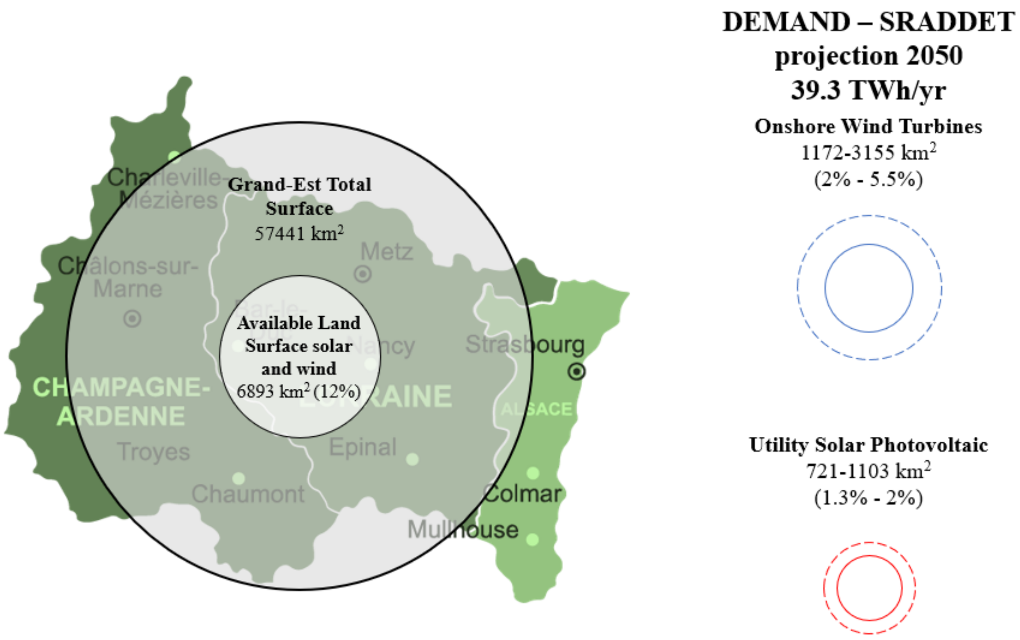


Figure 44 Land surface needed to meet 100% of SRADDET energy demand projection to 2050 for the Grand Est region of France using solar panels (red circles) or wind turbines (blue circles). The area available in the region for the installation of wind turbines and solar panels is represented by the small white circle.

Figure 45 shows the comparison between the available surface and the required surface to install photovoltaic panels and wind turbines in the Grand-Est and Cuba for different shares of intermittent energy in the mix as a percentage of the electricity demand.

In the Grand Est, the limit of the available surface is reached only when the wind energy production is 190% of the electrical energy demand, this at the least favorable location for wind energy production.

For the other cases, i.e., solar photovoltaics and wind turbines at more favorable locations, the available surface is enough to produce more than twice the yearly electricity demand. With solar energy, the available surface is enough to produce several times de electricity demand of the region.

In the case of Cuba, the potential of the solar and wind sources is much larger than in central Europe. For this, the need for surface for the augmentation of the solar and wind shares is smaller compared to the estimations for the Grand Est. For Cuba, even in the less favorable locations, the potential of intermittent energy production is enough to produce several times de demand.

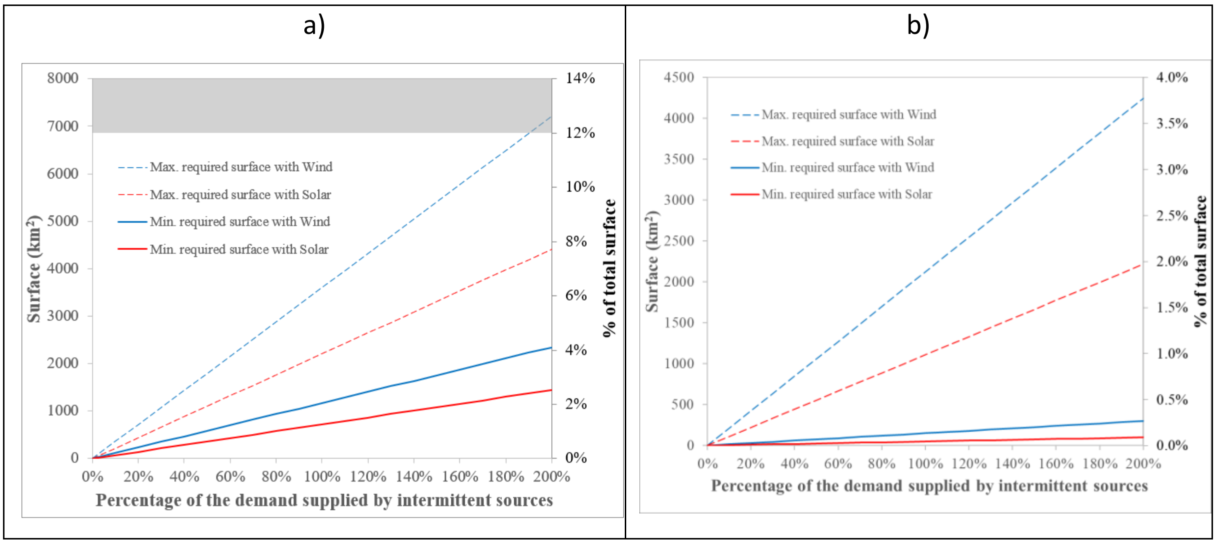


Figure 45 Land area (km²) required depending on the percentage of the introduction of wind energy (blue curves) or solar energy (red curves): a) Grand Est region of France with the demand of the SRADDET scenario, and b) Cuba. The solid curves correspond to favorable conditions for intermittent energy production, while the dotted curves correspond to more unfavorable production conditions. The gray color corresponds to the limit of the usable surface for the installation of wind turbines and solar panels in the Grand Est region.

SP4. Variation of solar and wind sources

The solar and wind energy sources' variations are considered in terms of their capacity factors hourly variations. The capacity factors are represented by equation SP4.1, where, CF_t is the capacity factor at the hour "t", EP_t and IC_t correspond to the energy production and the power installed capacity, and Δt is the time interval during the EP_t is produced(Thotakura et al., 2020). The EP_t depends of the main driver of the technology i.e., the solar radiation for the solar photovoltaics and the wind speed for the wind turbines.

$$CF_t = \frac{EP_t}{IC_t * \Delta t} \qquad \text{(SP4.1)}$$

Here we use the output of a high-resolution numerical NWP (Weather Prediction Model) to estimate the solar and wind energy potentials. The Figure 46 shows the wrf simulation domain configuration for the evaluation of the solar and wind hourly variation. In previous research, authors have conducted exploratory data analysis evidencing that numerical weather prediction model (NWP) output SWDOWN (Horizontal Short-wave downward direct Solar Radiation) is the primary driver of the prediction of photovoltaic energy production(Brabec et al., 2010).

For wind energy, the driver of energy production corresponds to the wind speed at the mean height of the rotor axis(IRENA, 2015b; Tiedemann, 2014). For this, the hourly wind speed at 80m height and the SWDOWN were retrieved from the WRF (Weather Research and Forecast) model results(Skamarock et al., 2019; Skamarock & Klemp, 2008).

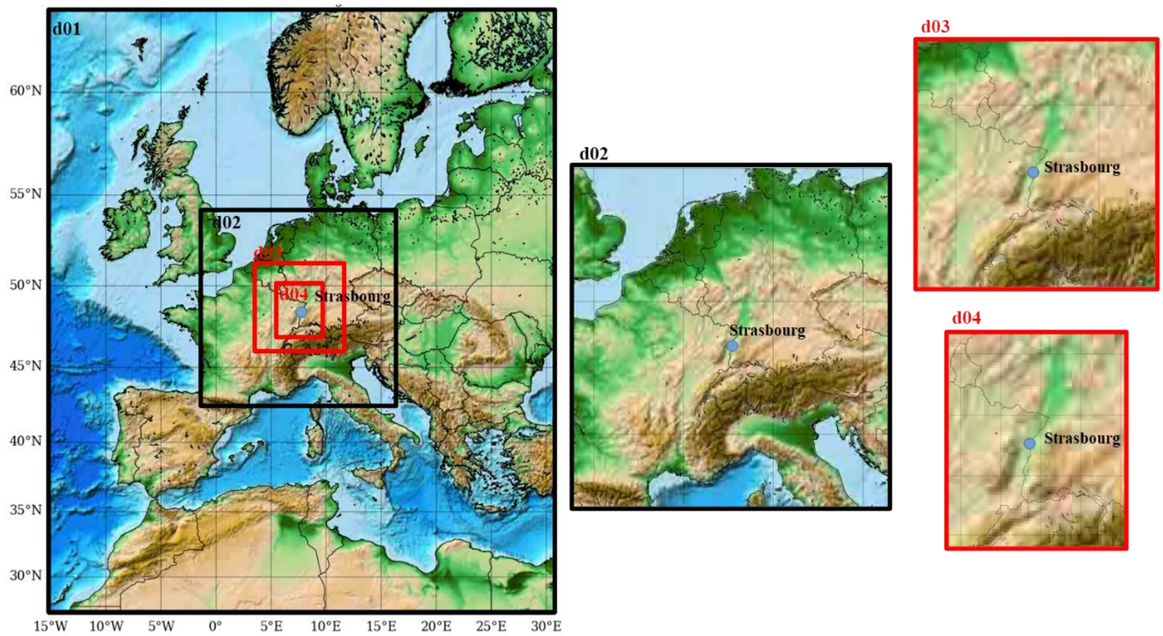


Figure 46 Configuration of the simulation domains of the weather forecast (WRF) model used for the estimation of the hourly variation of solar and wind energy production potentials in Europe.

Annex 3 Supplementary material - Chapter 3

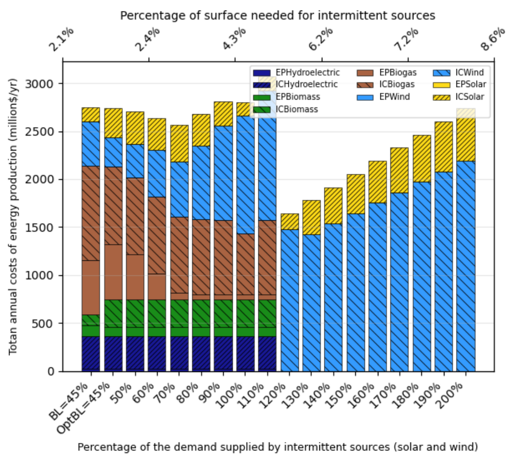
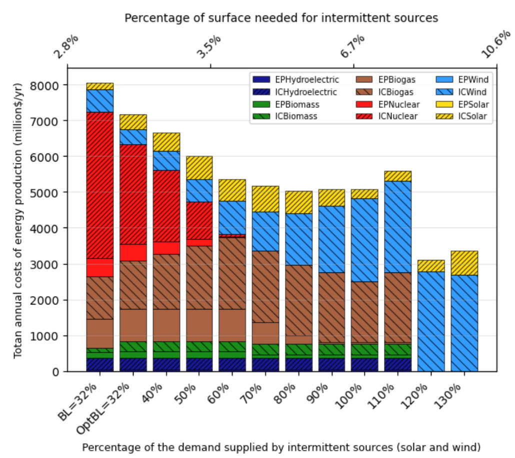
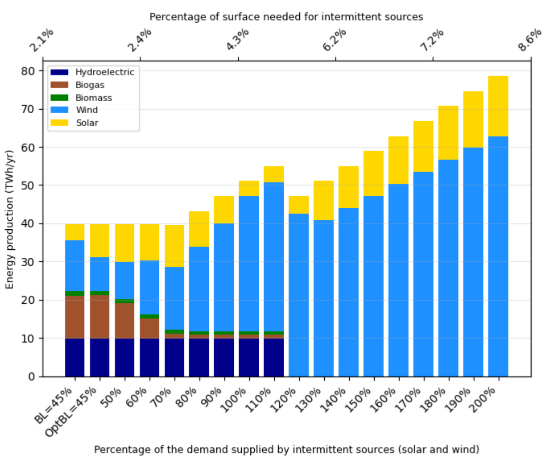
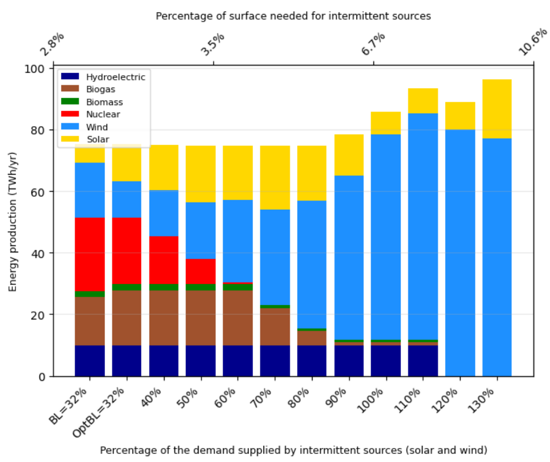
SP1. Limiting the percentage of storage max

Results for the scenarios with energy storage, limiting the storage capacity. Each scenario is characterized by the percentage of demand met by intermittent (solar and wind) sources in the energy mix. The storage capacity limit for each scenario is based on the maximum calculated storage capacity without any limit (maximum storage capacity). The limit can then be expressed as a percentage of this maximum storage capacity. Here, the results are shown for 80% and 50% of the maximum storage capacity.

Results are presented for the study cases of the Grand-Est region of France and Cuba. The results shown correspond to the energy mix in terms of energy production, installed capacity, and the total annual costs of the technologies in the system for each study case; and the indicators calculated, e.g., total annual costs, GHG emissions, imports, and use of non-RES.

SP1.1. Grand Est region of France

SP1.1.1. 80% of maximum storage capacity

<table>
<tr><th></th><th>Minimum demand (SRADDET)</th><th>Maximum demand</th></tr>
<tr><td>Total annual costs</td><td>a)

</td><td>d)

</td></tr>
<tr><td>Energy production</td><td>b)

</td><td>e)

</td></tr>
</table>

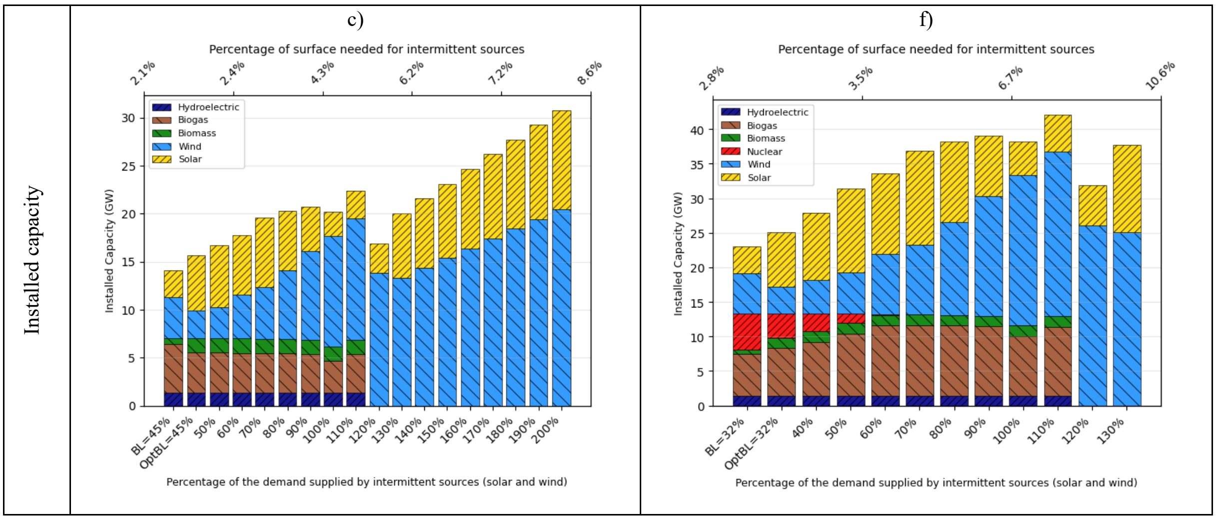


Figure 47 Total annual costs (a and d), energy production (b and e), and installed capacity (c and f) for the optimized scenarios with energy storage, limiting the storage capacity to a 80% of its maximum calculated capacity for the study case of the Grand-Est region of France. Parts a, b, and c correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts d, e, and f correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

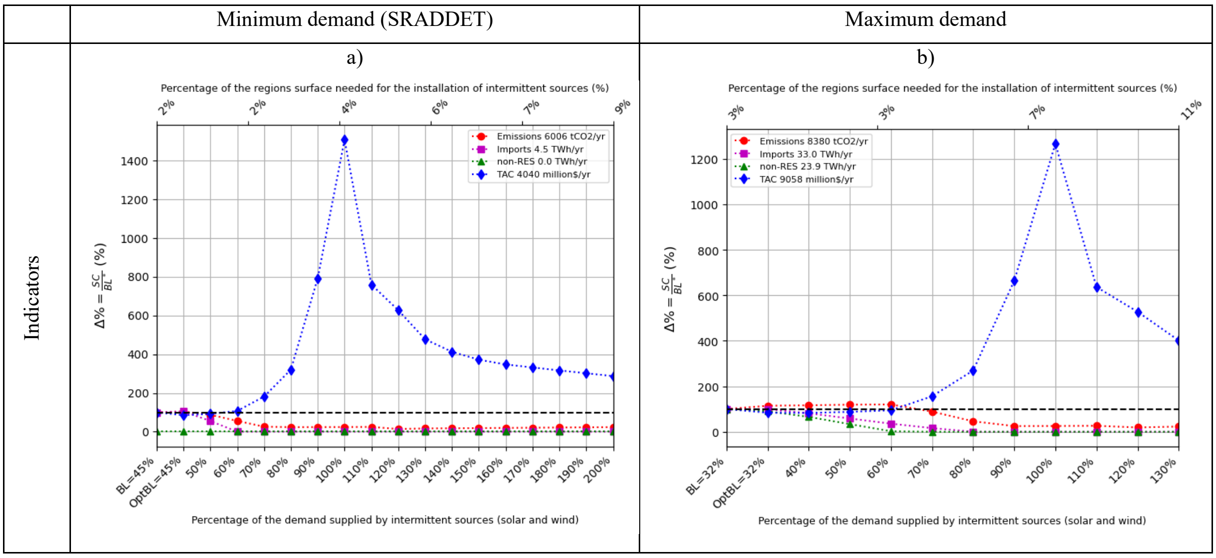


Figure 48 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, limiting the storage capacity to a 80% of its maximum calculated capacity for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Part a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The second horizontal axis represents the surface area required to install the solar panels and wind turbines for

each scenario.

SP1.1.2. 50% of maximum storage capacity

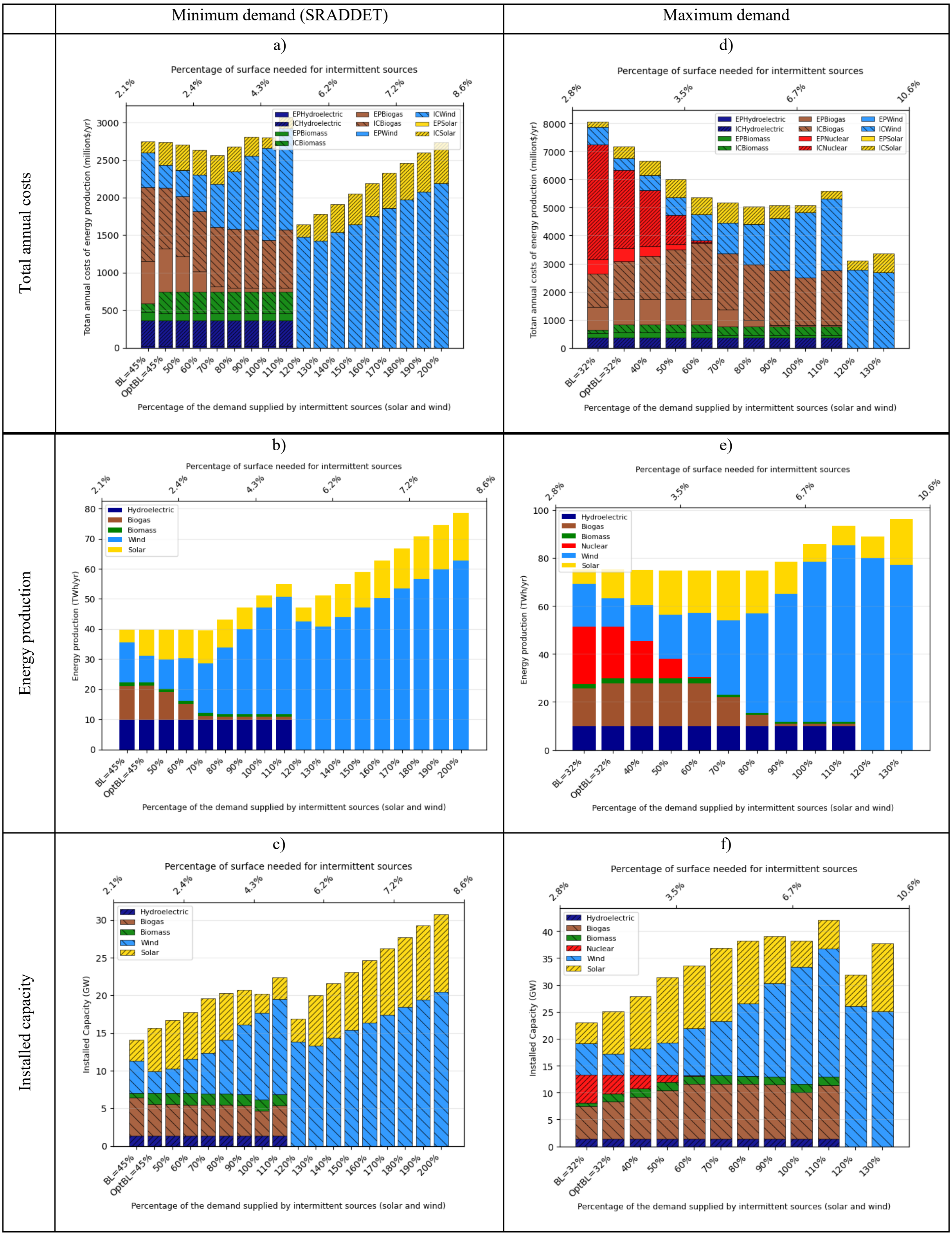


Figure 49 Total annual costs (a and d), energy production (b and e), and installed capacity (c and f) for the optimized scenarios with energy storage, limiting the storage capacity to a 50% of its maximum calculated capacity for the study case of the Grand-Est region of France. Parts a, b, and c

correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts d, e, and f correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

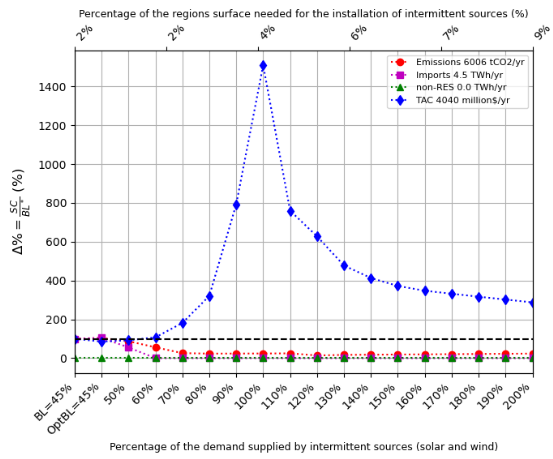
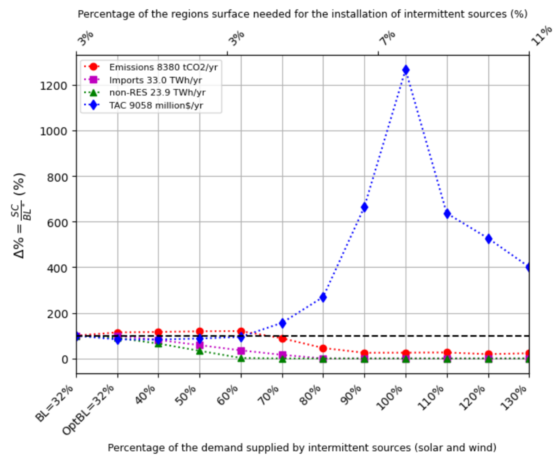
	Minimum demand (SRADDET)	Maximum demand
Indicators	a) 	b) 

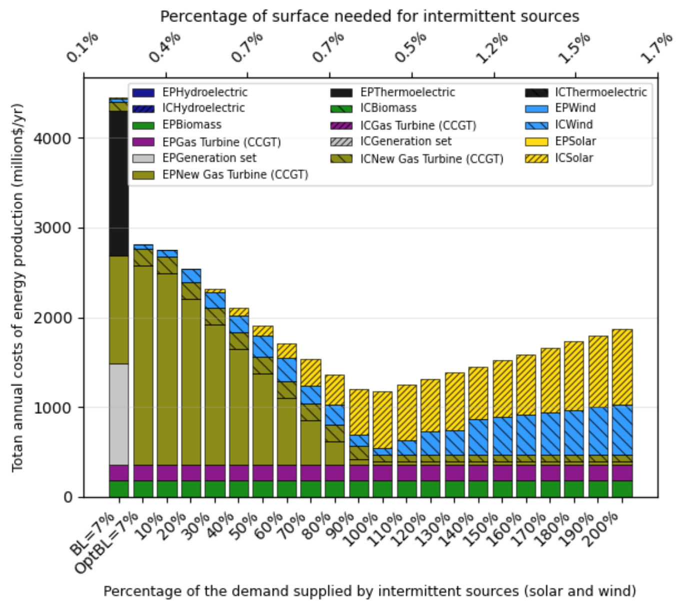
Figure 50 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, limiting the storage capacity to a 50% of its maximum calculated capacity for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Part a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP1.2. Cuba

SP1.2.1. 80% of maximum storage capacity

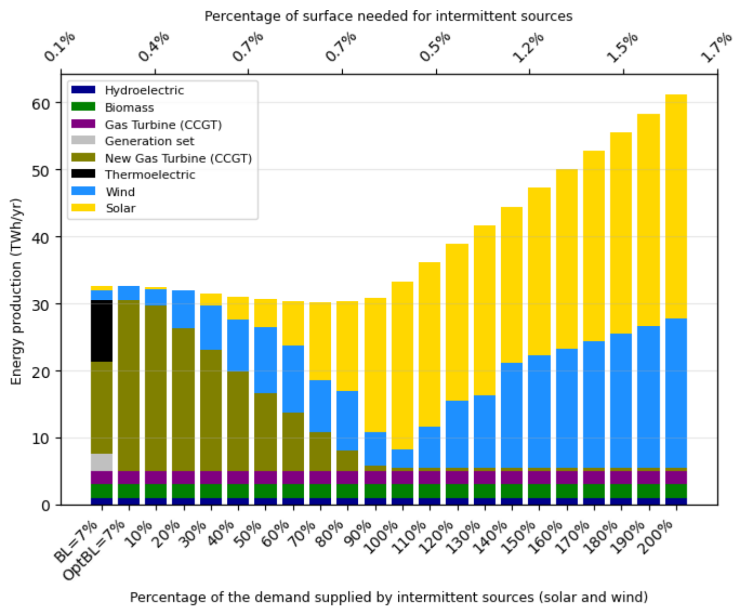
Total annual costs

a)



Energy production

b)



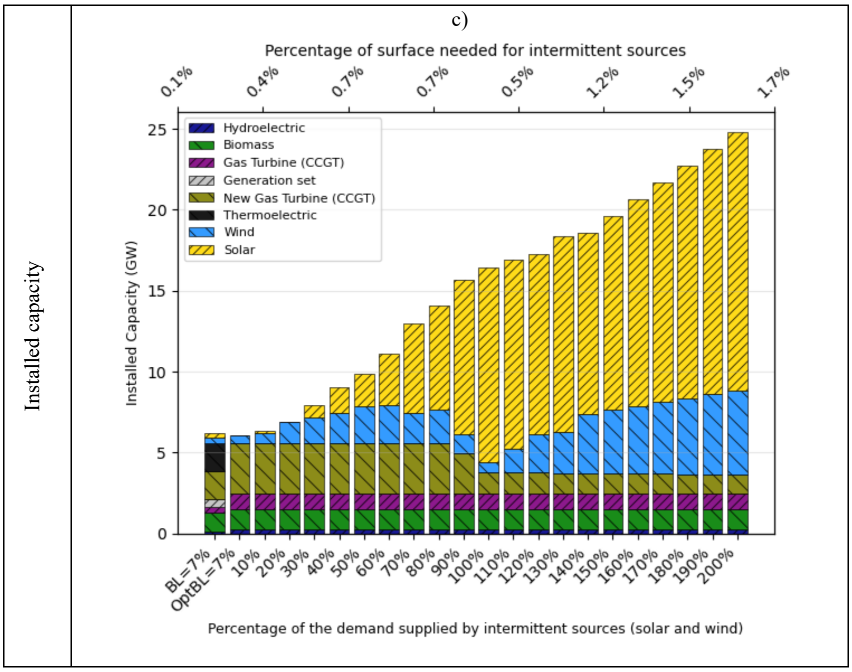


Figure 51 Total annual costs (a), energy production (b), and installed capacity (c) for the optimized scenarios with energy storage, limiting the storage capacity to a 80% of its maximum calculated capacity for the study case of Cuba. The scenarios were designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

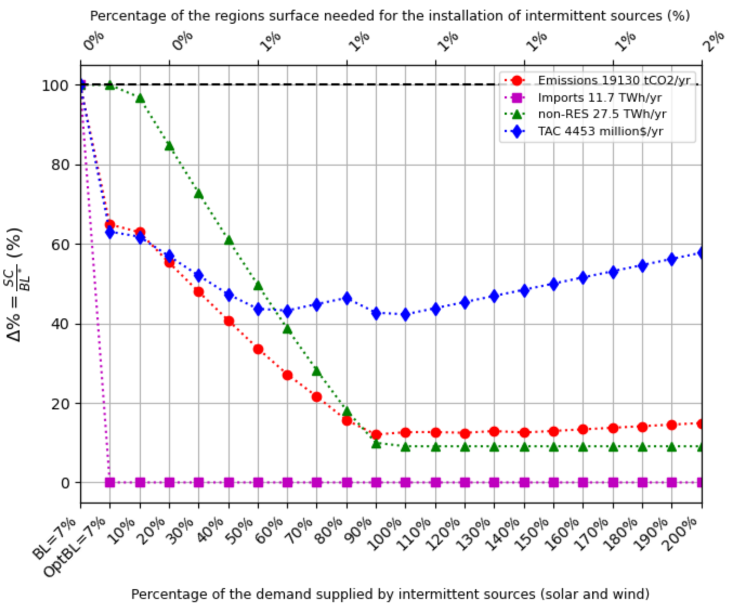


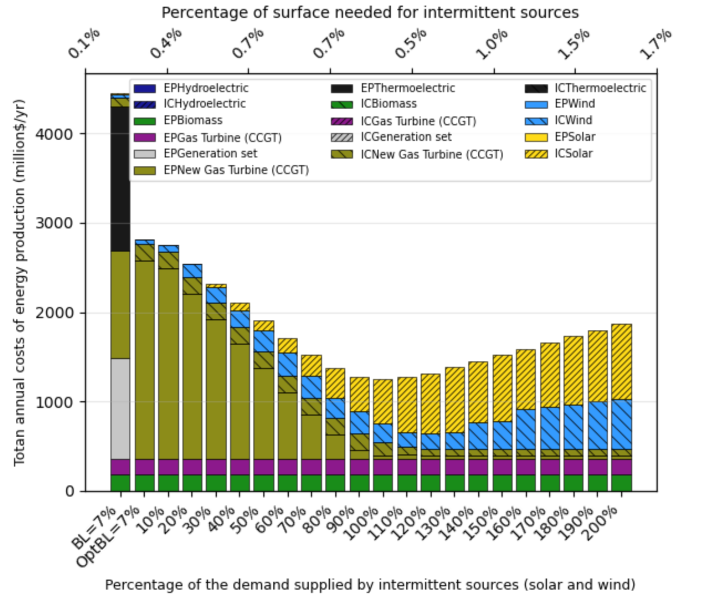
Figure 52 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, limiting the storage capacity to a 80% of its maximum calculated capacity for the study case of Cuba. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. The official baseline scenario and the

optimized baseline scenario are denoted as “BL” and “OptBL”. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP1.2.2. 50% of maximum storage capacity

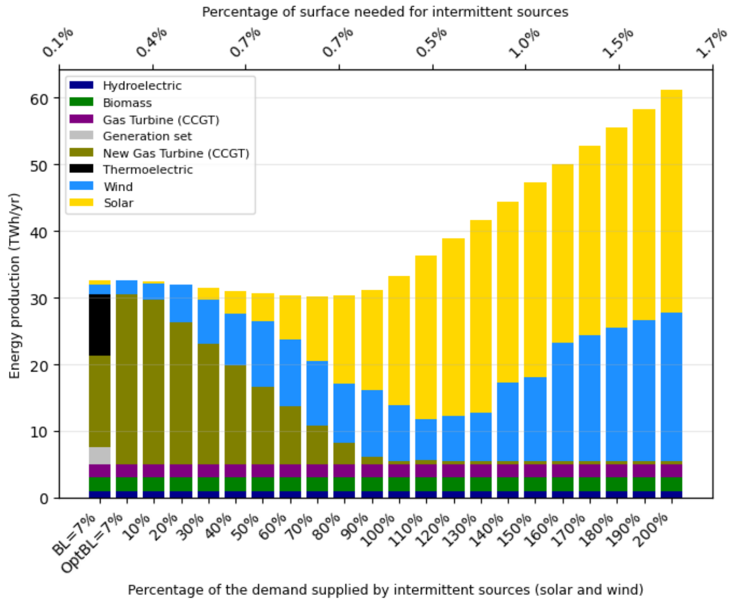
Total annual costs

a)



Energy production

b)



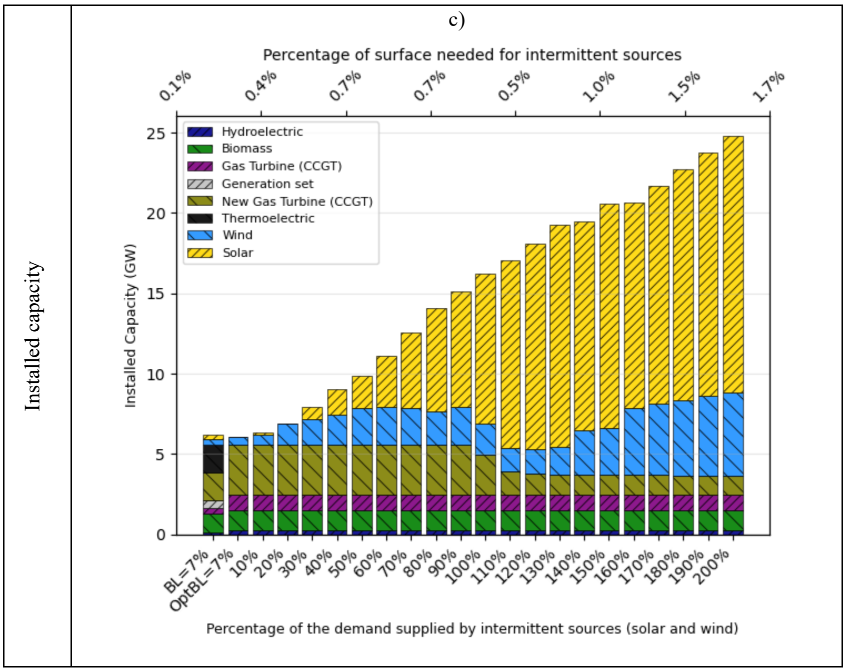


Figure 53 Total annual costs (a), energy production (b), and installed capacity (c) for the optimized scenarios with energy storage, limiting the storage capacity to a 50% of its maximum calculated capacity for the study case of Cuba. The scenarios were designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as “BL” and “OptBL”. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

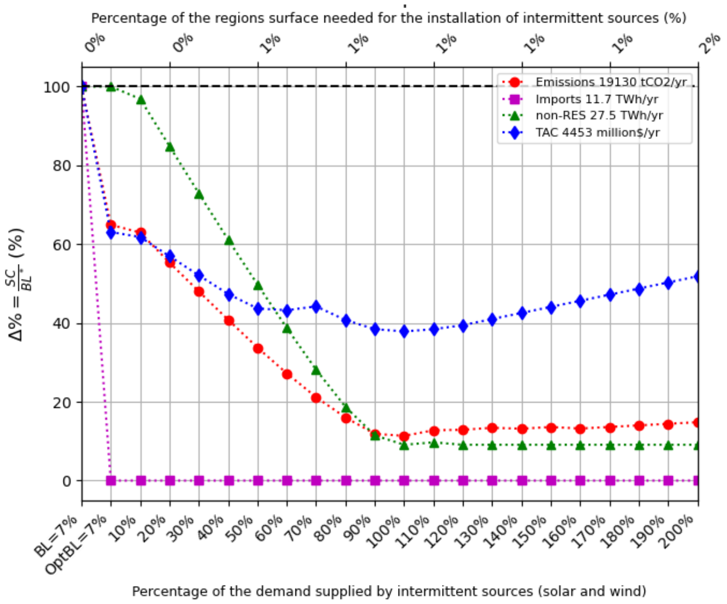


Figure 54 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, limiting the storage capacity to a 50% of its maximum calculated capacity for the study case of Cuba. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. The official baseline scenario and the

optimized baseline scenario are denoted as "BL" and "OptBL". The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2. Reducing the unitary costs of storage

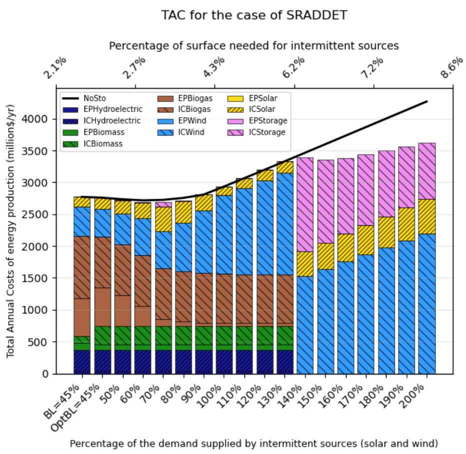
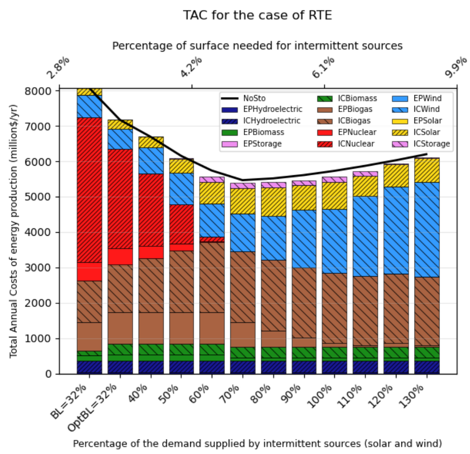
Results for the scenarios with energy storage, reducing the value of the unitary costs (or costing parameters) of energy storage. For this analysis, the unitary costs of energy storage are divided by a factor ranging from 10 to 1000, representing hypothetical conditions where storage costs are 10, 100, and 1000 times lower than the current reference costs. Results are presented for the study cases of the Grand-Est region of France and Cuba. Results are presented for the study cases of the Grand-Est region of France and Cuba. The results shown correspond to the energy mix in terms of energy production, installed capacity, and the total annual costs of the technologies in the system for each study case; and the indicators calculated, e.g., total annual costs, GHG emissions, imports, and use of non-RES.

The results are compared with the scenarios without energy storage.

Several storage capacity limits (percentages of maximum energy storage) were calculated. The results shown for each scenario correspond to the maximum energy storage capacity that minimizes the costs of the energy mix, it can be 100% the maximum storage capacity reduction (no storage) or 100% maximum storage capacity.

SP2.1. Grand Est region of France

SP2.1.1. Factor of reduction for the unitary costs of storage: 10

<table>
<tr><td></td><td>Minimum demand (SRADDET)</td><td>Maximum demand</td></tr>
<tr><td>Total annual costs</td><td>a)

</td><td>d)

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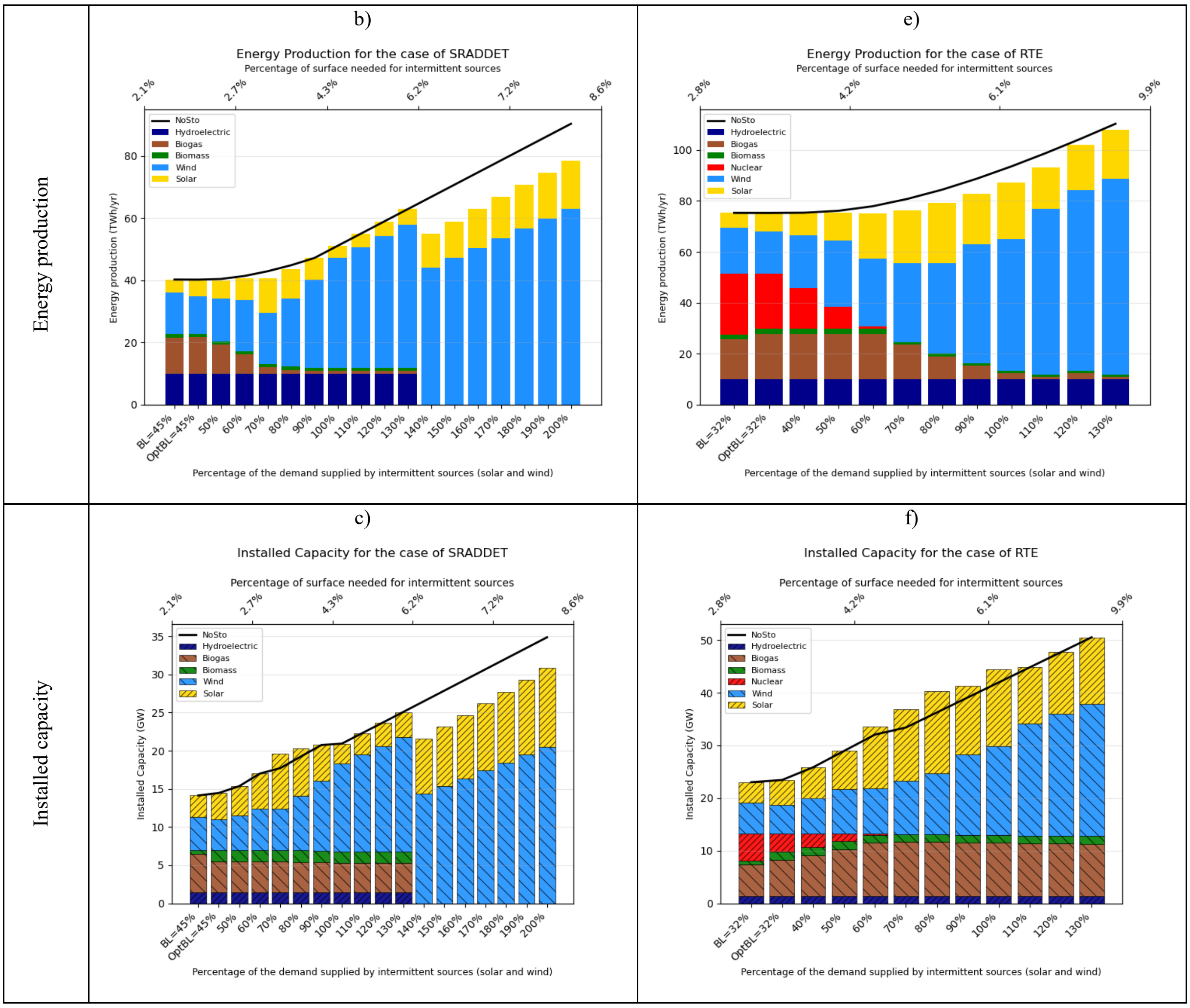


Figure 55 Total annual costs (a and d), energy production (b and e), and installed capacity (c and f) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 10, for the study case of the Grand-Est region of France. Parts a, b, and c correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts d, e, and f correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

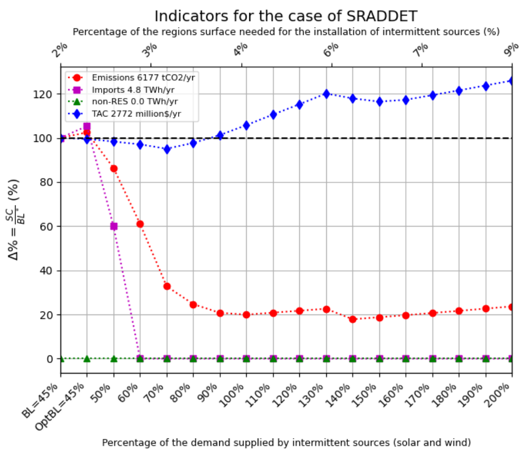
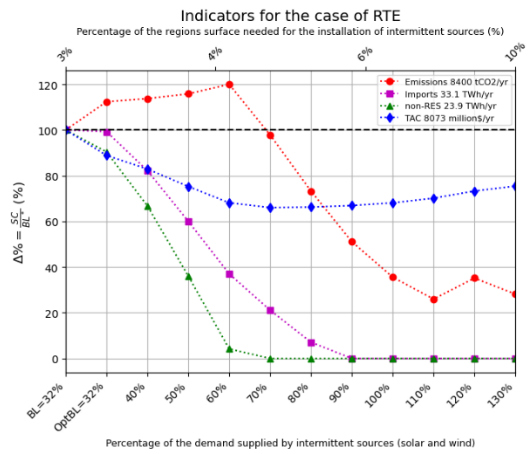
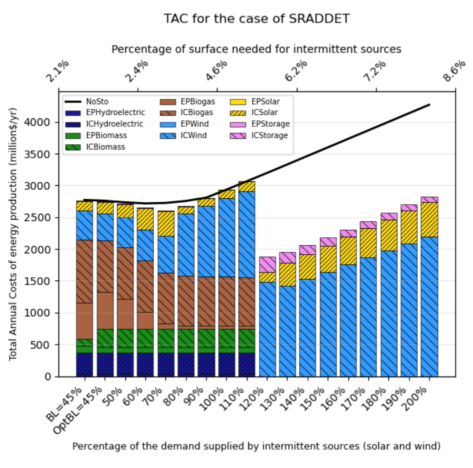
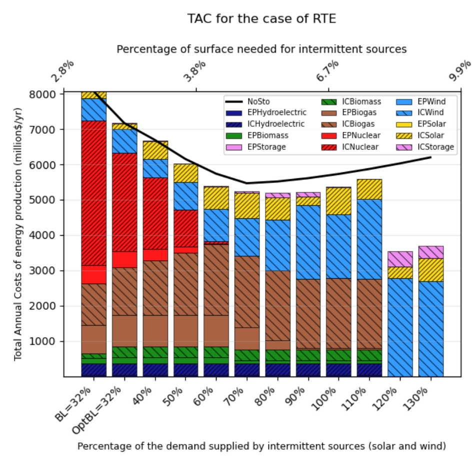
	Minimum demand (SRADDET)	Maximum demand
	a)	b)
Indicators		

Figure 56 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 10, for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Parts a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2.1.2. Factor of reduction for the unitary costs of storage: 100

	Minimum demand (SRADDET)	Maximum demand
	a)	d)
Total annual costs		

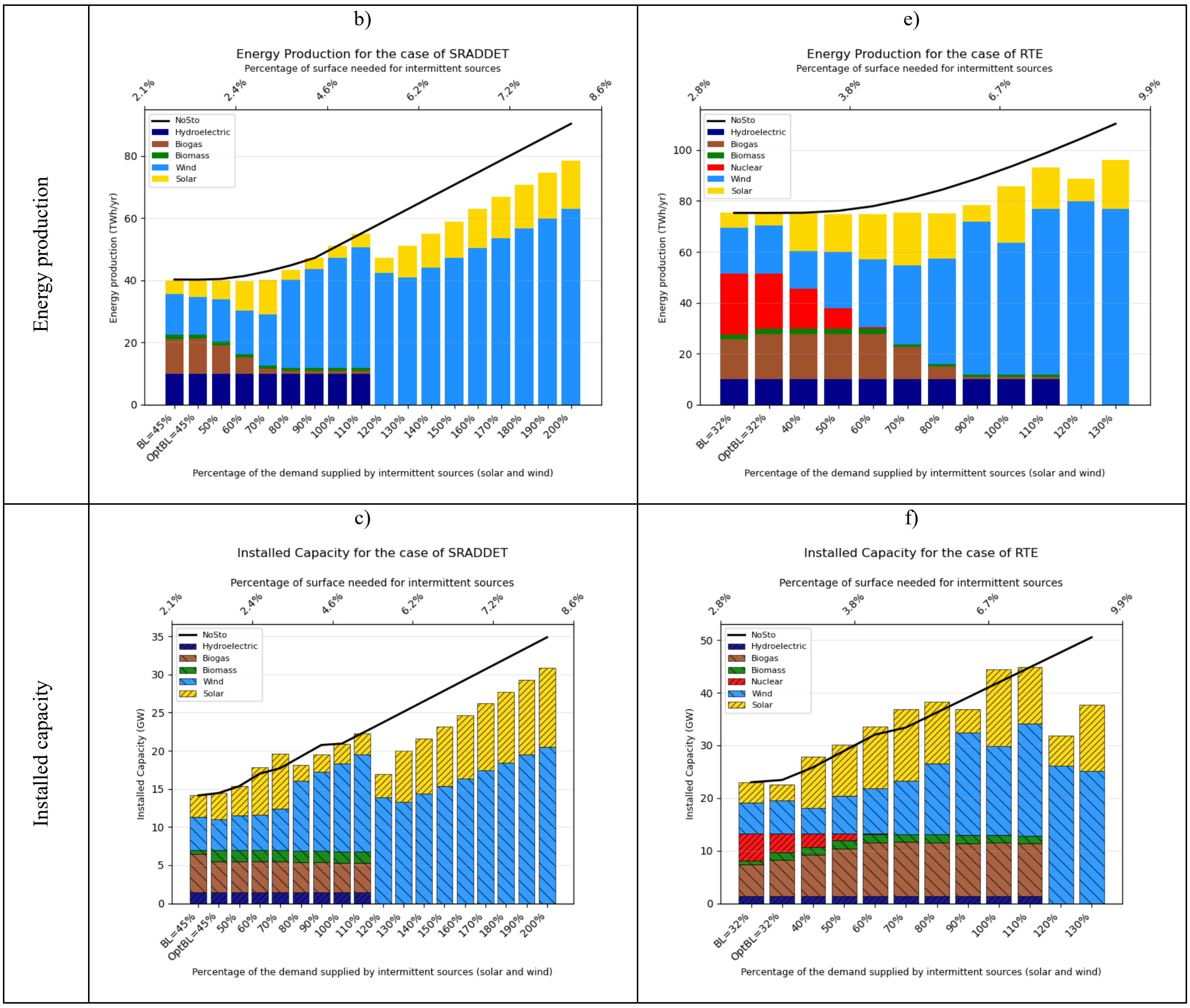


Figure 57 Total annual costs (a and d), energy production (b and e), and installed capacity (c and f) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 100, for the study case of the Grand-Est region of France. Parts a, b, and c correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts d, e, and f correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

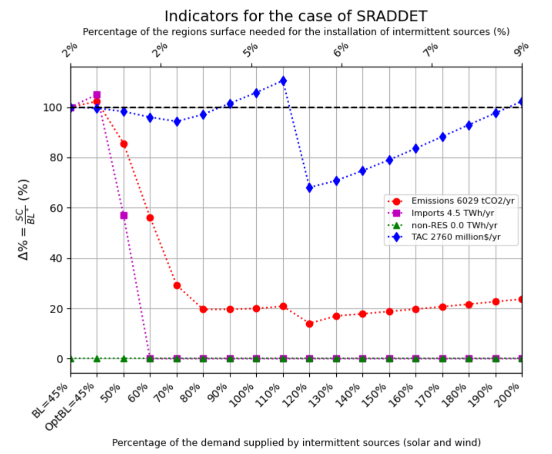
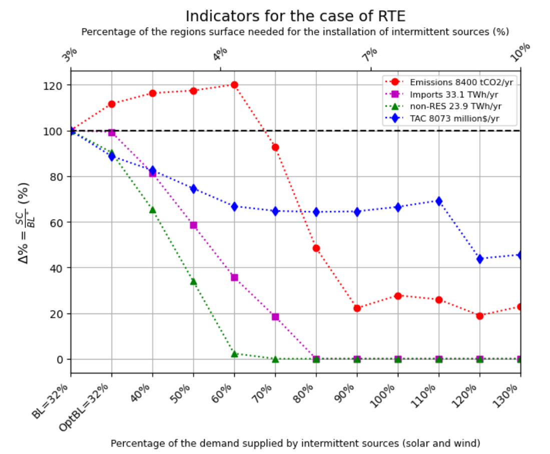
<table>
<tr><td></td><td>Minimum demand (SRADDET)</td><td>Maximum demand</td></tr>
<tr><td>Indicators</td><td>a)

</td><td>b)

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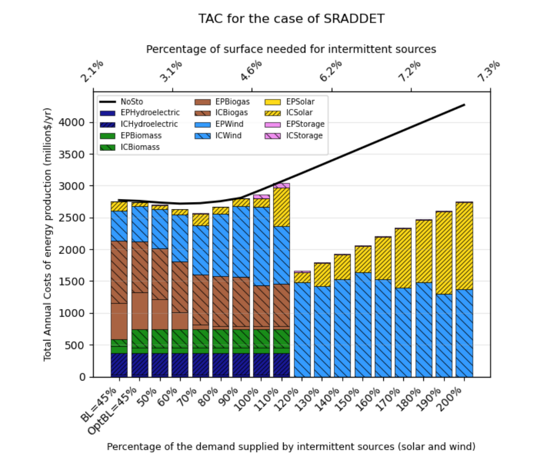
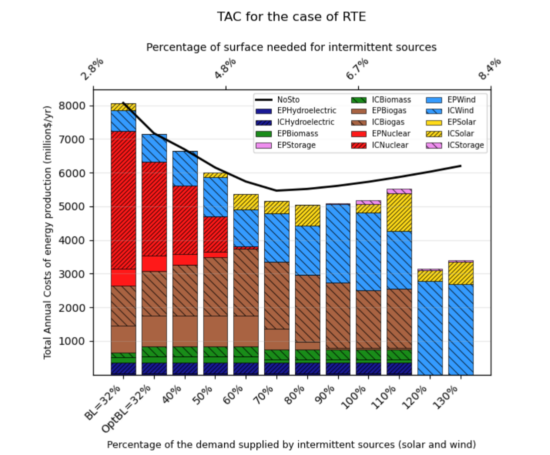
Figure 58 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 100, for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Parts a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2.1.3. Factor of reduction for the unitary costs of storage: 1000

<table>
<tr><td></td><td>Minimum demand (SRADDET)</td><td>Maximum demand</td></tr>
<tr><td>Total annual costs</td><td>a)

</td><td>d)

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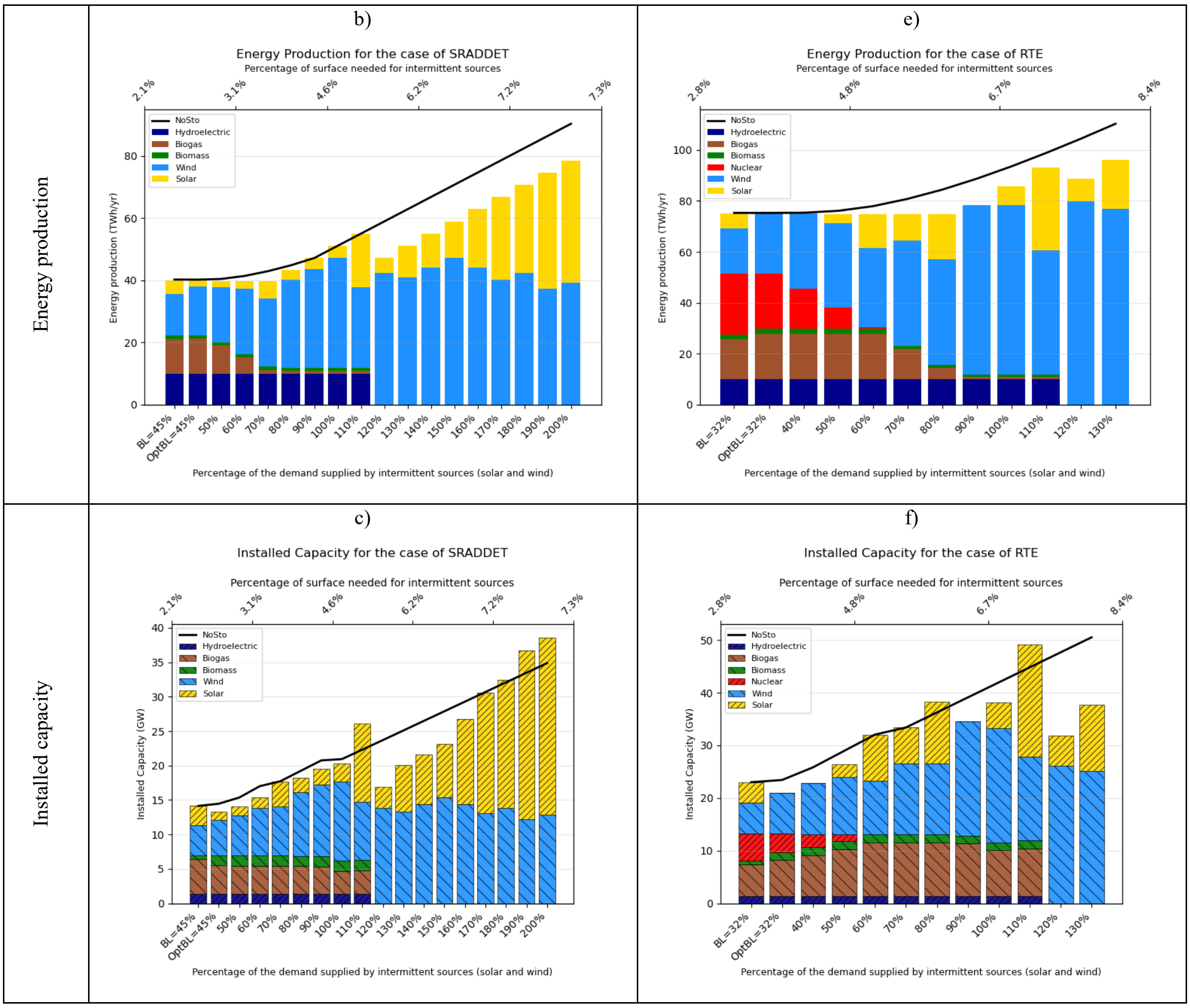
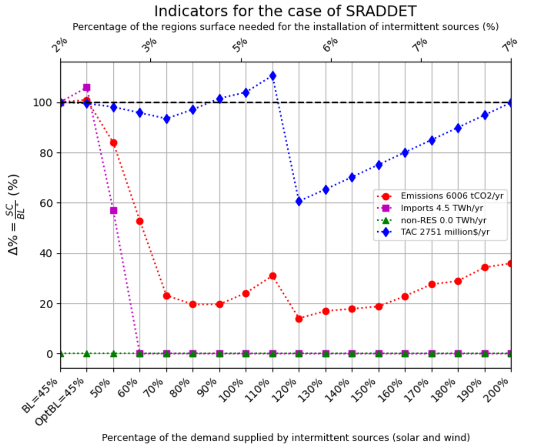


Figure 59 Total annual costs (a and d), energy production (b and e), and installed capacity (c and f) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 1000, for the study case of the Grand-Est region of France. Parts a, b, and c correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts d, e, and f correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

<table>
<tr><td></td><td>Minimum demand (SRADDET)</td><td>Maximum demand</td></tr>
<tr><td>Indicators</td><td>a)

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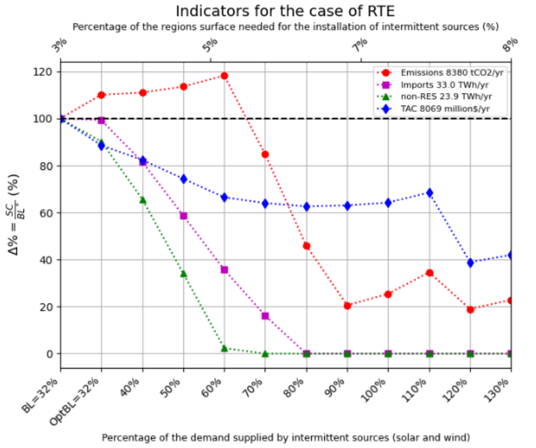
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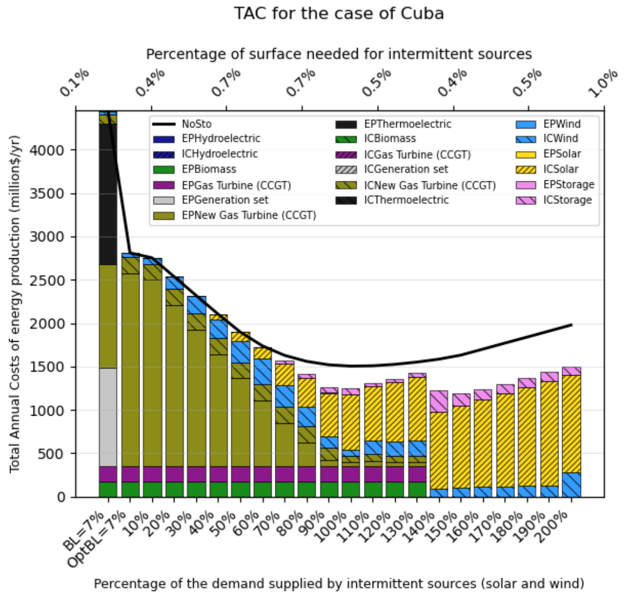
Figure 60 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 1000, for the study case of the Grand-Est region of France. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. Parts a corresponds to scenarios designed based on a minimum projected demand (official projection - SRADDET), and part b corresponds to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2.2. Cuba

SP2.2.1. Factor of reduction for the unitary costs of storage: 10

<table>
<tr><td>Total annual costs</td><td>a)

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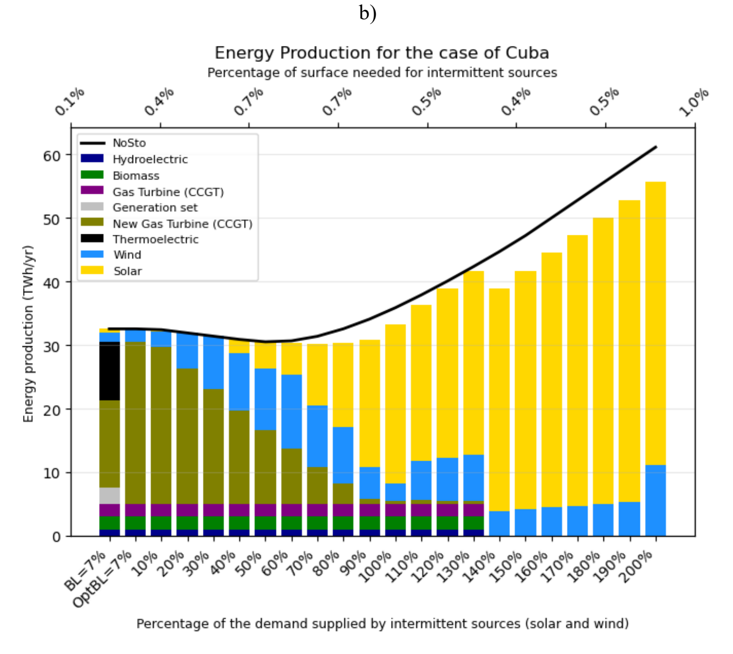
Energy production



Installed capacity

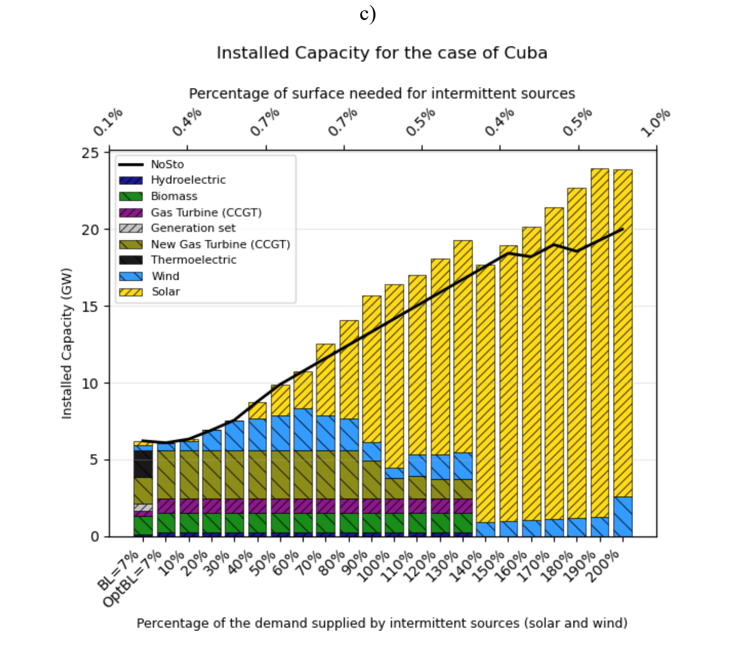


Figure 61 Total annual costs (a), energy production (b), and installed capacity (c) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 10, for the study case of Cuba. Parts a, b, and c correspond to scenarios designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

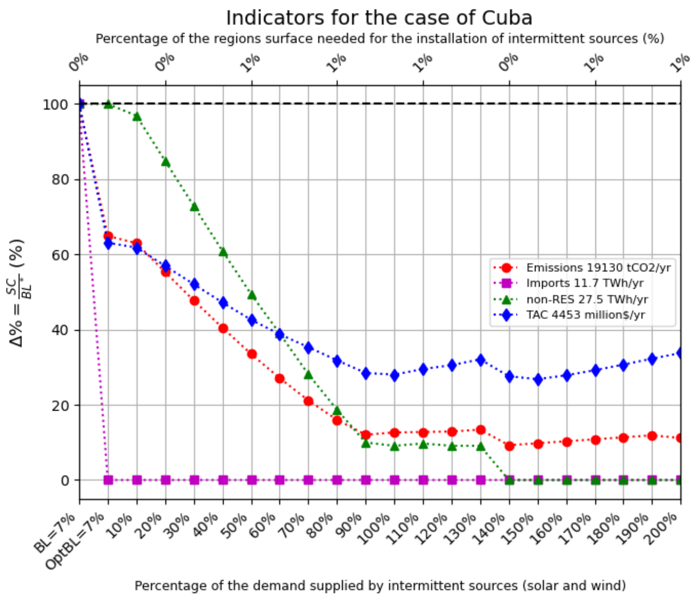
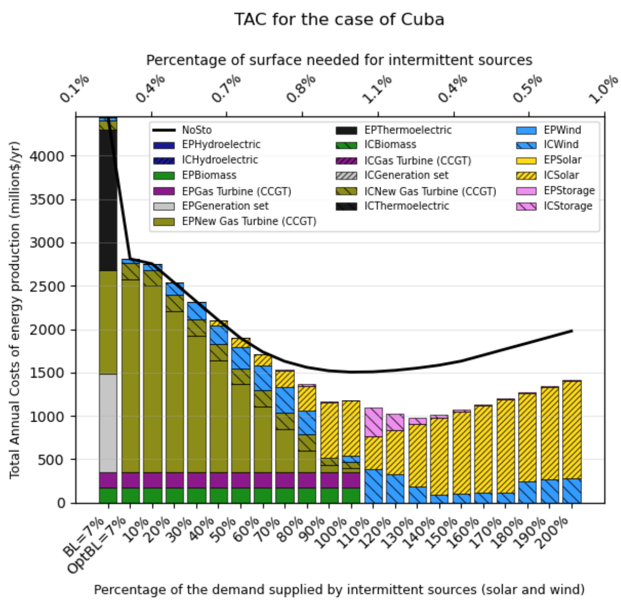


Figure 62 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 10, for the study case of Cuba. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2.2.2. Factor of reduction for the unitary costs of storage: 100

Total annual costs	a) 

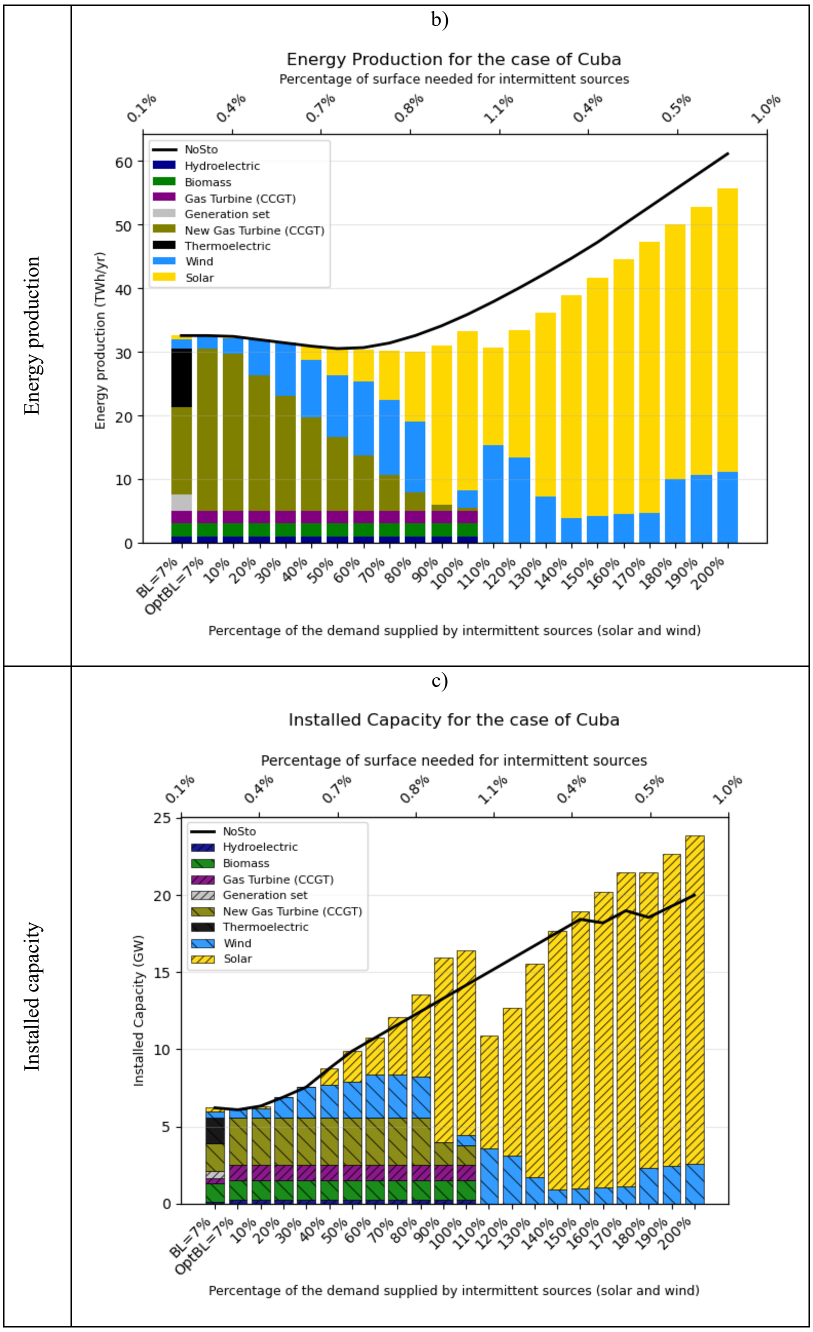


Figure 63 Total annual costs (a), energy production (b), and installed capacity (c) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 100, for the study case of Cuba. Parts a, b, and c correspond to scenarios designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

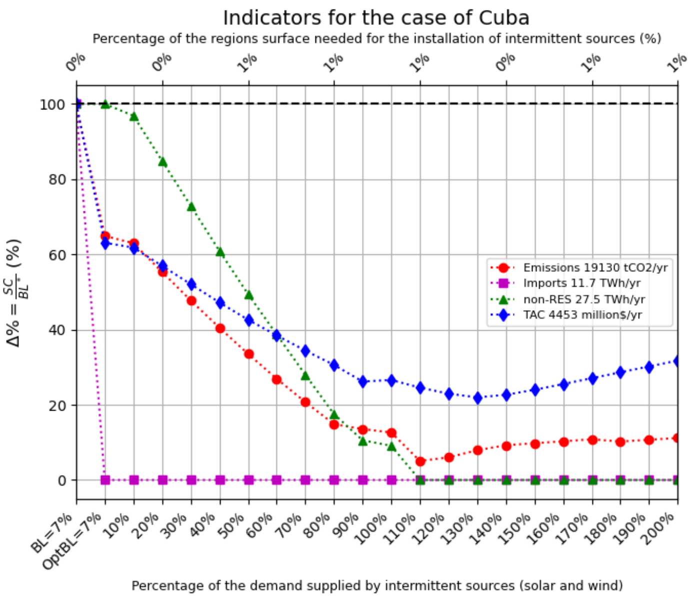
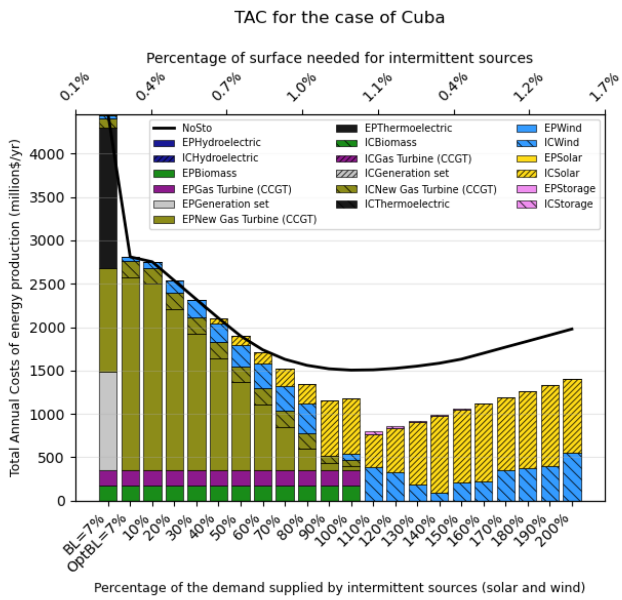


Figure 64 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 100, for the study case of Cuba. Scenarios correspond to increasingly progressive introduction of intermittent energy sources into the mix. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario.

SP2.2.3. Factor of reduction for the unitary costs of storage: 1000

Total annual costs	a) 

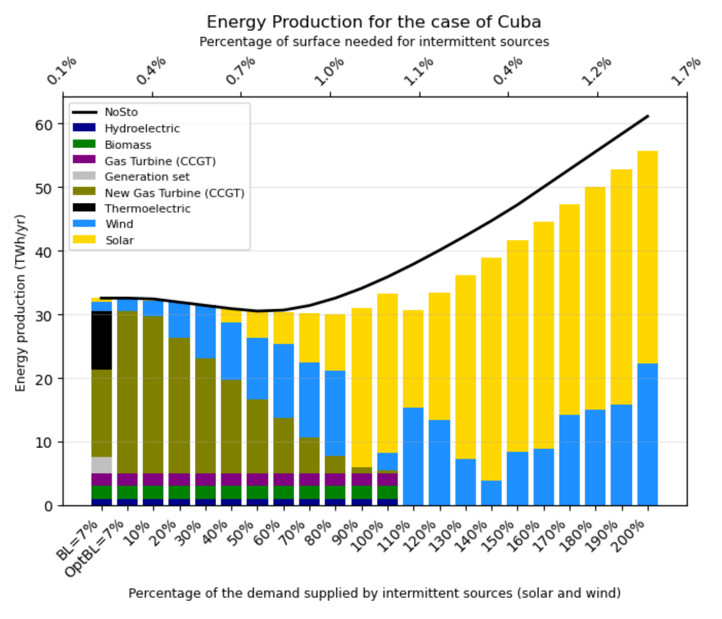
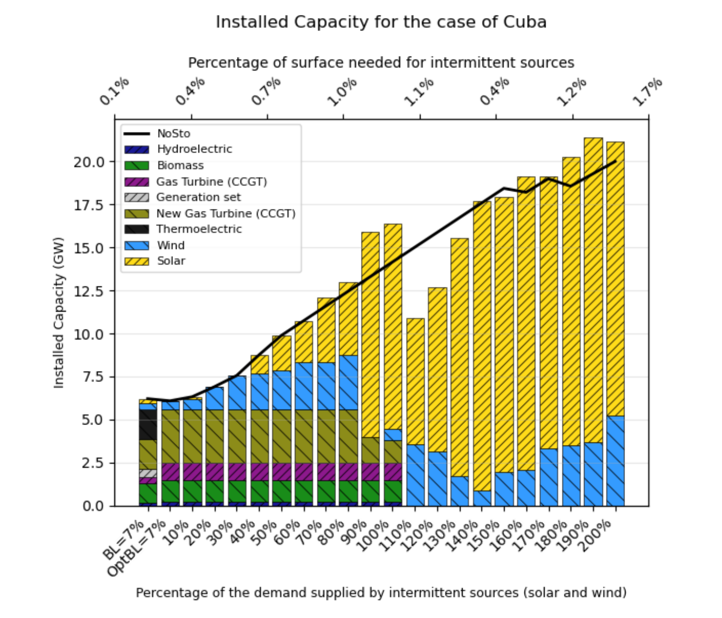
Energy production	b) 
Installed capacity	c) 

Figure 65 Total annual costs (a), energy production (b), and installed capacity (c) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 1000, for the study case of Cuba. Parts a, b, and c correspond to scenarios designed based on the official scenario and projected. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

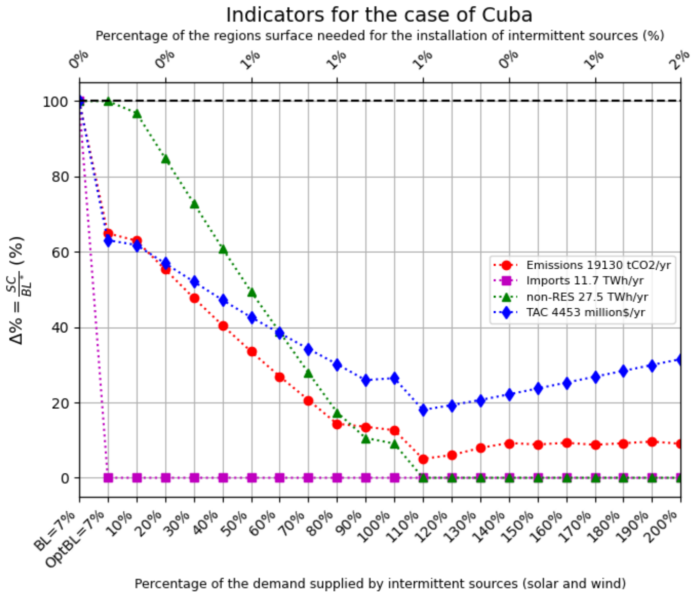


Figure 66 Evaluated indicators (total annual costs, GHG emissions, imports, and use of non-RES) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of the energy storage by factor 1000, for the study case of Cuba

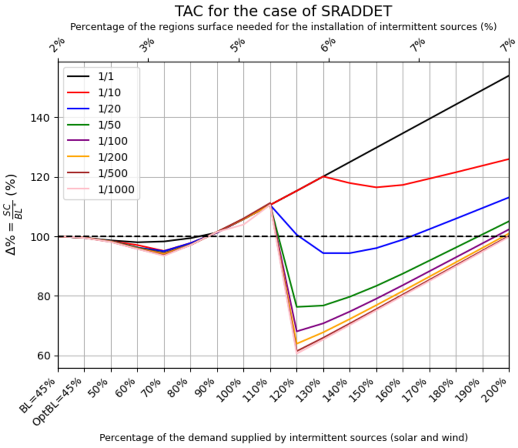
SP3. Effects of the unitary costs of storage on indicators

The effects of reducing the value of the unitary costs (or costing parameters) of energy storage on the indicators (e.g., total annual costs, GHG emissions, imports, and use of non-RES.) designed were explored more widely. For this analysis, the unitary costs of energy storage are divided by a factor ranging from 10 to 1000, representing hypothetical conditions where storage costs are lower than the current reference costs at different scales.

As before, several storage capacity limits (percentages of maximum energy storage) were considered. The results shown for each scenario correspond to the maximum energy storage capacity that minimizes the costs of the energy mix, it can be 100% the maximum storage capacity reduction (no storage) or 100% maximum storage capacity.

SP3.1. Grand Est region of France

<table>
<tr><th></th><th>Minimum demand (SRADDET)</th><th>Maximum demand</th></tr>
<tr><td>Total annual costs</td><td>a)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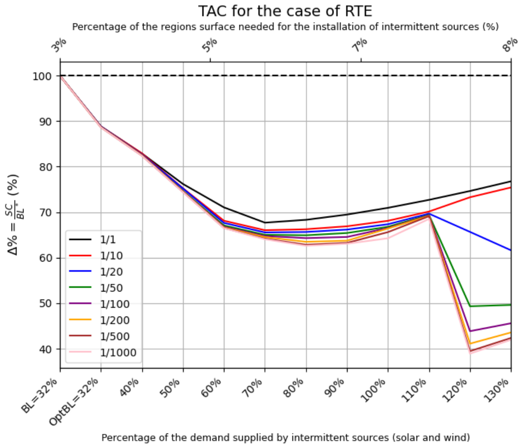
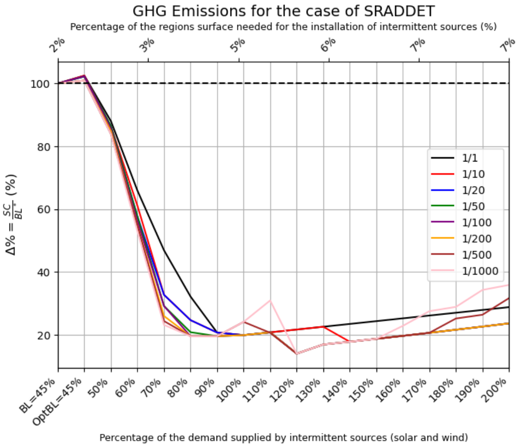
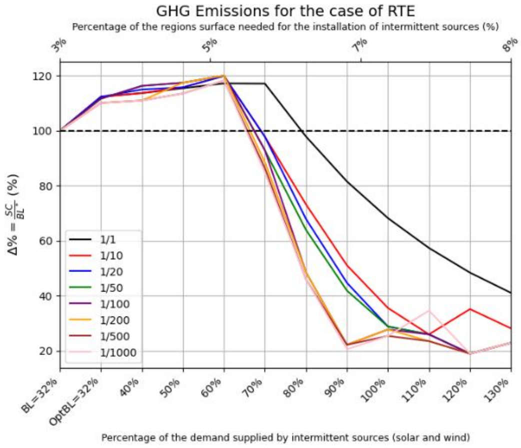
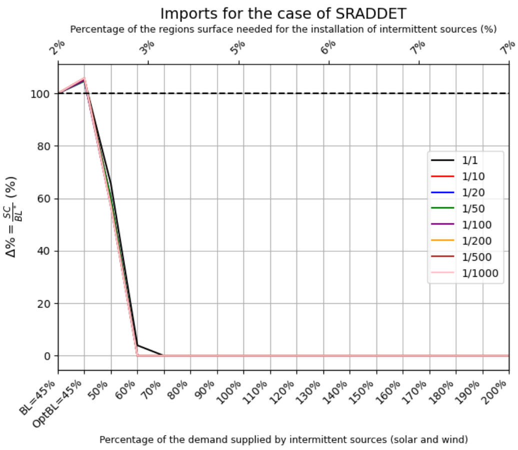

</td></tr>
<tr><td>GHG emissions</td><td>b)


</td><td>f)


</td></tr>
<tr><td>Imports</td><td>c)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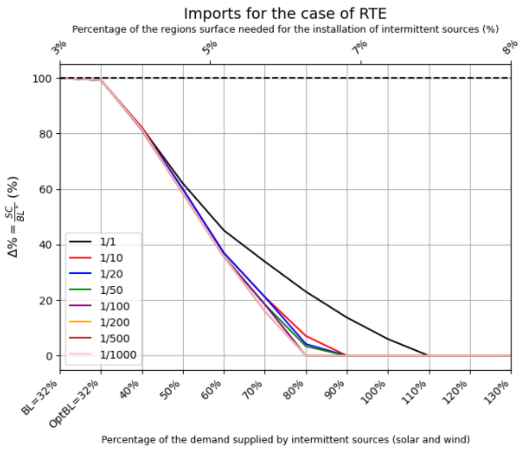
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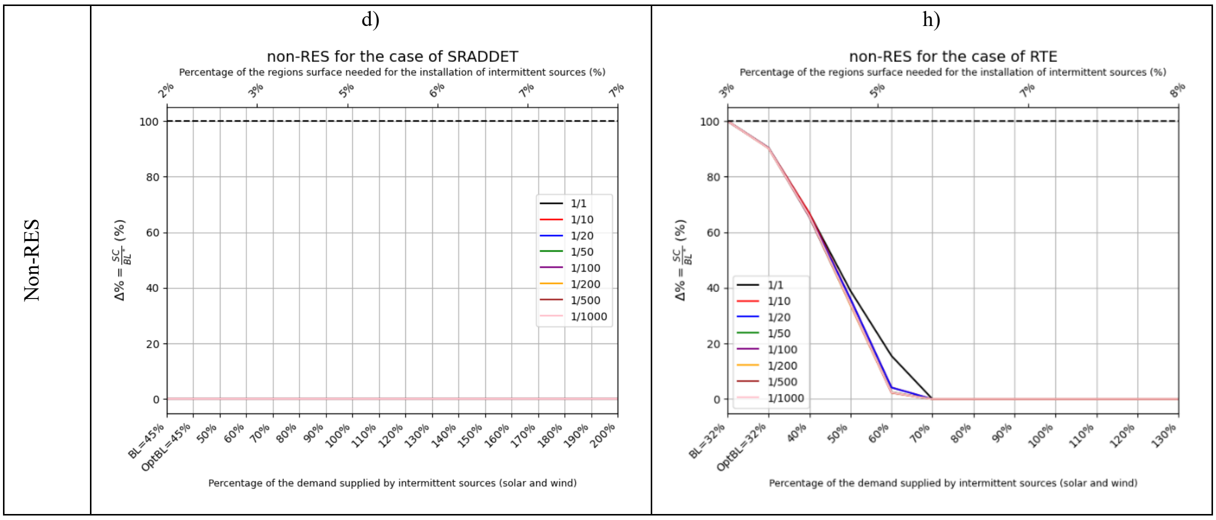
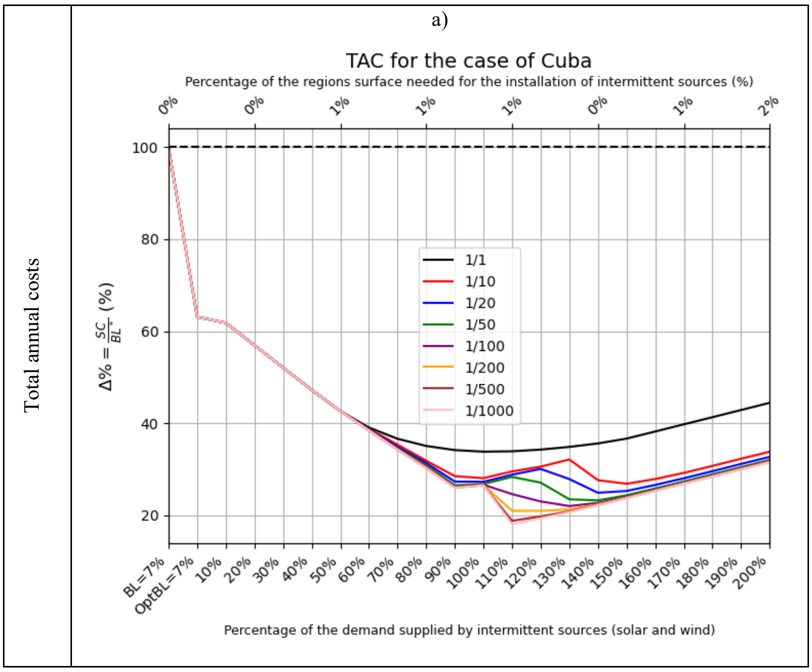
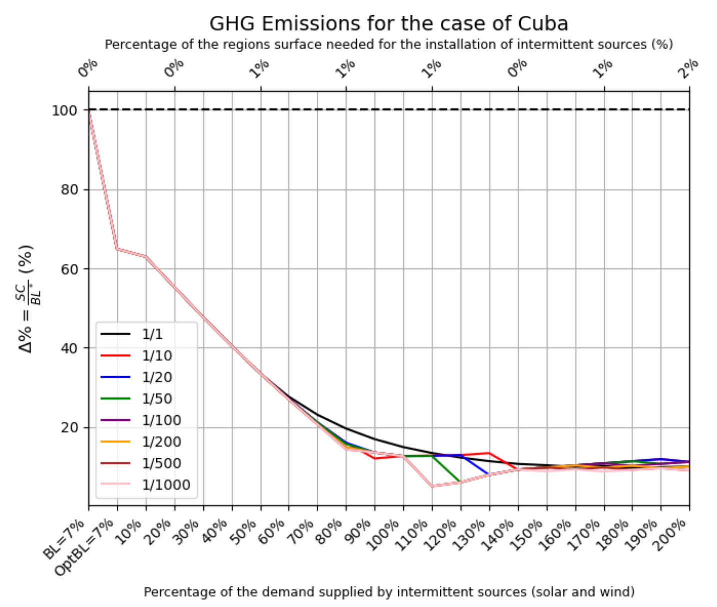
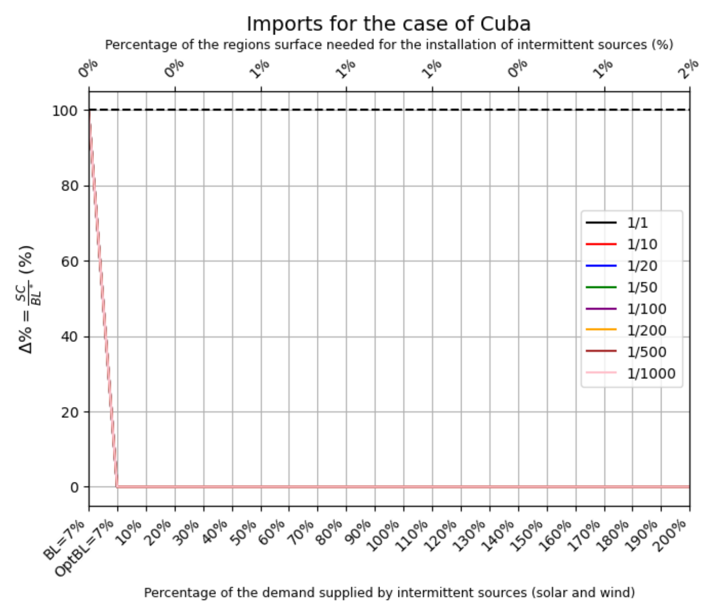


Figure 67 Effects of reducing the unitary costs of energy storage (costing parameters value) by factors between 1 and 1000 on the calculated indicators: total annual costs (a and e), GHG emissions (b and f), imports (c and g), and use of non-RES (d and h) for the optimized scenarios for the study case of Grand-Est region of France. Parts a, b, c, and d correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts e, f, g, and h correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP3.2. Cuba



GHG emissions	b) 
Imports	c) 

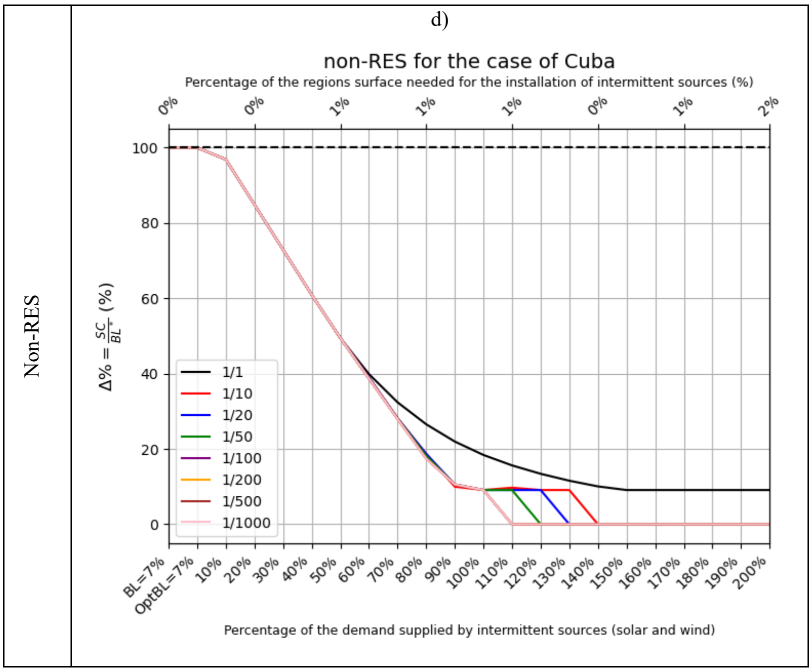


Figure 68 Effects of reducing the unitary costs of energy storage (costing parameters value) by factors between 1 and 1000 on the calculated indicators: total annual costs (a), GHG emissions (b), imports (c), and use of non-RES (d) for the optimized scenarios for the study case of Cuba. The scenarios designed are based on an official projection of the Cuban authorities. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4. Demand adaptation: Sensitivity analysis

This section shows the assembly of the results obtained for the adaptation of the demand to the energy production time variations in the hourly residual energy "R" for the cases: base case or original hourly variation (BC), adapted to interdaily ($\widehat{R_h}$), and interseasonal ($\widehat{R_s}$) time scales. The results are shown for the Grand Region of France (Central Europe) and Cuba. The results are reported in terms of economic costs of the scenarios with the different reconstructed demands and the indicators evaluated: total annual costs (TAC), GHG emissions, imports, and use of non-RES.

The indicators are compared between the demand with the full-time variation "BC" (or $\overline{R_h}$) and the adapted demand profiles (interdaily ($\widehat{R_h}$) and interseasonal ($\widehat{R_s}$) or simply R_h and R_s). The indicator values are compared with the results for the scenarios without energy storage for each adapted R profile.

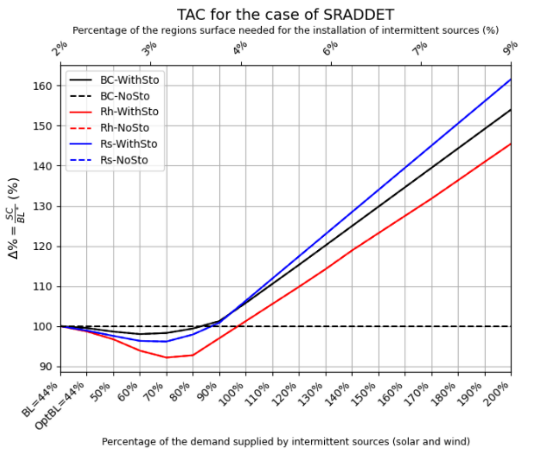
Also, results for demand adaptation are evaluated also with the effects of reducing the value of the unitary costs (or costing parameters) of energy storage. For this analysis, the unitary costs of energy storage are divided by a factor ranging from 10 to 1000, representing hypothetical conditions where storage costs are 10, 100, and 1000 times lower than the current reference costs.

Several storage capacity limits (percentages of maximum energy storage) were calculated. The results shown for each scenario correspond to the maximum energy storage capacity that minimizes the costs of the energy mix, it can be 100% the maximum storage capacity reduction (no storage) or 100% maximum storage capacity.

SP4.1. Grand Est region of France

SP4.1.1. Factor of reduction for the unitary costs of storage: 1

<table>
<tr><th></th><th>Minimum demand (SRADDET)</th><th>Maximum demand</th></tr>
<tr><td>Total annual costs</td><td>a)



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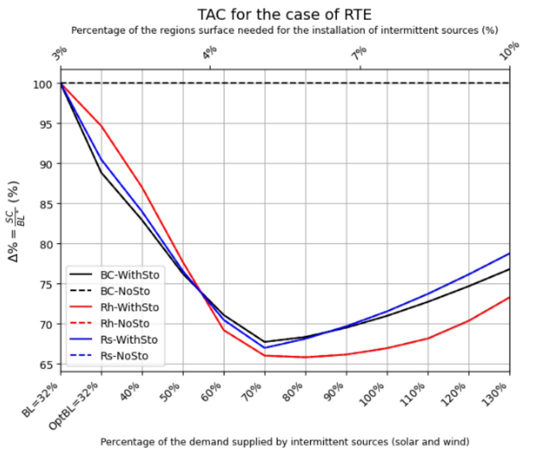
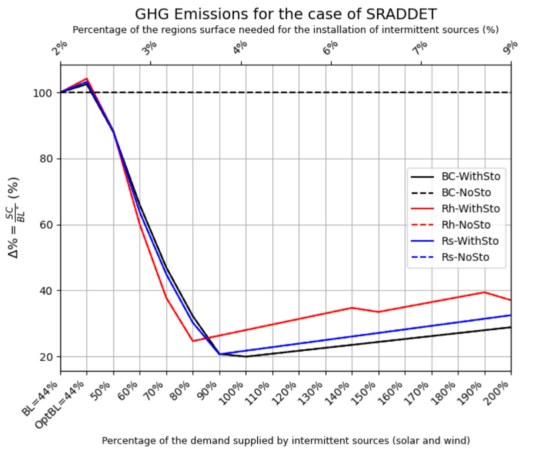
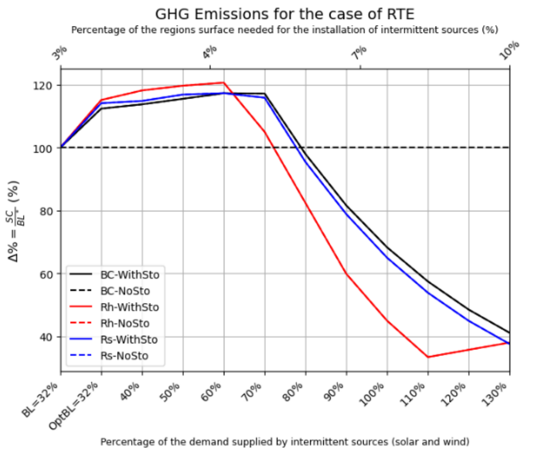


</td></tr>
<tr><td>GHG emissions</td><td>b)



</td><td>f)



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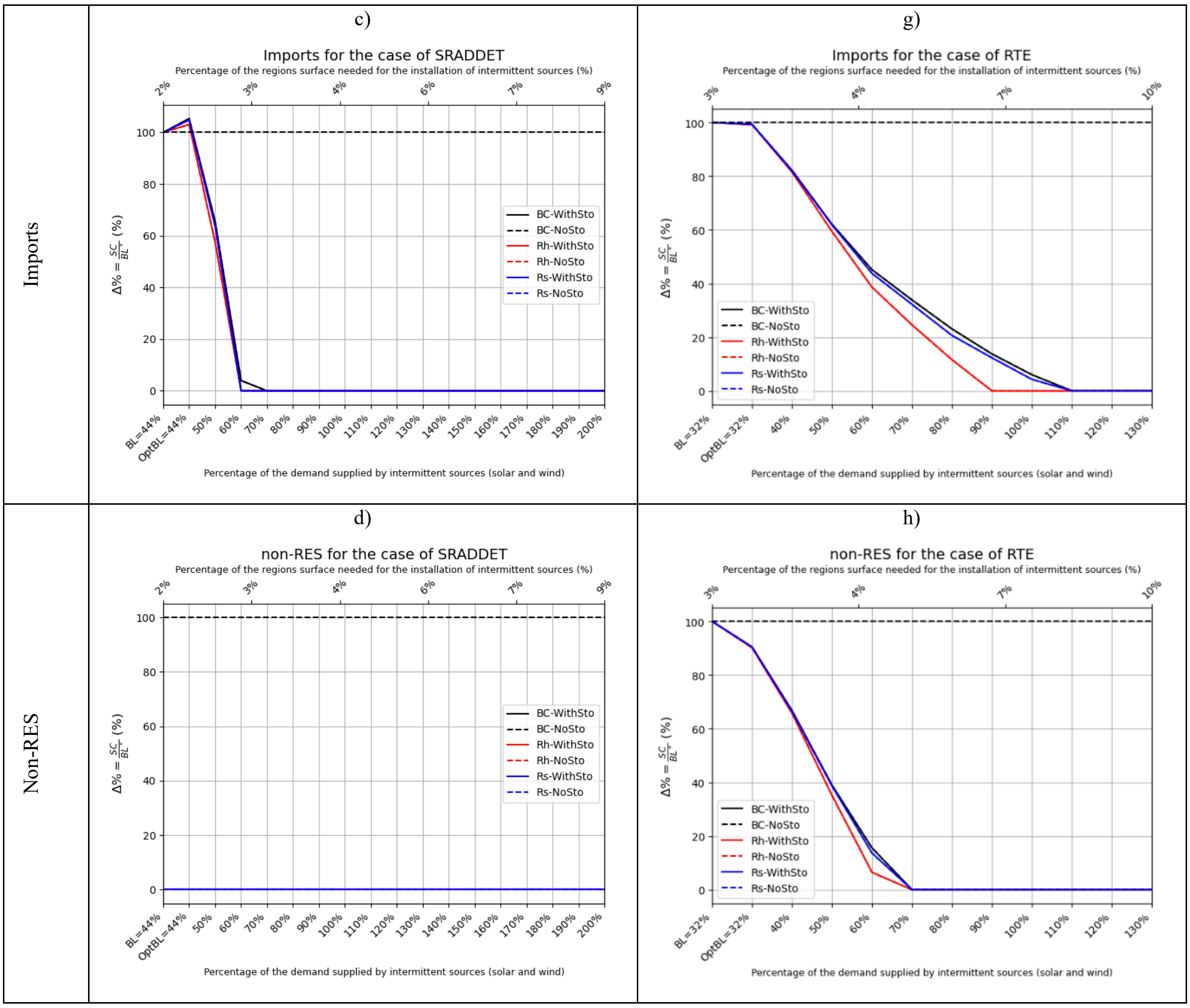
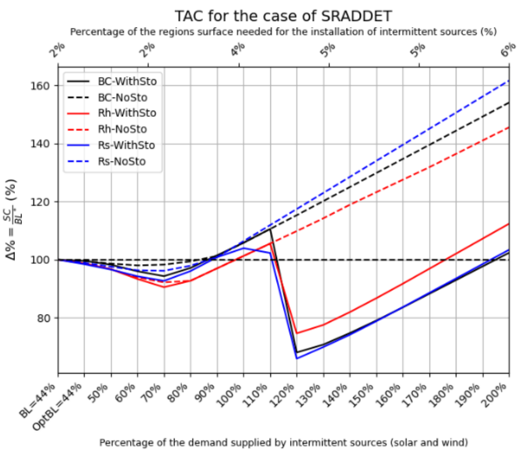
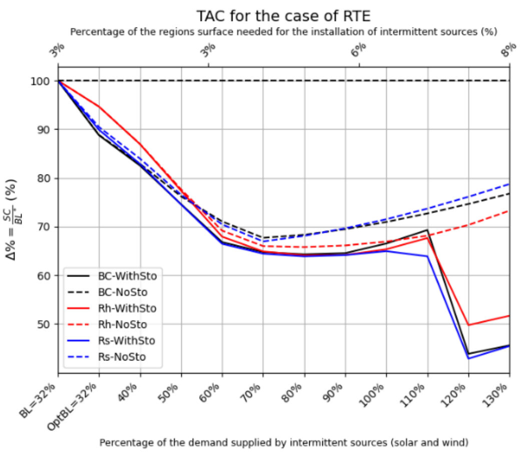


Figure 69 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a and e), GHG emissions (b and f), imports (c and g), and use of non-RES (d and h) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 1, for the study case of Grand-Est region of France. Parts a, b, c, and d correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts e, f, g and h correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4.1.2. Factor of reduction for the unitary costs of storage: 100

<table>
<tr><th></th><th>Minimum demand (SRADDET)</th><th>Maximum demand</th></tr>
<tr><td>Total annual costs</td><td>a)

</td><td>e)

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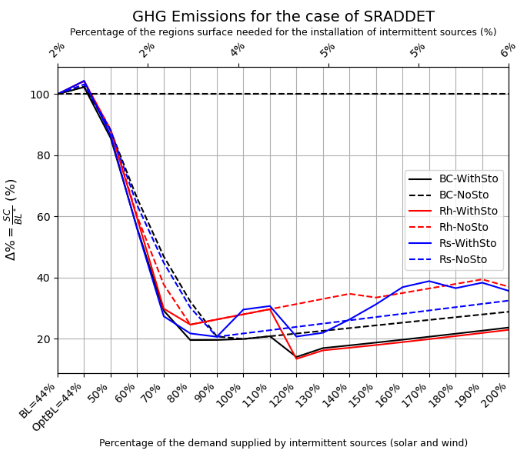
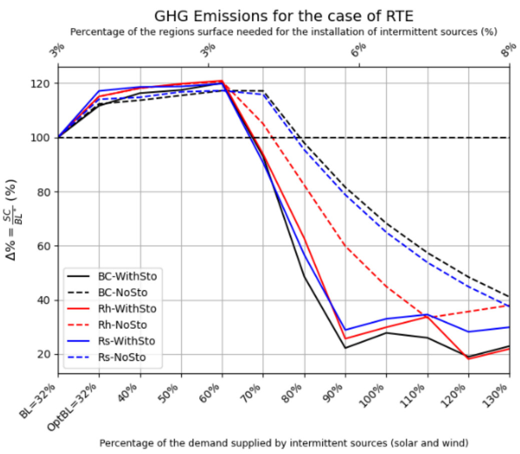
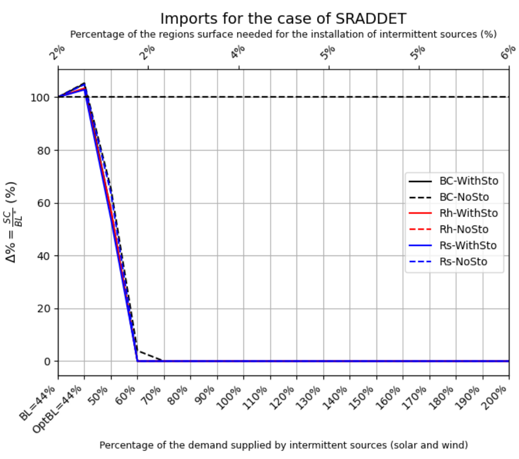
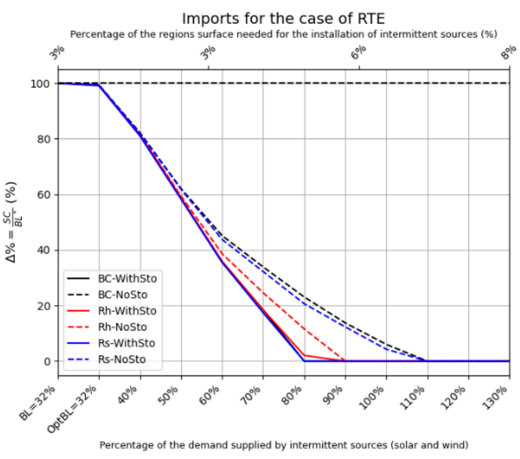
<tr><td>GHG emissions</td><td>b)

</td><td>f)

</td></tr>
<tr><td>Imports</td><td>c)

</td><td>g)

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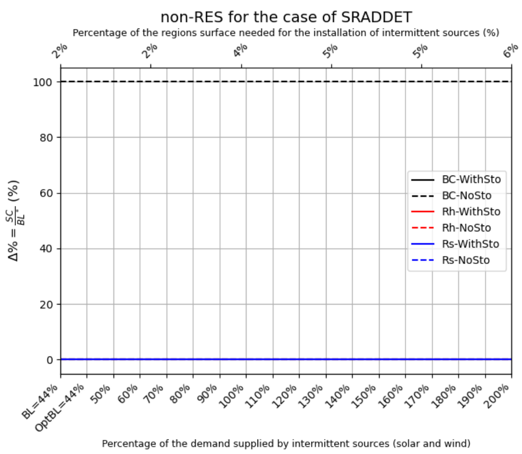
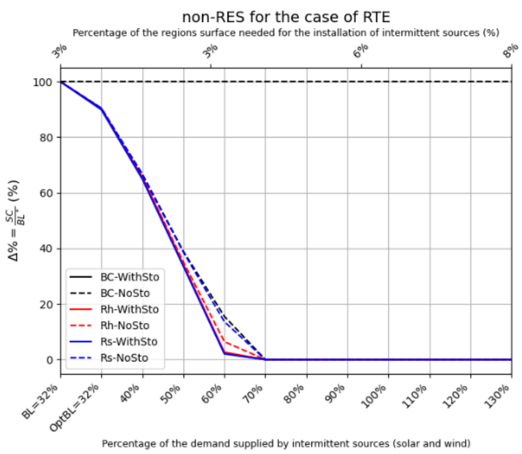
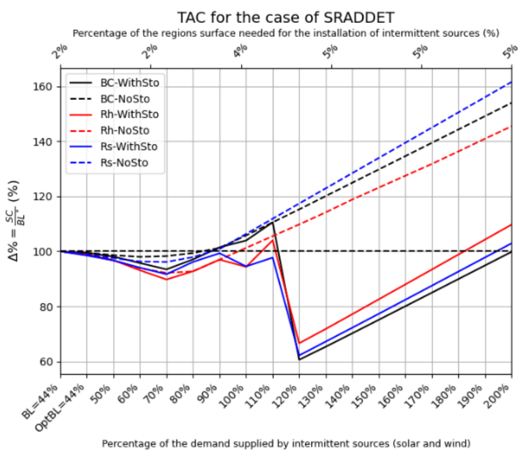
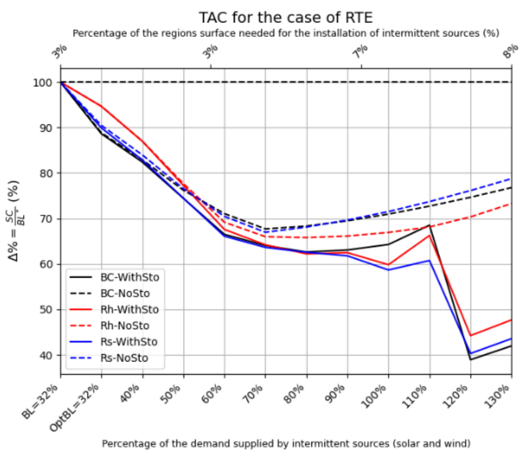
	d)	h)
Non-RES		

Figure 70 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a and e), GHG emissions (b and f), imports (c and g), and use of non-RES (d and h) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 100, for the study case of Grand-Est region of France. Parts a, b, c, and d correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts e, f, g and h correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4.1.3. Factor of reduction for the unitary costs of storage: 1000

	Minimum demand (SRADDET)	Maximum demand
	a)	e)
Total annual costs		

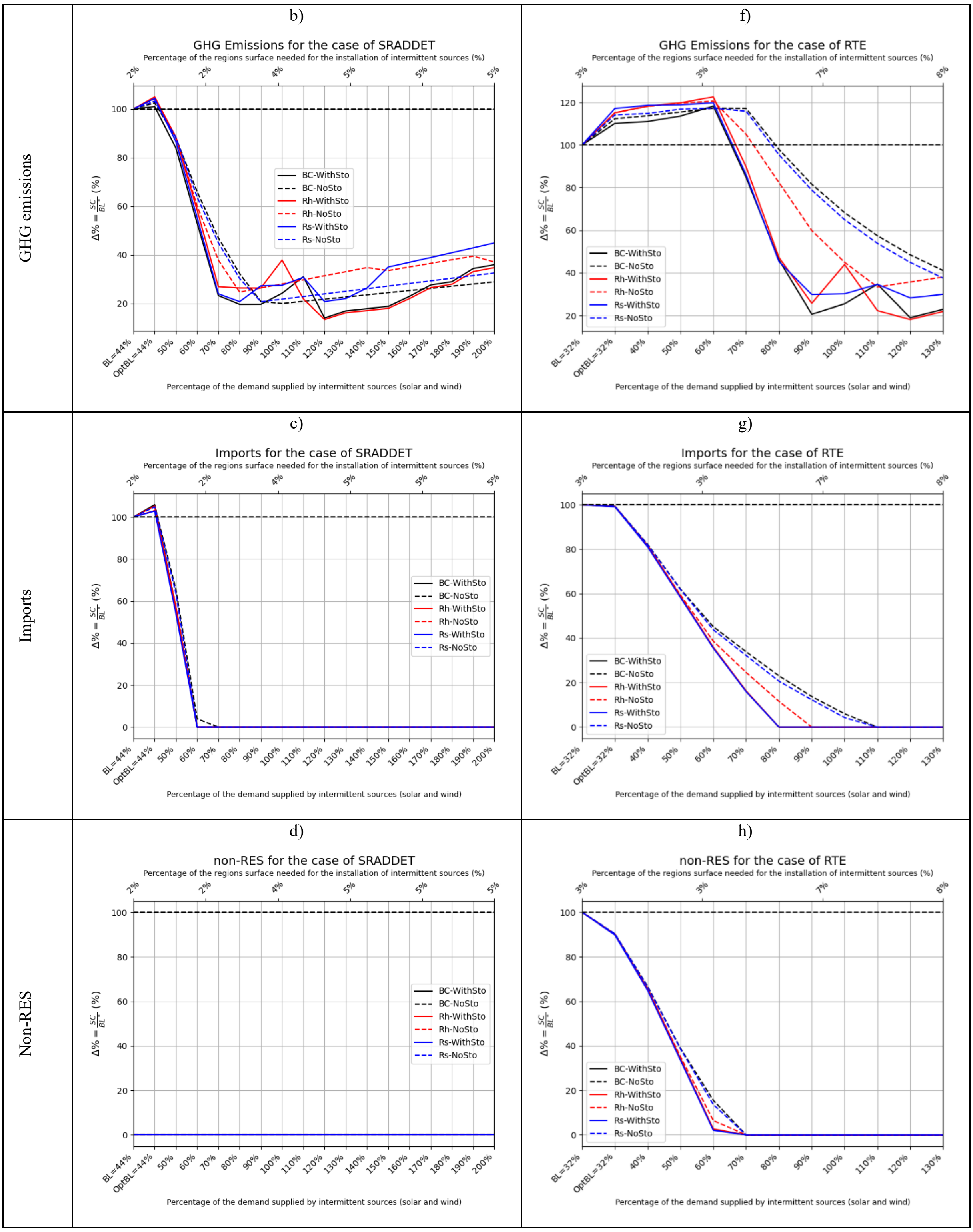


Figure 71 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a and e), GHG emissions (b and f), imports (c and g), and use of non-RES (d and h) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 1000, for the study case of Grand-Est region of France. Parts a, b, c, and d correspond to scenarios designed based on a minimum projected demand (official projection - SRADDET), and parts e, f, g and h correspond to scenarios designed based on a maximum demand estimation. The official baseline scenario and the optimized baseline scenario are denoted

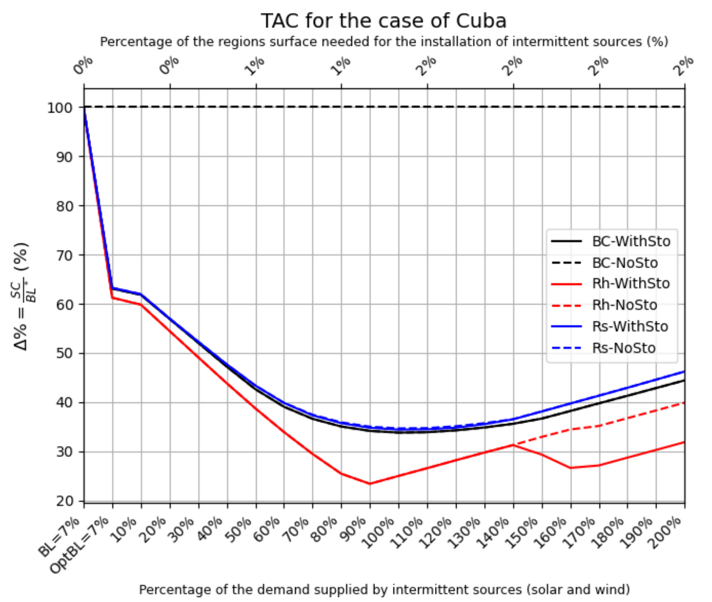
as “BL” and “OptBL”. The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4.2. Cuba

SP4.2.1. Factor of reduction for the unitary costs of storage: 1

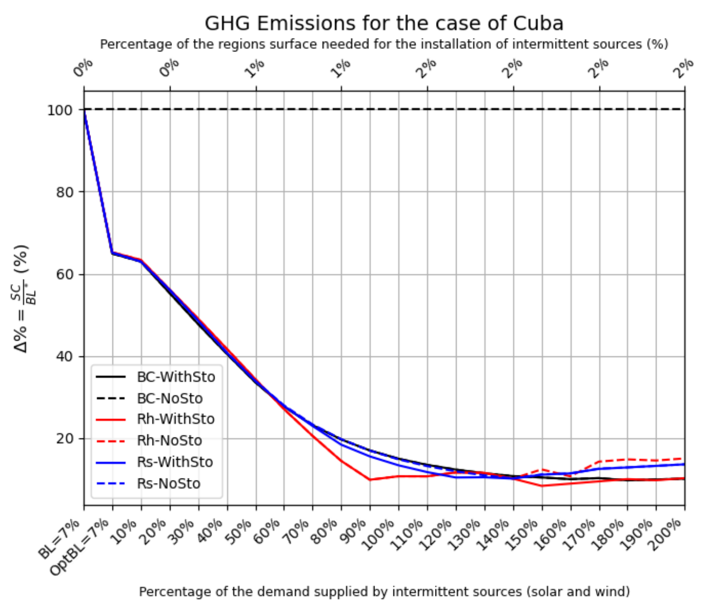
Total annual costs

a)



GHG emissions

b)



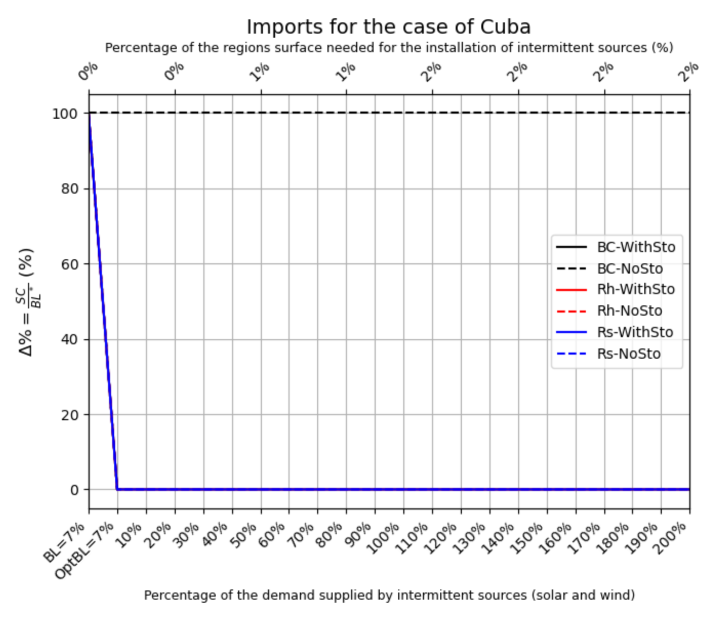
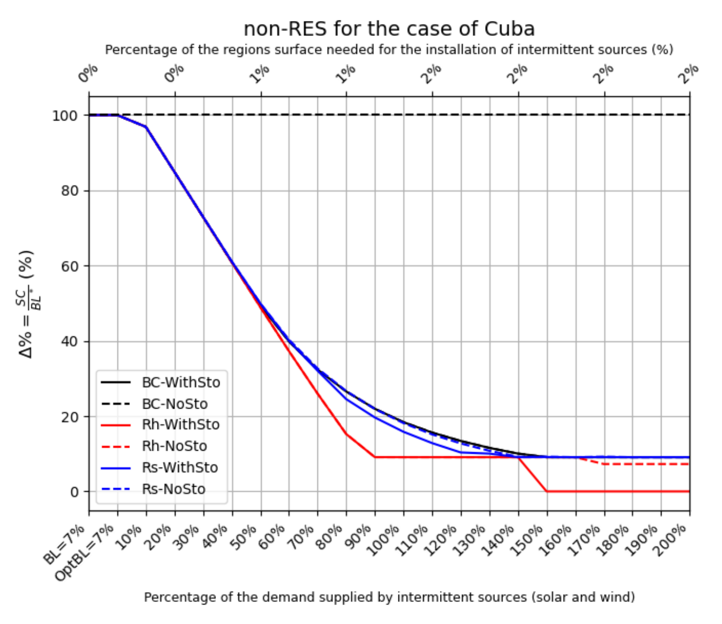
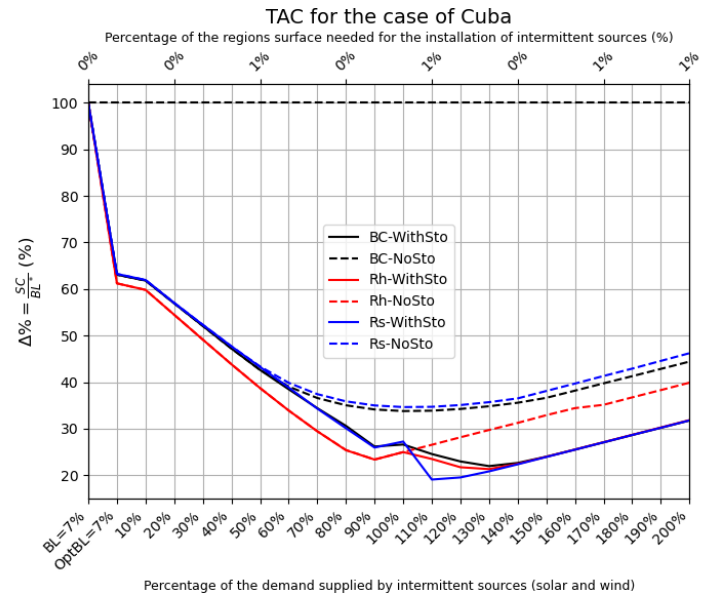
Imports	c) 
Non-RES	d) 

Figure 72 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a), GHG emissions (b), imports (c), and use of non-RES (d) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 1, for the study case of Cuba. The scenarios designed are based on the official projection of the Cuban authorities. The official baseline scenario and the optimized baseline scenario are denoted as “BL” and “OptBL”. The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4.2.2. Factor of reduction for the unitary costs of storage: 100

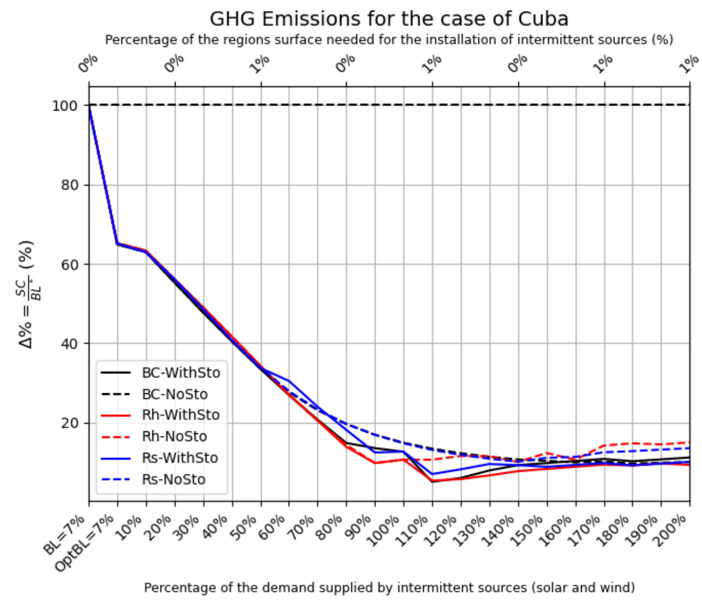
Total annual costs

a)



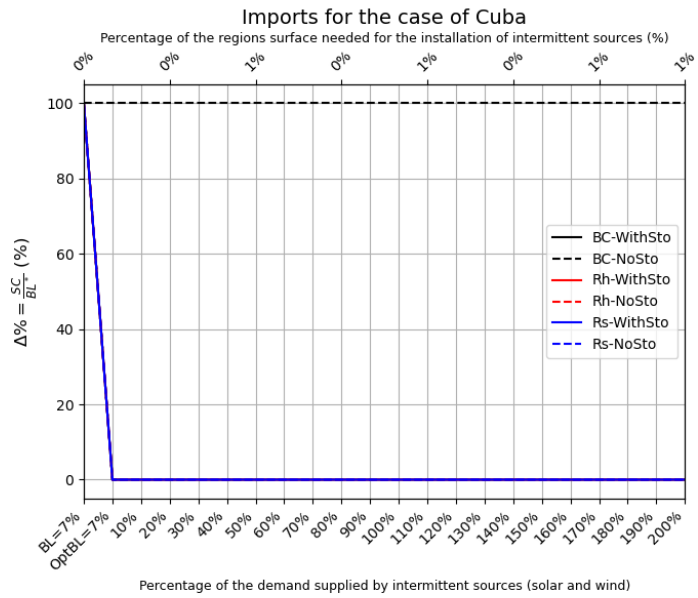
GHG emissions

b)



c)

Imports



d)

Non-RES

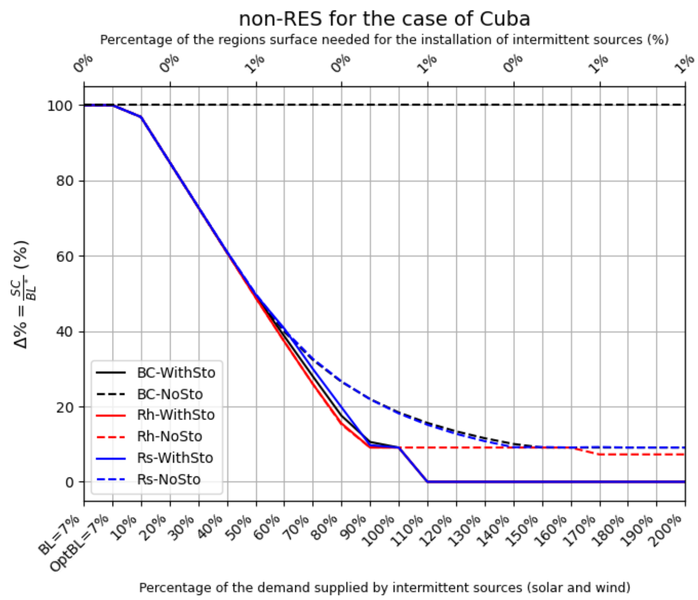
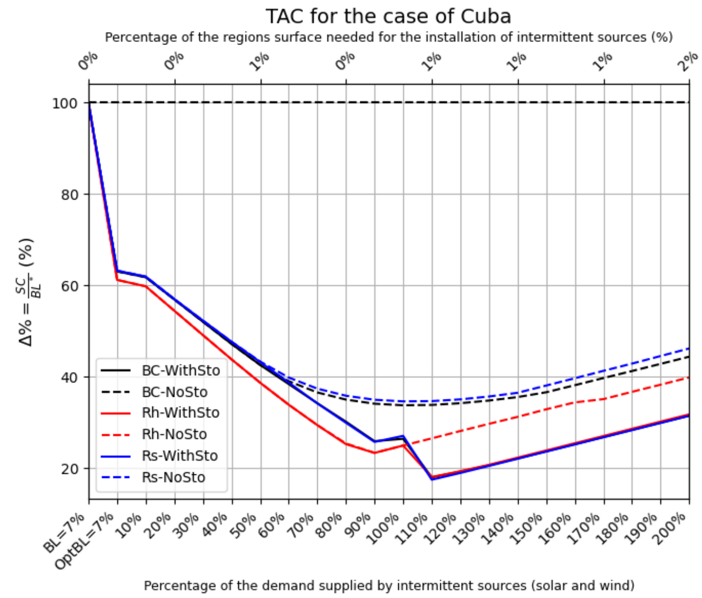
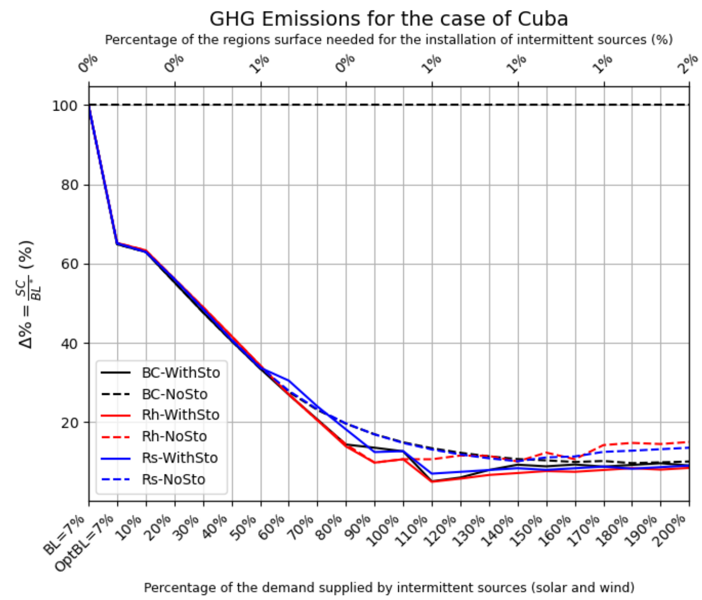


Figure 73 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a), GHG emissions (b), imports (c), and use of non-RES (d) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 100, for the study case of Cuba. The scenarios designed are based on the official projection of the Cuban authorities. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP4.2.3. Factor of reduction for the unitary costs of storage: 1000

Total annual costs	a) 
GHG emissions	b) 

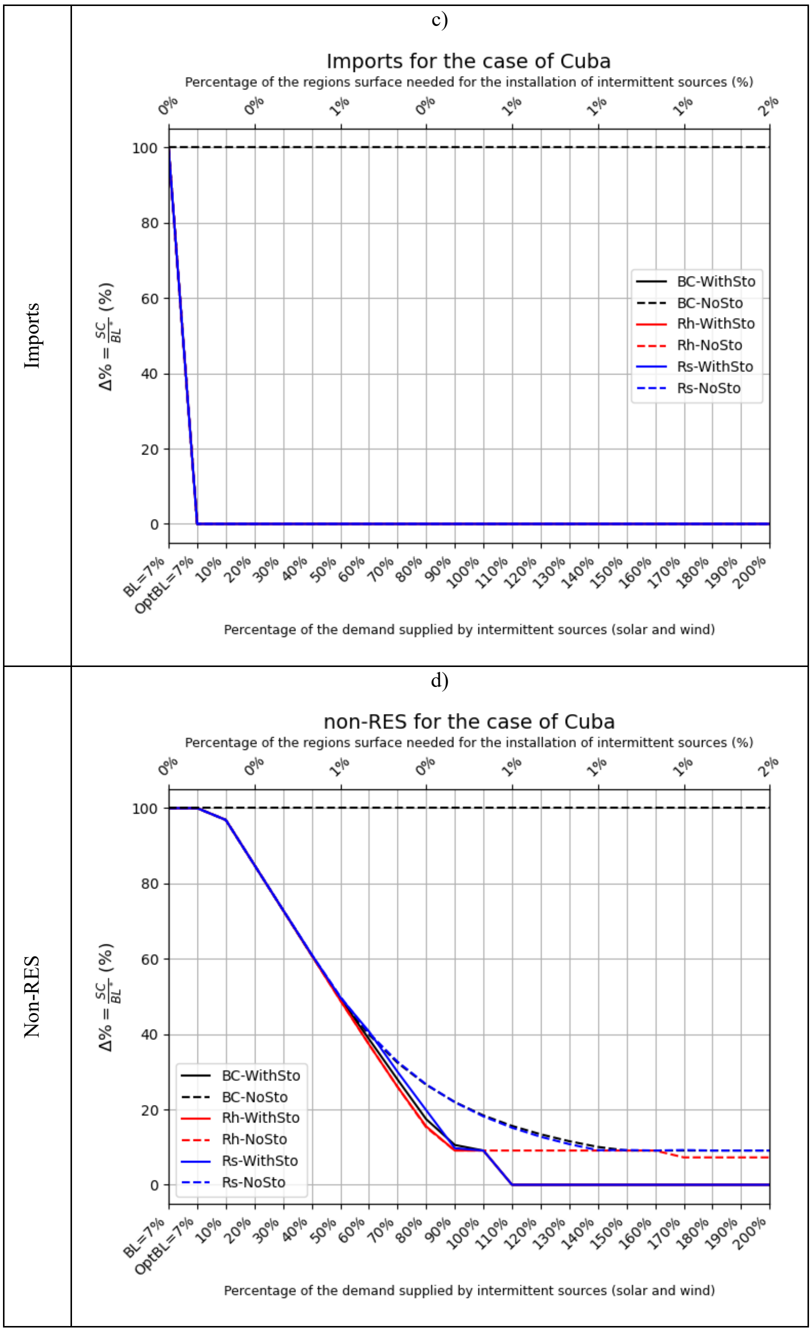


Figure 74 Sensitivity analysis to evaluate the effects of the demand adaptation on the calculated indicators: total annual costs (a), GHG emissions (b), imports (c), and use of non-RES (d) for the optimized scenarios with energy storage, reducing the unitary costs (costing parameters value) of energy storage by factor 1000, for the study case of Cuba. The scenarios designed are based on the official projection of the Cuban authorities. The official baseline scenario and the optimized baseline scenario are denoted as "BL" and "OptBL". The percentage of maximum storage capacity is selected as the one that minimizes the total annual costs for each scenario. Scenarios (bars) correspond to increasingly progressive introduction of intermittent (solar and wind) energy sources into the mix. The second horizontal axis represents the surface area required to install the solar panels and wind turbines for each scenario. Solid colors are associated with energy production and, consequently, variable costs, while hashed colors are linked to installed capacity (size of the facilities) and, therefore, investment and fixed costs.

SP5. Storage time

This section reports the result regarding the storage time for the cases of study in this research: the Grand Est region of France, and Cuba. The results plotted in this section also show the effects of the demand adaptation on the storage time and capacity.

SP5.1. Grand Est region of France

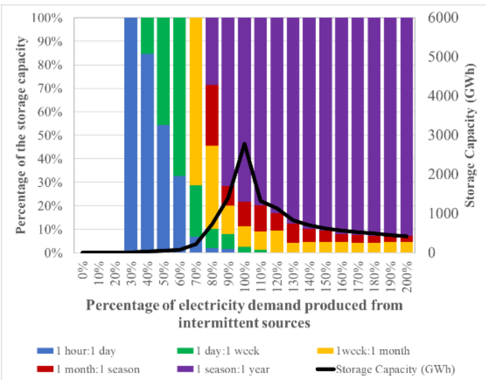
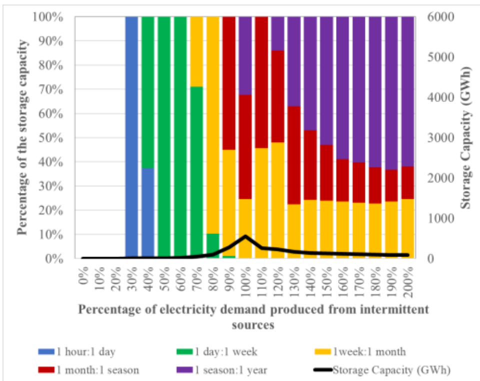
The Figure SP 5-1 and Figure SP 5-2 show the storage time and capacity for the Grand Est region of France without limit on the storage capacity and with limit on the storage capacity for the minimum demand projected (SRADDET) and with the maximum demand projected (RTE) respectively. The result with the modified (adapted) demand in the seasonal and daily time scales are also plotted.

Limiting storage capacity leads to shorter storage times. This effect is much more important in scenarios where demand is adapted to interseasonal variation in energy production ($\widehat{R_s}$). As a result, scenarios with a storage capacity limited to 10% of the maximum and with a demand adapted to interseasonal variation ($\widehat{R_s}$) require storing the energy during periods shorter than 3 months only if the percentage of intermittent is around 100%. The scenarios with 100% of intermittent sources in the mix and with limited storage capacity of the storage capacity used to store energy during more than 3 months (interseasonal time range) is 15% or less.

The daily adaptation of the demand ($\widehat{R_h}$) also helps to reduce the fraction of storage capacity used to store energy during long periods, but the reduction of the storage times is lower compared to the seasonal adaptation of the demand to the energy production.

In scenarios with no limit on storage capacity and with more than 80% of the energy produced by intermittent sources, a large percentage of the stored energy must be kept in storage for periods of more than one season (3 months).

The scenarios with production of intermittent energy greater than 100% of the demand, the storage times are greater than 1 week.

<table>
<tr><td></td><td>100%Smax</td><td>10%Smax</td></tr>
<tr><td></td><td>a)</td><td>b)</td></tr>
<tr><td>$\overline{R_h}$</td><td>
</td><td>
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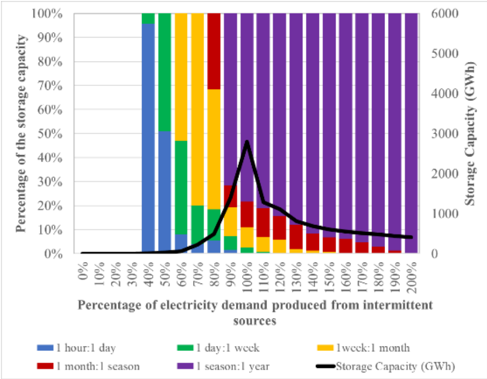
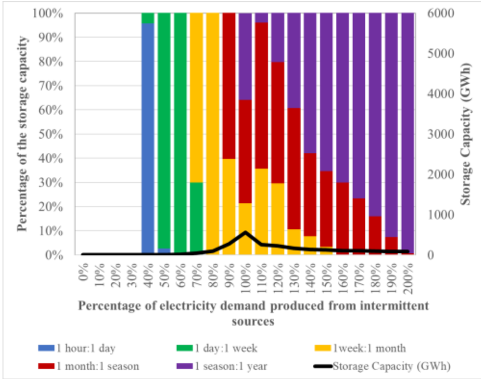
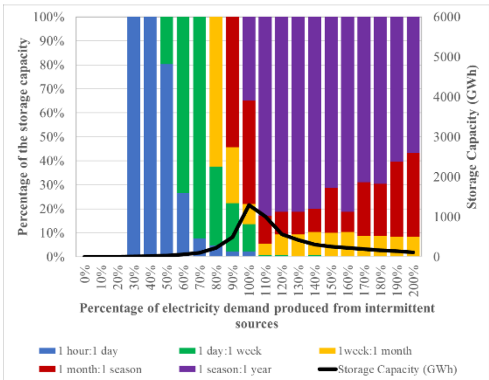
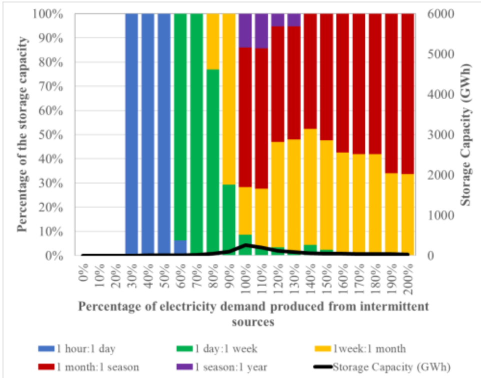
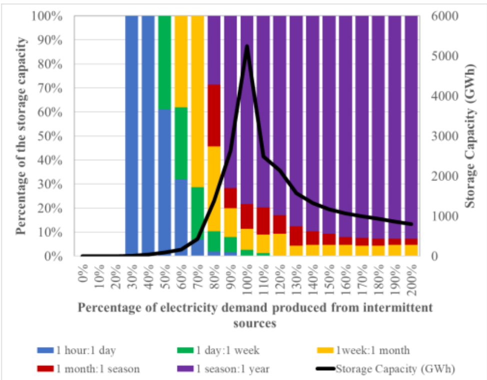
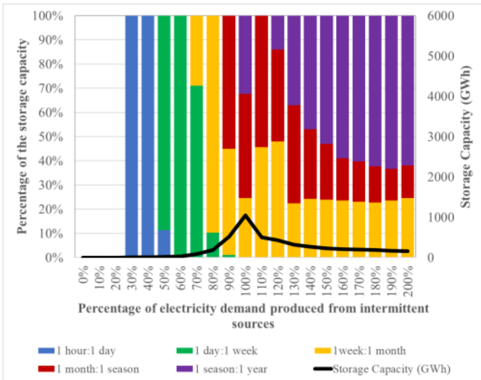
	c)	d)
$\widehat{R_h}$		
	e)	f)
$\widehat{R_s}$		

Figure 75 Storage time distribution for the scenarios considering the minimum electricity demand projected for the Grand Est region of France (SRADDET). The results to compare the demand adaptation are plotted, the fully time variation (BC) of the demand denoted by $\overline{R_h}$ (a and b), the demand adapted to the energy production in the daily denoted by $\widehat{R_h}$ (c and d) and seasonal denoted by $\widehat{R_s}$ (e and f) time scales. The results for the scenarios without storage limit (maximum storage capacity) are shown in parts a, c, and e; the results considering 10% of the maximum storage capacity are shown in parts b, d, and f.

	100%Smax	10%Smax
	a)	b)
$\overline{R_h}$		

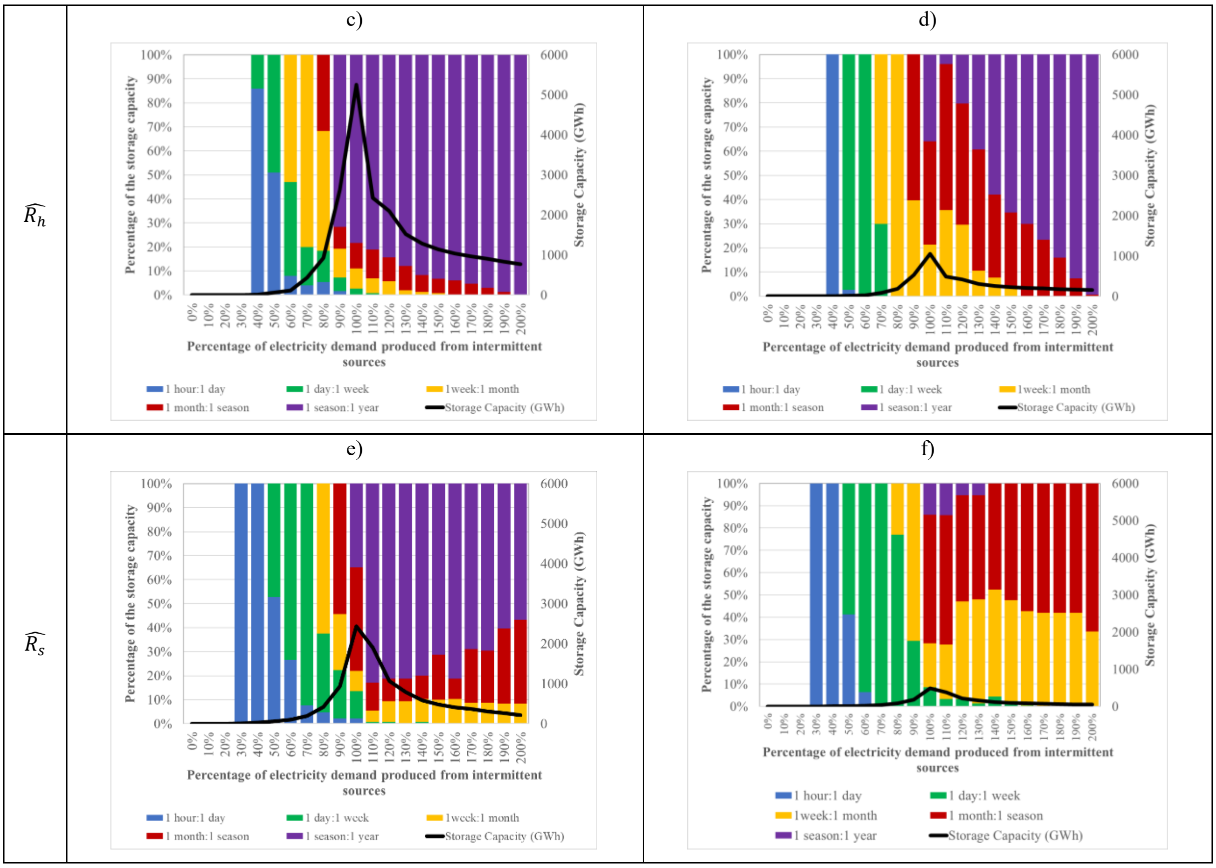


Figure 76 Storage time distribution for the scenarios considering the maximum electricity demand projected for the Grand Est region of France (RTE). The results to compare the demand adaptation are plotted, the fully time variation (BC) of the demand denoted by $\overline{R_h}$ (a and b), the demand adapted to the energy production in the daily denoted by $\widehat{R_h}$ (c and d) and seasonal denoted by $\widehat{R_s}$ (e and f) time scales. The results for the scenarios without storage limit (maximum storage capacity) are shown in parts a, c, and e; the results considering 10% of the maximum storage capacity are shown in parts b, d, and f.

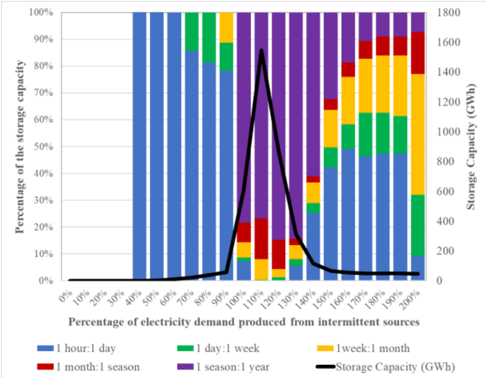
SP5.2. Cuba

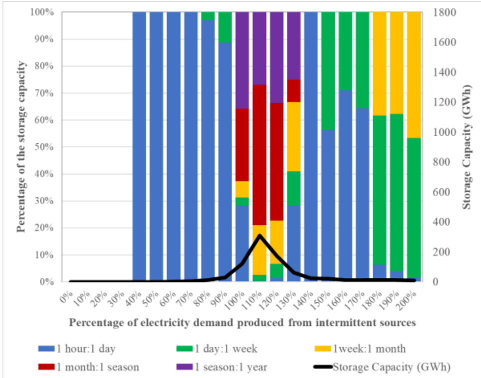
The Figure SP 5-3 shows the storage time and capacity for Cuba without limit on the storage capacity and with limit on the storage capacity.

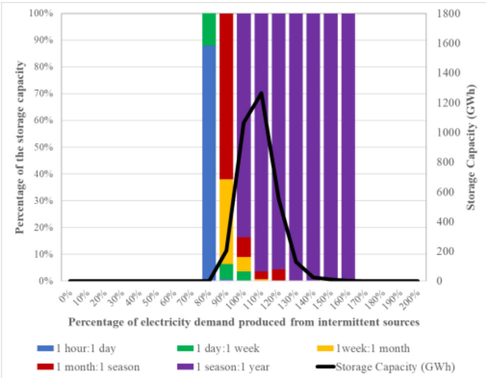
As for the case of the Grand Est region, limiting storage capacity leads to shorter storage times. Especially, for the demand adaptation to the seasonal variation of energy production, the scenarios do not need storage times longer than 3 months, and only a small fraction of the storage capacity is needed to store energy during times longer than one month in the scenario with 100% of the demand produced by the intermittent sources.

If the demand is not adapted, limiting the storage capacity also reduces the storage times. Only the scenarios with intermittent energy production between 100% and 130% of the demand need storage times longer than 3 months, and the fraction of the storage capacity used for this storage time range is reduced from around 80% to 30%.

The daily adaptation of the demand leads to reduce completely the need for storage in the scenarios with an introduction of intermittent sources below 80% and above 170%. The other scenarios with the daily adapted demand need long storage times.

<table>
<tr><td></td><td>100%Smax</td><td>10%Smax</td></tr>
<tr><td>$\overline{R_h}$</td><td>a)


</td><td>b)


</td></tr>
<tr><td>$\widehat{R_h}$</td><td>c)


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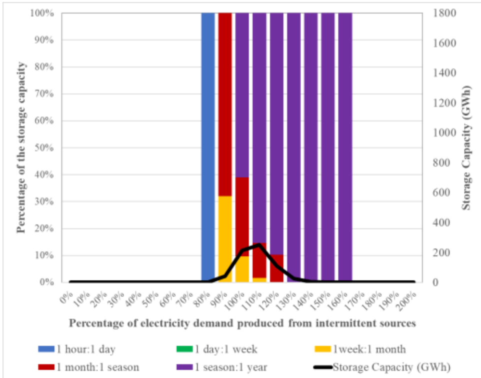

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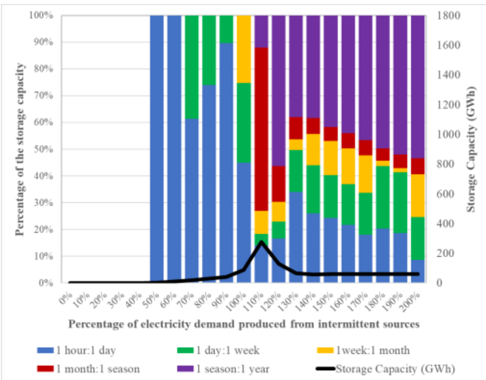
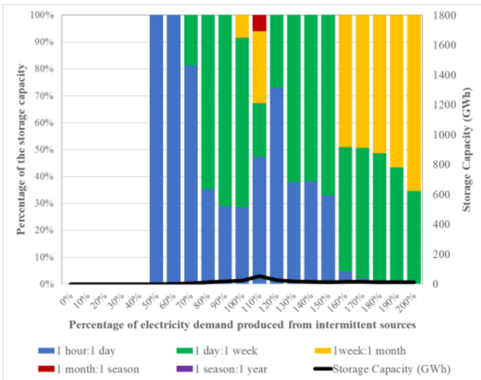
<tr><td>$\widehat{R_s}$</td><td>e)


</td><td>f)


</td></tr>
</table>

Figure 77 Storage time distribution for the scenarios considering for Cuba. The results to compare the demand adaptation are plotted, the fully time variation (BC) of the demand denoted by $\overline{R_h}$ (a and b), the demand adapted to the energy production in the daily denoted by $\widehat{R_h}$ (c and d) and seasonal denoted by $\widehat{R_s}$ (e and f) time scales. The results for the scenarios without storage limit (maximum storage capacity) are shown in parts a, c, and e; the results considering 10% of the maximum storage capacity are shown in parts b, d, and f.