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Dalla padella fossile alla brace nucleare

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Recentemente, il Governo Meloni ha ripreso con forza l'iniziativa nucleare in Italia, attraverso l'operato del Ministro Pichetto Fratin (MASE, Ministero dell'Ambiente e della Sicurezza Energetica) e l'introduzione, il 21 settembre 2023, della **“Piattaforma nazionale per un nucleare sostenibile (Pnns)”** con l'obiettivo di “definire in tempi certi un percorso finalizzato alla possibile ripresa dell'utilizzo dell'energia nucleare in Italia”. Il 22 gennaio 2025 il Ministro consegna formalmente il disegno di “Legge delega al Governo in materia di nucleare sostenibile”. Il 25 gennaio, Alleanza Verdi Sinistra e alcune organizzazioni ambientaliste proclamano il *“Green Energy Day: Giornata della Rivoluzione Energetica”*, con dibattiti e manifestazioni a Roma e numerose altre località in Italia, in particolare nei pressi delle centrali nucleari dismesse.

È qui che parte una nuova riflessione sull'energia nucleare e sulla sua reale possibilità di realizzazione in Italia (e nel mondo).

1. Nucleare “sostenibile”. La prima osservazione che merita di essere messa in rilievo è l'uso del termine “sostenibile”, attribuito all'energia nucleare. In effetti, questo termine non è stato mai chiaramente spiegato e non lo è nemmeno nei documenti-delega governativi. Per brevità, possiamo semplicemente sottolineare che per alcuni, una minoranza, il termine fa riferimento a un ipotetico minor costo economico rispetto al costo dei combustibili fossili o anche di alcune fonti rinnovabili. Per altri, la maggioranza, il termine deriva dalle minori emissioni di anidride carbonica e dunque maggiore sostenibilità ambientale. Per tale ragione, a volte viene utilizzato il sinonimo “nucleare verde”. Completamente assente l'idea che, oltre al beneficio di ridurre le emissioni serra, gli impianti nucleari contribuiscano ad altri impatti ambientali.

2. Costo ambientale del kWh nucleare. Tra i primi impatti possiamo certamente considerare la fase mineraria, un inevitabile passaggio per l'acquisizione del combustibile. È necessario fare mente locale al fatto che l'Italia non possiede miniere di uranio e dovrebbe acquistarlo dai paesi esportatori di tale risorsa. Questi paesi, soprattutto in Africa, Asia e America Latina, continuerebbero a scavare nelle proprie miniere, con ciò contaminando l'acqua potabile e il suolo agricolo locali e spesso sfruttando anche il lavoro minorile. E se questo impatto ambientale e sociale connesso all'estrazione non bastasse, va tenuto presente che il

funzionamento quotidiano dell'impianto, la preparazione del combustibile nucleare, il suo stoccaggio anche provvisorio dopo un certo numero di anni, il raffreddamento mediante notevoli quantità di acqua, comportano varie e note tipologie di impatto nell'aria, nell'acqua e nel suolo circostante miniere e impianti. Quando si indica come fattore importante il fatto che il nucleare non contribuisce in misura significativa al riscaldamento globale, ossia alla categoria di impatto "Emissioni di CO₂", è necessario ricordare innanzitutto che questo non è vero al 100% e, inoltre, che il nucleare contribuisce in misura notevole e superiore a qualunque altra fonte di energia all'emissione di radiazioni ionizzanti, come assodato da consolidate ricerche nel corso del tempo. Utilizzando l'analisi del Ciclo di Vita (LCA), è possibile confrontare le fonti fossili, la fonte nucleare e le altre fonti rinnovabili in un certo numero di categorie di impatto ambientale, con ciò verificando che non è tutto oro quel che luccica. Non solo la produzione elettrica da nucleare contribuisce a notevoli impatti da radiazioni ionizzanti, ma anche, per via della filiera mineraria e tecnologica (estrazione, lavorazione, smaltimento), a varie forme di tossicità (Ghisellini et al., 2010, 2013, 2025). E' stato dimostrato ampiamente che anche basse dosi di radiazioni possono generare impatti biologici di varia natura così che non abbia senso parlare di una soglia di sicurezza (Cieri et al., 1984; Soffritti et al., 2015; Ghisellini et al., 2023). E infine, la recente guerra tra Russia e Ucraina ha dimostrato gli enormi rischi ambientali che eventi bellici in prossimità di centrali nucleari possono generare (ad esempio, i bombardamenti avvenuti presso la centrale nucleare di Zaporiz'zja, 5.700 MWe).

3. Costo economico del kWh nucleare. Il costo dell'impianto varia a seconda della tipologia, della dimensione, di fattori assicurativi e altro, e oscillano tra i 5 e gli 11 miliardi di euro per GWe, una forbice "che dimostra una grande incertezza e una grande differenza nelle ipotesi", come illustrato da Antonino Neri su [energiaoltre.it](https://energiaoltre.it/quanto-costa-realizzare-una-nuovacentrale-nucleare-in-europa/) (<https://energiaoltre.it/quanto-costa-realizzare-una-nuovacentrale-nucleare-in-europa/>) e come recentemente testimoniato dagli impianti di Flamanville (Francia) e Olkiluoto (Finlandia).

Questi due fattori influenzano il costo finale del kWh prodotto. Ciò vale ovviamente per qualunque fonte energetica. La Figura 1 mostra i calcoli effettuati, relativamente al 2025, dal gruppo di ricerca finanziaria Lazard, presente in 22 paesi del mondo, tra cui anche a Milano dal 1960 (Lazard, 2025), ormai giunto alla diciottesima edizione del calcolo dei Levelized Costs of Energy, in cui si confrontano i costi dell'elettricità da diverse fonti. Tale valutazione, fa emergere chiaramente che l'energia nucleare non è competitiva né con le fonti rinnovabili né paradossalmente con le fonti fossili, soprattutto se si vanno a considerare i "costi nascosti" dello smantellamento, del trattamento delle scorie, dei danni alla salute e all'ambiente nei siti

minerari (e per le fonti fossili, l'inquinamento da combustione ed emissioni di gas serra). Nella Figura 1 solo il solare PV residenziale mostra risultati non competitivi, trattandosi, come è facile immaginare, di una situazione molto particolare (pannelli su tetti di abitazione residenziale), dove alcuni costi e alcuni aspetti tecnici sono specifici della singola abitazione.

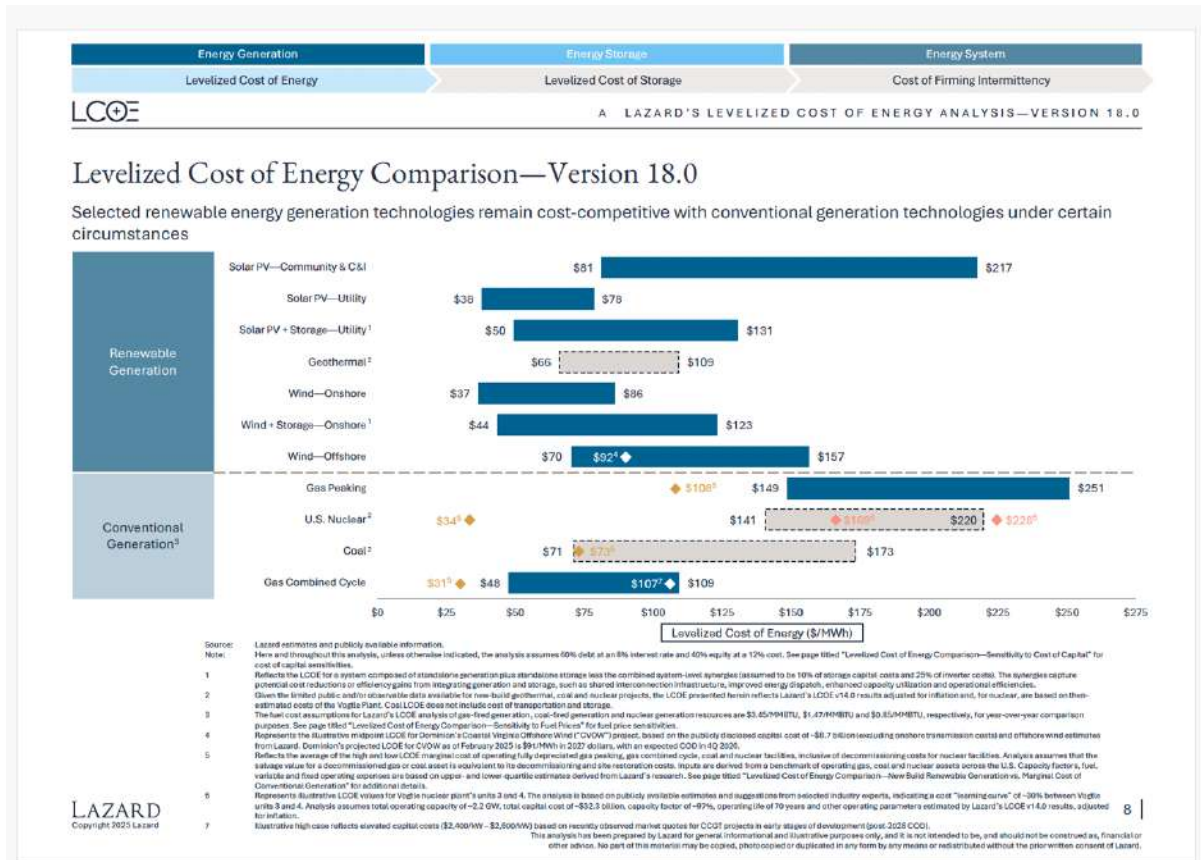


Figura 1. Levelized Costs of Energy (<https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energy-plus-report-pr/>)

4. Disponibilita' di Uranio per i nuovi reattori. Ad oggi la generazione da nucleare copre approssimativamente il 9,1% del mix elettrico a livello mondiale. Ciò avviene utilizzando le circa 50.000 tonnellate di uranio/anno scavate nelle miniere del pianeta e circa 10.000 tonnellate di Uranio riciclato. Il resto della produzione e del consumo elettrico mondiale proviene da fonti fossili e rinnovabili di varia natura. Le riserve totali di uranio (0,7% U²³⁵, 99,3% U²³⁸), sommando le RAR-Reasonably Assured Resources, ossia le quantità ottenibili a un prezzo minore o uguale a 130 US \$/kg U, e le Inferred Resources, ossia recuperabili, ma ancora con molta incertezza, al 2023 consistevano in circa 5.925.700 t U, stando a dati OECD, NEA & IAEA (<https://www.wise-uranium.org/umaps.html>). Le risorse totali (RAR+inferred)

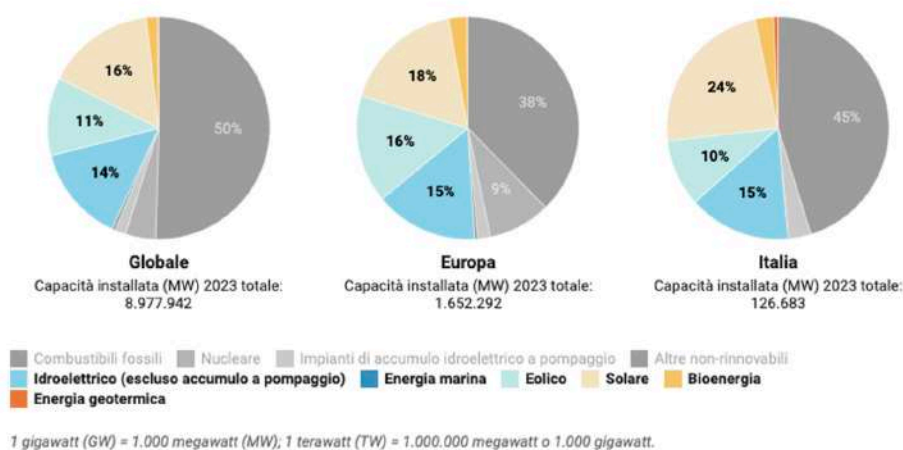
identificate entro un prezzo di 260 US \$kg U sarebbero invece circa 7.934.500 tonnellate U, il che determinerebbe comunque un notevole aumento del costo dell'elettricità prodotta.

Nel 2023, le centrali nucleari attive erano 440 in 33 paesi del mondo con una potenza di generazione elettrica pari a 398.553 MWe (398,5 GWe). Dunque, una potenza media di circa 0,90 GWe (900 MWe) per ogni centrale (assumendo in via teorica, per facilitare il confronto tra impianti esistenti, che tutte abbiano la stessa potenza). La figura 2 mostra una **capacità elettrica totale** mondiale installata (comprensiva di tutte le fonti rinnovabili e non rinnovabili) pari a 8.977,94 GWe, in cui la capacità elettrica nucleare rappresenta soltanto il 4,4%, le fonti rinnovabili circa il 43%, e le fonti fossili circa il 53%.

Nello stesso anno, la **produzione elettrica globale** complessiva ammontava a 29.472 TWhe, mentre quella da fonte nucleare è stata di 2.686 TWhe, come già detto, pari al 9,1% della produzione totale (Tabella 1). Le rinnovabili (compresa la fonte idroelettrica) hanno assorbito una share del 30%, mentre la percentuale di produzione da fonte fossile e da recuperi termici non rinnovabili è stata pari a circa il 60,6%. La maggiore percentuale di elettricità prodotta rispetto alla potenza installata nel caso del nucleare e delle fonti fossili va ovviamente attribuita al fatto che tali impianti funzionano a pieno regime (salvo eventuali problemi tecnici), mentre le fonti rinnovabili sono caratterizzate da una maggiore intermittenza, di cui è necessario tenere conto nella eventuale transizione verso tali forme di generazione elettrica.

Figura 2. Potenza elettrica installata nel mondo, in Europa e in Italia

Le rinnovabili hanno raggiunto 3.864.522 megawatt (quasi 3,9 terawatt), che corrispondono al 43% dei quasi 9 TW totali installati a livello globale nel 2023.



Fonte: IRENA- Renewable energy statistics 2024 -

<https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024>

Tabella 1. Potenza installata e produzione elettrica nell'anno 2023. (EMBER: <https://ember-energy.org/app/uploads/2024/05/Report-Global-Electricity-Review-2024.pdf>; IRENA: <https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024>)

Fonte energetica	Potenza elettrica installata (GWe)	%	Produzione elettrica (TWhe)	%
Nucleare	398,5	4,4	2.686	9,1
Rinnovabili (incluso idroelettrico)	3.864,5	43,1	8.932	30,3
Fossili (inclusi recuperi termici non rinnovabili)	4.714,9	52,5	17.854	60,6
Totale fonti	8.977,9	100	29.472	100

Facciamo adesso un po' di conti. Se volessimo (per una ipotesi assurda) eliminare completamente i combustibili fossili sostituendoli con l'energia nucleare (e assumendo per semplicità che le fonti rinnovabili mantengano la percentuale del 2023), dovremmo installare un numero di centrali nucleari tale da sostituire l'attuale potenza elettrica fossile, ossia $4.714,9 : 398,5 = 11,8$, pari a una quantità di reattori circa 11,8 volte quella attuale. Dato che la potenza nucleare installata nel 2023 ha utilizzato, come già detto, circa 50.000 t U, servirebbe una quantità di uranio pari a $11,8 \times 50.000 \text{ t U} = 590.000 \text{ t U/anno}$. In conclusione, l'Uranio RAR+Inferred diviso per l'Uranio totale usato annualmente, risulterebbe in circa 10,0 anni ($5.925.700 \text{ t U} : 590.000 \text{ t U/anno}$). Anche considerando le riserve attualmente stimate allo stratosferico costo di 260 US \$/kg, cioè una disponibilità mondiale pari a 7.934.500 t U, sarebbero sufficienti solo per i prossimi 13,4 anni circa ($=7.934.500 : 590.000$). Se invece le nuove installazioni di potenza nucleare andassero a sostituire solo la metà degli impianti fossili, lasciando ad altre strategie (ad esempio, l'aumento dell'efficienza energetica, l'economia circolare e ulteriori fonti rinnovabili) la riduzione dell'altra metà, le riserve di uranio esistenti a prezzo accessibile sarebbero sufficienti per 24 anni, ben prima della commercializzazione dei reattori a fusione. Alla fine, le centrali installate rimarrebbero, di fatto, senza combustibile, a meno di riconvertire tutto il patrimonio nucleare in reattori al plutonio, cosa che già parzialmente avviene in un piccolo numero di reattori nucleari nel mondo, con problemi tecnologici e ambientali di gran lunga maggiori.

E non è tutto. Per brevità elenchiamo sinteticamente una serie di altri problemi, per quanto riguarda l'Italia (ma non solo):

- A) **Acquisto di Uranio dall'estero.** L'uranio va importato dai paesi che hanno le maggiori riserve (Kazakhstan, Canada, Namibia, Australia,...ma anche Russia, Cina, India). Pur non considerando il presumibile aumento dei prezzi dell'Uranio determinato dalle logiche e dalle dinamiche del libero mercato, alcuni di questi paesi potrebbero anche preferire di tenerlo disponibile per proprio futuro utilizzo oppure venderlo a paesi appartenenti a diverse alleanze economiche o militari. Si finirebbe comunque col sostituire la dipendenza da importazioni fossili con la dipendenza da importazioni uranifere. (<https://www.wise-uranium.org/umaps.html>)
- B) **Aumentare le estrazioni minerarie di uranio** nei paesi produttori non è cosa realizzabile in tempi brevi, non solo a causa di evidenti problemi tecnici, ma anche a causa degli impatti delle nuove miniere sul suolo, sull'acqua e sull'aria (e globalmente sulla salute degli abitanti) dei paesi ricchi di riserve uranifere.
- C) **Accordi per l'importazione di uranio.** Dovrebbero avvenire in parallelo con la costruzione delle eventuali nuove centrali. Il rischio è di trovarsi con la centrale pronta e il combustibile non più disponibile o disponibile a prezzo elevatissimo.
- D) **Scelta dei luoghi idonei.** La costruzione di nuove centrali richiede l'individuazione di luoghi idonei (densità di popolazione, sismicità, corsi d'acqua e zone a rischio di alluvione, etc) in quantità uguale o maggiore alle centrali pianificate. L'individuazione dei luoghi è, solitamente, un problema di difficile soluzione a causa dell'opposizione delle popolazioni locali (spesso non adeguatamente informate) e delle forti criticità di individuazione di siti affidabili. Si consideri, infatti, che l'Italia è una delle nazioni europee a più alto rischio sismico (Ulgiati e Ghisellini, 2013, Figura 5).
- E) **Piano di smantellamento e depositi per le scorie.** Ogni centrale nucleare richiede un piano dettagliato per il deposito sicuro delle scorie e dei componenti derivanti dallo smantellamento a fine vita. Le scorie ad alta attività, per quanto riguarda l'Italia, sono state quasi completamente trasferite in centri di riprocessamento all'estero, per la separazione e recupero del combustibile ancora utilizzabile e lo stoccaggio permanente di quello non riutilizzabile. Resteranno parcheggiate in tali centri finché l'Italia non costruirà un deposito permanente.
- F) **Tempi per la costruzione.** La costruzione di una centrale nucleare richiede tempi intorno ai 6-8 anni (in teoria), ma in numerosi casi (ad esempio, Flamanville in Francia, Olkiluoto in Finlandia) ha superato anche i 10 anni, con ciò evidenziando il nucleare come uno

strumento poco idoneo all'urgenza dei piani di decarbonizzazione necessari a livello mondiale ed europeo per combattere il cambiamento climatico.

G) Investimenti complessivi. La costruzione di un adeguato numero di impianti nucleari di varia dimensione, inclusi i fantomatici *Small Modular Reactors* (SMR) e Advanced Modular Reactors (AMR) fino a 300 MWe e l'inesistente tecnologia nucleare di IV generazione, comporta costi variabili tra i 5 e i 10 miliardi di euro per GWe installato. Dunque, gli investimenti finanziari richiesti per la eventuale transizione al nucleare in Italia mediante l'installazione di almeno 15 GWe nucleari rappresentano un importo molto vicino a 150 miliardi di euro. Al di là di individuare una appropriata e certa fonte finanziaria, occorrerebbe predisporre un credibile piano finanziario in grado di far fronte ai numerosi rischi e incertezze che caratterizzano questo investimento.

H) La delega al Governo prevista dal DDL 2669. Prevede una serie di investimenti per la ricerca di siti adeguati, formazione di personale tecnico, costruzione di impianti elettrici, siti di stoccaggio temporaneo e permanente delle scorie, impianti di trattamento del combustibile, forme di compensazione dei territori che ospiteranno gli impianti, sicurezza per tali territori. La lista dei commi previsti nei 4 articoli del DDL 2669 e' estremamente dettagliata e richiederà tempi e costi di gran lunga superiori a quanto previsto.

In conclusione, è dunque molto probabile che la filiera nucleare continuerà ad essere una frazione ridotta rispetto alla domanda elettrica del mondo (almeno fino a quando non sarà disponibile ed operativa la fusione nucleare), concentrata per un tempo molto breve in un limitato numero di paesi, la cui tecnologia e la cui disponibilità finanziaria siano tali da consentirne l'utilizzo. Gli altri paesi del mondo continueranno a utilizzare i combustibili fossili (se in grado di affrontarne i costi) oppure (quelli in via di sviluppo soprattutto in Africa) a disporre soltanto di 3-4 ore giornaliere di disponibilità della rete elettrica, a meno che non riescano ad effettuare una veloce e improbabile transizione alle filiere rinnovabili. Investire (come Comunità Europea o singoli paesi) nella crescita delle energie rinnovabili anche in questi paesi potrebbe costituire in un vantaggio ambientale di decarbonizzazione molto maggiore dell'investimento in nucleare in Italia.

La politica del Governo Italiano e di alcune forze politiche anche non governative rischia di portare l'Italia in un vicolo cieco dove, dopo aver investito incredibili quantità di denaro ci si ritrovi dipendenti dall'estero per le importazioni di uranio (se ancora ce ne sarà disponibile). L'eventuale costruzione di reattori nucleari di nuova generazione rappresenta un grande punto

interrogativo circa il loro effettivo funzionamento e contributo, stante l'esiguo numero e l'incerto funzionamento di questi impianti nel mondo.

Sarebbe bene che ogni proposta di nuovi impianti venisse accompagnata da una chiara e preventiva indicazione della località in cui si intende costruirli, così da consentire un'analisi preventiva da parte di esperti indipendenti e un chiaro confronto con le popolazioni locali interessate.

Invece di cercare nuove fonti di energia fossile o nucleare dall'estero, sarebbe finalmente il caso di modificare le forme di produzione e consumo energetico nel nostro paese, aumentando gli investimenti per le risorse energetiche rinnovabili (solare, eolico, biomasse), l'efficienza in alcuni settori (industria, settore abitativo), riducendo consumi inutili e sprechi (economia circolare, recupero di risorse e energia dai rifiuti e dalle acque reflue), modificando gli stili di vita (mobilità individuale e collettiva, pendolarismo, educazione al consumo, ecc.). Solo così il nostro paese potrà evitare di passare dalla padella fossile alla brace nucleare.

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ENVIRONMENTAL, ECONOMIC AND FINANCIAL UNCERTAINTIES OF NUCLEAR ELECTRICITY

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ABSTRACT

The so-called nuclear *revival* worldwide is investigated for environmental impact, technical feasibility, nuclear fuel availability, market competition, financial risk and macroeconomic impacts. The resulting picture, based on a review of more than one hundred LCA literature studies worldwide points out the existence of a large uncertainty on all the main aspects of the nuclear energy system, thus preventing the policy maker from relying on a stable and certain set of feasibility indicators. Uncertainty therefore becomes the driving concept in decision making about nuclear energy.

Keywords: nuclear energy, energy prices, uncertainty

1. INTRODUCTION. THE NUCLEAR RENAISSANCE.

The first years of the new millennium seem characterized by a renewed interest in nuclear energy (Adamantiades and Kessides, 2009), the so called "nuclear revival" (Owen, 2006). In developing countries thirty plants are in construction against the five in OECD countries (two in Europe: France and Finland) (ARPA, 2009; WNA, 2009). The Italian energy policy is also influenced by this interest wave, after the nuclear phase-out decided in 1987. This resurgence of interest is mainly based on claims that nuclear energy is cheaper, has lower price volatility compared to fossil fuels, it is secure in supply (Linares and Conchado, 2009) and does not contribute to climate change.

1.1 The search for carbon free energy

Low nuclear GHG emissions is perhaps the most emphasized, studied and debated aspect. According to Sovacool (2008a), advocates of nuclear power consider it "the only non-greenhouse gas emitting energy source that can effectively replace fossil fuels and satisfy global demand". A 1000 MW_{el} coal power plant releases about 6 millions tons of CO₂ per year, while nuclear is claimed by its supporters to be quite CO₂ free. According to the international Nuclear Energy Agency (NEA, 2002) in the last 40 years nuclear has contributed to avoid 1,200 million tons per year of carbon dioxide. Opponents have objected that "nuclear plants are poor substitutes to other less intensive greenhouse gas generators": wind and hydroelectricity have respectively one-third and one-fourth less CO₂-equivalent emissions than nuclear power. The Oxford Research Group (Sovacool, 2008a) predicts that, assuming constant nuclear capacity, 2050 nuclear CO₂ emissions per kWh would equal those from gas fired power plants due to decreasing uranium ore grade.

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1.2 Radioactive waste

The contribution to climate change is only a part of the story. Other relevant aspects include “high capital cost, proliferation of dangerous materials, nuclear terrorism, operation safety and radioactive waste disposal” (Toth and Rogner, 2006; Romerio, 2007; IAEA, 2008; Lenzen, 2010). Large amounts of nuclear waste have been accumulated in USA (Lior, 2006; Lenzen, 2010) and worldwide and there is no easy solution for radioactive waste disposal or destruction (Lior, 2008). No country has yet adopted a successful disposal after fifty years of nuclear civil programs. The first commercial geological repository is expected to open in Sweden by 2018 (ARPA, 2009); the solution to the nuclear waste issue (short-term and long-term nuclear waste management and spent fuel processing) is a prerequisite for further expansion of nuclear industry (Abu-Khader, 2009).

1.3 Market uncertainty

The actual competitiveness of nuclear must be analyzed in a wider perspective. It cannot only rely on the analysis of greenhouse gas emissions, since nuclear is a very complex and expensive technology and many more aspects come into play. The liberalization of electricity markets shows that the fate of nuclear is strongly affected by energy market structure. The loss of some main favorable conditions (governmental support, certainty of demand, a price regime based on recovering the production cost increase by charging higher prices to consumers, etc), lead to a drop of the number of nuclear plants built from 1990 to 2005 to only 1.7 nuclear plants per year (mainly in developing countries) compared to 17 nuclear plants per year built in the period 1970-1990 (ARPA, 2009). In liberalized electricity markets decisions about energy technologies are driven by the expected returns, taking into account the risks (afforded by the company, rather than by consumers as in a monopoly regime) linked to costs and revenues (Gross et al., 2009). Moreover, nuclear energy has to face new competitors such as renewable source technologies, characterized by a lower carbon content, better environmental footprint, increased population acceptance and higher growth rates favoured by cost reduction driven by technological innovation.

2. NUCLEAR ENERGY. A WORLD OVERVIEW

About 440 reactors are presently in operation in 30 countries with a total installed capacity of 372 GW_{el}. Compared to fossil fuels, used in power generation, residential, commercial, industrial and transport sectors, nuclear energy is only used for electricity generation. Electricity from all sources has a market share of about 17.1% worldwide and 21.1% in OECD countries, in terms of final energy consumption. The nuclear share of world electricity supply during the period 1973-2008 increased from 3,3% (1973) to about 18% (1990), then decreased to 13.5% (2008) (De Paoli, 2008; IEA, 2010). Oil powered electricity declined its share from 24.7% (1973) to 5.5% (2008). Natural gas and to a lesser extent coal expanded their share in the same period (IEA, 2010).

Nuclear energy supplies about 34% of the total electricity produced in the European Union. Italy does not have nuclear plants in operation but imports about 15% of its electricity mainly from France, where 77% of electricity comes instead from nuclear (ENEA, 2009). The global nuclear electricity generation (except for China and India) is projected to increase at rates lower than the overall electricity generation by 2030 (Lenzen, 2010). IEA (2008) foresees an installed capacity increase to 415-519 GW_{el} in 2030, EIA (2010) predicts an increase to 481 GW_{el}, and OECD-NEA projections predict up to 600 GW_{el} (Lenzen, 2010). Such a lower growth rate can be attributed to public concerns about safety, proliferation risks, restrictions in supply chains due to skilled labor shortage and insufficient enrichment capacity, lack of experienced contractors, lack of solutions for spent fuel disposal. According to Lenzen (2010) promises of performance

improvement (higher resources sustainability, inherent safety, substantial reductions in radioactive waste volumes and lifetime) rely on the new generation-IV reactor and fuel cycle technology, foreseen by 2030.

2.1 Uranium market: a gap between demand and supply

The annual world uranium production has been around 50,772 t_U in 2009 covering about the 77.5% of annual demand (that is around 65,500 t_U) (WNA, 2010a). The gap between demand and production has been (and still is) met by secondary sources such as low enriched uranium (LEU) from the dismantling of nuclear warheads, re-enrichment of depleted uranium tails and spent fuel reprocessing (NEA, 2010). Two main periods of high uranium exploration can be identified. The first one, in the 1950s, was driven by the demand of weapon industry while the second one, in the 1970s, was due to the fast development of nuclear civil programs as a reaction to the 1973 oil embargo (Remme et al., 2007). Prices have been recently rising after about twenty years of decreasing trend (WNA, 2010a), thus stimulating new exploration activities and leading to an increased resource supply (Lenzen, 2010). World uranium Reasonably Assured Resources (RAR) and inferred resources were 3.2 Mt_U in 2003, increasing to 4.7 Mt_U in 2005, 5.5 Mt_U in 2007 (Lenzen, 2010) and finally 6.3 Mt_U in 2009 (D'Urso, 2010). RAR and inferred resources should provide uranium for the next 100 years at current production rates (Lenzen, 2010). Mudd and Diesendorf (2008) highlight that, despite perceived resource scarcity, the last two nuclear programs (nuclear weapon race in the 1940s and civil nuclear development in the 1960s) have been followed by new resource discovery. As with all fossil fuels, it is expected that the new deposits explored in the future will be deeper compared to most of the presently exploited deposits. The average ore grade mined is also expected to be lower as far as the best deposits are exploited, although Canadian newly discovered deposits show an increasing trend (Mudd and Diesendorf, 2008; Heinberg, 2009).

2.2 A “peak” for uranium?

The gap between demand and supply of uranium raises concerns for a possible peak of world uranium. Compared to oil, uranium is relatively abundant but difficult to find at economically attractive concentration grades. The trend of production and the increase in price are signals of the gradual depletion of the best deposits and the need for exploiting new deposits that could require higher investments and extraction costs. Uranium is having the same trend as oil, where scarcity and increasing extraction costs are causing the so-called “oil peak”. Some authors suggest that uranium is also near to or has already passed its peak (Bardi, 2006; Heinberg, 2009), although this trend is not easy to be confirmed because of the irregular production activities. The future of nuclear power will be heavily affected by either the scarcity of uranium resources and the increase of extraction costs, so that it might be difficult to keep the promises of cheap nuclear energy.

3. THE NUCLEAR FUEL CYCLE

Nuclear electricity is the final product of several upstream activities from mining to processing and finally converting the nuclear fuel. These activities, together with downstream disposal and processing of used fuel, constitute the nuclear fuel cycle (WNA, 2010b). A fuel cycle can, in turn, be classified into two types: “once-through” (open) and “closed”. The latter types “reuse the nuclear materials extracted from irradiated fuel” (IAEA, 2009) while the former ones do not reuse nuclear materials and discharge them directly into disposal sites (Sovacool, 2008a). The choice between “open” or “closed” cycles is an important national policy decision (IAEA, 2009). At present most of the nuclear reactors operate adopting the “once-through” cycle (Owen, 2006; Sovacool, 2008a). Reactors operating with closed cycles, separate waste products from the still

fissionable material, that is reprocessed and re-used. The reprocessing activity has the double advantage to reduce both the upstream demand for natural uranium and the downstream waste that must be disposed of (Lenzen, 2008; Sovacool, 2008a). Closed-cycle reactors have however disadvantages linked to the reprocessing costs, proliferation risks and problems with fuel cycle safety (Sovacool, 2008a).

3.1 The five steps of nuclear cycle

The two nuclear cycle types share at least five interconnected stages: (1) upstream or “front-end” activities, in which uranium is extracted from ore (open pit, underground mining or in situ leaching), milled, converted to uranium hexafluoride, enriched and finally used to make the fuel element; (2) power plant construction; (3) plant operation and maintenance; (4) downstream or “back-end” activities, in which the spent fuel is conditioned, reprocessed and disposed in final repositories (if any); (5) plant decommissioning and mine site reclamation (Sovacool, 2008a). Other related activities (heavy water and zirconium alloy production) and transport of the materials among the different steps must also be taken into account (Owen, 2006; IAEA, 2009).

4. ENVIRONMENTAL ANALYSIS OF NUCLEAR ENERGY FUEL CYCLE

We reviewed 9 LCA studies published since 2000, dealing with the nuclear fuel cycle at a different level of detail and scope. Four of them are actual LCAs of specific cycles (Lee *et al*, 2000, 2002; Dones *et al*, 2005; Wissel and Spohn, 2008), while the other five are in turn reviews of the existing literature (Gagnon *et al*, 2002; Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008; Fthenakis and Kim, 2009), making up for more than one hundred of cases compared and summarized.

4.1 Main focus on greenhouse gases

Most of the reviewed studies are focused on greenhouse gas emissions over the nuclear fuel cycle (Lenzen, 2008; Sovacool, 2008a) or on the comparison with other fossil or renewable energy cycles (Gagnon *et al*, 2002; Dones *et al*, 2005; Fthenakis and Kim, 2007). The latter also include indicators different than greenhouse gas emission, such as radioactive emissions (noble gases, H₃, C¹⁴, aerosols, Actinides; Dones *et al*, 2005); SO₂, and NO_x emissions, and direct land requirements (Gagnon *et al*, 2002; Fthenakis and Kim, 2009), indirect land requirements (Fthenakis and Kim, 2009), energy payback ratio (Gagnon *et al*, 2002; Lenzen, 2008), and energy requirements (Lenzen, 2008).

4.2 Comparing CO₂ emissions from nuclear with other electricity generation processes

A comparison of the average CO₂ emissions from different types of power plants powered by either renewable and nonrenewable sources (Table 1) shows a very large range of options, with nuclear ranking low compared to fossil fuels and still high compared with wind, hydro and other renewables. The most surprising aspect in the reviewed studies is the large spread of estimates of CO₂ emissions from nuclear. Sovacool (2008a) calculates an average emission of 66 g CO₂/kWh_{el}, but due to the spread based on very different assumptions the real meaning of such an average is questionable and therefore scarcely useful for nuclear policy planning.

4.3 Dealing with uncertainty

Some authors (Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008) investigated the causes that contribute to the uncertainty of LCA estimates about nuclear GHG emissions in the literature. For Sovacool (2008a) the main reasons are: scope (e.g.

some studies do not include all the stages of fuel cycle); assumptions about the quality of uranium ore (decreasing uranium grade in ore increases GHG emissions, as the lower the grade of uranium ore the higher the quantity of rock to be extracted and handled, the higher the energy needed and the GHG released); type of mining (methods of extraction and source of energy used for the extraction; for example uranium extracted closer to industrial centers releases less GHG emissions than the one extracted from mines in remote areas that rely on less efficient sources of energy); enrichment method (diffusion method is an older technology that requires much more energy than the centrifuge one); spatial focus (some studies assess emissions from specific reactors while others assess national and global average emissions based on industry data (individual cases in general provide a variety of estimates, while an average emissions approach always provides higher estimates); measurement of historical or marginal/future emissions (some of the studies refer to historical emissions while others look at future emissions for some type of plants, e.g. Dones et al., 2005); reactor type (the different design of reactor affects the GHG emissions: CANDU is considered by many as one the most GHG efficient commercial reactors); site selection (the location is a factor that in many ways affects a reactor's GHG performance; for example Canadian nuclear life cycles are associated to less GHGs than Chinese ones); operational lifetime (lifetimes and capacity factors vary in the reviewed studies yielding different estimates); the LCA applied (economic input-output based LCA, process-based LCA, and hybrid LCA have been applied, generating different GHG emission estimates; according to Fthenakis and Kim, 2007, the first method gives emissions 10-20 times higher than the process-based one). Lenzen (2008) identifies ore grade and enrichment method as the main factors that affect the energy and GHG performances in LWRs (also depending on the energy mix of the country), while only the ore grade affects HWRs, since the latter do not require enriched uranium. Fthenakis and Kim (2007) highlight enrichment, production and operation stages.

Table 1. CO₂ emissions from different typologies of power plant

Technology/fuel	Power/typology	Emissions range (gCO ₂ /kWh _{el})
Wind	2.5 MW, offshore - 1.5 MW onshore	9-10
Hydroelectric	3.1 MW, reservoir - 85 MW reservoir	10-12
Solar thermal	80 MW, parabolic	13
Biomass (short rotation forest and waste wood)	Co-combustion with hard coal- steam turbine-reciprocating engine	14-41
Solar PV	CdTe-Polycrystalline silicon-CIS	19-70
Geothermal	80 MW, hot dry rock	38
Nuclear	300/1600 MW/Various reactor types	1-290
Natural gas	300-700 MW/Various combined cycle turbines	398-450
Geothermal	20 MW, hot water/wet steam field	380-650
Hydrogen from nat gas reforming	Fuel cells (stand alone or hybrid with gas turbine)	493-664
Diesel and Heavy oil	320 to 1280 MW/Various generators and turbine types	778-923
Coal	320 to 1280 MW/Various generators and turbine types	960-1100

Source: after Brown and Ulgiati, 2002; Dones *et al*, 2005; Fthenakis and Kim, 2007; Lenzen, 2008; Wissel and Spohn, 2008; Sovacool, 2008a; Ulgiati et al, 2010.

4.4 Looking out of the “global warming” boundaries

The potentialities of an LCA are related to the possibility to identify the most environmentally significant stages as well as the process contribution to more than one impact category. Providing a global picture of the environmental impacts, not only GHG emissions, is very important for transparent information to the society. In particular, out of the 9 studies reviewed, only Lee et al. (2000) and Lee and Koh (2002) carried out an LCA

purposefully with these objectives as well as “to solve the problem when LCA is applied to facility releasing the radioactive wastes” (Lee et al., 2000). Their results show that the nuclear fuel cycle causes important environmental impacts also in other impact categories. Lee et al. (2000) included in the study the upstream activities, the nuclear power plant, the waste treatment (once-through cycle) and all transportation steps. The functional unit was the delivery of 1 GWh of electricity from 11 PWRs in commercial operation in 1998 in Korea. The authors found that the main environmental impacts caused by nuclear fuel cycle were abiotic depletion (73.3 g/yr), human toxicity through air (40.9 g-body Wt/yr) and global warming (27.7 g-CO₂/yr). They also identified mining and milling as the dominant stages in the cycle. These steps contribute to the largest depletion of abiotic resources (ADP) (96%), ecotoxicity through aquatic pattern (ECA) (98%) and human ecotoxicity through water (HCW) (78%). Lee and Koh (2002) applied LCA to three different nuclear cycle alternatives (once-through fuel cycle, with direct use of PWR spent fuel in CANDU reactor (DUPIC process) and recycling with plutonium and uranium recovery (PUREX process). The latter option resulted to be the less environmental loading. Internal exposure was identified as the most radiologically significant step.

Fthenakis and Kim (2009) focused on the life-cycle direct and indirect land use, measured as land transformation and land occupation, respectively for conventional and renewable sources. According to these authors, the electricity generation pattern that is less demanding in terms of land is nuclear (120-150 m²/GWh_{el}), followed by coal (depending on the typology of mining: 100-900 m²/GWh_{el}), photovoltaics (land demand 164-600 m²/GWh_{el}, with potential of much better values in case of rooftop PV), natural gas (260 m²/GWh_{el}), wind electricity (1000-2000 m²/GWh_{el}), and finally biomass (12500 m²/GWh_{el}). Gagnon *et al* (2002) estimated direct land use for renewables (hydro with reservoir, hydro run-of-river, biomass plantation, sawmill wastes, solar photovoltaic, wind power), coal cycles and nuclear. For nuclear they presented two values: without/with the land needed for the long-term waste. In the first case they estimated a value of 5000 m²/GWh_{el}, a much higher value compared to other sources. In the second case the direct land requirement for nuclear increased to 100000 m²/GWh_{el} (assuming that: “0.1 km²/Wh_{el} is required for waste disposal, multiplied by 30,000 years, applied to 30 years of generation”).

4.5 Lack of standardized procedures, lack of consensus

It clearly appears that the different assumptions, perceptions of Authors and evaluation methods heavily affect the final results in many ways, by providing different estimates or by disregarding some steps or impact categories. In spite of the standardized LCA procedure called for by ISO 14040/2006 and ISO 14044/2006 norms, with clear requirements about boundaries, procedures, and impact categories, a large uncertainty is introduced into the set of results by a kind of reluctance to compare on the same basis. In so doing, in spite of the large number of studies performed and reviewed, consensus about impacts is far from being achieved.

5. ECONOMIC AND FINANCIAL RISKS OF NUCLEAR POWER

Within the context of liberalization of worldwide electricity market the evaluation of investments plays a central role to complement the scientific debate (Holgner and Langlois, 2000; Adamantiades and Kessides, 2009; Linares and Conchado, 2009). Two economic and financial methodologies are adopted to this purpose: the consolidated Net Present Value (Rothwell, 1997, 2003; Greenpeace 2008) and the Real Option Value, considered more suitable for decision making in high and dynamic uncertainty contexts (Pindyck, 1993; Dixit and Pindyck, 1994; Holt et al. 2010). In both cases, risk analysis is one of the key tools to judge nuclear competitiveness as an investment option.

From a strictly economic point of view three main risk factors are considered: (a) construction time, (b) investment costs and (c) variability of operating costs. Most of the

existing plants have been built under a monopolistic regime, with governmental guarantees and controlled market prices, low capital costs and low investment risk (Owen, 2006). The investment risk, and the capital cost increased with deregulation of energy markets and were charged to electrical companies, penalizing capital intensive investments projects with long time return on investment and low technological flexibility (Romerio, 2007). Instead, investments in alternative power sources, be they combined cycle gas turbine plants and smaller renewable plants have been favored (Zorzoli, 2005). In such a context, investments on nuclear sector became uncertain and very variable. Considering a medium size nuclear plant (1000-1600 MW), construction costs are up to 10 or 15 times higher than those required for the construction of a natural gas plant (100-700 MW) per MW installed (Clò, 2008). The projected costs also tend to increase due to the extension of construction time (cost overruns) (Linares and Conchado, 2009). Finally, costs for nuclear plants decommissioning are estimated as about 25% of the original investment costs. The total costs of a nuclear plant can be splitted into about 60-75% *fixed* costs (capital repayments, interest allowed, decommissioning costs) and 25-40% *variable* costs (for instance, the cost of uranium and labor) (Owen, 2006). Unlike gas and carbon plants, the share of nuclear fuel cost on total production costs is small (Owen, 2006; Lenzen, 2010). This is due to two factors: 1) the amount of uranium still available, capable to satisfy the present nuclear industry requirements (demand); 2) the nuclear reactor capability to store the uranium for a long time (Owen, 2006). As the fuel cost is low companies in OECD countries are trying to capitalize this advantage extending reactor working life. While the cost of electricity obtained from nuclear energy is not particularly affected by fluctuations of raw material price, other uncertainty factors related to security aspects, licensing, escalation of decommissioning costs (De Paoli, 2008), radioactive wastes disposal, might contribute to increase the financial risk perceived from private investors and, consequently, the level of expected return (Lenzen, 2010). The risks associated to the construction of a new nuclear plant reduce the international rating of the companies involved. Moody's suggests that after beginning the construction the downgrade risk increases sensitively (Moody's 2009). Therefore if a company is on category "A" before the plant construction, it could be downgraded to the "Baa" category (neither highly protected nor poorly secured) during the following 5-10 years, when the construction costs reach the peak and the main credit parameters are (lower) or negative. In this situation, within an inefficient credit market, it could be more difficult for the company to obtain further credit, while instead the interest rate and, consequently, the cost per kWh_{el} are likely to increase. Some authors (Sovacool, 2008b; Lazard, 2009; MIT, 2009;) calculated the levelized cost of nuclear electricity production, which is an international indicator of the average costs of electricity produced by a plant in one year. Linares and Conchado (2009) provide details of the shortcomings of this indicator in deregulated markets. Such a methodological approach takes into account *internal* costs (implementation, maintenance, fuel and operating costs) and *external* costs, both rather uncertain (De Paoli, 2008). According to a recent study (MIT, 2009) the levelized cost of nuclear electricity is 8.4 \$ cent/kWh_{el}, higher than the costs of coal (6.2 \$ cent/kWh_{el}) and gas powered electricity (6.5 \$ cent/kWh_{el}). Lazard (2009) provides higher estimates (nuclear electricity between 9.8-12.6 \$ cent/kWh_{el}, coal electricity between 7.4-13.5\$ cent/kWh_{el} and solar termal power between 9-10.4 \$ cent/kWh_{el}, and even higher costs for natural gas, biomass and wind power). Rogner and Langlois (2000) highlight that the future of nuclear power depends on the competitiveness strategies that industries, supported by technological innovation, will adopt to guarantee the economic and financial sustainability and reduce the safety risks. Such targets require strong political support to the nuclear industry. For instance, the problems related to waste disposal and safety involve suitable technological solutions and communication, able to achieve social consensus. Therefore, an energy policy which includes the use of nuclear power among its energy sources will have to handle three problems: overcoming the scarcity of public funds, choosing the best nuclear technology available, and finally conducting a cost-benefit analysis to compare nuclear with others renewable sources (Linares and

Conchado, 2009). As a consequence, a macroeconomic analysis to evaluate these aspects in the light of the above listed risks is an unavoidable step.

6. ANALYSIS OF THE MACROECONOMICS EFFECTS OF A NUCLEAR PROGRAM

After the 1973 oil crisis many oil-importing countries developed strategies to reduce their dependence on fossil fuels also by implementing suitable energy alternatives (Toth and Rogner, 2006; Romerio, 2007). The new energy policy "paradigm" translated into plans for increased share of nuclear electricity. Such a paradigm was challenged by the antinuclear opposition and destabilized by the technical and economic problems encountered by the nuclear sector itself, although the Kyoto protocol has also indirectly contributed to reconsider the nuclear option (Romerio, 2007). Governmental intervention in support of nuclear is perceived by industrial sectors and analysts as a policy to achieve energy security and therefore a public good. In fact "it may be argued that market imperfections would lead to an underprovision of energy security". Supply security can be analyzed qualitatively through the identification of the external and internal factors that can undermine it, their possible effects and the tools of mitigation as well as the possible indicators that give information about the level of energy security.

6.1 The case of nuclear energy in U.K.

Watson and Scott (2009) investigated the supply security in UK and the role of new nuclear plants in addressing it. They identified four factors (internal and external) that can affect supply security:

1) Fossil fuel scarcity and external disruption: fossil fuel availability has affected the economies of oil importing countries (and some exporting ones) through rapidly rising prices (there are a few cases of supply shortages after a sudden price increase). The development of nuclear or renewable sources or even demand reduction are believed to be able to mitigate these negative effects (Awerbuck and Sauter, 2005). The role of nuclear needs to be compared with gas-fired generation, as it is the most likely investment option for large scale power generation.

2) Lack of domestic investment in infrastructure: nuclear can contribute in UK to replace the power generation capacity needs foreseen over the next two decades, but its long implementation time compared to gas-fired generation should also be considered. The lack of investment in infrastructure to generate and supply energy to customers likely leads to price variability and possible disruptions too. Moreover, the UK's renewable commitment by 2020 (UK-DECC, 2009) affects nuclear plans, as they are both base load power, not flexible in responding to short-term peaks in demand. Additional measures to develop flexible plants as well as capacity of storage and demand management are required in order to increase the resilience of the energy system.

3) Technology and infrastructure failure: this type of threat can lead to serious problems to local and international populations (as in the case of Three Mile Island and Chernobyl accidents). Problems may also arise from scarce technology diversification in the power system (e.g. class failures of new generation gas turbines in the 1990s, malfunctioning of nuclear plants in France because of the intense heat in summer 2003).

4) Domestic activism or terrorism: it can be challenged by reactor design which can incorporate protection systems to several risks but they are very costly (Watson and Scott, 2009). These authors conclude that U.K. nuclear would contribute to mitigate negative effects of supply security problems (such as fossil fuel price increase and scarce technological diversification), in particular in a scenario of replacement and expansion of electricity capacity but its role could lead to the increase of other types of risk.

Kennedy (2007) investigated UK costs (predevelopment, construction, operation and maintenance, fuel supply, waste disposal, decommissioning and cost of capital) and benefits (environmental benefits and security supply) of new nuclear compared to gas-fired generation, on-shore and off-shore wind, coal CCS (retrofit and new), and marine.

The welfare balance of new nuclear for the different scenarios hypothesized (assuming different nuclear, gas and carbon prices) is negative at low gas prices/high nuclear costs across the ranges of CO₂ prices and positive in case of central gas price depending on the CO₂ price and in high gas price/low nuclear cost case across the range of CO₂ prices (including a zero CO₂ price). According to Kennedy (2007), nuclear generation could have an advantage in a political framework characterized by a continued commitment to carbon emission reduction and the presence of steadily increasing gas prices.

7. CONCLUSION

The picture that results from our review of more than one hundred studies worldwide is a rather *uncertain* scenario about the majority of aspects of nuclear energy development. The future availability of suitable grade uranium is uncertain. Nuclear development scenarios seem to be associated to higher costs and prices than in the past. Shortages in the nuclear supply chain as well as the indefinite state of spent fuel worldwide could create additional barriers. Significant *uncertainties* are also linked to environmental impacts (uncertain GHG emission estimates, scarce knowledge of the contribution to other impact categories); to financial analysis (nuclear investment in competitive market is penalized compared to renewable sources and gas-fired generation, as it is characterized by high capital costs, long time return on investment and low flexibility; these factors contribute to increase the financial and economic risk for investors) as well as to macroeconomic analysis (it is uncertain the role that nuclear could have in addressing energy security; since gas-fired generation is the major competitor of nuclear in a cost-benefit perspective, the potential benefit of new nuclear is strongly affected by gas prices, carbon prices and nuclear costs).

In the presence of such large and diverse uncertainties, a wise policy is not just "learning by doing", nor even relying on expected "innovation" or "science results". Choices may generate conflicts among equally legitimate interests, which calls for participatory decision-making and planning. Once further and more reliable information is made available, the usual top-down decision-making process must be converted into a participatory procedure that involves all the stake-holders and the affected communities. In particular, when "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1991), the concept itself of "feasibility" must be converted from "technical and economical feasibility" into a more complex framework that includes aspects of "post-normal" science, namely the shift from the expert community to an "extended peer community" consisting of all those affected by an impact who are ready to enter into dialogue on it. They bring in alternate points of view, that include local knowledge and expertise not generally accounted for in normal scientific reports as the ones reviewed in this paper. It is not, therefore, a "to-do" list that should emerge out of such studies, but instead a call for multicriteria strategies and the awareness of the need for more complex evaluation tools and participatory planning.

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Science and the citizen

Science and the citizen

Contemporary issues and controversies

edited by Marco Mamone Capria

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Environmental, Economic and Financial Uncertainties of Nuclear Energy: A Closer Look Worldwide and in Italy

1. Introduction. The Nuclear Renaissance

The first years of the new millennium were characterized by a renewed interest in nuclear energy [2], the so-called “nuclear revival” [42]. In developing countries thirty plants are in construction against the five in OECD countries (two in Europe: France and Finland) [3, 59]. The Italian energy policy was also influenced by this interest wave, after the nuclear phase-out decided in 1987. This resurgence of interest was mainly based on claims that nuclear energy is cheaper, has lower price volatility compared to fossil fuels, it is secure in supply [33] and does not contribute to climate change. The Fukushima accident in 2011 put an abrupt stop to nuclear industry expectations, forcing Governments to rethink their choices and energy plans.

1.1 The search for carbon free energy

Low nuclear *greenhouse gas* (GHG) emissions is perhaps the most emphasized, studied and debated aspect. According to Sovacool [49], advocates of nuclear power consider it «the only non-greenhouse gas emitting energy source that can effectively replace fossil fuels and satisfy global demand». A 1000 MW_{el} coal power plant releases about 6 millions tons of CO₂ per year, while nuclear is claimed by its supporters to be quite CO₂ free. According to the international Nuclear Energy Agency (NEA) [39] in the last 40 years nuclear has contributed to avoid 1,200 million tons per year of carbon dioxide.

Opponents have objected that «nuclear plants are poor substitutes to other less intensive greenhouse gas generators»: wind and hydroelectricity have respectively one-third and one-fourth less CO₂-equivalent emissions than nuclear power. The Oxford Research Group [49] predicts that, assuming constant nuclear capacity, by 2050 nuclear CO₂ emissions per kWh would equal those from gas fired power plants due to decreasing uranium ore grade.

1.2 Radioactive waste

The contribution to climate change is only a part of the story. Other relevant aspects include «high capital cost, proliferation of dangerous materials, nuclear terrorism, operation safety and radioactive waste disposal» [53, 43, 22, 32]. Large amounts of nuclear waste have been accumulated in USA [34, 32] and worldwide and there is no easy solution for radioactive waste disposal or destruction [35]. No country has yet adopted a successful disposal after fifty years of nuclear civil programs. The first commercial geological repository is expected to open in Sweden by 2018 [3]; the solution to the nuclear waste issue (short-term and long-term nuclear waste management and spent fuel processing) is a prerequisite for further expansion of nuclear industry [1].

1.3 Market uncertainty

The actual competitiveness of nuclear must be analysed in a wider perspective. It cannot only rely on the analysis of greenhouse gas emissions, since nuclear is a very complex and expensive technology and many more aspects come into play.

The liberalization of electricity markets shows that the fate of nuclear is strongly affected by energy market structure. The loss of some main favourable conditions (governmental support, certainty of demand, a price regime based on recovering the production cost increase by charging higher prices to consumers, etc.) led to a drop of the number of nuclear plants built from 1990 to 2005 to only 1.7 nuclear plants per year (mainly in developing countries) compared to 17 nuclear plants per year built in the period 1970-1990 [3]. In liberalized electricity markets decisions about energy technologies are driven by the expected returns, taking into account the risks (afforded by the company, rather than by consumers as in a monopoly regime) linked to costs and revenues [21].

Moreover, nuclear energy has to face new competitors such as renewable source technologies, characterized by a lower carbon content, better environmental footprint, increased

population acceptance and higher growth rates favoured by cost reduction driven by technological innovation.

1.4 The Fukushima accident

The earthquake in Japan (March 11, 2011) and the consequent ongoing melting of the Fukushima nuclear power plant reactors (6 reactors for a total power of 4,200 MW) have raised new questions on the fragility of the nuclear industry. Japan is no doubt one of the countries worldwide where the safety of urban and industrial buildings and plants was pursued with the strictest normative requirements and highest technical quality. The accident showed very clearly to the eyes of the world that even such high performance was not a sufficient guarantee against the risks of human errors and natural disasters. The claimed low probability of a nuclear accident does not mean that it cannot happen (as it has always been suggested), and must be read differently: the disaster *can* happen, although not frequently. That the failure could be attributed to the conventional part of the plant (cooling pumps, emergency electric supply) makes the picture even worse, not better, since this makes it apparent that the safety of a highly risky technology depends on very conventional devices, designed for "normal" emergencies and therefore even more likely to collapse when huge natural disasters and crucial human errors occur.

The high Japanese standards of life demanded huge energy (mainly electricity) supply, in a country that has no local energy resources. The Japanese way of living will have to be re-designed towards a lower energy intensity of production and consumption patterns, with huge consequences on its national and worldwide economic systems.

If nuclear energy becomes difficult or impossible to implement, then fossil fuels may become once again the main choice of industrialized and developing economies (with coal as the cheapest option). The likely increase of fossil fuels prices, hard competition for their supply as well as related environmental concerns, call for urgent, worldwide rethinking of standards of life, de-growth

policies, and larger reliance on energy conservation and renewables. This is the major challenge that the whole planet is facing and nobody can predict at present if and to what extent this is likely to happen in the short or medium run.

2. Nuclear energy: a world overview

About 435 reactors are presently in operation in 31 countries with a total installed capacity of 368 GW_{el} [12]. Compared to fossil fuels, used in power generation in the residential, commercial, industrial, and transport sectors, nuclear energy is *only used for electricity generation*.

Electricity from all sources has a market share of about 17.1% worldwide and 21.1% in OECD countries, in terms of final energy consumption.

The nuclear share of world electricity supply during the period 1973-2008 increased from 3,3% (1973) to about 18% (1990), then decreased to 13.5% (2008) [6, 26].

Oil powered electricity declined its share from 24.7% (1973) to 5.5% (2008). Natural gas and to a lesser extent coal expanded their share in the same period [26].

Nuclear energy supplies about 34% of the total electricity produced in the European Union. Italy does not have nuclear plants in operation but imports about 15% of its electricity mainly from France, where 77% of electricity comes instead from nuclear [11]. The global nuclear electricity generation (except for China and India) was projected – even before the Japanese accident – to increase at rates lower than the overall electricity generation by 2030 [32]. IEA [25] foresees an installed capacity increase to 415-519 GW_{el} in 2030, EIA [10] predicts an increase to 481 GW_{el}, and OECD-NEA projections predict up to 600 GW_{el} [32]. Such a lower growth rate can be attributed to public concerns about safety, proliferation risks, restrictions in supply chains due to skilled labor shortage and insufficient enrichment capacity, lack of experienced contractors, lack of solutions for spent fuel disposal.

According to Lenzen [32] promises of performance improvement (higher resources sustainability, inherent

safety, substantial reductions in radioactive waste volumes and lifetime) rely on the new generation-IV reactor and fuel cycle technology, foreseen by 2030. How these forecasts of nuclear development will be affected by the Fukushima accident and the need for increased safety devices and strategies is still to be seen, thus adding uncertainty to uncertainty.

Some countries (e.g., Germany, Switzerland) are planning a slow phase out of the nuclear power, while others seem oriented to keep their nuclear route, due to their heavy dependence on such energy modality. For instance, although nuclear plants in Japan have been closed for inspections, economic reasons push for restarting; in France concerns about nuclear energy are slowly emerging.

Italy decided to exit nuclear power, after a referendum held in June 2011.

2.1 The uranium market: a gap between demand and supply

The annual world uranium production has been around 50,772 t_U in 2009, covering about the 77.5% of annual demand (that is around 65,500 t_U) [60]. The gap between demand and production has been (and still is) met by secondary sources such as low enriched uranium (LEU) from the dismantling of nuclear warheads, re-enrichment of depleted uranium tails and spent fuel reprocessing [40]. Two main periods of high uranium exploration can be identified.

The first one, in the 1950s, was driven by the demand of weapon industry while the second one, in the 1970s, was due to the fast development of nuclear civil programs as a reaction to the 1973 oil embargo [44].

Prices have been recently rising after about twenty years of decreasing trend [59], thus stimulating new exploration activities and leading to an increased resource supply [32]. World uranium Reasonably Assured Resources (RAR) and inferred resources were 3.2 Mt_U in 2003, increasing to 4.7 Mt_U in 2005, 5.5 Mt_U in 2007 [32], 6.3 Mt_U in 2009 [9] and finally 7.1 Mt_U as of January 2011 [41]. RAR and inferred resources should provide uranium for the next 100 years at current production rates [32]. Mudd and Diesendorf [36]

highlight that, despite perceived resource scarcity, the last two nuclear programs (nuclear weapon race in the 1940s and civil nuclear development in the 1960s) have been followed by new resource discovery. As with all fossil fuels, it is expected that the new deposits explored in the future will be deeper compared to most of the presently exploited deposits. The average ore grade mined is also expected to be lower as far as the best deposits are exploited, although Canadian newly discovered deposits show an increasing trend [38, 22].

A summary of world uranium producers is provided in Figure 1. It clearly appears that the uranium market is dominated by very few countries, similarly to the market of fossil fuels (and maybe even more).

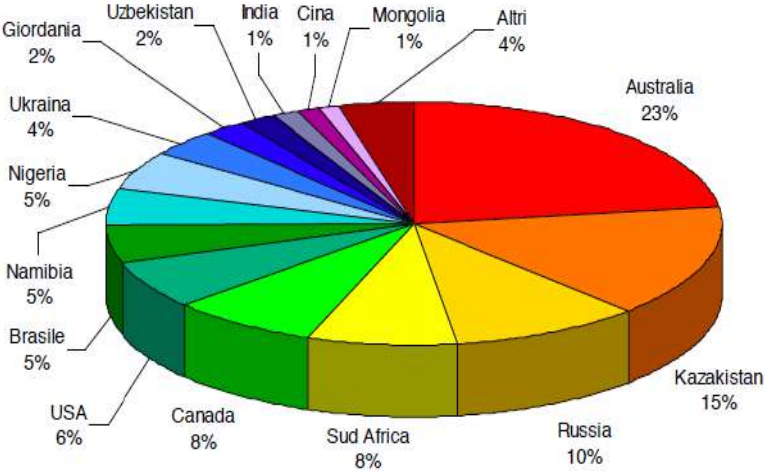


Figure 1. Overview of world uranium producers [58].

2.2 A "peak" for uranium?

The gap between demand and supply of uranium raises concerns for a possible peak of world uranium (Figure 2). Compared to oil, uranium is relatively abundant but difficult to find at economically attractive concentration grades. The trend of production and the increase in price are signals of the gradual depletion of the best deposits and the need for exploiting new deposits that could require higher investments and extraction costs. Uranium is having the

same trend as oil, where scarcity and increasing extraction costs are causing the so-called “oil peak”.

Some authors suggest that uranium is also near to or has already passed its peak [4, 22], although this trend is not easy to be confirmed because of the irregular production activities. The future of nuclear power will be heavily affected by either the scarcity of uranium resources and the increase of extraction costs, so that it might be very difficult to keep the promises of cheap nuclear energy, even without taking into account the cost increase determined by the demand for better technologies.

3. The nuclear fuel cycle

Nuclear electricity is the final product of several upstream activities from mining to processing and finally converting the nuclear fuel. These activities, together with downstream disposal and processing of used fuel, constitute the *nuclear fuel cycle* [61].

A fuel cycle can, in turn, be classified into two types: *once-through* (open) and *closed*. The latter types «reuse the nuclear materials extracted from irradiated fuel» [24] while the former ones do not reuse nuclear materials and discharge them directly into disposal sites [49].

The choice between “open” or “closed” cycles is an important national policy decision [24]. At present most of the nuclear reactors operate adopting the “once-through” cycle [42, 49]. Reactors operating with closed cycles, separate waste products from the still fissionable material, that is reprocessed and re-used. The reprocessing activity has the double advantage to reduce both the upstream demand for natural uranium and the downstream waste that must be disposed of [31, 49]. Closed-cycle reactors have however disadvantages linked to the reprocessing costs, proliferation risks and problems with fuel cycle safety [49].

3.1 The five steps of nuclear cycle

The two nuclear cycle types share at least five interconnected stages (Figure 3):

- (1) upstream or "front-end" activities, in which uranium is extracted from ore (open pit, underground mining or in situ leaching), milled, converted to uranium hexafluoride, enriched and finally used to make the fuel element;
 - (2) power plant construction;
 - (3) plant operation and maintenance;
 - (4) downstream or "back-end" activities, in which the spent fuel is conditioned, reprocessed and disposed in final repositories (if any);
 - (5) plant decommissioning and mine site reclamation [49].
- Other related activities (heavy water and zirconium alloy production) and transport of the materials among the different steps must also be taken into account [42, 24].

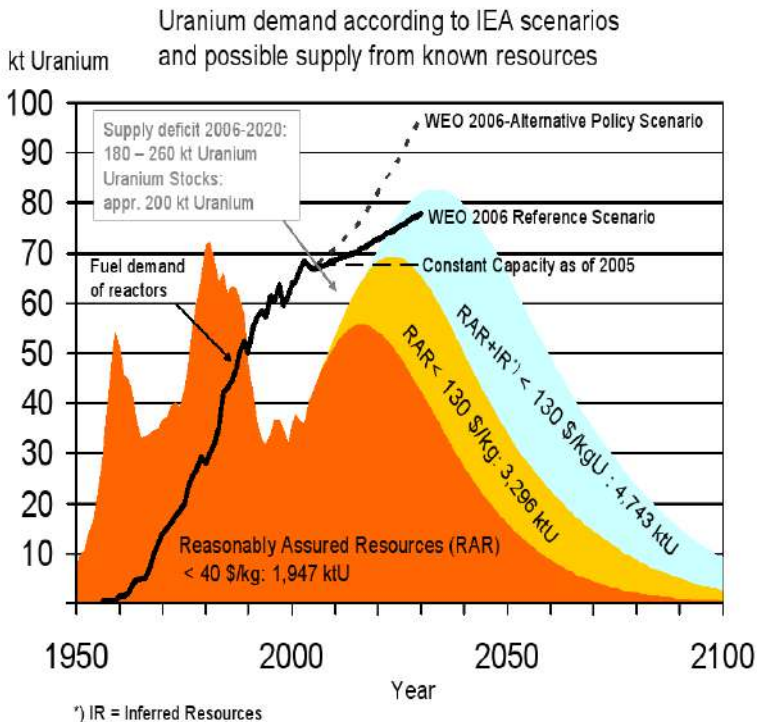


Figure 2. Estimates of available uranium stocks at different price compared to the present uranium demand for existing reactors [15].

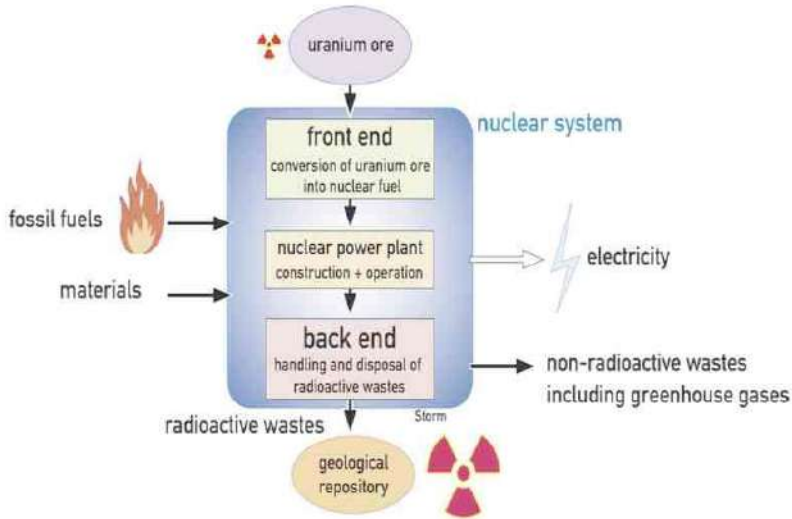


Figure 3. *The nuclear fuel cycle* [54].

4. Environmental analysis of nuclear fuel cycle

The present review is based on 9 *life-cycle assessment* (LCA) studies published since 2000, dealing with the nuclear fuel cycle at different levels of detail and scope. Four of them are actual LCAs of specific cycles [29, 30, 8, 57], while the other five are in turn reviews of the existing literature [19, 16, 49, 31, 17], making up for more than one hundred cases compared and summarized.

4.1 Main focus on greenhouse gases

Most of the reviewed studies are focused on greenhouse gas emissions over the nuclear fuel cycle [31, 49] or on the comparison with other fossil or renewable energy cycles [19, 8, 16]. The latter also include indicators different than greenhouse gas emission, such as radioactive emissions (noble gases, H_3 , C^{14} , aerosols, Actinides [8]; SO_2 , and NO_x emissions, direct land requirements [19, 17], indirect land requirements [17], energy payback ratio [19, 31], and energy requirements [31].

Table 1. CO₂ emissions from different typologies of power plant

Technology/fuel	Power/typology	Emissions range (gCO ₂ /kWh _e)
Wind	2.5 MW, offshore - 1.5 MW onshore	9-10
Hydroelectric	3.1 MW, reservoir - 85 MW reservoir	10-12
Solar thermal	80 MW, parabolic	13
Biomass (short rotation, forest and waste wood)	Co-combustion with hard coal- steam turbine-reciprocating engine	14-41
Solar PV		
Geothermal	CdTe-Polycrystalline silicon-CIS	19-70
Nuclear	80 MW, hot dry rock	38
Natural gas	300/1600 MW/Various reactor types	1-290
Geothermal	300-700 MW/Various combined cycle turbines	398-450
Hydrogen from nat gas reforming	20 MW, hot water/wet steam field	380-650
Diesel and Heavy oil	Fuel cells (stand alone or hybrid with gas turbine)	493-664
Coal	320 to 1280 MW/Various generators and turbine types	778-923
	320 to 1280 MW/Various generators and turbine types	960-1100

Source: after Brown and Ugliati, 2002; Dones et al, 2005; Fthenakis and Kim, 2007; Lenzén, 2008; Wissef and Spohn, 2008; Sovacool, 2008a; Ugliati et al, 2010.

4.2 Comparing CO₂ emissions from nuclear with other electricity generation processes

A comparison of the average CO₂ emissions from different types of power plants powered by either renewable and nonrenewable sources (Table 1) shows a very large range of options, with nuclear ranking low compared to fossil fuels

and still high compared with wind, hydro and other renewables. The most surprising aspect in the reviewed studies is the large spread of estimates of CO₂ emissions from nuclear. Sovacool [49] calculates an average emission of 66 g CO₂/kWh_{el}, but due to the spread based on very different assumptions the real meaning of such an average is questionable and therefore scarcely useful for nuclear policy planning.

4.3 Dealing with uncertainty

Some authors [17, 49, 31] investigated the causes that contribute to the uncertainty of LCA estimates about nuclear GHG emissions in the literature. For Sovacool [49] the main reasons are:

- scope (e.g. some studies do not include all the stages of fuel cycle);
- assumptions about the quality of uranium ore (decreasing uranium grade in ore increases GHG emissions, as the lower the grade of uranium ore the higher the quantity of rock to be extracted and handled, and therefore the higher the energy needed and the GHG released);
- type of mining (methods of extraction and source of energy used for the extraction; for example uranium extracted closer to industrial centers releases less GHG emissions than the one extracted from mines in remote areas that rely on less efficient sources of energy);
- enrichment method (diffusion method is an older technology that requires much more energy than the centrifuge one);
- spatial focus (some studies assess emissions from specific reactors while others assess national and global average emissions based on industry data; individual cases in general provide a variety of estimates, while an average emissions approach always provides higher estimates);
- measurement of historical or marginal/future emissions (some of the studies refer to historical emissions while others look at future emissions for some type of plants, e.g. [8]);

- reactor type (the different design of reactor affects the GHG emissions: CANDU is considered by many as one the most GHG efficient commercial reactors);
- site selection (the location is a factor that in many ways affects a reactor's GHG performance; for example Canadian nuclear life cycles are associated to less GHGs than Chinese ones);
- operational lifetime (lifetimes and capacity factors vary in the reviewed studies yielding different estimates);
- the LCA applied (economic input-output based LCA, process-based LCA, and hybrid LCA have been applied, generating different GHG emission estimates; according to Fthenakis and Kim [16], the first method gives emissions 10-20 times higher than the process-based one).

Lenzen [31] identifies ore grade and enrichment method as the main factors that affect the energy and GHG performances in *light water reactors* (LWRs), also depending on the energy mix of the country, while only the ore grade affects *heavy water reactors* (HWRs), since the latter do not require enriched uranium. Fthenakis and Kim [16] highlight enrichment, production and operation stages.

4.4 Looking out of the "global warming" boundaries

The potentialities of an LCA are related to the possibility of identifying the most environmentally significant stages as well as the process contribution to more than one impact category. Providing a global picture of the environmental impacts, not only GHG emissions, is very important for transparent information to the society. In particular, out of the 9 studies reviewed, only [29, 30] carried out an LCA purposefully with these objectives as well as «to solve the problem when LCA is applied to facility releasing the radioactive wastes» [29]. Their results show that the nuclear fuel cycle causes important environmental impacts also in other impact categories; [29] included in the study the upstream activities, the nuclear power plant, the waste treatment (once-through cycle) and all transportation steps. The functional unit was the delivery of 1 GWh of electricity from 11 *pressurized water reactors* (PWRs) in commercial operation in 1998 in Korea. The authors found that the main environmental impacts caused by nuclear fuel cycle

were abiotic depletion (73.3 g/yr), human toxicity through air (40.9 g-body Wt/yr) and global warming (27.7 g-CO₂/yr). They also identified mining and milling as the dominant stages in the cycle. These steps contribute to the largest depletion of abiotic resources (96%), ecotoxicity through aquatic pattern (98%) and human ecotoxicity through water (78%).

Lee and Koh [30] applied LCA to three different nuclear cycle alternatives (once-through fuel cycle, with direct use of PWR spent fuel in CANDU reactor (DUPIC process) and recycling with plutonium and uranium recovery (PUREX process). The latter option resulted to be the less environmental loading. Internal exposure was identified as the most radiologically significant step.

Fthenakis and Kim [17] focused on the life-cycle direct and indirect land use, measured as land transformation and land occupation, respectively for conventional and renewable sources. According to these authors, the electricity generation pattern that is less demanding in terms of land is nuclear (120-150 m²/GWh_{el}), followed by coal (depending on the typology of mining: 100-900 m²/GWh_{el}), photovoltaics (land demand 164-600 m²/GWh_{el}, with potential of much better values in case of rooftop PV), natural gas (260 m²/GWh_{el}), wind electricity (1000-2000 m²/GWh_{el}), and finally biomass (12500 m²/GWh_{el}).

Gagnon and collaborators [19] estimated direct land use for renewables (hydro with reservoir, hydro run-of-river, biomass plantation, sawmill wastes, solar photovoltaic, wind power), coal cycles, and nuclear. For nuclear they presented two values: without/with the land needed for the long-term waste. In the first case they estimated a value of 5000 m²/GWh_{el}, a much higher value compared to other sources. In the second case the direct land requirement for nuclear increased to 100,000 m²/GWh_{el} (assuming that «0.1 km²/Wh_{el} is required for waste disposal, multiplied by 30,000 years, applied to 30 years of generation»).

4.5 Lack of standardized procedures, lack of consensus

It clearly appears that the different assumptions, authors' perceptions, and evaluation methods heavily affect the final

results in many ways, by providing different estimates or by disregarding some steps or impact categories. In spite of the standardized LCA procedure called for by ISO 14040/2006 and ISO 14044/2006 norms, with clear standardization requirements about boundaries, procedures, and impact categories, a large uncertainty is introduced into the set of results by a kind of reluctance to compare on the same basis. In so doing, in spite of the large number of studies performed and reviewed, consensus about impacts is far from being achieved. Instead of providing a picture for informed decision making, lack of consensus adds up to the uncertainty, raising an ethical question about the actual possibility to make a decision about nuclear, in the presence of uncertainty about costs and benefits.

As the Three Mile Island (1979), Chernobyl (1986) and Fukushima accidents have clearly shown, the potential consequences of an even unlikely accident are so catastrophic that they offset all the benefits to the economy and welfare that they might have provided before the accident. In business-as-usual times, the main benefits go to the investor, while the environmental burden and the risk is most likely transferred to the general public (radioactive waste repository, consequences of accidents on health and global economy, etc.).

5. Economic and financial risks of nuclear power

Within the context of liberalization of the global electricity market the evaluation of investments plays a central role to complement the scientific debate [45, 2, 33]. Two economic and financial methodologies are adopted to this purpose: the consolidated Net Present Value [47, 48, 20] and the Real Option Value, considered more suitable for decision making in high and dynamic uncertainty contexts [43, 7, 23]. In both cases, risk analysis is one of the key tools to judge nuclear competitiveness as an investment option.

From a strictly economic point of view three main risk factors are considered: (a) construction time, (b) investment costs and (c) variability of operating costs. Most of the existing plants have been built under a monopolistic

regime, with governmental guarantees and controlled market prices, low capital costs and low investment risk [42]. The investment risk, and the capital cost increased with the deregulation of energy markets and were charged to electrical companies, penalizing capital-intensive investment projects with long-time return on investment and low technological flexibility [46]. Instead, investments in alternative power sources, be they combined cycle gas turbine plants and smaller renewable plants, have been favoured [62].

In such a context, investments on the nuclear sector became uncertain and very variable. Considering a medium-size nuclear plant (1000-1600 MW), construction costs are up to 10 or 15 times higher than those required for the construction of a natural gas plant (100-700 MW) per MW installed [5]. The projected costs also tend to increase due to the extension of construction time (cost overruns) [33]. Finally, costs for nuclear plants decommissioning are estimated as about 25% of the original investment costs. The total costs of a nuclear plant can be split into about 60-75% *fixed* costs (capital repayments, interest allowed, decommissioning costs) and 25-40% *variable* costs (for instance, the cost of uranium and labor) [42].

Unlike gas and carbon plants, the share of nuclear fuel cost on total production costs is relatively small [42, 31]. This is due to two factors: 1) the amount of uranium still available, capable to satisfy the present nuclear industry requirements (demand); 2) the nuclear reactor capability to store the uranium for a long time [42]. As the fuel cost is low, companies in OECD countries are trying to capitalize this advantage extending the reactors' working life.

While the cost of electricity obtained from nuclear energy is not particularly affected by fluctuations of raw material price, other uncertainty factors related to security aspects, licensing, escalation of decommissioning costs [6], radioactive wastes disposal, might contribute to increase the financial risk perceived from private investors and, consequently, the level of expected return [32]. The risks associated to the construction of a new nuclear plant reduce the international rating of the companies involved. Moody's

suggests that after beginning the construction the downgrade risk increases sensitively [37]. Therefore if a company is on category "A" before the plant construction, it could be downgraded to the "Baa" category (neither highly protected nor poorly secured) during the following 5-10 years, when the construction costs reach the peak and the main credit parameters are (lower or) negative.

In this situation, within an inefficient credit market, it could be more difficult for the company to obtain further credit, while instead the interest rate and, consequently, the cost per kWh_{el} are likely to increase. Some authors [50, 28, 36] calculated the levelized cost of nuclear electricity production, which is an international indicator of the average costs of electricity produced by a plant in one year. Linares and Conchado [33] provide details of the shortcomings of this indicator in deregulated markets. Such a methodological approach takes into account both *internal* costs (implementation, maintenance, fuel and operating costs) and *external* costs, both being rather uncertain [6].

According to a recent study [36] the levelized cost of nuclear electricity is 8.4 \$ cent/kWh_{el}, higher than the costs of coal (6.2 \$ cent/kWh_{el}) and gas powered electricity (6.5 \$ cent/kWh_{el}). Lazard [28] provides higher estimates:

- nuclear electricity between 9.8-12.6 \$ cent/kWh_{el},
- coal electricity between 7.4-13.5\$ cent/kWh_{el},
- solar termal power between 9-10.4 \$ cent/kWh_{el}
- photovoltaics between 10 and 15 cent/kWh_{el},
- wild electricity between 4 and 9 cent/kWh_{el},

and finally efficiency and energy conservation between 0 and 5 cent/kWh_{el}.

Rogner and Langlois [45] highlight that the future of nuclear power depends on the competitiveness strategies that industries, supported by technological innovation, will adopt to guarantee the economic and financial sustainability and reduce the safety risks. Such targets require strong political support to the nuclear industry. For instance, the problems related to waste disposal and safety involve suitable technological solutions and communication, able to achieve social consensus. Therefore, an energy policy which

includes the use of nuclear power among its energy sources will have to handle three problems: overcoming the scarcity of public funds, choosing the best nuclear technology available, and finally conducting a cost-benefit analysis to compare nuclear with others renewable sources [33].

5.1 The failure of statistics in risk assessment

All the conservative figures provided above as well as economic and financial estimates carried out up-to-date can be highly questioned and made even worse by the consequences of the Fukushima accident on the Japanese and world economies. In spite of the claims that some accidents are highly unlikely, it cannot be denied that if they happen the consequences are very heavy. According to Stiglitz [51],

[the] wizards of finance [...] didn't understand the intricacies of risk, let alone the danger posed by "fatal distributions" – a statistical term for rare events with huge consequences, sometimes called "black swans". Events that were supposed to happen once in a century – or even once in the lifetime of the universe – seemed to happen every ten years. Worse, not only was the frequency of these events vastly underestimated; so was the astronomical damage they would cause – something like the meltdowns that keep dogging the nuclear industry.

The precautionary principle [55], dismissed and discredited by some as formalizing an emotional behaviour, must become the guideline when making decisions with huge potential consequences, i.e. when dealing with the «emergence of increasingly unpredictable, uncertain, and unquantifiable but possibly catastrophic risks».

6. Nuclear electricity in Italy

6.1 First steps

Italy moved its first steps towards nuclear electricity in 1963, with the operation of a small gas-graphite nuclear reactor in Latina (160 MW) followed by two BWR – Boiling Water Reactors (Garigliano, 150 MW; Caorso, 860 MW), and a PWR (Trino, 260 MW).

In 1988, as a result of the popular referendum held in 1987, after Chernobyl accident, the Italian Government decided to stop the nuclear energy generation. Moreover it blocked the construction of two new reactors in Montalto di Castro (2 x 1000 MWe BWR) and Trino (2 x 1000 MWe PWR), whose operation were planned to start in 1990. As a consequence of such decision, the four Italian reactors were stopped and the decommissioning procedure started (although slowly and still in progress). Only one small research reactor (1 MW) is still operative in the ENEA headquarters, Anguillara, Rome.

6.2 A nuclear-free country

The governmental decision following the 1987 referendum made Italy a country without nuclear energy, although surrounded by European nations which heavily rely on nuclear (France, Germany, Switzerland) and from which Italy imports electricity (Figure 4).

A common claim of nuclear energy supporters is that Italy would not be safe anyway in case of major accidents in these countries. While this is certainly true, it should be rather read as a proof that decisions about nuclear must be jointly taken by all the interested countries, not just by each country individually. This awareness calls for new forms of international laws and enforced control by international agencies, instead of advocating the dismissal of any form of control while spreading sophisticated technologies in spite of population density, seismic hazard, and unlikely economic return.

6.3 Nuclear "revival" in Italy

The first official step to re-introduce nuclear energy in Italy after the phase out was the approval by Italian Parliament of the Enabling Act No. 99 of July 23, 2009. This Act, under the neutral title "Development and internationalization of enterprises, as well as miscellaneous energy issues" assigned to the Government the power to decide all the further steps for the reintroduction of nuclear energy, localization of power plants, the localization of the nuclear waste repository, and the choice of power plant typologies.



Figure 4. Nuclear power plants in Europe (Google Maps, 2011).

The article 25 stated that the activities related to nuclear energy must be considered activities of pre-eminent public interest and, as such, the final decisions will be made by the Ministry of Economic Development in agreement with the Ministry of Environment and the Ministry of Infrastructures, without any involvement of local communities and administrations. The same article foresees a campaign to inform the population «about nuclear energy, with special reference to its safety and economic benefits» (!). Finally, likely due to uncertainty about how populations may react to these «benefits», the article 39 allows the possibility that some energy related plants be left under the direct control of the National Army or built within military areas.

After the Fukushima event, the Italian government decided a one-year moratorium, in order to concede a pause for thought, while continuing to implement all the other actions and decisions needed, at the end of the moratorium period, to proceed speedily toward plant constructions. In fact, the moratorium only applied to procedures related to the construction of new nuclear power plants in Italy, not affecting the ongoing procedures for the disposal of radioactive waste, including the construction of a national

repository. The decision was criticized by the opponents to nuclear energy as a time-wasting move, only aimed at weakening the anti-nuclear referendum scheduled for June 2011.

In response to these Governmental decisions, the national referendum held on June 12-13, 2011, cancelled, with a 95% majority of voters, most articles of the Enabling Act 99/2009 and previous related laws on the same topic, thus banning nuclear again within the Italian boundaries.

6.4 Electricity demand and installed power

According to official data by TERNA, the society in charge for the electricity distribution in Italy (see its 2009 report, "Statistical data about electricity production in Italy"), the total installed power in Italy is about 105 GW. The peak demand of power was 57 GW in the summer 2007, and 52 GW in the summer 2009. As a consequence, it is not the installed power the energy problem of the country. The country would certainly benefit from a decrease of imported fossil energy sources. Uranium, according to Figure 1, is also imported and therefore its use would not solve any dependence on foreign sources.

The total consumption of energy in Italy has been 320.3 TWh in the year 2009, about 5.7% less than in the previous year. About 86% of such electricity was generated inside the country, mainly from thermoelectric power plants. The reason the remaining 14% was imported nuclear electricity is that it was cheaper to purchase it, at low cost, mainly from France, than generating further fossil power internally. In fact, since nuclear plants cannot be switched off overnight, it is profitable for France to sell the surplus (for less), in order to optimize its costs.

Had the Italian Government completed the construction of the planned four nuclear power plants (no longer allowed, after the new referendum...), they would have provided a maximum electricity production of 56 TWh, i.e. about 17% of total yearly electricity demand. The latter would require about 12 MTOE to be produced in Italian power stations,¹

¹ In terms of heat content, 1 MTOE = 11.63 TWh. However, considering thermodynamic conversion losses in power plants, 1 MTOE only produces about 4.9 TWh of electricity (42% average conversion

which is only about 6% of the total national energy use (amounting to 180.343 MTOE for 2009).

6.5 Seismic hazard and population density

Italy is characterized by a higher seismic hazard than most European countries. Figure 5 compares the situation of Italy and the Balcanic area with the rest of Europe. It can be clearly seen that Italy – especially over the Appennini mountain chain – is among the countries where the construction of nuclear power plants should absolutely be discouraged. Moreover, there are active volcanoes in the Tyrrhenian sea, some of which under the sea and still active (e.g. Marsili, which is the Europe's largest undersea volcano). If eruptions were to occur in this area, nobody could rule out the possibility of large and destructive tsunamis, events that already occurred in the Tyrrhenian area [14].

The potential consequences of a nuclear accident in Italy are made even worse by the fact that Italy is a high population-density country compared to the rest of Europe. Figure 6 shows that most of the areas potentially candidate to host a nuclear power plant (Northern Italy, Tyrrhenian coast, Puglia region, among others) are very densely populated compared to all other regions of Europe that already host nuclear plants. In case of accidents, much more people would be affected and it would be very difficult to evacuate them to safer areas.

6.6 The potential for renewable energy

Finally, Italy is a country with a huge renewable energy potential, especially solar insolation that could be used to develop photovoltaic electricity. Figure 7 shows the solar irradiation in kWh/m², much higher than in most parts of Europe. According to Figure 7, 1 kWp of photovoltaic power installed generates between 1200 and 1400 kWh, requiring in central-southern Italy 0.7-0.8 m² of installed module. The photovoltaic potential is already being exploited thanks to the feed-in tariffs of the so-called "Conto energia". Installed photovoltaic electricity was 0.7 GWp in 2009 and more than 2 GWp at the end of 2010 (and keeps growing). Wind

efficiency in Italy), while the remaining fraction is converted into waste heat.

power plants increased from 1.1 GW in 2004 to 4.9 GW in 2009.

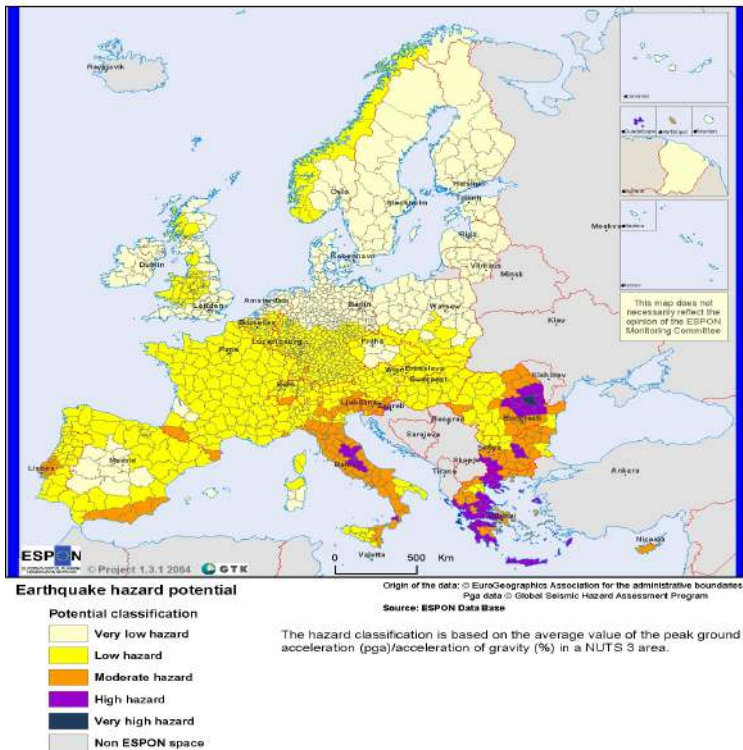


Figure 5. Seismic hazard potential of Italy compared to Europe [13].

8. Conclusion

The picture that results from our review of more than one hundred studies worldwide as well as of the Italian situation concerning planned nuclear energy is a rather uncertain scenario about the majority of aspects of nuclear energy development, made day-by-day even worse by the news from the Fukushima power plant, and the classification of the accident at the level 7, the highest possible risk level according to the International Nuclear and radiological Event Scale (INES).

The future availability of suitable grade uranium is uncertain. Nuclear development scenarios seem to be associated to higher costs and prices than in the past. Shortages in the nuclear supply chain as well as the

indefinite state of spent fuel worldwide could create additional barriers.

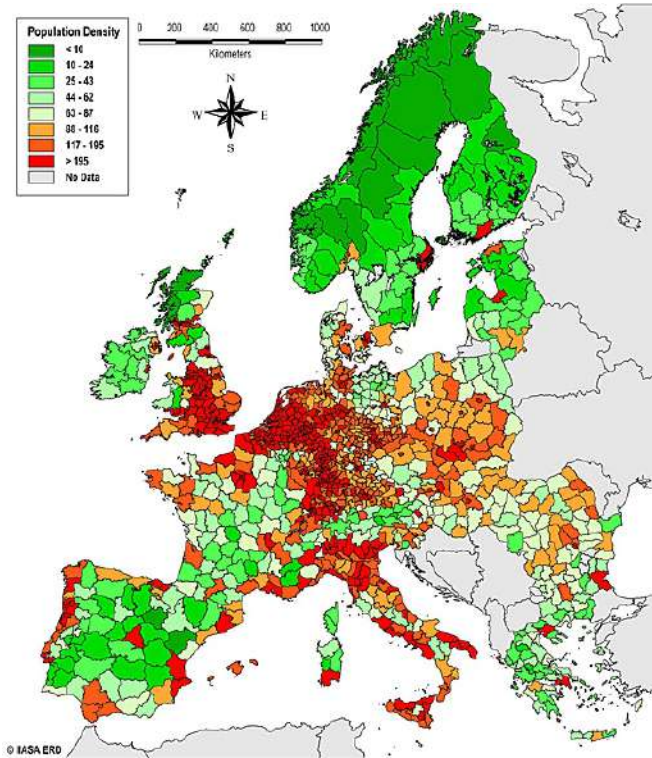


Figure 6. Population density of Italy compared to Europe [27].

Significant *uncertainties* are also linked to environmental impacts during normal operation (uncertain GHG emission estimates, scarce knowledge of the contribution to other impact categories), not to talk about the catastrophic consequences of accidents such as the meltdown in the Fukushima reactors; other uncertainties are associated to financial analysis (nuclear investment in competitive market is penalized compared to renewable sources and gas-fired generation, as it is characterized by high capital costs, long time return on investment and low flexibility; these factors

contribute to increasing the financial and economic risk for investors) as well as to macroeconomic analysis.²

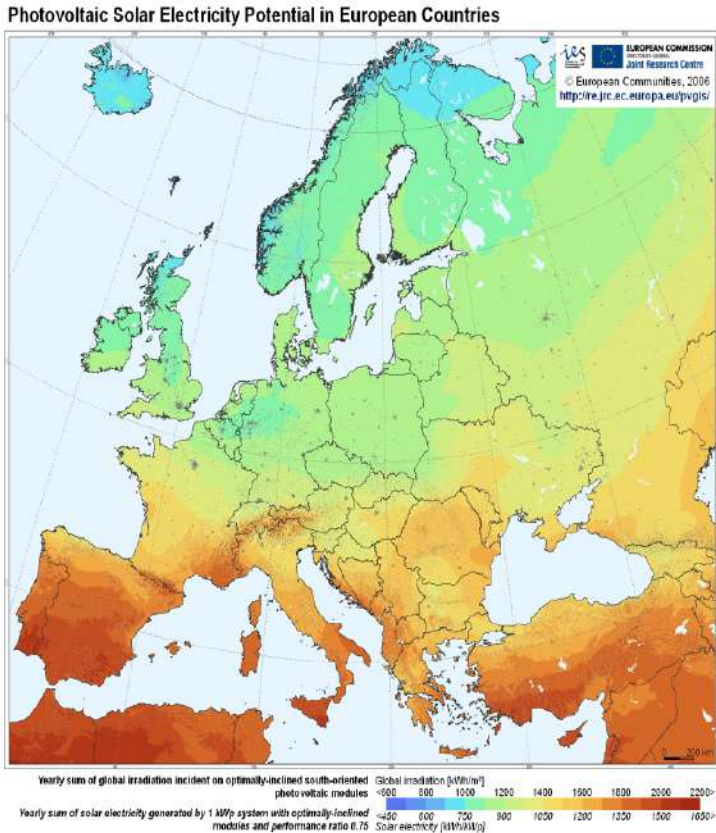


Figure 7. *Solar insolation and photovoltaic electricity generation potential of Italy compared to Europe [52]*

The Fukushima accident made the uncertainty scenarios even worse, by adding the awareness of the catastrophic potential of “claimed unlikely” events. Although some Italian nuclear supporters still suggest nuclear energy as the unavoidable solution to future energy shortages, in spite of the popular referendum results, a careful evaluation

² It is uncertain which role nuclear could have in addressing energy security. Since gas-fired generation is the major competitor of nuclear in a cost-benefit perspective, the potential benefit of new nuclear is strongly affected by gas prices, carbon prices and nuclear costs.

of the Italian situation concerning energy policy, seismic hazard, population density, and solar insolation potential, makes a nuclear revival in Italy very unlikely. Moreover, the environmental, economic and technical considerations made in this paper, suggest nuclear to be *an unsafe and uneconomic solution not only for Italy, but also for the rest of the world.*

In the presence of so large and diverse uncertainties (the only certainty being that of infrequent but potentially disastrous events), a wise policy is not just "learning by doing", nor even relying on expected "innovation" or new "science results". Choices call for participatory decision-making and planning. Once further and more reliable information is made available, the usual top-down decision-making process must be converted into a participatory procedure that involves all the stake-holders and the affected communities. In particular, when «facts are uncertain, values in dispute, stakes high and decisions urgent» [18], the concept itself of "feasibility" must be converted from "technical and economical feasibility" into a more complex framework that includes aspects of "post-normal" science, namely the shift from the expert community to an "extended peer community" consisting of all those affected by an impact who are ready to enter into dialogue on it. They bring in alternate points of view, that include local knowledge and expertise not generally accounted for in normal scientific reports as the ones reviewed in this paper. It is not a "to-do" or a "to-do-not" list that should emerge out of such studies, but a call for multicriteria strategies and the awareness of the need for more complex evaluation tools and participatory planning.

References

Labels

ARPA: Agenzia Regionale Prevenzione ambiente

EIA: US Energy Information Administration

ENEA: Ente per le Nuove Tecnologie, l'Energia e l'Ambiente

ENS: European Nuclear Society

ESPON: European Spatial Planning Observation Network

EWG: Energy Watch Group

IAEA: International Atomic Energy Agency
IEA: International Energy Agency
IIASA: International Institute for Applied Systems Analysis
MIT: Massachusetts Institute of Technology
TERNA: Trasmissione Elettrica Rete Nazionale
WNA: World Nuclear Association

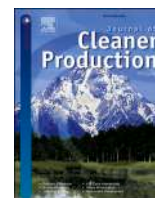
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Assessing the environmental sustainability and justice dimensions of nuclear electricity under circular economy and energy transition frameworks

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ABSTRACT

This study is framed within the international political context that shows on one side the risks of nuclear plants of being under attack in conflicts among countries (e.g., the present war between Russia and Ukraine) and on the other side the decarbonization policies of many countries including EU members, focused on equalizing nuclear and renewable sources for the generation of electricity. A systematic literature review is adopted, with the goal of understanding if nuclear electricity is environmentally sustainable as well as environmental and socially just in circular economy (CE) and energy transitions. According to some scenarios based on a higher role of nuclear electricity, results suggest the need to take into account the increase of ionizing radiations, Uranium depletion and water consumption. The impact of nuclear is also higher when compared with renewables (e.g. wind) in terms of total material requirement and, again, water consumption. LCA studies included in this review also highlight the impacts of the nuclear fuel cycle and in particular the Uranium stage as well as the decommissioning stage where the impacts of open cycles versus partially closed or totally closed cycles are compared. The analysis of the sample assessment of environmental and justice dimensions in the nuclear fuel cycle show that the selected articles focus on the whole life cycle of nuclear electricity and three main stages such as Uranium mining, decommissioning operations and identification of sites for spent nuclear fuel disposal. The integration of justice dimensions in the study resulted important in improving the understanding of the impacts of the nuclear fuel cycle on local communities in mining regions, or those who live near nuclear power plants or disposal facilities. The challenges of LCA in assessing the impacts of nuclear energy have been analysed suggesting the strong need for considering further impact categories and more comprehensive frameworks when evaluating its sustainability and role in decarbonization scenarios. In that, this study acknowledges that it is essential to take into consideration the nexus between CE and energy transitions. Finally, the case study of the Italian Nuclear Programme is also discussed in the light of current critical narrative on nuclear energy.

1. Introduction

The current conflict between Russia and Ukraine has drawn the attention worldwide on the risks and safety of nuclear energy (Klingelhöfer et al., 2024).¹ In Ukraine 15 pressurized water reactor plants are currently operative. Six of them are installed in the Zaporizhia

nuclear power plant.² The latter plant has been occupied by Russia since the early 2022 and has been subject recently (April 8, 2024) to a new drone attack.³ Despite of this, at the G7 Meeting of 29–30 April 2024, held in Turin (Italy), the Ministers of Climate, Energy and the Environment renewed their interest in favour of nuclear energy.⁴ In the summary of the Meeting, they also supported the study by the

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¹ In this study, nuclear electricity, nuclear energy and nuclear power are considered similar terms.

² https://www.oecd-nea.org/jcms/pl_66130/ukraine-current-status-of-nuclear-power-installations.

³ <https://www.bbc.com/news/world-europe-68757082>.

⁴ <https://www.ans.org/news/article-6021/g7-pledges-support-for-nuclear-at-italy-meeting/> last accessed May 13, 2024.

International Energy Agency's Clean Energy Market Monitor and the reported results about the avoided GHGs emissions in the last four years thanks to 5 clean energy technologies such as solar PV, wind power, nuclear power, electric cars, and heat pumps (G7 Italy7, 2024). In the IEA study nuclear power is considered a clean energy source like solar PV, wind and hydro.

The international literature shows that electricity from nuclear plants contributes, in some cases, to Global Warming Potential (GWP) more than renewable technologies, such as hydropower (Wang et al., 2019). The contribution of nuclear power to GWP is very variable (Le Boulch et al., 2024a) and differs depending on the type of plant (Pomponi and Hart, 2021) as well as from the grade of Uranium ore and the enrichment stage (Pucciarelli et al., 2024). Moreover, nuclear electricity generates higher impacts than renewable technologies (in particular wind) to other relevant impact categories such as total material requirement (Nakagawa et al., 2022) and water consumption (Ding et al., 2019; Jin et al., 2019) and keeps the unresolved problem of the permanent disposal of nuclear high level radioactive waste in all nuclear countries among which United States (Bell, 2023) and France (Orano, 2024). U.S. is the country with the highest production of electricity from nuclear source (771.6 TWh in the year 2021) (NEA-OECD, 2023). Furthermore, recent LCA studies evaluating electricity mix scenarios in France (Cassoret et al., 2023) and Italy (Ghisellini et al., 2023) with a potentially higher fraction of nuclear power show a challenging increase of Ionizing Radiation Potential, IRP.

The emphasis in the political agenda is always high on the lower contribution of nuclear to the GWP (Kinefuchi, 2021) while there is less interest to the impacts of nuclear to the other environmental categories (Pieńkowski, 2024) and to themes of environmental and social justice (Karim, 2024).

Recent literature reviews published in the last five years have mainly focused their analysis on the impacts in terms of GHGs emissions of nuclear electricity (Le Boulch et al., 2024a; Liu et al., 2023) comparing such indicator with that of renewable technologies (Guidi et al., 2023). Other authors have reviewed the international literature with the purpose of understanding the environmental indicators used to compare energy sources on the basis of a multicriteria approach (Dorning et al., 2019). Moreover, Barros et al. (2020) reviewed the LCA literature (from 2013 to the year 2018) adopting a systematic literature review with the goal of providing a state of the art of LCA research about global electricity production systems.

These latter literature reviews focus their attention on a wider set of environmental indicators in the assessment of the sustainability of energy sources and systems. Anthropogenic activities have been causing the surpassing of six out of 9 planetary boundaries such as climate change, biosphere integrity, land system change, freshwater change, biogeochemical flows of N and P (Richardson et al., 2023). Furthermore, the continuous focus on single environmental categories (e.g. climate change) disregards the nonlinear relations that could impact on the conditions of the whole Earth system (Richardson et al., 2023). Therefore, this study collects data from the review of the international literature about the environmental impacts of nuclear energy and adopts a wider perspective of analysis not only focusing on GWP, but also integrating the current research with the state of the art of the impacts of nuclear electricity, to better address the planetary boundary's concept (Richardson et al., 2023).

Moreover, the topic of "just transition" is increasingly acquiring importance in the context of the circular economy (CE) research (Ghisellini et al., 2024; Kirchherr, 2021) as well as in the European policy agenda (Vassillo, 2024), also by means of funding research projects that explore which factors could enable or hamper a more socially aware orientation of the current CE model (Passaro et al., 2024).

The energy transition is an important component of the CE transition and both of them are crucial in the sustainability transition (Ghisellini and Ulgiati, 2020). As a matter of fact, early scholars involved in CE research recognized a key role to the redesign and implementation of the

principles of CE in industrial activities, to improve their energy performances as well as to the development of renewable energies to become the most important sources of energy in the CE (Preston, 2012), in so paving away the fossil fuel economy (Ellen Macarthur Foundation, 2012).

The term "Just Transition" within the energy context started to be used by the trade unions in United States in response to the need of assuring social justice and protection in favour of workers losing their jobs in coal mining regions (Schroeder, 2020). This term has also been applied to the actions to tackle climate change and low-carbon transitions within the Paris Agreement to support decent working conditions and high-quality jobs for workers (Schroeder, 2020). In the case of nuclear energy, social justice concerns have been raised by several scholars to highlight the human and environmental health consequences of e.g. Uranium mining activities, operativity of nuclear power plants, as well as also pointing out the issue of nuclear waste generated in the whole life cycle and its intra- and inter-generational implications (Höfken and Ramana, 2024). As a result, the assessment of the sustainability of nuclear energy should necessarily encompass a multidisciplinary approach (Klingelhöfer et al., 2024) and the consideration of environmental and social justice dimensions (Hanaček and Martínez-Alier, 2022), because deciding about nuclear energy development (Karim, 2024) will have impacts within and across generations (Peterson, 2024).

This study investigates the environmental impacts and environmental and social justice dimensions of nuclear energy over its life cycle with the goal of responding to the following main research question: "Is nuclear electricity an environmentally sustainable source for the CE and energy transition in line with the principles of social and environmental justice?"

For the sake of completeness, the definition of environmental sustainability adopted in this study is the one suggested by Khan et al. (2021): "Environmental sustainability is a conservation concept which is the meeting of services and resources of present and future generations without affecting the health of the ecosystems that provide them". According to these authors, environmental sustainability represents a limit for the current generations and the satisfaction of their needs, to assure the environmental supporting to the future generation needs (Kaswan et al., 2019).

In this vein, the concept of environmental justice can be conceived as the equal allocation of environmental costs in the whole life cycle of products or services encompassing all the stages from the extraction of natural resources until waste disposal and eventual recycling, reuse or other circular patterns (Pansera et al., 2024). The concept integrates: "equal protection from burdens, meaningful involvement in decisions, and fair treatment in access to benefits" (Jenkins, 2018).

About social justice a definition of United Nations considers the concept essential for creating relations within countries and among them based on peace and prosperity. In practice, social justice supports equality in "gender, age, race, ethnicity, religion, culture, or disability and the rights of all people" and encourages the elimination of the obstacles that prevent equality (Taylor and Francis, 2024).

The European Union is currently highly committed toward the goal of social justice, inclusiveness and well living in its sustainability transition policies and programmes. Both the Green Deal and the European Pillars of social rights are important guiding documents with principles, policy measures and strategies for enhancing the transition towards a just sustainability. Such policies emphasize the main dimensions of justice, namely: distributional in the allocation of costs and benefits, participation of all the stakeholders in decision-processes, attention to the diverse cultures and opinions and provision of a compensation in case of damages to people, species and ecosystems (so-called "restorative justice" (European Environment Agency, 2024).

Overall, this study aims to contribute to the improvement of the current understanding about nuclear electricity and its impacts (in particular environmental and social) (Charnley-Parry et al., 2024) by stimulating a wider discourse on the latter in academic research as well as a science-based policy-decision making, beyond the still dominant

narrative that advocates nuclear energy as “Green and Safe” (Kinefuchi, 2021; Pichetto Fratin, 2024). This study also reminds the recommendations of the G7 of Science held in Italy this year 2024, underlining the importance that policy-decision making takes into account the recommendations of scientists.

This research is organized as follows: section 2 presents the global availability of Uranium resource and the annual requirements of the operating nuclear power plants. Section 3 describes the method for searching and selecting the literature. Section 4 summarizes the main features of the two samples of selected articles. Section 5 analyses the contents of Sample 1 (life cycle environmental impacts of nuclear electricity) and Sample 2 (environmental and social justice of nuclear fuel cycle), while Section 6 discusses the main results in the light of the main research question of this study. A case study is also offered to show how the Government in Italy is communicating its intention of reintroducing nuclear electricity in the country. Section 7 concludes the overall research presenting the main results, the implications as well as discusses the limitations and future research directions.

Table 1 summarizes all the abbreviations and their full term.

2. Availability of uranium resource and electricity generation from nuclear source

2.1. Overview of the current production and availability of natural uranium

World Uranium production, according to data available in the year 2020, amounted to 47,342 tonnes, covering about 74% of the annual

Table 1
List of Acronyms used in this study and their full meaning.

Acronym	Full term
EU	European Union
LCA	Life Cycle Assessment
CE	Circular Economy
G7	Group of Seven
GHGs	Greenhouse Gases
PV (Solar)	Photovoltaic
IEA	International Energy Agency
GWP	Global Warming Potential
NEA	Nuclear Energy Agency
OECD	Organization for Economic Cooperation and Development
N	Nitrogen
P	Phosphorus
RAR	Reasonable Assured Resources
U	Uranium
Pu	Plutonium
HLW	High-level waste
PB-LCA	Planetary Boundaries Life Cycle Assessment
SoSOS 1	Safe Operating Space 1
SoSOS 2	Safe Operating Space 2
CSP	Concentrated Solar Power
CCS	Carbon capture and storage
CC	Climate Change
POFP	Photochemical Ozone Formation Potential
AP	Acidification Potential
TEP	Terrestrial Eutrophication Potential
IRP	Ionizing Radiation Potential
FDP	Fossil Depletion Potential
OLDP	Ozone Layer Depletion Potential
TAP	Terrestrial Acidification Potential
HTP	Human Toxicity Potential
PSP	Photochemical Smog Potential
POCP	Photochemical Ozone Creation Potential
GWP	Global Warming Potential
MI	Material Input
WD	Water Deprivation
TMR	Total Material Requirement
FEP	Freshwater Ecotoxicity Potential
HTP	Human Toxicity Potential (non-cancer effects, cancer effects)
LCOE	Levelized Cost of Energy

Uranium required by the operating reactors (442) that was 60,100 tonnes (NEA-OECD, 2023). Most of the reactors were in United States (94 reactors), France (56 reactors), China (50 reactors), Russia (38 reactors), Japan (33 reactors), Korea (24 reactors), India (22 reactors), Canada (19 reactors).

The gap between supply and demand of primary Uranium has been covered in the year 2020, by secondary sources that consists of stock-piles of natural and enriched Uranium, blending of Uranium for weapons use, reprocessing of spent fuel and re-enrichment of spent Uranium residues (NEA-OECD, 2023).

The world’s largest Uranium producer in the year 2021 has been Kazakhstan. This country supplies about the half of the entire world production of Uranium (46%). The remaining half of the demand has been covered by the following countries in order of production relevance: Namibia, Canada, Australia, Uzbekistan, Russia, Niger, China, India and Ukraine. It is interesting to note that Kazakhstan, Australia, Namibia, Uzbekistan and Niger are producers but not consumers of Uranium since there are no reactors in these countries, while other countries that are not producers such as France have to import the Uranium or use secondary sources to feed their reactors (NEA-OECD, 2023).

The natural stock of Uranium is limited and concentrated in some countries (Takao, 2023). Identified conventional Uranium resources (Reasonable Assured Resources, RAR) consist of Uranium deposits known in their size, grade and morphology. These are exploitable within a specific cost range and available mining technologies.⁵ Fig. 1 shows that RAR, in the year 2023, with costs of extraction up to \$40/kg were mainly located in a low number of countries with Kazakhstan having the largest Uranium deposits accounting to more than the half of the global RAR (252,000 t). The other countries (Brazil, China, Spain, Uzbekistan) have smaller Uranium deposits.

Uranium resources (RAR) shifting to higher costs for their extraction and in particular comprised between \$40/kg U and \$130/kg U are more distributed. Fig. 2 shows that the richest deposits of Uranium resources within this costs range are located in Australia (1,238,700 t and 32% of the world total deposits), Canada (489,700 t, 13% of the world total deposits), Kazakhstan (367,800 t and 9.6% of the world total deposits) (Fig. 2).

2.2. Global production of electricity from nuclear

Fig. 3 shows the shares of the various sources that contributed to the global electricity generation from the year 1971 until the year 2019. As it can be seen, coal still represents the most important source in electricity generation (35.2%), followed by renewables (26.5%), natural gas (23.6%), and nuclear (10.4%). The share of coal has remained substantially stable over time (slightly decreasing in 2019 compared to 1971), while that of renewables increased since the beginning of the years 2000 surpassing in the year 2013 the share of natural gas. The nuclear source, after reaching in the year 1996 a pick shares equal to 17.68% of total electricity production, began a decline, progressively decreasing until reaching around 10% of global electricity production. The role of oil has continued to decline over this period.

In the year 2022, EU produced 21.8% of its electricity from nuclear source. France was the EU country with the largest fraction of electricity from nuclear source (62.8%). Slovakia (60.2%) and Belgium (46.4%) come after France. On the contrary, the Netherlands (3.1% of the total electricity mix) was the country with the lowest share of electricity produced from nuclear (EUROSTAT, 2023). Italy has no nuclear power plants but imports some electricity produced from nuclear sources from other European countries such as France, Switzerland and Slovenia (TERNA, 2021).

⁵ U.S. Energy Information Administration: RAR definition, available at: <http://www.eia.gov/tools/glossary/?id=nuclear>.

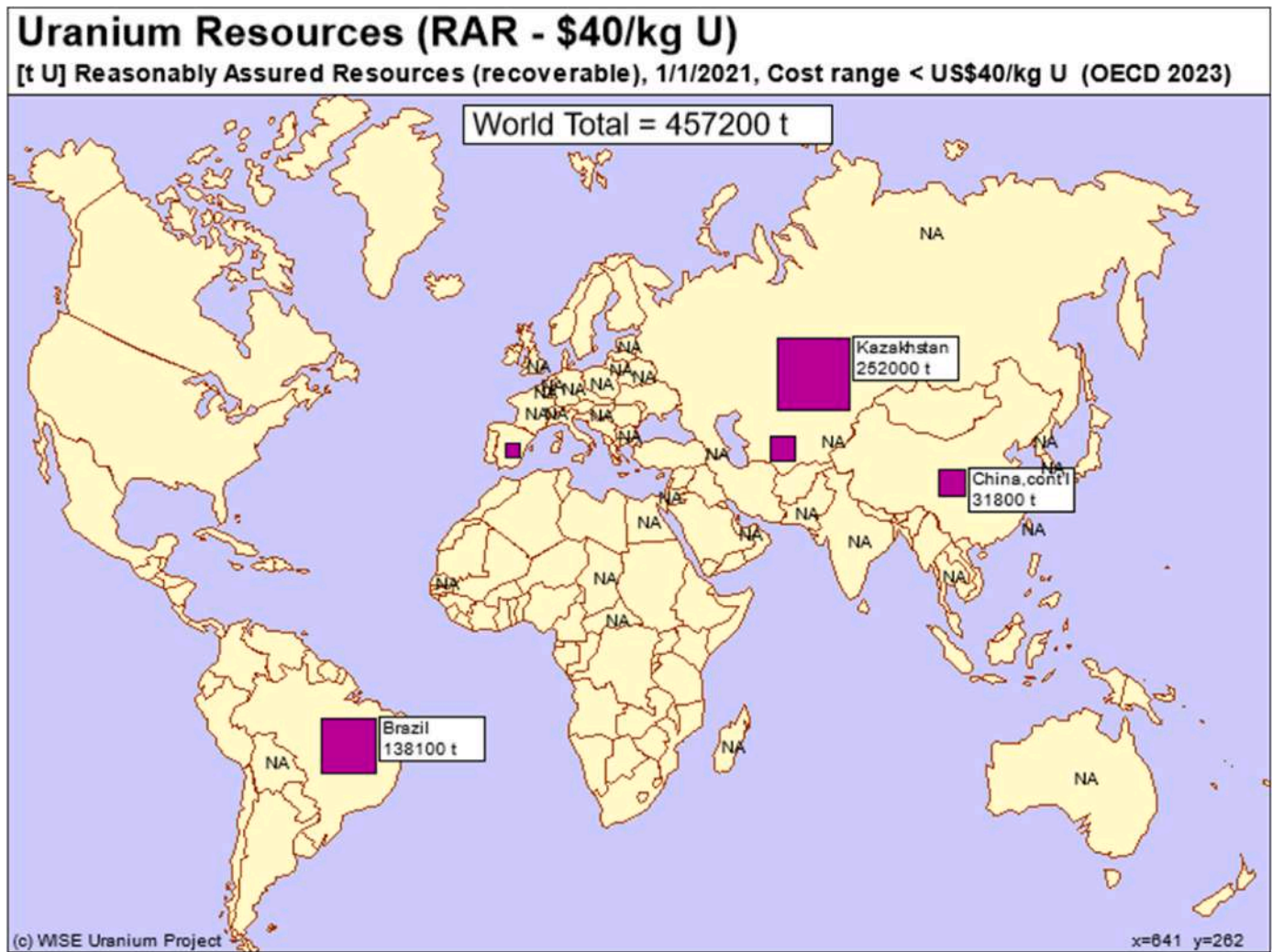


Fig. 1. Global distribution of RAR with costs lower than \$40/kg U. Source: <https://www.wise-Uranium.org/umaps.html>.

According to the data by EUROSTAT (2023), European nuclear energy production increased by 26.9% in the period 1990–2004, while in the subsequent period (2004–2021), nuclear electricity first stabilized (period 2004–2006), and then significantly reduced by 33.4% from 2006 until the year 2022, due to the significant reduction in Germany’s electro-nuclear energy production. The production of the latter country decreased from 152,468 GWh (year 1990) to 34,709 GWh produced in the year 2022. Finally, in 2022, the total electricity from nuclear in the EU mainly derived from France (52% of the total EU), Spain (9.6%), Sweden (8.5%) and Belgium (7.2%).

3. Materials and methods

This study assessed the most recent LCA literature on nuclear electricity with the purpose of responding to the main research question mentioned in the second part of the introduction. A systematic literature review has been considered appropriate as a method to reach the intended goals of this study, in that a systematic literature review is a survey of the relevant literature about a particular topic (Greenhalgh, 1997), conducted in a way that can be replicated (Greenhalgh, 1997). The review has been handled by means of several steps (Petticrew and Roberts, 2006; Pittaway et al., 2004) starting from the first one that involve the definition of the keywords and the query strings and the selection of the database where perform the search of the literature. At this latter regard Scopus and Web of Science have been selected for this

review, due to their wider use in bibliometric analysis of the general literature (Singh et al., 2021). Both databases have been used in the assessment with LCA of the impacts of electricity systems or technologies (Barros et al., 2020), with multicriteria indicators for comparing the environmental effects of primary energy sources (Dorning et al., 2019) and for evaluating the sustainability and justice of energy transition (Arias et al., 2023).

The results for each query string have been the following for each one of the two databases:

In Web of Science Database: the search has been performed on “All Database” and “by Topic”:

- 1) (((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental impacts)) AND TS=(life cycle assessment): 157 results (from January 1, 2019 to October 18, 2024), 26 articles selected;
- 2) (((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental sustainability)) AND TS=(life cycle assessment): (from January 1, 2019 to October 18, 2024): 61 results: 9 articles selected, 8 duplicates of the previous search of bullet point 1 and 1 duplicate with the search B of Scopus;
- 3) (((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(circular economy): 97 results, selected 3 articles (from January 1, 2019 to October 18, 2024: 1 duplicate with

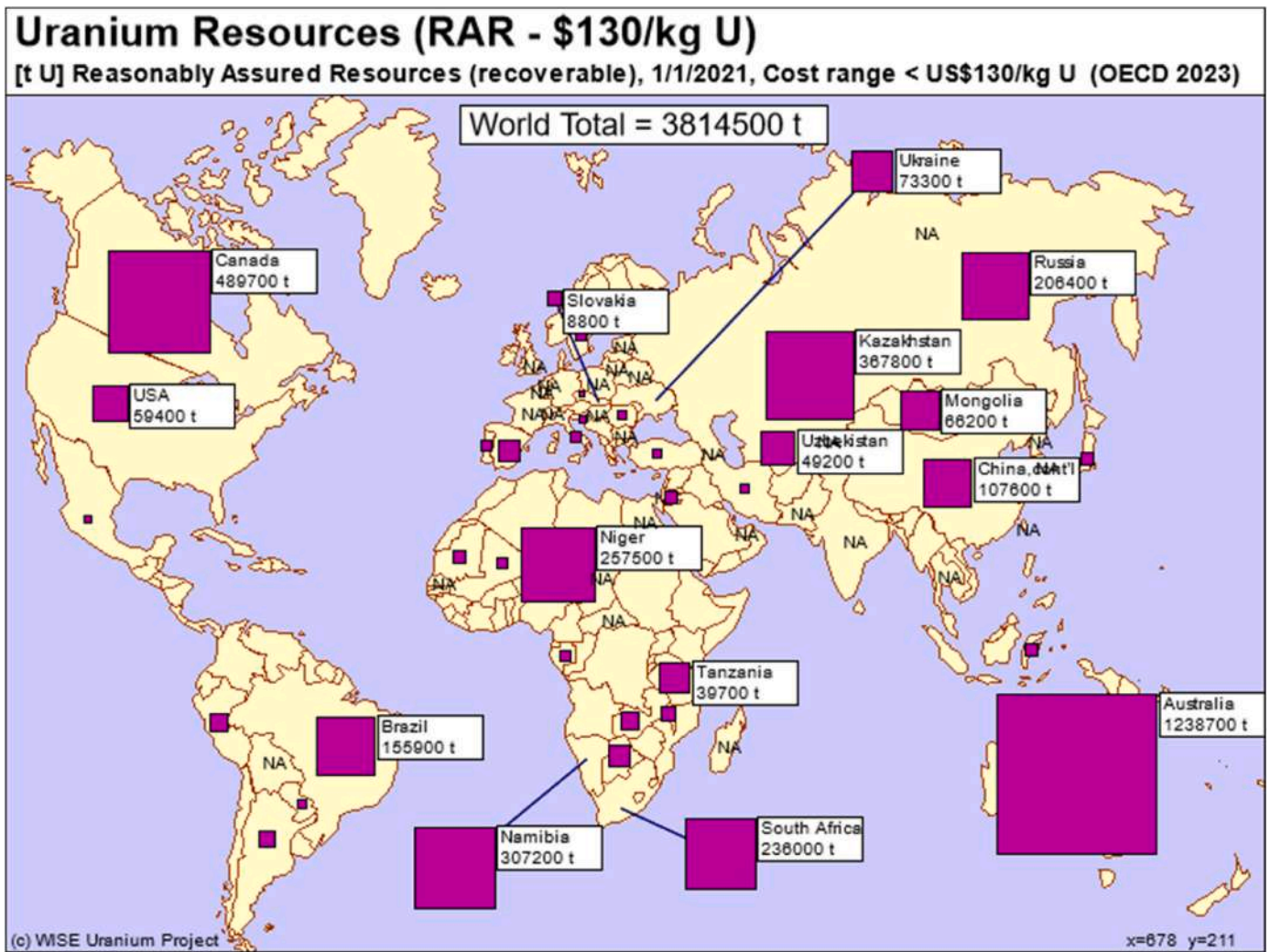


Fig. 2. Global distribution of RAR with costs lower than \$130/kg U. Source: <https://www.wise-Uranium.org/umaps.html>.

- the search on the bullet point 1, 1 article selected but unfortunately not available for downloading);
- 4) (((((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental justice)) AND TS=(social justice): 45 results selected 14 (from January 1, 2019 to October 18, 2024) 1 selected article was not available for downloading;
 - 5) (((((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental justice)) AND TS=(social justice)) AND TS=(developing countries) (from January 1, 2019 to October 18, 2024), 1 result, selected 0;
 - 6) (((((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental justice)) AND TS=(social justice)) AND TS=(Global South) (from January 1, 2019 to October 18, 2024); 1 results, selected 0;
 - 7) (((((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(justice)) AND TS=(Uranium communities)) (from January 1, 2019 to October 18, 2024); 5 results, 2 selected articles duplicates with previous searches, 1 article not available for downloading;

A further search has been made combining the two query strings of the bullet points 1 and 2 with the bullet point 4 to verify if there could be a gap in the existing literature.

- 8) ((((((TS=(nuclear energy)) OR TS=(nuclear power))) OR TS=(nuclear electricity)) AND TS=(environmental sustainability)) AND TS=(life cycle assessment)) AND TS=(environmental justice)) AND TS=(social justice); 0 results (from January 1, 2019 to October 18, 2024);
- 9) ((((((TS=(nuclear energy)) OR TS=(nuclear electricity)) OR TS=(nuclear power)) AND TS=(environmental impacts)) AND TS=(life cycle assessment)) AND TS=(environmental justice)) AND TS=(social justice) (from January 1, 2019 to October 18, 2024), 1 results1 duplicate of the search at bullet point 1

In the Scopus database the search was focused on “Title, Abstract and Keywords”. The adopted keywords and query strings have been the following:

- A. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear electricity") OR ("nuclear power") AND ("environmental impacts") AND ("Life cycle assessment") AND PUBYEAR >2018 AND PUBYEAR <2025 AND PUBYEAR >2018 AND PUBYEAR <2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Life Cycle") OR LIMIT-TO (EXACTKEYWORD, "Environmental Impact") OR LIMIT-TO (EXACTKEYWORD, "Life Cycle Analysis")): 308 documents (search performed on October 25, 2024) and selected 23 (17 are duplicates of articles already resulted in the search of Web of Science);

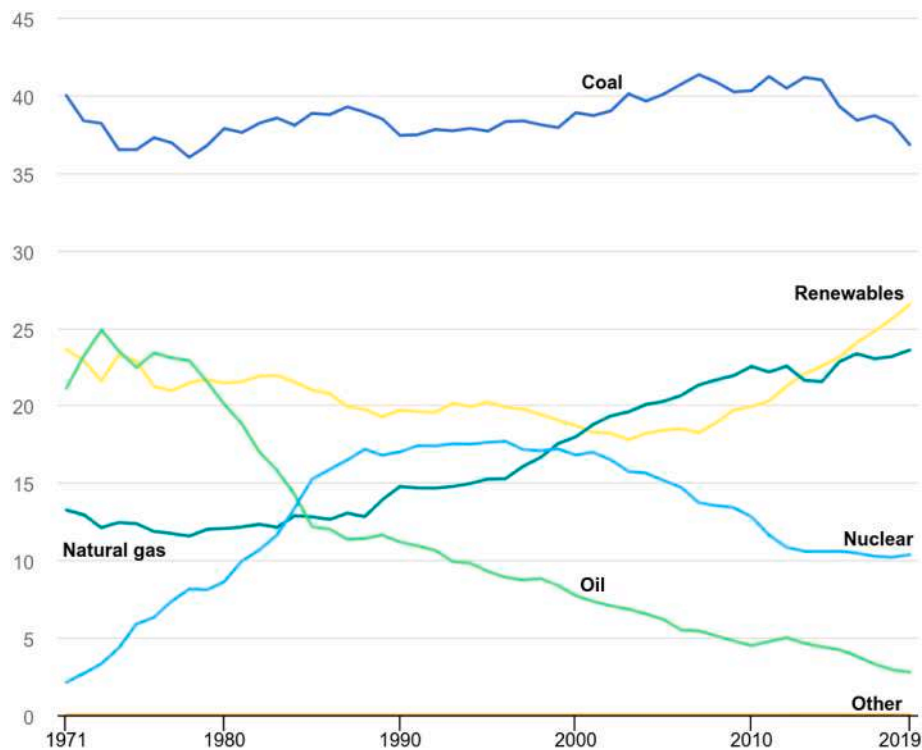


Fig. 3. Global electricity production by fuel in the period 1971–2019. Source: International Energy Agency: <https://www.iea.org/data-and-statistics/charts/world-electricity-generation-mix-by-fuel-1971-2019>.

- B. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear electricity") OR ("nuclear power") AND ("environmental sustainability") AND ("Life cycle assessment") AND PUBYEAR >2018 AND PUBYEAR <2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")): 260 results (search performed on October 25, 2024): 4 articles selected (all articles duplicate of the previous search in Web of Science and Scopus);
- C. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear electricity") OR ("nuclear power") AND ("circular economy") AND PUBYEAR >2018 AND PUBYEAR <2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Circular Economy")): 105 results (search performed on November 4, 2024): 3 articles selected (2 articles duplicates of the search on Web of Science bullet point 3 and 1);
- D. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear power") OR ("nuclear electricity") AND ("environmental justice") AND ("social justice") AND PUBYEAR >2018 AND PUBYEAR <2025: results: 175 articles (search performed on October 25, 2024): selected 11 articles (5 duplicates with Web of Science and 1 article non available for downloading);
- E. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear power") OR ("nuclear electricity") AND ("environmental justice") AND ("social justice") AND "developing countries" AND PUBYEAR >2018 AND PUBYEAR <2025: 33 results (search performed on October 25, 2024): 0 selected;
- F. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear power") OR ("nuclear electricity") AND ("environmental justice") AND ("social justice") AND "Global South" AND PUBYEAR >2018 AND PUBYEAR <2025: 33 results (search performed on October 25, 2024): 1 article selected (1 duplicate with the previous search on bullet point D);
- G. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear power") OR ("nuclear electricity") AND ("social justice") AND ("Uranium

- communities") (search performed on October 25, 2024): 19 results: 3 articles selected (3 duplicates with previous strings);
- H. TITLE-ABS-KEY ("nuclear energy") OR ("nuclear electricity") OR ("nuclear power") AND ("environmental impacts") AND ("life cycle assessment") AND PUBYEAR >2018 AND PUBYEAR <2025 AND ("environmental justice") AND ("social justice") AND PUBYEAR >2018 AND PUBYEAR <2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ed")): 4 results out of topic (1 environmentally climate-smart radiation oncology care; 1 article focused on the analysis of the sustainability of megaprojects; 1 article on offshore wind conflicts in South Korea, 1 article on the transition to environmentally climate-smart radiation oncology care; 1 article on hydrogen transition and 1 on offshore wind) (search performed on October 25, 2024).

The initial search with the strings on Web of Science (1, 2, 3, 4) and Scopus (A, B, C, D) having as timeframe (January 2019–May 2024) has been repeated in the period October–November 2024 in order to rely on the most recent literature. The search also has been performed by using new keywords and strings (5, 6, 7 in Web of Science and E, F, G in Scopus). Two samples of articles have been constructed from the searches on both databases at the end of the screening of the abstracts and an in-depth assessment of the content of the selected articles. The Sample 1 contains 34 articles dealing with the life cycle environmental impacts of nuclear electricity while the Sample 2 has 27 articles analysing the relation between nuclear fuel cycle and environmental and social justice and critically analyse nuclear energy in the sustainability framework. Overall, the resulting articles from the searches on both databases have been 1295, i.e. 368 (Web of Science) and 927 (Scopus). The selected articles before the removal of duplicates resulted 56 in Web of Science and 45 in Scopus. The duplicates were 16 in Web of Science and 33 in Scopus, so that the final number of articles after the removal of duplicates resulted composed of 52 articles (40 from Web of Science and 12 from Scopus). Finally, Google Scholar search added 9 articles obtaining a total number of 61 articles.

In the case of Sample 1, articles have been selected if they used an LCA as the main evaluation method for the analysis of the environmental profile of electricity mixes, in order to point out a wide range of environmental indicators (Carvalho et al., 2022; Barros et al., 2020), but also of social indicators as in the case of the endpoint indicators for the categories related to human health, species and resources (Ghisellini et al., 2023). Data and information have been collected and classified according to selected topic areas of the investigated papers (e.g. the nuclear life cycle, boundaries of the studies, their methods, the main results, conclusions).

For Sample 2, the main criteria adopted in the selection of the articles have been the analysis of environmental and/or social justice issues in the life cycle stages of nuclear fuel cycle, such as in the Uranium stage, operativity of the nuclear power plant or decommissioning stage. Sample 2 articles have been also identified and selected if focused e.g. on the potential inequalities towards different social groups (e.g. native people), the local impacts of Uranium mining on communities and differences between nuclear energy use in Global North and Global South.

Moreover, recent studies that questioned the current narrative on the role of nuclear energy in addressing sustainability have also been searched and selected on Google Scholar and added to Sample 2. The keyword/query used in Google Scholar has been the following: Questioning the sustainability of nuclear energy (with timeframe 2019–November 20, 2024). The search with this latter keyword has been also previously performed on Web of Science and Scopus but the search did not result in articles useful for this study. This justifies the use of Google Scholar. The most recent articles have been selected on Google Scholar.⁶

In order to assure the replicability of the literature review process, all the articles resulted from the searches on Web of Science and Scopus databases have been included in the supplementary material in Microsoft Excel Files.

4. Overview of the selected literature

This section starts with the analysis of some of the characteristics of the two samples of articles evaluating nuclear electricity and its environmental sustainability (Sample 1) and environmental and social justice (Sample 2).

4.1. Distribution of selected articles over time

Fig. 4 depicts the evolution of the selected LCA literature, Sample 1. The trend seems increasing since the year 2022. The years 2022, 2023 and 2024 gather about half of the LCA literature, while the previous years include 5 articles published in the year 2019 and 3 articles both year 2020 and 2021.

Fig. 5 shows the articles of the Sample 2. The year 2024 collects the highest number of articles compared to the other years. Four articles have been published in the year 2023, 5 articles in the years 2020 and in the year 2021 while 2 articles in the year 2019.

4.2. Distribution of selected articles across journals

Fig. 6 highlights that the selected LCA articles in Sample 1 are widely distributed in the international Journals. Seven articles out of 34 have been published in the Journal “Energies”, followed by 2 articles published in “Applied Energy”, 2 in “International Journal of Life Cycle Assessment”, 2 in “Journal of Cleaner Production”, 2 “Journal of Environmental Management” 2, “Sustainability” and 2 “Sustainable Production and Consumption”. It is also interesting to note that most of the

selected articles are published in journals of the area “energy” in many of its subfields such as renewable energies, energy policy, energy research. Further represented journal areas are those about environmental management, sustainability and life cycle assessment.

Fig. 7 shows that the articles of Sample 2 are published in a wide range of international journals. Six articles have been published in the journal “Energy Research and Social Science”, 3 in the Journal “Extractive Industries and Society” and 2 in “Wiley Interdisciplinary Review Energy and Environment” while the rest (16 articles) in other journals in research areas of economic and sustainable development, energy, risk and safety, legislation, nature-society.

4.3. Object of analysis of the selected articles

In Sample 1 more than the half of the selected literature (62% of the total) analysed the environmental impacts of electricity generation from nuclear source and compared the latter with other sources: renewable (e.g. Hydro, wind offshore and onshore, solar photovoltaic) and non-renewable (e.g. coal, oil and natural gas). The rest, 38% of the whole sample of articles assessed the impacts of only nuclear fuel cycle (Table A1, Appendix).

In Sample 2 almost all the articles except two of them (Sovacool et al., 2019, 2021) deal with only the injustices of nuclear energy in the whole life cycle or mainly in three stages of the latter: Uranium mining, operativity of nuclear plants, decommissioning and spent fuel disposal (Table A2, Appendix). Sovacool et al. (2021) analyse four case studies of injustices in energy and CE transitions: the negative impacts of solar energy development in Germany, the challenging local relations between the nuclear energy plants and winery areas in France, the external costs of electronic waste bulked in Ghana, the dramatic health conditions of children miners in the Democratic Republic of Congo employed in the extraction of cobalt needed for the manufacturing of batteries for electric vehicles. Sovacool et al. (2019) critically analysed four low carbon transitions in the EU, including nuclear energy in France, developing a framework composed of the four dimensions of justice namely distributive, procedural, cosmopolitan and recognition. Finally, some articles also analysed nuclear energy and its role in sustainable energy transition (Pieńkowski, 2024) with insights into its economic unsustainability as an investment compared to other sources (Haywood et al., 2023) or focused the analysis on the uncertainties related to the economic competitiveness of last nuclear technologies such as small modular reactors (Böse et al., 2024; Mignacca et al., 2020) and Generation IV nuclear reactors (Tassone et al., 2024).

4.4. System boundaries of selected articles in the nuclear fuel cycle

The nuclear fuel cycle is the set of stages that lead to the generation of electricity from Uranium by means of the nuclear reactors (IAEA, 2011). Fig. 8 shows that the nuclear fuel cycle is composed of upstream processes inside the so-called front-end cycle and downstream processes within the back-end of the life cycle (Le Boulch et al., 2024a; Takao, 2023). Between these two main cycles there are the activities associated to the construction of the reactor, the operativity of the nuclear power plant for the production of electricity and its decommissioning (Le Boulch et al., 2024a; Takao, 2023). In detail, the front-end of the life cycle includes the extraction of Uranium from different types of mines, its crushing and chemical treatment in order to allow its conversion and enrichment to enhance the share of U-235 isotope. After this activity the enriched Uranium (UF₆) is transformed into Uranium oxide (UO₂), prepared in the form of fuel pellets and uploaded inside the nuclear reactor where the nuclear fission will generate the splitting of U-235. The reaction will produce heat energy needed for boiling water and release high pressure steam for running a turbine linked to a generator for the production of electricity (IAEA, 2011). After the generation of electricity and the use of the nuclear fuel in the reactor (about 3–4 years in a lightwater nuclear reactor), the spent nuclear fuel undergoes a

⁶ The 9 selected articles are: Böse et al. (2024); Charnley-Parry et al., 2024; Pieńkowski (2024); Tassone et al. (2024); Haywood et al. (2023); Kinefuchi (2021); Redvers et al. (2021); Marsh and Green (2020); Rock and Ingram, 2020.

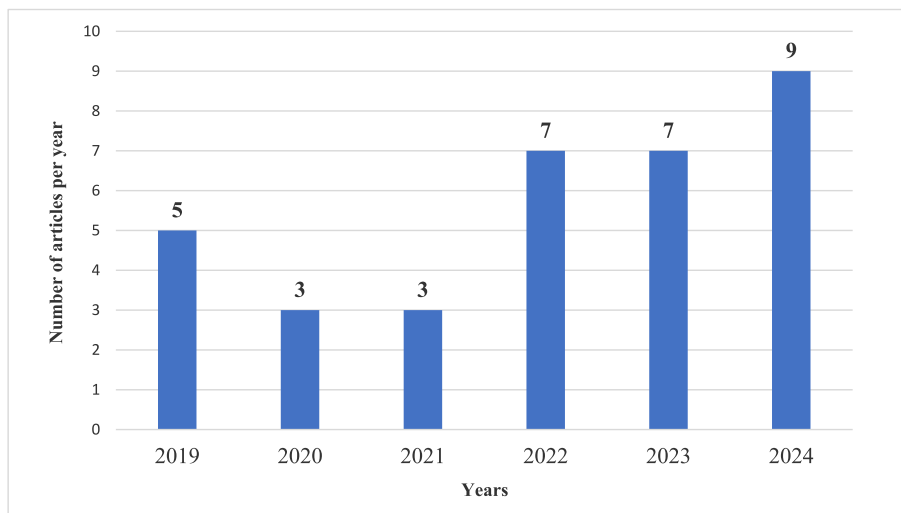


Fig. 4. Distribution of the LCA literature over the investigated period (Sample 1).

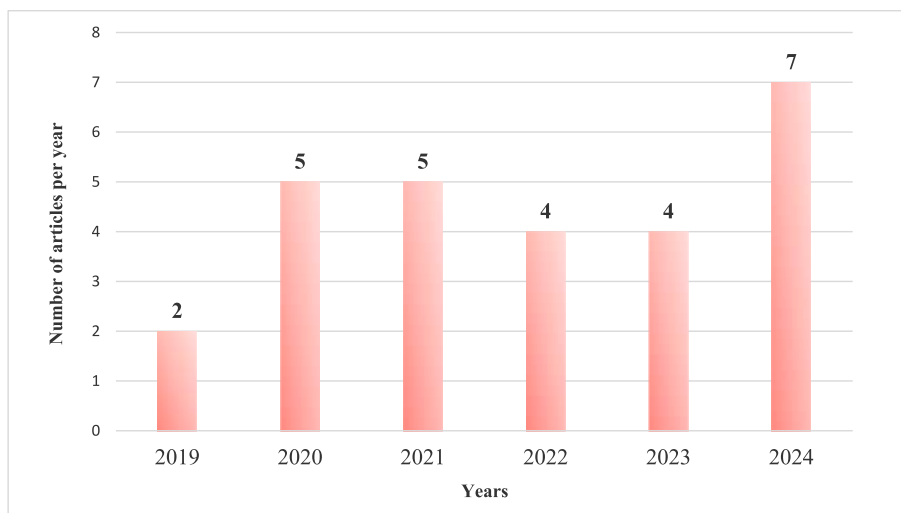


Fig. 5. Distribution of the environmental and social justice literature over the investigated period (Sample 2).

period of cooling in the pools ranging from 2 to 5 years and is subsequently stored in an interim storage site or sent for recycling by chemical separation (reprocessing). In this second case, the recovered materials, i. e. U and Pu, can be reused for the manufacture of new fuel (Takao, 2023). The spent nuclear fuel is composed of U (95%) and Pu (about 1%) and other fission products and minor actinides (Takao, 2023).

The whole nuclear fuel cycle generates waste and other impacts. Uranium is radioactive and is not available in isolation but in combination with other elements that are generated as a consequence of the decay of Uranium. Starting from the Uranium mining stage there is the production of radioactive elements such as in particular radon-222. The further steps such as milling generate a relevant quantity of waste that is generally polluted with toxic heavy elements as well as with radioactive materials. Enrichment of Uranium also produces as byproducts the so-called depleted Uranium, that suddenly became noted during the U.S. attacks on Iraq. Furthermore, after the normal operativity and use in the nuclear reactors the spent nuclear fuel must be managed and disposed of or reprocessed. The management of nuclear waste even in the case of low-level radioactive waste expose people to a high risk of cancer and other health problems (Höffken and Ramana, 2024).

The nuclear fuel cycle can be open, partially closed or entirely closed depending on the inclusion of the reprocessing and partial reuse of the

exhausted nuclear fuel (Taylor et al., 2022). The reprocessing offers the advantage of reusing the spent nuclear fuel composed of a high percentage of U and Pu (IAEA, 2011) and avoid in particular the impacts of the extraction of natural Uranium (Pucciarelli et al., 2024). Moreover, by means of the reprocessing step the volume of nuclear waste with a high level of radioactivity (HLR) can be reduced while at the same time it must be adequately treated, being characterized by a very high level of radioactivity for more than 10,000 years (Takao, 2023).

Fig. 9 shows that Sample 1 of this review is composed by more than the half of LCA studies that assess the processes from “cradle to grave”, while a lower number focused on mining and milling at the front end of the life cycle (2 studies) or adopt a “cradle to gate” approach (5 studies). The others assess the decommissioning (1 study) or one stage in the back-end of nuclear fuel cycle (e.g. reprocessing) (2 studies) or nuclear waste disposal (2 studies),

Fig. 10 sheds light on the boundaries of analysis of the articles of Sample 2. Almost 50% of the articles have analysed the issues of environmental and social justice associated to whole life cycle of nuclear energy. Six articles have examined the injustices in Uranium mining stage and the others considered the injustices related to the operation of nuclear power plants (5 articles) and disposal of the spent nuclear fuel and its siting (4 articles).

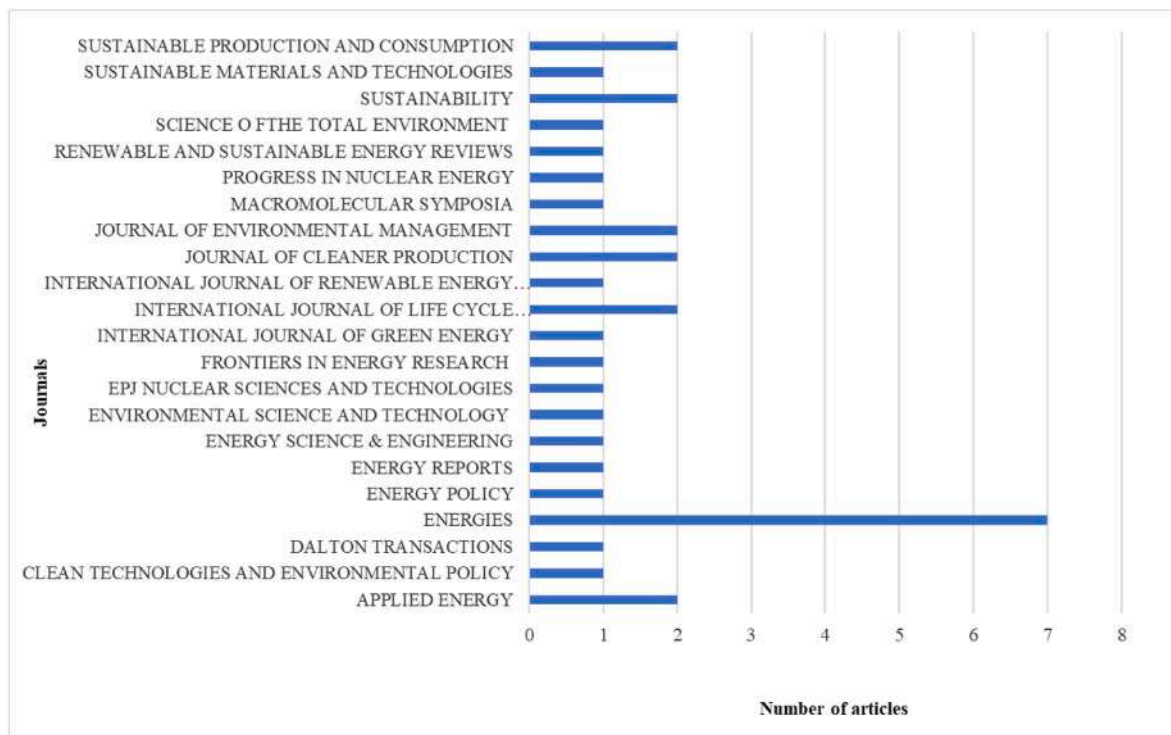


Fig. 6. Distribution of the selected LCA literature (Sample 1, Total number of articles: 34) on the basis of the publishing journals.

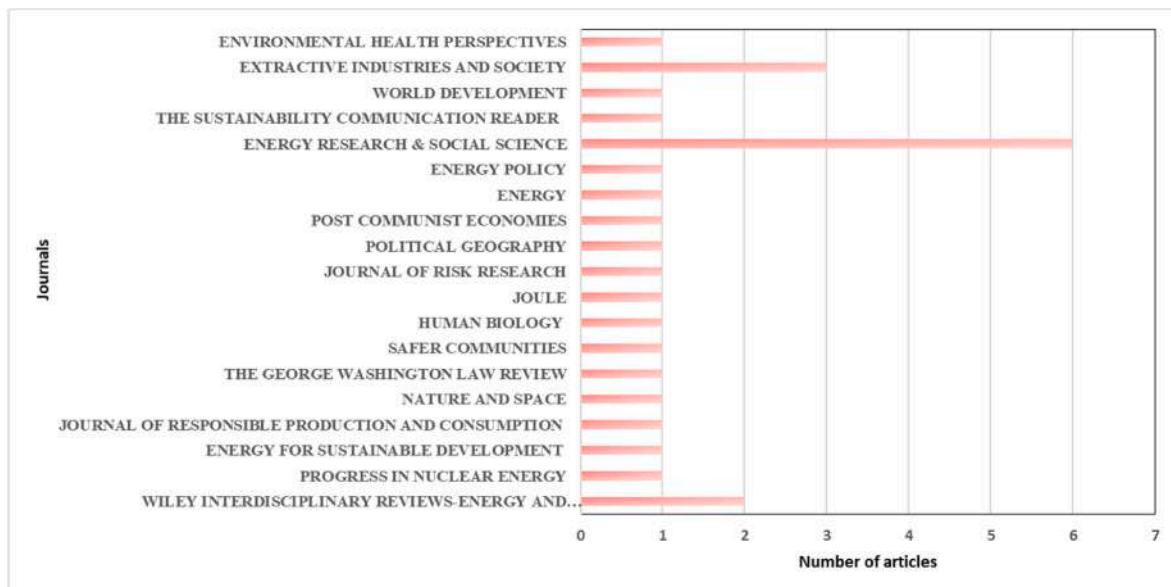


Fig. 7. Distribution of the selected environmental and social justice literature (Sample 2, Total number of articles: 27) on the basis of the publishing journals.

5. Results

The presentation of results is organized into two sub-sections (5.1, 5.2) respectively according to papers selected as Sample 1 and Sample 2.

Sub-section 5.1 includes the results emerged from the evaluation of the contents of the selected literature assessing the impacts of nuclear electricity and comparing the latter with other sources on the basis of a wide range of environmental impact categories (Sample 1). It is important to remark that even if the results and then the impacts of nuclear (and other sources in some cases) are presented in different sub-sections, the whole nuclear cycle is depicted in Fig. 8.

Sub-section 5.2 analyses the results of the environmental and social justice issues associated to the nuclear fuel cycle emerged from the selected literature (Sample 2).

5.1. The environmental sustainability of nuclear fuel cycle

This sub-section 5.1 is divided into four further sub-sections, according to aspects that emerged from the reviewed literature:

5.1.1, LCA studies assessing the impacts from cradle to grave, where the nuclear cycle is fully assessed (from mining to final disposal), most often together with (and compared to) other electricity sources;

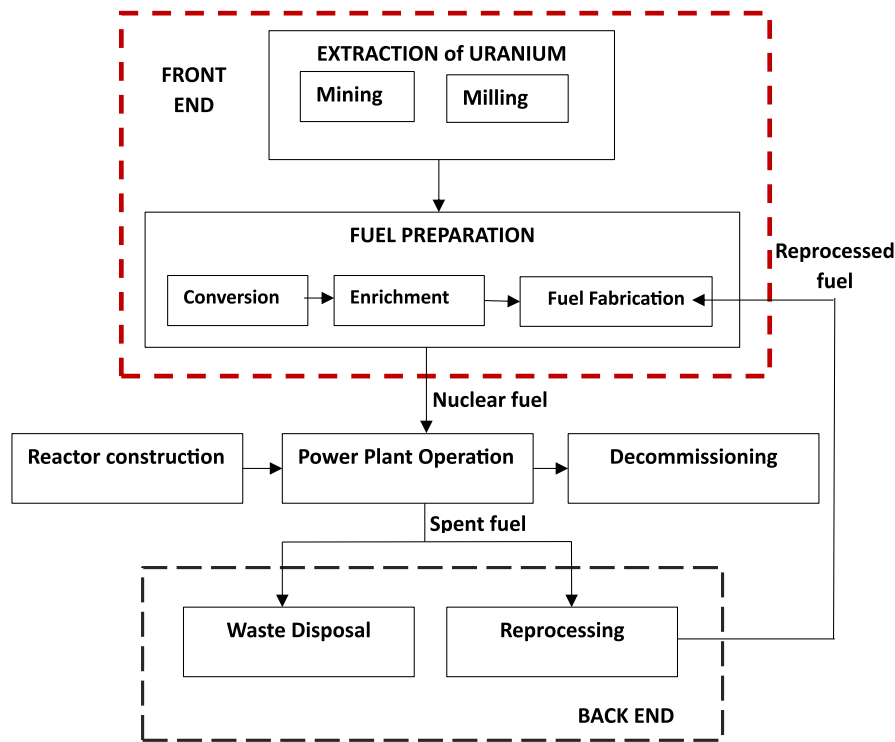


Fig. 8. The nuclear fuel cycle across its stages. Source: Adapted after Le Boulch et al., 2024a.

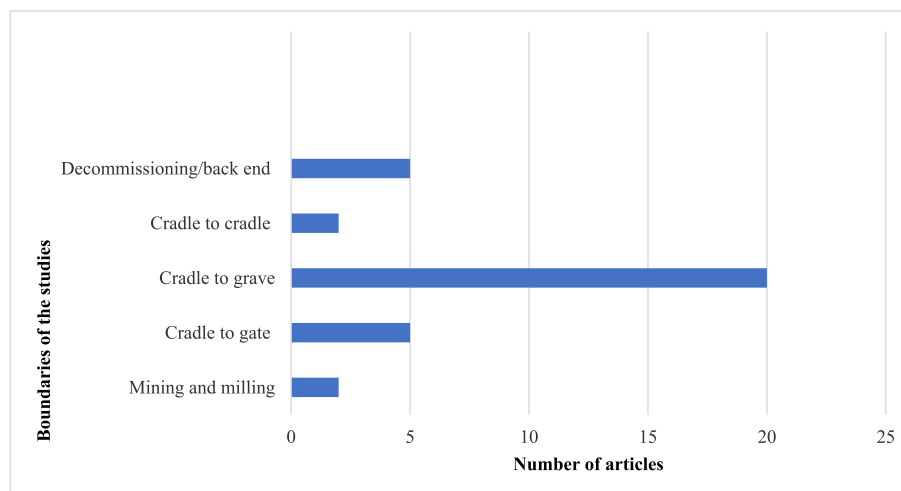


Fig. 9. Distribution of the selected articles in the first sample across to the different types of LCA approaches.

5.1.2, LCA studies assessing the impacts from cradle to gate, where only the upstream steps are assessed, from mining to plant construction (gate), without including the impacts of the operating and disposal steps;

5.1.3, LCA studies assessing the impacts at the end-of-life/backend stages, where only the decommissioning of nuclear power plants, eventual reprocessing of the spent nuclear fuel and final impacts of radioactive waste management and disposal steps are dealt with;

5.1.4, LCA studies assessing greenhouse gas emissions of nuclear fuel cycle, where the nuclear cycle is only assessed with focus on its ability to affect the greenhouse gas emissions and compared with other sources.

5.1.1. LCA studies assessing the impacts from cradle to grave

This sub-section includes LCA studies whose goal is assessing and comparing the impacts of worldwide electricity scenarios from upstream

to downstream steps, trying to highlight how nuclear cycle affects the specific impact categories. Of course, comparison results depend on the inclusion or exclusion of specific steps (e.g. mining or final disposal), which may have different impacts to the nuclear and other scenario cycles.

Stranddorf et al. (2023) have conducted a Planetary Boundaries Life Cycle Assessment (PB-LCA) with the goal of investigating the environmental sustainability of electricity in the EU-28 countries for the period 2020–2050. The authors considered three scenarios (Base, Green and Net Zero). In particular, their Green Scenario 2050 has a high share of renewables in the electricity mix (74%) (hydro, wind onshore and offshore, solar PV and Concentrated Solar Power (CSP), bioenergy (wood chips), carbon capture and storage (CCS) and nuclear (21%). Further, in the EU electricity context Carvalho et al. (2022) assessed the life cycle impacts of the 2018 and 2030 electricity mixes for Italy and

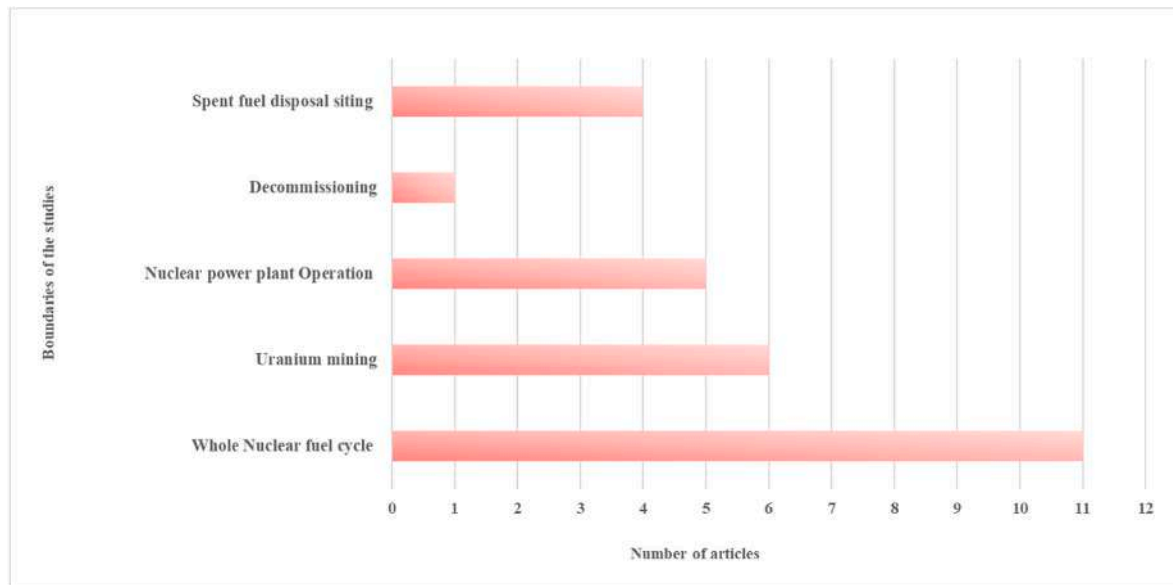


Fig. 10. Distribution of the selected articles of Sample 2 across the analysed stages of the nuclear fuel cycle.

other EU countries. The European reference scenario was considered for the EU countries, while an Integrated National Energy and Climate Plan was accounted for the year 2030 for Italy. The major changes occurring in the EU mix in the evolution between the two scenarios (from the year 2018 until the year 2030) are the growth of electricity share from wind and the decline of the share from nuclear in particular in Belgium and Germany (where a whole phasing out of that source was in progress). The results of the LCA impacts reflect an evolution of the shares of the different sources composing the electricity mix, with a reduction for the impact categories CC, POFP, AP and TEP, and an increase for the categories IRP and Mineral, Fossil and Renewable Resource Depletion.

Future low carbon scenarios for European countries and North Africa, have been also assessed by Junne et al. (2021), who proposed the analysis of the economic costs and impacts in terms of GHGs emissions as well as the associated co-benefits and negative collateral impacts to the environmental categories Ecosystem quality, Human Health and Resources to the year 2050. Their results evidence that scenarios aimed to mitigate the GHGs emissions by considering an increase of the share of nuclear should also take into account the negative impacts of Ionizing Radiation Potential IRP, Uranium depletion and water consumption. The increase of potential IRP impact category is also confirmed by Cassoret et al. (2023) who evaluated different electricity scenarios in France by the year 2035 compared to the year 2019. The 2035 scenario has the largest share of electricity from nuclear (70%), while the shares of renewables (19%) and fossils (9%) are much lower. In contrast, the other scenarios analysed by Cassoret et al. (2023) (namely, scenarios Ampere, 2035; Hertz, 2035; Volt, 2035; Watt, 2035) have reduced shares of nuclear in favour of a higher role of renewables. In this regard, the Watt scenario 2035 has the lowest share of nuclear power (11%) and the highest one from renewables (71%) and fossils (18%). Their results obtained by using the impact assessment method ReCiPe 2016; Huijbregts et al., 2017) and examining the impacts of plant construction and use stages show that the Watt scenario 2035 generates the lowest impacts to the potential IRP category, marine eutrophication, mineral resource scarcity and water consumption.

In the life cycle of 1 kWh of electricity the highest contribution to the IRP indicator is due almost entirely to the mining (Gibon and Menacho, 2023) and milling stages (Sokka et al., 2024), while other studies indicate the electricity generation and the spent fuel management as the most relevant phases to IRP (Le Boulch et al., 2024b). The energy and emissions of waste treatment phase as well as the flows of conventional and radioactive waste have been accounted for. Moreover, IRP indicator

was integrated by a qualitative analysis of radionuclide emissions. It is interesting to analyse the life cycle inventory of the study, from which it is possible to understand the geographical distribution of Uranium mining for the production of electricity in France. The Uranium is extracted in Australia (16%), Canada (21%), Namibia (10%), Niger (17%), Russia (18%), Kazakhstan (18%). The Uranium in Canada is extracted totally from underground mines, while in Namibia from open-pit mines and in Kazakhstan totally by applying the in-situ leaching.

In the Finnish context, Sokka et al. (2024) assessed the carbon emissions potential of the LDR-50 low-temperature nuclear reactor designed for district heating. These Authors consider the nuclear technology for heat production an appropriate tool to replace the fossil fuel technology, which is a relevant source of CO₂ emissions in countries with cold climate such as Northern and Eastern Europe. The carbon footprint of the proposed LDR-50 nuclear reactor is very low (2.4 g CO₂/kWh) compared to other fuels for district heating such as hard coal (515 g CO₂/kWh), natural gas (282 g CO₂/kWh), biogas (50 g CO₂/kWh), wood chips (10 g CO₂/kWh) wood pellet (47 g CO₂/kWh). However, the nuclear impacts (IRP indicator) are much higher compared to other sources used for district heating. Deepening the analysis on further EU countries, Šerešová et al. (2020) assessed the environmental impacts of electricity generation from different sources (black coal, natural gas, nuclear, solar PV, hydro and wind) in Czech Republic. This country is committed to gradually replace coal in its energy mix. In the year 2022, coal (44.1%) and nuclear (36.6%) were the main sources for electricity generation. The Government aims to consolidate nuclear in the electricity mix and put beside renewables in the achievement of climate goals (IEA 50, 2022). The CC impacts of nuclear resulted lower than the other impact categories namely water scarcity and particulate matter compared with lignite and coal plants, but higher than most of the renewables. The authors point out, however, that in the case of nuclear, their study did not consider the environmental impacts of future management of exhausted nuclear fuel and those related to the construction and functioning of a deep geological facility for the disposal of nuclear waste due to lack of data. This places a non-negligible challenge to the actual reliability of nuclear as a low impact source.

Three LCA studies (San Miguel and Cerrato, 2020; Pérez et al., 2023; Berridy-Segade et al., 2024) focused on the evolution of the electricity mix in Spain and its environmental and socio-economic impacts. San Miguel and Cerrato (2020) applied LCA to the environmental assessment, while using the levelized cost of energy (LCOE) and direct

contribution to employment for the economic and social dimensions. Surprisingly, the impact categories only included CC, Fossil Depletion Potential (FDP), Ozone Layer Depletion Potential (OLDP), Terrestrial Acidification (TAP), Human Toxicity Potential (HTP), Photochemical Smog Potential (PSP), fully disregarding IRP (Ionizing Radiation Potential). Their results show the change of the contribution to the impact categories and how they are affected by the energy policies and the economic expansion as well as by the recession occurred from the years 2008–2010. The carbon intensity of the electricity mix reduced from the year 2007 (0.56 t CO₂/MWh) to the year 2014 (0.38 t CO₂/MWh) because of the use of natural gas in the mix and the strong promotion of Spanish Government towards the development of renewables. Then, in their scenarios to the year 2030 and 2050, the impacts to CC are expected to reduce, with a strong role of renewables and the decrease of the share of oil and coal in the electricity mix.

Pérez et al. (2023) enriched the analysis of San Miguel and Cerrato (2020) by applying a life cycle sustainability assessment associated to 1 GWh of electricity in three scenarios (years 2019, 2030 and 2050), by means of a more complete set of impact categories. The study considers for each sustainability dimension a number of impact categories, sub-categories and indicators. For example, for the environmental pillar the LCSA comprises 11 environmental indicators (GWP, ODP, ETP, EPMFP, IRP, POFM, AP, TEP, FWEP, MWEP, EP, NSTP, RDP). The economic pillar takes into account the economic costs as category and the levelized cost of energy as indicator. The social pillar analyses three social categories (workers, local population and society) and related subcategories and indicators. The results show the environmental benefits to GWP and ODP from reducing fossil fuels in favour of renewables as well as social benefits to local population reducing the risks of large coal mining accidents. Pérez et al. (2023) underline that several previous LCAs did not include the impacts of IRP on human health and ecosystems, although being these impacts entirely due to the nuclear source in the electricity mix: therefore, IRP can be considered an important indicator for decision making about nuclear energy use. The phasing out of nuclear plants would result in significant reductions of IRP.

Finally, the social impacts and risks of the Spanish electricity mix in the period 2010–2022 have been assessed by Berridy-Segade et al. (2024) who applied a social life cycle assessment. The authors draw their particular attention to the results emerged to four categories of stakeholders (workers, local community, society and value chain) and related indicators (child labour, contribution of the sector to the economic development, frequency of forced labour, women in the sectoral labour force). The social impacts of the electricity mix of Spain to the analysed social categories increased or remained constant between the years 2010 and 2020. The most significant social negative impacts of the Spanish electricity mix resulted that associated to child labour category for the production of solar PV plants in China, the extraction and refining of fossil fuels (in producing countries such as Algeria) used in natural gas combined cycle Spanish plants (social category: frequency of forced labour) while the social negative impacts generated by hydro-power dam, cogeneration and nuclear plants in the construction and operativity stages were significant to the social category women in the sectoral labor force.

Moving beyond the analysis of the electricity mix of European Union countries, Ovalle Flores et al. (2024) combined the LCA method (cradle to grave) to a survey including experts and citizens and to the Analytical Hierarchy Process, to rank the sources of the current electricity generation in Mexico according to the identified technological, economic, social and environmental indicators. Their results suggest that when considering the environmental indicators, the nuclear, coal and thermoelectric are the less polluting in the construction step, while in the use stage and decommissioning the less impacting are nuclear, hydro and PV plants. The ranking of the energy technologies by the citizens shows that the first ranked resulted wind energy and nuclear in economic terms, thermoelectric and geothermal (technical criteria) and turbo gas and thermoelectric (social criteria). For the surveyed citizens nuclear

technology resulted the least preferred in the social and technical dimensions. However, the Ovalle Flores et al. (2024) study only focuses on the construction, use and decommissioning stages and not on the whole life cycle and for the ranking only 7 environmental indicators are considered, such as GHGs emissions, Acidification, Eutrophication, Area availability and urban obstacles, Visual impact, Noise, Waste production. The Authors do not include critical indicators such as IRP, that, as just above mentioned in Pérez et al. (2023), is important to consider when nuclear is part of the electricity mix. Assumptions made for the decommissioning of nuclear plants are not included. This stage is still a challenge in cradle to grave LCA studies, but the environmental impacts can be significant compared to the other stages (Wang et al., 2019) also due to the treatment, storage, and long times for the final disposal of nuclear radioactive waste (Seier and Zimmermann, 2014).

Merino et al. (2019) assessed the environmental impacts of a reference scenario for Chile representing the year 2018 and four scenarios to the year 2050 based on a higher development of renewable energies supported by a share of natural gas or nuclear that in the study are supposed to be more stable in relation to the intermittence of renewable energies. The best scenario (scenario 3) resulted that with a share by 75% of renewable energies and 25% of nuclear energy for electricity production and prefigure a complete independence from fossil fuels such as coal, natural gas and oil “while maybe a new dependence on nuclear”. The assumptions about nuclear land use requirements seems very low for nuclear in this study (51 km²/GW) compared to the values of the renewable sources (e.g. wind: 283 km²/GW and solar PV: 176 km²/GW). Fthenakis and Kim (2009) calculated for nuclear about 30 m²/GWh while in the case of solar PV average rooftop, values close to zero.

Other authors such as Wang et al. (2019) have assessed and compared the impacts of hydro, nuclear and wind power in a case study for China. Their results show that the contribution to GWP 100 was the highest for wind electricity (28.3 g CO₂-eq/kWh) while the lowest for hydroelectricity (3.84 g CO₂-eq/kWh). Nuclear was found more or less in the middle (12.4 g CO₂-eq/kWh) between the values of the two renewable sources. The study evidenced that in the case of nuclear the highest amount of GHGs emissions was found in the decommissioning stage of the life cycle.

In the same Chinese context, the contribution to three impact categories: GWP, Material Input (MI) and Water Deprivation (WD) across 5 electricity generation technologies: thermal, nuclear, hydroelectric, wind and PV solar has been analysed by Ding et al. (2019). The normalized results highlight that for MI, wind generates the lowest impacts (9.81E-05 Pt/kWh) while thermal production (2.7E-02 Pt/kWh) generates the highest ones followed by PV solar (1.33 E-03 Pt/kWh), hydroelectric (1.64E-04 Pt/kWh) and nuclear (1.01E-04 Pt/kWh).

Wang et al. (2021) in their study calculated the emissions intensities of CO₂, SO₂ and NO₂ released by nuclear electricity and technologies composing the Chinese mix⁷ and their spatial distribution in Chinese provinces and areas while Nakagawa et al. (2022) compared the use of resources in the nuclear life cycle taking into account different Uranium mining techniques typologies of nuclear reactors (PWR and BWR), nuclear fuels cycles (open versus closed) as well as other electricity sources for comparison. In the nuclear fuel cycle, the steps of mining, enrichment and reprocessing resulted the most significant ones in terms of TMR. The enrichment of 1 kg of Uranium requires 8.31 kg of yellow cake (U₃O₈). Moreover, the extraction of Uranium by means of open pit resulted the most resource demanding among the mining techniques. The TMR coefficient does not change in case of nuclear reactors PWR and BWR, while it resulted lower in the closed cycle compared to the open cycle, because the closed cycle involves the reprocessing of U and the reduction of extracted U for the new nuclear fuel cycle. Currently, almost 60% of the whole Uranium is extracted by means of in-situ leaching due to the advantages in terms of costs and some

⁷ These are classified as low radioactive waste (Wagadare and Gupta, 2024).

environmental impacts but in-situ leaching also requires the use of acid and alkali liquid that cause the pollution of the local environment.

Several indicators associated to water consumption have been analysed by Jin et al. (2019) by means of a global meta-analysis in the fuel cycle of coal, natural gas, nuclear and biomass shows that natural gas has the lowest median water consumption (128 L/MWh) while oil the largest median values ranging from 891 L/MWh for conventional oil and 1658 L/MWh for sand and oil shales. Nuclear (156 L/MWh), coal (231 L/MWh) show intermediate levels. Operational water use refers to the water utilised in the operativity of the plants. The study also underlines that water use change across countries for the same power technology (e.g. China consumes more water than U.S. for nuclear) as well as within countries depending on the location of the regions and their climate conditions.

Finally, a study by Gibon and Menacho (2023) was based on the LCA of 1 kWh generated by a pressurized nuclear reactor and is indicative of the year 2020 and the global level. The potential contribution to GWP resulted of 6.1 g CO₂ eq. per 1 kWh of electricity. Almost the half of the emissions originates in the Uranium stage. The emissions in the back-end cycle account for 13% of the total GHGs emissions. The highest contributions to freshwater ecotoxicity potential come from the open pit mining technique while milling mainly contribute to IRP. The operativity of the nuclear power plant is almost entirely dominated by the consumption of water for cooling of the reactors. The contribution is estimated of 2.39 L of water per 1 kWh of electricity.

5.1.2. LCA studies assessing the impacts from cradle to gate

Whole processes from cradle to gate were investigated by Wagadare and Gupta (2024), who examined the impacts of nuclear energy, shedding light in particular on the impacts of Uranium mining. The authors have shown that mining operations are characterised by the generation of waste rocks and other type of waste residues resulting from crushing Uranium ore,⁸ when considering underground mining. In the case of open mining, damages to the landscape should be accounted for. Water pollution should also be considered due to the presence of heavy metals in wash water. Further impacts and damages derive from the large use of chemical corrosive substances, high withdrawn of dust and pollution from transport, relevant consumption of water and finally production of wastewater.

The comparative LCA performed by Farjana et al. (2018) assessed the impacts of the three methods of extraction of Uranium: underground, open-pit and in-situ leaching. The authors have found that underground mining is the method characterized by the highest radioactivity impacts due to the release of radon-222 and radon-226. The in-situ leaching generates the most relevant contributions to the impact categories Human Toxicity Potential (cancer and non-cancer effects), EP, Mineral fossil & resource depletion potential, and CC. The high impacts originate from the high utilization of energy (in the form of heavy fuels and electricity from diesel) and chemicals. In a further study, Farjana et al. (2019) reviewed the literature about the impacts of mining and mineral processing activities including Uranium mining. Besides the contribution in terms of CO₂, the authors analyse the impacts of Uranium mining techniques and in particular of in-situ leaching compared to open pit mining and underground mining. The impacts of in-situ leaching are relevant to the analysed impact categories except to IRP. On the contrary, underground mining generate negative impacts to IRP.

As a corollary to this section, the analysis performed by Tran and Egermann (2022) assessed and compared the energy footprint indicator in three countries: Vietnam, Finland and New Zealand. They calculated the energy footprint as the sum of the land required to produce the energy of the country and the land required to compensate the emissions of CO₂ by means of forests sequestration capacity. Their analysis highlights that the CO₂ emissions per MWh produced in both Vietnam and

Finland in the past (year 2010), current (years 2017 and 2018) and future scenarios (year 2030) are at similar levels (about 0.020 t CO₂/MWh). However, the values for the energy footprint indicator for Vietnam and New Zealand are much lower (about 10 m²/MWh for both countries) compared to the past, present and future values of the indicator of Finland (in the range 72–82 m²/MWh). The land required is expected to increase in the years to come because of the increase of electricity consumption. As a consequence, for Vietnam and Finland the land devoted to other social uses beyond that of electricity is expected to become very small. It is projected for Finland that a shift from 39 million of hectares of the year 2010 to 41 million of hectares will be required in the year 2030 because of the lower yields of wood source in the mix. In that, the authors underline that Finland is already exceeding the available land for energy purposes without leaving land for social purposes and the eventual land that should be considered in the case of a possible nuclear accident.

5.1.3. LCA studies assessing the impacts at the end-of-life/backend stages

Worldwide more than half of the existing nuclear power plants (60%) are close to their service life end, since they have accumulated more than 30 years of operativity (Iguider et al., 2024). Some countries (e.g. Germany) are also deciding the full phasing-out of their nuclear power plants. This means that all these plants will enter in the decommissioning stage in a near future. The decommissioning is the last stage of a plant life cycle, after the construction and operation. In general terms, the decommissioning includes the removal of the fuel, the decontamination of the structures, the demolition of the buildings and, finally, the radiological characterization of the site. This stage is also characterized by the need for managing the radioactive waste that are stored in temporary repositories and recover for recycling all the other materials produced by the dismantling of the plant, such as iron, copper or concrete. When a nuclear power plant is demolished and the radioactive waste is ready to be transferred to the final repository, if any, the so-called “brown field” is achieved. The last state (“green field”) implies the return of the nuclear power plant area to other uses, after the dismantling of the temporary storage facilities and the absence of radiological issues (Sogin, 2024). Literature reviews until the year 2021 confirmed that the back-end processes e.g. decommissioning should be much more ad-hoc investigated via LCA with goals, boundaries and functional unit specific of this stage. Moreover, the back-end stage including the decommissioning should be included in LCA analysing the whole nuclear fuel cycle (Clayton et al., 2024) also by means of input-output LCA methods (Henriques and Sousa, 2023). It is also recommended the use of LCA in the analysis of the environmental impacts of new treatment and conditioning technologies for waste processing and management (Clayton et al., 2024).

An interesting study by Iguider et al. (2024) assessed the environmental impacts of the decommissioning stage of the Fessenheim nuclear power plant located in France and close to the Germany border. The goal is understanding which are the activities in the decommissioning stage among dismantling, clean up and demolition, that mainly contribute to the total burden. The results show that the demolition contribute significantly to the total burden of the 11 selected impact categories accounting from 85.1% to 87.8% of the total. The dismantling accounts for about 11% of the total contribution to the whole selected 11 impact categories. Analysing the contribution of the subprocesses in each one of the three activities it emerges that metal cutting contributes the most to the impact categories (5 out of 11 have been selected for this analysis). The radioactive waste conditioning contributes by 20.9% to the total GWP impacts of the dismantling activity, while in the clean-up phase the contribution to total GWP of radioactive waste accounts by 24.1%. In the clean-up activities the decontamination subprocess contributed to Human toxicity by 28.9%, to Freshwater aquatic ecotoxicity by 21.8% and to Terrestrial ecotoxicity by 10.8%. The authors also underline that the contribution of radioactive waste management to the impacts in the whole life cycle of a nuclear power plant has been found relevant in

⁸ <https://www.gov.uk/government/news/uk-first-for-the-nuclear-industry>.

previous studies (Poinssot et al., 2016). In this study, radioactive waste are 5% of the total waste generated in the decommissioning of the Fesseneheim nuclear plant. However, the burdens of the long transport of the radioactive waste towards their disposal and their incorporations in specific devices provide a contribution that is from 1.8 to 6.6 times higher than non-radioactive waste.

The other studies have focused on the analysis of the management of the spent nuclear fuel in the diverse type of cycles (open, partially and totally closed) (Takao, 2023), assessing and comparing the environmental impacts by means of LCA of the latter cycles (Pucciarelli et al., 2024; Taylor et al., 2022; Alwaeli and Mannheim, 2022; Paulillo et al., 2020).

Currently, spent nuclear fuel is mainly stored in temporary repositories in countries that apply the open or once-through cycle. Its main constituent materials such as U and Pu can also be recycled after chemical separation (Takao, 2023) into mixed oxide fuel (in the so-called twice-through cycle partial recycling or recycled in the fully closed cycle (Taylor et al., 2022).

As said above, a large part of the nuclear countries applies the open cycle, while e.g. France, China, Japan the closed cycle (Paulillo et al., 2020). In countries that adopt the open cycle, the spent nuclear fuel is mainly stored in the proximities of the nuclear plants, since there are technological issues or public resistance to its recycling or identification of a final disposal repository (Alwaeli and Mannheim, 2022). By 2050 it is expected that the amount of spent nuclear fuel accumulated worldwide will be about half million tonnes (Taylor et al., 2022). The storage of the spent fuel is a temporal solution and thus advances in final disposal repositories or recycling processes are needed to face the increasing amount of spent nuclear fuel (Taylor et al., 2022; Alwaeli and Mannheim, 2022). Moreover, a large part of the countries prefers the final disposal in deep geological repositories instead of their reprocessing. This contributes to increase the amount of nuclear waste with a high level of radioactivity to be disposed of safely in deep geological repositories (Alwaeli and Mannheim, 2022).

Taylor et al. (2022) reviewed the LCA literature assessing the impacts of open and partial-total closed fuel cycles. They have found that the partial and total cycles offer advantages in terms of Uranium resource savings. These latter benefits can be further extended in advanced cycles with multiple recycling, offering the opportunity of improving the sustainability of nuclear fuel cycle (Taylor et al., 2022) and its circularity (Takao, 2023). In particular, advanced cycles with actinide recycling seem offer benefits in terms of lower space required by the waste in the deep geological repository as well as their level of radioactivity.

Takao (2023) deeply examined the several alternatives for nuclear waste management as well as the potential applications for depleted Uranium. Currently, nuclear reactors exclusively depend on Uranium extracted on Earth but Uranium is a non-renewable resource and therefore issues of resource security necessarily arise creating uncertainties and calling for searching alternative sources of U. Other authors (Paulillo et al., 2020) assessed the environmental impacts of reprocessing spent nuclear fuel in the thermal oxide reprocessing plant available in UK until the year 2018. The normalization results show that IR has the highest impacts (1.4 E+04 person equivalent) compared to the other impact categories (e.g. ecotoxicity and resource depletion), while the hot-spot assessment shows that most of the impacts (88%) come from the thermal plant for the reprocessing and the rest (12%) is due to the waste treatment plant. Direct impacts arise from the emissions to air of the reprocessing plant, while the indirect emissions are associated to the production of uranyl nitrate that is used in the separation of U and Pu. Finally, Pucciarelli et al. (2024) use LCA for the assessment of the environmental impacts of two recycling strategies. The first one considers the recycling of zirconium alloy hulls instead of their incorporation in specific waste devices for their disposal in a geological repository. The second case entails the evaluation of the impacts of replacing natural Uranium with depleted Uranium for the production of

uranyl nitrate. Overall, the analysis of the two CE strategies confronted with a linear scenario with no recycling of alloy hulls and uranyl nitrate produced from natural Uranium reveals the reduction of resource use, energy carriers (−94% for both case studies), respiratory inorganics (about −50%), water scarcity, resource use (minerals and metals), ecotoxicity freshwater (−30%). The release of GHGs emissions would decline only by 6% and the radiological impacts of direct operational emissions and those associated to the disposal of nuclear waste would decrease by 18% and 2% respectively.

5.1.4. LCA studies assessing greenhouse gas emissions of nuclear fuel cycle

In the sample of 6 articles out of 34, the impacts to GWP and the released GHGs emissions in the whole nuclear life cycle have been analysed (Le Boulch et al., 2024a; Guidi et al., 2023; Liu et al., 2023; Zhu et al., 2022; Marashli et al., 2022; Pomponi and Hart, 2021) and summarised in Table 2. The most recent one by Le Boulch et al. (2024a) conducted a meta-analysis with the aim to investigate the contribution to GWP as well as shed light on the most significant factors over the life

Table 2

Selected articles of Sample 1 analysing only the impacts in terms of GHGs emissions in the nuclear fuel cycle.

Authors	Main results	Method
Le Boulch et al. (2024a)	Mean life cycle GHGs emissions resulted: 12.4 g CO ₂ eq./kWh; Median life cycle GHGs emissions: 6.36 g CO ₂ eq./kWh; Minimum and maximum: 3.09 and 43.2 g CO ₂ eq./kWh.	Meta Analysis
Liu et al. (2023)	Confronted GHGs emission over seven types of nuclear reactors: LWR, PWR, BWR, HWR, FR, FBR, GCR. The PWR had the highest variability comprised between 2 and 337.42 g CO ₂ eq./kWh. The emissions resulted higher in the front-end of the nuclear fuel cycle due to the activities of Uranium extraction, milling and enrichment.	Literature review
Guidi et al. (2023)	The GHGs emissions of the analysed technologies resulted: <ul style="list-style-type: none"> • Wind: 9.4–18.1 g CO₂eq/kWh; • Hydro: 18.8 and 26 g CO₂eq/kWh; • Solar Photovoltaics: 17 and 45.6 g CO₂eq/kWh; • Concentrated Solar Power: 20.5 and 33.2 g CO₂eq/kWh; • Geothermal: 13.7 and 47 g CO₂eq/kWh; • Nuclear: 3 g CO₂ eq./kWh of the FBR and 45.5 g CO₂ eq./kWh of the HWR • Coal-fired: 899.8 g CO₂ eq./kWh; • Coal-fired with carbon storage: 316 g CO₂ eq./kWh. 	Literature review
Marashli et al. (2022)	The GHGs emissions of the analysed technologies resulted: <ul style="list-style-type: none"> • Wind: 13.45 g CO₂ eq./kWh; • Hydro: 22.7 g CO₂ eq./kWh • Solar Photovoltaics: 38.88 g CO₂ eq./kWh; • Biomass: 62.4 g CO₂ eq./kWh; • Nuclear: 26.9 g CO₂ eq./kWh; • Coal: 936 g CO₂ eq./kWh; • Oil: 730 g CO₂ eq./kWh; • Natural Gas: 502 g CO₂ eq./kWh; 	Literature review
Zhu et al. (2022)	The GHGs emissions of the analysed technologies resulted: <ul style="list-style-type: none"> • Wind: 30.5 g CO₂ eq./kWh; • Hydro: 4.0 g CO₂ eq./kWh; • Solar Photovoltaics: 36.2 g CO₂ eq./kWh; • Biomass: 57.4 g CO₂ eq./kWh; • Nuclear: 7.5 g CO₂ eq./kWh; • Thermal: 1079.3 g CO₂ eq./kWh; 	Research article
Pomponi and Hart (2021)	Their results are comprised within 8 g CO ₂ eq./kWh to 64 g CO ₂ eq./kWh, with the following average values for the three LCA approaches: <ul style="list-style-type: none"> • 16.97 g CO₂ eq./kWh (process-based); • 24.89 g CO₂ eq./kWh (input/output); • 27.63 g CO₂ eq./kWh (hybrid). 	Research article

cycle of GHGs emissions and deepen further on the variability of the values of GHGs emissions available in the literature about nuclear electricity generation. In the sample of literature studies, 16 out of 22 considered the whole life cycle of nuclear electricity. The variables with the highest correlation resulted the GHG emissions intensity of the enrichment stage and the energy needed for the extraction of Uranium. Other authors (Liu et al., 2023) reviewed the literature on nuclear electricity since the year 2000 until the year 2021 by analysing the GHGs emission over the three main stages of the nuclear fuel cycle (front-end, construction and operation and back-end) and across the different types of nuclear reactors: Light Water Reactor (LWR), Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), Heavy Water Reactor (HWR), Fusion Reactor (FR), Fast Breeding Reactor (FBR), Gas Cooled Reactor (GCR). They evidenced that the variability is due to the different GHGs emissions released in the nuclear fuel cycle, assessment methods and system boundaries.

A further literature review by Guidi et al. published in the year 2023, assessing the LCA studies on electricity production published in the last ten years. Their goal was comparing electricity generation across the different technologies to identify the one with the lowest impacts to GWP. Their analysis highlights the average GHGs emissions (weighted mean of the mean value) of nuclear change depending on the different type of reactors and comprised between 3 g CO₂ eq./kWh of the FBR and 45.5 g CO₂ eq./kWh of the HWR. The GHGs emissions from renewables resulted the lowest for wind being between 9.4 g CO₂ eq./kWh and 18.1 g CO₂ eq./kWh followed by hydro, solar PV, CSP and Geothermal.

Marashli et al. (2022) conducted a literature review with the main goal of analysing thoroughly the environmental data from LCA studies regarding GHGs emissions from wind (onshore and offshore), solar energy (rooftop and others) and concentrated solar power. The results evidence that wind farms onshore generated the lowest potential contribution to GWP compared to solar PV, CSP and the other sources for electricity generation including natural gas, biomass, coal, oil and nuclear.

The study by Zhu et al. (2022) elaborated the life cycle inventory for six electricity sources (thermal, nuclear, biomass, wind, hydro and solar PV) composing the mix for China and assessed their GHGs emission intensity per kWh and the impacts of the life cycle stages to the total impacts. The authors also evaluated the GHGs emission at the Chinese regional scale providing useful feedbacks about the optimization of the regional electricity development. In that, at regional level, each region should develop renewables on the basis of their geographical features. For example, the lowest GHGs intensity can be achieved in regions such as Inner Mongolia that have a high solar radiation while coastal areas with stronger winds could achieve the lowest GHGs intensities by favouring wind power development. Finally, Pomponi and Hart (2021) conducted an LCA using three different approaches (process-based, input/output and hybrid) of this method to assess the GHGs emissions from electricity produced by an EPR under construction in the UK.

5.2. Environmental and social justice assessment of nuclear energy (sample 2)

This section presents the results of the analysis of the second sample of articles. These latter are classified according to the stages of the nuclear fuel cycle (Table A2, Appendix) to align the results of the justice dimensions with those of the Sample 1. Environmental and social justice issues requires the investigation of further aspects beyond those analysed by LCA covering the environmental consequences and costs on the most vulnerable people such as Aboriginal Australians populations (Marsh and Green, 2020), and Native Indians in U.S (Redvers et al., 2021; Rock and Ingram, 2020), poor and ethnic minorities (Huang and Chen, 2021) and e.g. the degradation and pollution of the natural environment where they live with effects on drinking water (Redvers et al., 2021), the impoverishment of forests and the loss of biodiversity, the dispossession of their lands challenging their role as custodians and

their rights on the lands (Marsh and Green, 2020). Further, social justice requires attention to the relationship between investments and public efforts on nuclear power, to be compared to the health at risk, to the creation of jobs (Kim et al., 2019), to the reduction of freedom in land management (Marsh and Green, 2020), to the economic return for the population (Kim et al., 2019), to the governance and democracy at risk because of the lack (Kim et al., 2019) or limited participation and public consultation in energy policies decisions (Charnley-Parry et al., 2024).

5.2.1. Environmental and social justice issues of uranium mining and operativity of nuclear plants

Environmental and social injustices are generated in the nuclear fuel cycle since the mining stage. At this regard, several authors discussed about the injustices suffered in particular by the indigenous and marginalized communities living and working in geographical areas of Uranium mining countries such as Australia (Marsh and Green, 2020), U.S. A (Fegadel and Lynch, 2024; Malin and Alexis-Martin, 2020; Redvers et al., 2021; Rock and Ingram, 2020), India (Kaur, 2021)). In U.S.A the Navajo nations has more than 500 abandoned mining sites while the largest open Uranium mine of Jackpile-Paguete in New Mexico is still under remediation after being closed at the beginning of 1980 (Malin and Alexis-Martin, 2020).

Fegadel and Lynch (2024) analysed the injustices, health impacts and environmental degradation generated on Native Americans and their lands since the periods of booming of the nuclear programs in U.S in 1950. The most involved Native communities were those living in the Colorado Plateau where the Uranium was extracted in mines as well as most mines have been abandoned by the large multinationals with large amounts of stocked radioactive waste. Other Native Americans suffered the same problems as directly reported by the authors: “Native Americans in the Northwest and Northern Plains share similar stories regarding their Uranium experiences – from working in the poorly ventilated mines and handling the toxic yellowcake in the processing facilities, to contamination of their crops, livestock and water sources and to the numerous family members and friends who succumbed to cancer or are living with a myriad of diseases and disorders”. The authors conclude evidencing that the nuclear renewal and the need for transitioning beyond fossils could provide further pressure on the land of Native Americans and exacerbating the phenomenon of “nuclear colonialism”. Despite the existence of agreements and policies, Native Americans have been rarely engaged before the beginning of Uranium extraction activities on their areas or in their proximities. As a result, it would be important collaborating with Native Americans for the development of alternative energies rather than further focusing on the exploitation of the residual Uranium that would also require higher amount of water and energy compared to the previous Uranium explorations (Fegadel and Lynch, 2024). The development of renewable energies and in particular wind would be more aligned with the cultural traditions of Native American and their goals of minimizing the impacts to the environment.

Rock and Ingram (2020) emphasize that it is also essential the involvement of Native Americans in the development of environmental policies for addressing the contamination of Uranium mining activities in the Navajo Nation. Most often, environmental policies in Navajo Nation have been adopted by non-native Americans without the involvement of Native Americans resulting in harming them. Instead, the recognition of Native Americans laws and ecological knowledge would provide them with the opportunity of conserving their cultural traditions in the contamination of the environment.

Furthermore, Malin and Alexis-Martin (2020) pointed out that the available cases of Corporate social Responsibility (of mining corporations to enter in relations with the local communities of mining areas) have showed that the latter has been mainly applied to the communities with a high influence in the advancement of the mining projects (Heisler and Markey, 2013). Marsh and Green (2020) analysed the colonising practices of nuclear industry towards the lands of Aboriginal Australians where are located important Uranium mines and the limited power

attributed to the latter and to the protection of their rights by the State and Commonwealth laws. The authors argue that these cases show that power is not equally distributed between Aboriginal on one side and nuclear industry and State on the other. In that, legal struggles and continuous resistance against nuclear projects are laid down by the Aboriginal Australians with the support and involvement of stakeholders of civil society. On the contrary, the ambiguous tentative of community involvement handled by the Government resulted in conflicts and failures as efforts of involving Aboriginal Australians. Consequently, such case reveals the importance of taking into account the dimension of procedural justice in energy decisions avoiding top-down approaches. Kaur (2021) focused on the Indian nuclear context and the creation of death conditions and subalternity of the population opposing to the nuclear power plant of Kudankulam in Southern India. Such conditions worsened the more the population mobilised against the nuclear power plant. Huang and Chen (2021) argue (on the basis of lessons learned from the political process aimed to shift away nuclear in Taiwan) that the promotion of general public participation, the provision of adequate information and the opportunity of expressing public opinion play a pivotal role in assuring policy legitimacy and injustices avoidance.

In this vein, Kim et al. (2019) analysed the injustices reflected in the production, distribution and consumption of electricity in South Korea. The authors claimed that in the production stage the unequal distribution of benefits and costs of siting coal and nuclear power plants was due to the absence of local public involvement or more importantly not taking into account their contrariety to such energy decisions. In the transmission stage, there was an imbalance between the rural regions producing electricity from coal and nuclear and the beneficiaries of such electricity produced that also generated injustices in the transmission infrastructures with effects on the local environment. In the consumption stage, there were differences in the price paid by the industrial sector and households with effects on the electricity consumed. Finally, the authors analysed the process of waste disposal siting by means of some case studies. The first in Buan showed that most of the people in a referendum voted in opposition to the siting of a nuclear waste disposal facility. The authors underline that the central government recognized legally the referendum only as a conciliatory solution to the conflicts with the population. After that, the national Government presented a referendum for the siting of the nuclear waste disposal facility in other four local areas including the city of Gyeongju where the referendum was approved by 89,5% of the population. However, the construction of the facility has been continually delayed due to the fragile soil. The local population closing to the facility was not informed about such geological issues. The authors also evidenced that the residents of cities closing to Gyeongju where not consulted nor expected to have a financial compensation despite sharing the same similar risks of Gyeongju. Issues related to the potential contamination of groundwater have been also signalled by the authors. The latter also evidenced that the population approved the referendum for economic reasons but in return they had little economic support because they have been mainly used for other purposes. Moreover, the people close to the facility lives with the risks of supporting the further construction of other nuclear waste disposal facilities due to the achievement of the full capacity of the facility. The authors concluded underlying that “*peripheralization acts to site noxious facilities in regions that already have similar facilities. The process of peripheralization seems to create a vicious cycle of injustice*”.

Sovacool et al. (2019) explored different type of injustices (distributive, procedural, cosmopolitan, recognition) in low carbon transition by means a multimethod approach (surveys, focus groups, internet forums) applied to some case studies: France (nuclear power), Great Britain (smart meters), Norway (electric vehicles), Germany (solar energy).

The analysis shows that nuclear power programme in France has caused an unequal distribution of the social costs and benefits of such source (e.g. in terms of jobs and costs to sustain the nuclear

development) and of the risk of accident. A respondent in the forum revealed that no one would like to live near a nuclear power plant.

In terms of procedural injustices emerged the lack of transparency and involvement of people in energy decisions and scarce consideration of the results of consultations on nuclear issues. A respondent pointed out that “*nuclear in France has had a very non-democratic character in nature ... nuclear power is intrinsically centralized, heavily planned, and therefore much contrasting with community interests and plans*”. Emerged cosmopolitan injustices have been associated to Uranium mining and export to other countries (with scarce safety measures) of nuclear equipment as well as to the risks of accident pending on countries and their communities living near France such as those of Belgium, Germany, Luxemburg, Italy and Switzerland. Finally, the last type of injustice namely recognition in nuclear France is associated to the creation of a vision of France centred on electricity also with regard to the production of heat. In that, households were given in the past the cheapest heating equipment. This model is beneficial to households until electricity prices were low but now especially the poor people are struggling in paying electricity bills due to higher prices.

Sovacool et al. (2021) in a further study have analysed the impacts generated by the nuclear reactors available in a particular area of France devoted to winery production and how the co-existence of nuclear reactors is lived by the local communities of such area. The authors underline that due to the need for relying on water resources a consistent part of French nuclear reactors (58) are located near winery areas such as the one of Rhône Valley where is localized the nuclear plant of Tricastin (3660 MW) along with other type of plants dedicated to fuel reprocessing, enrichment and storage. The whole complex provides a work to about 8000 people. The authors highlighted that several incidents occurred at the nuclear complex since the half of 1980 with impacts to the winery industry and the image and touristic attractiveness of the winery area. One of incidents, that of the year 2008, caused the pollution with radioactive elements of local rivers and the consequent adoption of measures to prevent radioactive contamination by irrigation of the agricultural areas and of local population who had to rely on external sources of water.

Finally, other social injustices (differences due to e.g. the ethnicity, race, gender, age, class) have been reported in the normal operativity of nuclear power plants by Hanaček and Martinez-Alier (2022) who analysed several case studies extracted from the Global Atlas of Environmental Justice. The latter is an on-going project that collect information about cases of environmental injustices all over the world. A search with the word “nuclear” reported 266 cases where a large part are in EU (EJ Atlas – Global Atlas of Environmental Justice, 2024).

5.2.2. Environmental and social justice issues in the decommissioning and nuclear waste disposal siting

Some authors evidence that nuclear energy development cannot be in agreement with the concept of “justice” because of the characteristics of nuclear waste generated at each stage of the nuclear fuel cycle. Nuclear waste has different levels of radioactivity and even in the case of low-level radioactive waste (which radioactivity will decay in about 300 years) they raise issues about environmental justice across generations. Not to mention that medium-high radioactive waste remains dangerous for thousands or hundreds of thousands of years (Höffken and Ramana, 2024).

Kinsella (2020) underlines that despite the urgency of tackling CC, the overall problem of nuclear waste should not be set aside since the further development of nuclear in response to the climate crisis would enlarge the problems of waste. In his essay, Kinsella (2020) argues about three types of problems related to nuclear waste: the long time and uncertainties about their management that raise concerns of social justice so far scarcely taken into account. The problem of nuclear waste is an urgent ethical issue that demands collective decisions because of the effects on present and future subjects: human and non-humans.

Vilhunen et al. (2022) have analysed how the concepts of justice and

trust are perceived in two nuclear communities of residents in Finland located in Eurajoki and Pyhäjoki. The two municipalities have been selected by the nuclear company as alternative candidates for the location of a facility for the disposal of the spent nuclear fuel. Both were not asked for their consent for the analysis of the site by the nuclear company. Vilhunen et al. (2022) addressed a gap in the literature about the perception of people and their acceptance of a plant for the spent nuclear fuel final disposal. The authors compared the perceptions of justice and trust in the two nuclear communities and how they are related with their approval of the disposal facilities. The two communities were involved in different stages of the decommissioning since Eurajoki is a nuclear oasis while Pyhäjoki is a greenfield community. The results of the survey revealed that both communities share the same positive opinion about the trust in safety regulations while about half of the community of Eurajoki consider that electricity from nuclear is ethically justified compared to 57% of the community of Pyhäjoki. Both communities perceived concerns of distributional and procedural injustices. About the procedural injustices the perception regarded e.g. the insufficient information that both communities received about the siting of the facility for the spent nuclear fuel. Further, shared perceptions of both communities resulted about the decision process of the siting that did not give sufficient attention to the disadvantaged people. Moreover, both communities perceived that the siting of the facility should be decided by means of a referendum.

About distributional justice, 60% of the community of Eurajoki and almost 50% of those of Pyhäjoki perceived that the benefits and risks related to the facility for the spent nuclear fuel were not equally distributed in the society. Interestingly, with regard to intergenerational justice, 38% of the respondents of Eurajoki and 40% of those in Pyhäjoki perceived that the siting of the facility was not a just solution for the future generations. A great consensus resulted around the responsibility of the current generation of deciding for the facility of the spent fuel. The authors conclude highlighting, among other aspects, that it is important to take into account the desires of the local communities at the planning stage to avoid negative perceptions of justice and trust in the siting of nuclear spent fuel disposal. Therefore, the authors emphasize the relevance of trust as a factor for the approval of the spent nuclear fuel disposal defined as a high-risks project. The role of trust should be further investigated in future research to understand how it can be strengthened between the nuclear communities and the companies involved in siting the disposal of the spent fuel.

Other authors (Cruz, 2023; Bell, 2023; Richter et al., 2022) have analysed the issue of siting of the repositories for nuclear waste in United States. In this regard, Cruz (2023) indicates that there are 80,000 tonnes of spent nuclear fuel stored within the nuclear power plants of United States. There is uncertainty about the final disposal site of the spent nuclear fuel even if there is agreement on the importance of adopting an approach shared with the stakeholders (consent-based approach). This approach should incorporate the principles of environmental and social justice. As a result, Cruz stresses that the Department of Energy (DOE) adopts a shared political declaration that also recognizes the principles of environmental and social justice in the process of siting of spent nuclear fuel final disposal. Richter et al. (2022) evidence that since about a decade ago the DOE has started to change its approach into a more equitable one for the siting of nuclear waste in United States. The authors suggest that the DOE should further improve its efforts in creating public trust. If well adopted the process based on consent for the siting of nuclear waste facilities provides with the opportunity of paving away the previous technocratic approach of siting. Bell (2023) focuses the analysis on the process of siting nuclear fuel led by the Nuclear Waste Management Organization (NWMO) in Canada. The adopted approach of siting introduced by this organization is called Adaptive Phased Management and is based on public engagement. In the document of the NWMO the main concern is the attention to the inclusion of different knowledges. This aspect enters in conflict when applied in practice. Therefore, there is a tension between the policy framework claimed to

be inclusive and its application in practice. The author argues on the article about the challenges of applying inclusiveness in practice at the local level in contexts dominated by the nuclear industry and their approach focused on supporting nuclear discourse at the expenses of local indigenous knowledge.

Hirose and McCauley (2022) analysed the policy framework and the opinion of local communities involved in the decommissioning of two nuclear sites in United Kingdom (UK) such as Bradwell (in Essex) and Dounreay to understand the social and economic consequences and risks in the transition to the decommissioning and the weaknesses of the legislative framework. Bradwell Magnox plant has been the first nuclear plant to go in the so-called “Care and Maintenance” stage in the year 2018⁹ that entails placing the site in a safe and secure condition useful for the radiations to decay naturally during the time. Dounreay has been the first to achieve the interim end-state. The interviews shed light on different aspects including the challenges faced by the workers in the decommissioning due to the shift from a routine work which was that about the generation of electricity to a more skilled one required by the decommissioning operations. The impacts on the local communities resulted different in terms of engagement since Dounreay is located in a remote area of Scotland and is the main economic attractiveness of the area while the other nuclear plant of Bradwell is not far from London. The opinion of the respondents of the local community of Dounreay was of hope for a positive future away from nuclear towards e.g. the renewable sources while less engaged and interested about the future economic impacts for the community of Bradwell since they were less economically impacted by the closure of the nuclear plant. Interestingly, the interviews also collected information about the decommissioning activities and the existence of the radiation effects that workers claimed to be a unique feature of nuclear plants not found in the decommissioning of other types of plants. Further, the workers of the Bradwell plant pointed out the feature of unpredictability and the complexity of the decommissioning operations. The decommissioning operations were also more difficult for the Dounreay plant because this is an experimental reactor where many trials have been executed. Moreover, from the interviews emerged problems with the external contractors since doing the job quickly could compromise the safety of the operations. Interesting insights resulted from the analysis of the intergenerational aspects. Respondents of both nuclear plants also evidenced the problems experienced in the decommissioning due to the low attention to such stage in the design, construction and operativity of the nuclear plants. The Magnox type of reactor has not been designed to be dismantled with the consequent problems in the disposal of the high quantity of graphite of which it is made because it became radioactive during the operativity.

6. Discussion

This section analyses the created framework within this study for the assessment of environmental sustainability of nuclear energy in the light of the previous literature with the purpose of understanding the added value provided to the existing research. The main challenges in assessing the sustainability of nuclear energy are discussed as well as how the local context influences the sustainability of nuclear and other energy sources. The last section discusses the case study of the Nuclear Italian Programme in the framework of the current critical narrative that questions the sustainability of nuclear energy.

6.1. The environmental sustainability of nuclear energy

The analysis of cradle to grave LCA studies in Sample 1 points out the contribution of current and future scenarios of several national electricity mixes to a wide range of impact categories beyond CC. In so

⁹ <https://world-nuclear.org/information-library/country-profiles/country-profiles/australia>.

doing, this study integrates the previous recent literature, mainly focused on the GHG emissions of nuclear fuel cycle (Le Boulch et al., 2024a; Liu et al., 2023) and the comparison with renewable and non-renewable sources (Guidi et al., 2023; Marashli et al., 2022). The results of some Sample 1 studies, such as Junne et al. (2021), reveal that in the year 2050 the GHGs emissions of EU countries and North Africa might be reduced up to 95% compared to the year 1990, but the increase of the share of nuclear would significantly worsen other impact categories such as IRP, Uranium depletion and water consumption, not to talk of the still unsolved problems of nuclear plants full and safe decommissioning and final storage of radioactive waste. The electricity scenarios for France investigated by Cassoret et al. (2023) (scenarios Ampere, 2035; Hertz, 2035; Volt, 2035; Watt, 2035; previously mentioned) suggest reducing shares of nuclear in favour of a higher role of renewables. The Watt scenario 2035 shows the lowest share of nuclear power (11%) and the highest one from renewable (71%) and fossil sources (18%) and would generate the lowest impacts to the IRP, marine eutrophication, mineral resource scarcity and water consumption categories. These results are in line with a previous LCA study performed by Ghisellini et al. (2023), who compared a business-as-usual scenario for Italy (year 2021) with the emergency Government Plan scenario (2021–2023), adopted after the start of the conflict between Russia and Ukraine and further scenarios where natural gas is replaced by an increased share of nuclear or renewable sources. The results evidence that although by replacing 30% of the electricity produced from natural gas with that of nuclear the impacts to CC would be lower compared to the business as usual, yet other categories such as IRP and water consumption worsen in so just replacing a problem with another one. The stage of operativity of the nuclear power plant is dominated by the impacts to water consumption (Gibon and Menacho, 2023; Jin et al., 2019) and this aspect cannot be disregarded due to the present increasing scarcity of global water resources (Whieldom and Kuykendall, 2020) and the more recurrent water droughts (European Commission, 2024). The European Commission underlined that the droughts in the year 2022 have caused the reduction of the electricity from hydro, thermal and nuclear sources and that water for cooling accounts for 32% of the annual freshwater withdrawals in the EU.

Some authors have highlighted how it is critical to define nuclear energy as sustainable due to the nature of nuclear waste which impacts affect both current and future generations (Höfken and Ramana, 2024) for a very long time. Moreover, the unsustainability of nuclear is also due to the uneven distribution of environmental and social costs on Native and Aboriginal populations in the mining operations as well as to the operativity of the nuclear power plants as shown by the case of Tricastin in France (Sovacool et al., 2021) and India (Kaur, 2021) and the difficult location and construction of permanent nuclear waste disposals (e.g., South Korea, Kim et al., 2019).

The aspects of lack of participation and effective community involvement have largely emerged from the analysis of the studies of sample 2. Authors pointed out the need for avoiding top-down approaches and favour an active participation of the general public, citizens and local communities instead of only adopting consultation forms that do not have any effectiveness of influencing the energy policies and decisions (Charnley-Parry et al., 2024).

A distorted and partial image of the sustainability of nuclear energy is currently offered in view of the climate crisis (Malin and Alexis-Martin, 2020) with the risks that without a change in the narrative of “clean and safe” (Kinefuchi, 2021) the huge environmental and social injustices will continue to dominate in a context of “capitalist market expansion, global geopolitical tensions, and the meta-power of nuclear states” (Malin and Alexis-Martin, 2020). Therefore, future research has the important task to link environmental LCA and social LCA for deepening the life cycle impacts of nuclear energy and shed more lights on how natural ecosystems and communities living close to the mines or nuclear plants are affected. Most often such people live in areas very far from the final consumers of nuclear energy who could not even perceive

the environmental and social costs of consumed nuclear electricity. In this view, current nuclear programmes assume the features of green-washing as they only emphasize the climate benefits disregarding much of social life cycle costs (Pieńkowski, 2024).

6.2. Challenges in evaluating the sustainability of nuclear electricity

The joint use of Environmental LCA and Social LCA resulted particularly useful to show the contribution of national electricity mixes to the investigated impact categories, as well as to identify the geographical distribution of the impacts, in so linking the environmental impacts assessment to the concept of environmental and social justice. In this regard, the inventory of the study by Le Boulch et al. (2024b) shows the link of each worldwide Uranium mine to 1 kWh of electricity generated by the main electricity French provider EDF (Électricité de France). In this case, the Uranium used for France electricity is 100% dependent from abroad exports and a non-negligible 20% of the whole Uranium comes from mines in Russia.

Some studies have analysed the impacts of selected country electricity mixes (Spain and Mexico) to some social categories (workers, local community, society and value chain) and social indicators (child labour, contribution to the economic development, frequency of forced labour and women in the labour force of the specific sector under analysis) by means of a social life cycle assessment (S-LCA) providing evidence on the most negatively influenced social groups (and their geographical distribution), where it is urgent for them to find solutions to reduce the inequalities (Berridy-Segade et al., 2024). However, for nuclear, in S-LCA the mining stage did not result as a relevant stage as found in LCA studies (Le Bouch et al., 2024; Gibon and Menacho, 2023). Moreover, cases of injustices at mining stage emerged from the analysis of the Sample 2 articles to the most important countries producing Uranium such as Australia (Marsh and Green, 2020) that is an exporter of Uranium to the EU countries including Spain (World Nuclear Association, 2024,¹⁰) but, again, these concerns did not result as hotspots in the S-LCA of the Spanish electricity mix.

A study by Ovalle Flores et al. (2024) combines the environmental LCA with the analysis and ranking of economic, technical and social criteria. It is interesting to note that when considering technical and social criteria both experts and common people ranked nuclear plants as the least preferred compared to the other plants for electricity generation in Mexico. This necessarily raises the important need for considering further dimensions beyond CC, land use and water use in LCA.

Pérez et al. (2023) underline that several previous LCA did not include the impacts to IRP on human health and ecosystems but it is important to do so because they are entirely due to the nuclear source and then IRP is an important indicator for energy decision making.

Some authors also highlight that promoting increasing support to nuclear electricity in EU and USA as a strategy for reducing the contribution to GWP to the year 2030 is not the good choice for addressing climate urgency and not supported by the evidence since nuclear has shown in its recent development high construction costs and long times for the construction of nuclear power plants (Haywood et al., 2023). The nuclear projects of Flamanville in France as well as in Olkiluoto in Finland have proved that the construction costs much exceeded the initial planned costs (Haywood et al., 2023).

Construction timelines are for nuclear in the range of more than 10 years (including the planning) while that of PV plants and wind farms are of 4 years for the planning process and from 6 to 12 months for the construction times.¹¹

A further critical impact category that characterizes nuclear

¹⁰ <https://energyaction.com.au/nuclear-power-versus-renewable-energy/>.

¹¹ Hearing of the fact-finding inquiry “The role of nuclear energy in the energy transition and in the decarbonization process” Honorable Gilberto Pichetto Fratin

electricity is the accounting of the decommissioning stage in LCA (Iguider et al., 2024; Seier and Zimmermann, 2014). It is source of uncertainty because the selected studies of this review provide only a few details of such stage or do not consider it or the assumptions are not adequate (e.g. in terms of time) on the basis of the current decommissioning projects. Furthermore, the time of the decommissioning is not compared to the times of other electricity technologies such as wind or solar PV.

At this regard, one of the four Italian plants, namely the Caorso plant has been definitively shut down in the year 1990. At present the activities of the decommissioning have achieved almost the half of the total after its start in the year 1999 (Regione Emilia Romagna, 2023). The end of the decommissioning activities should be by the year 2031 but it will be probably delayed since the National Repository for the final disposal of nuclear waste is not yet identified while its operativity is expected to start in the year 2039 (Pichetto-Fratin, 2024).

The results of this study show that the contribution to Resource Depletion resulted the highest in France which electricity mix contains a relevant share of nuclear (Carvalho et al., 2022). The aspect of scarcity of the Uranium resource is rarely mentioned in the selected LCA studies. Only Takao (2023) underlines the non-renewability of Uranium resources and the current exclusive reliance of Uranium from mines raising concerns about the future availability of Uranium. At the current consumption levels (60,100 t in the year 2021), Uranium resources (RAR: 4,272,000 t) would be enough for less than 100 years. However, of course, the increase of Uranium consumption due to a potential expansion of nuclear reactors would reduce the future availability of the amount of Uranium resources.

Other indicators for the evaluation of sustainability of nuclear electricity are that of capital costs and cost per kWh. The capital costs of nuclear energy generation technology are in the order of \$ 8475–13,925 for every kilowatt of capacity. In comparison a wind + storage – onshore plant have much lower capital costs: \$ 1375–2250 per kW as well as a Solar PV plant (rooftop residential) which capital costs are between \$ 2230 and 4150 per kW (Lazard, 2023). The levelized cost of energy (\$/MWh) are for the renewable energy generation technologies: Wind + Storage – Onshore (42–114 \$/MWh) and Solar PV plant, rooftop residential (117–282 \$/MWh) while that of nuclear technology are between 141 and 221 \$/MWh (Lazard, 2023). In that, life cycle sustainability assessments (integrating LCA + LCC + S-LCA methods) such as that conducted by Pérez et al. (2023) are much more adequate to evaluate in a thorough perspective the sustainability of nuclear energy.

Finally, the development of nuclear inevitably bears the risk of nuclear weapons proliferation while nuclear power plants are also potential targets in military conflicts (Haywood et al., 2023) as shown the repeated attacks to the Ukrainian nuclear plants of Zaporizhia that also comprised its facilities of radioactive material and the disabling of power lines that are important in assuring the safety of the plant.

6.3. The role of local context in shaping the sustainability of nuclear energy

The LCA as a method offers the opportunity to relate the local context with the global one, by tracking over time and space the history of a product or a service such as electricity. In the case of global impacts such as the use of resources and the GHGs emissions the results of the LCA show the weight of the local systems in affecting the global sustainability.

In this regard some studies are particularly illuminating. Zhu et al. (2022) focused on the analysis of GHG emissions of the regional electricity systems of China. On the basis of their results the authors underline the importance that the development of renewables occurs on the basis of the geographical features of the region to minimize the impacts to CC. Therefore, the lowest impacts to CC can be achieved in regions such as Inner Mongolia that have a high solar radiation or by coastal areas that will have the capacity of taking advantage of the

strong winds. Similarly, the research by Tran and Egermann (2022) show the difference in energy footprint indicator among three countries such as Vietnam, Finland and New Zealand. The value of the indicator is very high for Finland compared to the other two countries because the energy policies are centred on the development of wood source which yields are low due to the geographical position of the country. Jin et al. (2019) show that the consumption of water changes even within countries using the same power technology (e.g. China consumes more water than U.S. for nuclear) as well as within countries with a different geographical localization and climate conditions. The use of water in the operation stage varies up to 24% due to of the climate regional differences (north versus south regions).

6.4. The nuclear energy programme in Italy. A case study

Currently Italy does not have nuclear power plants in operation. The country decided to halt the further expansion of its nuclear programme through a popular referendum held in the year 1987 in reaction to the Chernobyl nuclear accident (1986). At the same time, the problems regarding the siting of their final disposal are still pending¹² confirming the difficulties evidenced in the literature (such as in Cruz, 2023; Bell, 2023) of moving towards the adoption of an inclusive approach in practice.

In the mid-1960s, Italy has been an important country in nuclear power generation, with the United States and the United Kingdom. At that time the first three nuclear plants were completed – each with only one reactor – in Latina in 1963 (using a graphite reactor and natural Uranium), in Garigliano in 1964 (Boiling water reactor and enriched Uranium) and in Trino Vercellese in 1965 (using a pressurized water reactor and enriched Uranium) for a total installed capacity of 500 MW. In the year 1977 the National Energy Plan was expected to build 20 more nuclear plants. In 1978 the fourth nuclear plant located in Caorso was connected to the grid. The plant falls into the category of second-generation of nuclear power plants and was equipped with a 2651 MW thermal nuclear steam generator and a turbo-alternator group with a net electrical power generation capacity of 870 MW. The reactor is the direct cycle boiling water type with recirculation of the primary coolant through the core, of the GEBWR4 type (Sogin, 2024). However, this latter nuclear plant had a very short service life since it was involved in an extraordinary program of safety tests requested by the Ministry of Industry after a series of failures and the Chernobyl accident.

In the year 1990 the Caorso power plant entered in the decommissioning stage after the results of a popular referendum. In the last decade, two of the co-authors of this study have been involved in the framework of a master degree project in the analysis of the decommissioning stage of the Caorso power plant and of the environmental data related to the management of the spent fuel sent to the enrichment plant in France by means of a total of 13 deliveries (started at the end of the year 2007 and ended in August 2009). The Environmental Protection Agency of Piacenza is in charge of the monitoring of the local radioactivity of the although spent nuclear power plant of Caorso as well as of the 13 deliveries of the spent fuel from the plant to the railway station of Caorso. Nowadays, according to the data of the year 2023, the decommissioning stage has achieved more than the 50% of the planned activities started in the year 1999.

The idea of reintroducing nuclear energy in the electricity mix started to emerge in the last decade and strengthen after the beginning of the conflict between Russia and Ukraine (Orlandi, 2024).

The Minister of Environment in a recent parliamentary hearing (Pichetto-Fratin, 2024) discussed “the role of nuclear energy in the

¹² Six type of nuclear technologies are part of the Generation IV nuclear energy systems such as: Gas Cooled Fast Reactor, Lead Cooled Fast Reactors; Molten Salt Reactors; Super Critical Water Reactor, Sodium Cooled Fast Reactor, Very High Temperature Reactor (Tassone et al., 2024).

energy transition and decarbonization process". He pointed out that the goal of an energy transition that is secure and competitive can be achieved only by considering all the technologies, including nuclear energy. According to him, in the case of this latter source its examination has to be only scientifically based without ideological judgements.

For the purpose, the Minister confirmed the creation of the National Platform for the Sustainable Nuclear, grouping the most important stakeholders involved in the development, research, regulation of nuclear energy, to represent one of the first step useful to acquire data and technical environmental and economic assessments. The Minister also indicated that there is a particular interest towards the so called SNRs (small nuclear reactors) and underlined that nuclear energy, being a planned source, could contribute in an effective manner to support the full integration of renewable energies in the Italian energetic system. The scenarios modelled for the future Italian energetic system to the year 2050 seem confirming that nuclear energy is the most economically and energy competitive. As a result, the Minister explained that the choice of the Government behind nuclear is due to its features of being green, safe and competitive. In that, his communication strategy in the parliamentary hearing follows the well-known narrative adopted by other Governments such as e.g. that of Poland (Pieńkowski, 2024) and Japan (Kinefuchi, 2021). Nuclear energy is safe, according to the Minister, because the nuclear technology would be developed by western countries including Italy as well as the Uranium would come from Australia and Canada ensuring a very low geopolitical risk. Moreover, nuclear is sustainable because it does not generate CO₂ emissions and has a low impact to the landscape and a limited land use compared to the renewables. Further, in a framework of free energy markets, the Minister pointed out that the economic competitiveness of nuclear would be decided by the market and therefore it is important to take into account all the energy sources only on the basis of science and technique without ideological judgements.

These statements seem not coherent both on the current trends of the cost of kWh and the increasing competitiveness of renewables, which costs per kWh show a decreasing trend since the year 2010 (Haywood et al., 2023) and then on the role of the Government and the State in the energy transitions since nuclear should be probably supported to favour its reintroduction. Moreover, it is important to remark that in the light of the transition towards the goal of sustainable development also promoted by the United Nations the process of planning, deliberation, negotiation, implementation and evaluation should also be just and inclusive (Lehtonen, 2022). Certainly, this process implies a more careful and thorough assessments of the benefits and costs of nuclear following the methods proposed in this study compared to those presented by the Minister who never mention about the aspects of justice.

The Minister also evidenced the attention focused on the small nuclear reactors which level of safety would be very high compared to the existing nuclear plants and would have limited land use. At this regard, some recent studies highlight that the new reactors bear the same risks and impacts of the previous ones (Höffken and Ramana, 2024). The new reactors are expected to demand a smaller time for their construction and lower investments costs, but at present their adoption is low and some factors (perceived investment risks and lack of competitiveness with other electricity technologies) obstacle their construction (Mignacca et al., 2020). Further authors (Böse et al., 2024) have also evaluated the technical and economic feasibility of three types of reactors namely light water reactors (LWR), small modular reactors SMR, and non-light water-cooled reactors (also defined "new" or "advanced" reactors) in view of the decarbonization programme worldwide and the proposals of a more large-scale deployment of nuclear. The study confirmed that LWR are very costly with long times for their construction. SMR seem more appealing because of the potential lower construction times but have diseconomies of scales. Further, also SNR have high costs and are more technically complex due to the use of sodium as cooling factor. Tassone et al. (2024) reviewed the scientific and industrial literature on the economics and finance of lead cooled fast reactors

(LFR) (Generation IV nuclear reactors)¹³ and found that the economic and financial literature is limited and there are uncertainties related to the methods and assumptions adopted in the studies. Moreover, there is a wide range in the estimation of the capital costs (1500–25000 \$/kWe) and electricity costs (30–350 \$/MWh). As a result, incoherence and uncertainties characterize the current nuclear Italian programme.

7. Concluding remarks

The goal of this study is to understand if nuclear electricity is an environmentally sustainable source for the Circular Economy and energy transition in line with the principles of social and environmental justice. Therefore, this study reviewed systematically the international literature analysing the impacts of nuclear electricity according to different boundaries of analysis (cradle to grave, cradle to gate and back-end stages) and its environmental and social justice's dimensions. The results have shown that the environmental sustainability has been evaluated in the whole life cycle on the basis of a wide range of environmental categories beyond GHGs emissions and the contribution to GWP, such as e.g. IRP, water consumption, TMR. Certainly, the GWP is still considered an important indicator for evaluating the environmental performances of electricity systems, due to the urgent need to address climate change problems, but integration with other indicators is much needed, due to the overcoming of six planetary boundaries out of 9 (Richardson et al., 2023), that is a signal of a continuous and never-ending environmental degradation, well beyond the need for natural environmental conservation claimed in the definition of environmental sustainability. Nuclear electricity relies on natural Uranium that is a non-renewable and reserve-limited resource and generates large and diverse amounts of radioactive waste, compared to conventional waste. Therefore, countries generating electricity from nuclear in the mix have a high responsibility towards the current and future generations since environmental and social injustices have been reported by the selected articles sampled in this study in the whole life cycle encompassing the Uranium extraction stage, the operativity of the nuclear plant and the nuclear waste siting and management. The assessment of the environmental sustainability of nuclear fuel cycle as well as that of environmental and social justice dimensions of nuclear electricity, as investigated in this study, represents an added value with implications both for research and policy decision-making.

7.1. Policy and practical implications within the context of circular economy and energy transitions

The results of this study have policy implications for countries such as Italy which energy policies are oriented in the last decade towards a reintroduction of the use of this source for the production of electricity (Catanzaro, 2023) but also for other countries providing useful insights on how to evaluate the sustainability and justice of nuclear development. To the best of our knowledge, LCAs of the Italian nuclear fuel cycle have not yet been published. This study focuses both on cradle to grave LCA as well as on LCAs having as boundaries only the front-end or the back-end stages. While it is undoubtedly relevant that an LCA include the whole nuclear life cycle (Clayton et al., 2024), at the same time, the focus on only part of the cycle, e.g. the back-end stages, may provide a deeper understanding on its impacts and hotspots. The analytical framework created in this study is focused on both perspectives of analysis and could be particularly useful both for policy makers and LCA practitioners for the development of future LCA on nuclear.

CE and energy transitions can be considered as sub-transitions in the wider framework of sustainability transitions (Ghisellini and Ulgiati, 2020). Both CE and energy transitions promote the shift towards renewable energies for the purpose of reducing the dependence on fossil fuels and in general from non-renewable resources (Preston, 2012). Moreover, CE suggest to redesign and rethink the way resources and energy are used in the society to improve the efficiency of the resources

and reduce their overall consumption (Preston, 2012; Tiwari et al., 2024). In that, some authors argue that it is key to recognize the existence of a nexus between the CE and energy transition (Röcken and Moloney, 2023). On one side the CE stimulates to use in a more efficient manner the available energy and mainly bases the electricity mix on renewable energies. On the other side the energy transition needs CE implementation because the further development of renewables also requires materials that are available in a limited amount and for this reason have to be comprised in a circular model where materials and products circulate again and again (Röcken and Moloney, 2023).

Finally, the electricity generation within both CE, energy transitions and sustainability transitions, should be considered not only a process of change of the sources composing the electricity mix (Huttunen et al., 2021) but more importantly as an innovation process in environmental and social justice dimensions (Gutberlet, 2023) to avoid to perpetuate the same impacts of linear processes. The results of this study agree with the results of Pieńkowski (2024) who pointed out that nuclear energy cannot not be considered within sustainable energy transitions programs due to the fact that it does not meet the features of decentralization and civil participation as well as safety and renewability.

7.2. Future research directions

Future research could gain important insights from the studies included in the two samples previously investigated (Sample 1 and Sample 2 in Section 5) and further explore the impacts of nuclear with LCA, S-LCA, LCC and further methods and impact categories as well as integrate with further assessments the studies on justice dimensions. The environmental impacts are strictly linked with the concept of environmental and social justice and their integration in a unique framework is highly encouraged. The integration of environmental and social justice dimensions in S-LCA is more evident than in LCA but the results of this study show that a deeper integration also in S-LCA is needed since, e.g. for nuclear, the mining stage did not result as a hotspots while LCA studies show that mining stage is relevant in the nuclear fuel cycle compared to the other stages. Moreover, the research field of Sample 1 resulted more developed than that of Sample 2 and for this reason the results are more abundant. There seems also a concentration of cases in the literature of environmental and social injustices in some countries such as in particular United States while a lack of studies of injustices in African countries. In that, this study agrees with the study by Meyer and

Sérandour (2024) that this contributes to invisible the support of such countries to the nuclear industry. This limitation calls for more future research on the topic areas and stages of the nuclear fuel cycle presented in Sample 2.

7.3. Limitations of this study

Further limitations of this study regard the approach followed in searching the literature. Two databases such as Scopus and Web of Science database have been selected almost neglecting other databases. This choice as well as the selection of keywords might have excluded relevant articles on the analysed topics providing further evidence. Moreover, the interpretation of the results has been limited to the main research questions and goal of this study. As a result, this study mainly investigated the environmental dimension of sustainable development and in a much lower extent the economic aspects. These latter could have provided further important insights on how to evaluate the sustainability of nuclear energy deserving future research efforts.

CRediT authorship contribution statement

Patrizia Ghisellini: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Renato Passaro:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Sergio Ulgiati:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.144818>.

APPENDIX

Table A1
Articles considered in Sample 1 with electricity sources investigated along with the nuclear source.

Authors	Coal (hard coal, black coal, lignite)	Oil	Nat. Gas	Peat	Hydro (run-of-river, reservoir, pumped storage)	Wind Offshore	Wind onshore	Geo-thermal	Nuclear	Concentrated solar power	Photovoltaics (open ground, roof top)	Biomass	Marine
Berridy-Segade et al. (2024)*	*		*		*		*		*		*		*
Clayton et al. (2024)									*				
Le Boulch et al. (2024a)									*				

(continued on next page)

Table A1 (continued)

Authors	Coal (hard coal, black coal, lignite)	Oil	Nat. Gas	Peat	Hydro (run-of-river, reservoir, pumped storage)	Wind Offshore	Wind onshore	Geo-thermal	Nuclear	Concentrated solar power	Photovoltaics (open ground, roof top)	Biomass	Marine
Le Boulch et al. (2024b)									*				
Iguider et al. (2024)									*				
Ovalle-Flores et al. (2024)	*		*		*	*		*	*		*	*	
Pucciarelli et al. (2024)									*				
Sokka et al. (2024)									*				
Wagadare and Gupta, 2024									*				
Cassoret et al. (2023)	*	*	*		*	*			*		*	*	*
Gibon and Menacho, 2023									*				
Guidi et al. (2023)	*	*	*		*	*	*	*	*	*	*		
Liu et al. (2023)			*		*	*			*	*	*	*	
Pérez et al., 2023									*				
Stranddorf et al. (2023)	*		*		*				*	*	*	*	
Takao (2023)									*				
Alwaeli and Mannheim (2022)									*				
Zhu et al. (2022)	*	*			*		*		*		*	*	
Carvalho et al. (2022)	*	*	*		*	*	*	*	*		*	*	
Marashli et al. (2022)	*	*	*		*		*		*	*	*	*	
Nakagawa et al. (2022)	*	*	*			*			*		*		
Taylor et al. (2022)									*				
Tran and Egermann (2022)	*	*	*	*	*	*		*	*		*	*	
Pomponi and Hart (2021)									*				
Wang et al. (2021)	*		*		*	*			*		*	*	
Junne et al. (2021)			*		*	*			*	*	*		
Šerešová et al., 2020	*		*		*	*			*		*		
San Miguel and Cerrato (2020)	*	*	*		*	*			*	*	*	*	
Paulillo et al. (2020)									*				
Ding et al. (2019)	*	*	*		*	*			*		*		
Wang et al. (2019)					*	*			*				
Merino et al. (2019)	*	*	*		*	*			*		*	*	
Farjana et al. (2019)									*				
Jin et al. (2019)	*	*	*		*	*	*	*	*	*	*	*	

Table A2
Selected articles of Sample 2 classified according to the stages of the nuclear fuel cycle.

Stages of the nuclear fuel cycle	Authors	Article Title	Year of publication
Whole nuclear fuel cycle	Böse et al.,	Questioning nuclear scale-up propositions: Availability and economic prospects of light water, small modular and advanced reactor technologies	2024
	Charnley-Parry et al.,	The role of nuclear energy in the sustainable energy transition: a scoping review into the complexity of decision-making trade-offs and public participation in the UK	2024
	Haywood et al.,	Why investing in new nuclear plants is bad for the climate	2023
	Höfken and Ramana	Nuclear power and environmental injustice	2024
	Kim et al.,	Social justice, fairness and exclusion in the South Korean electricity sector	2019
	Kinefuchi	Nuclear power and narrative of sustainable energy: A lesson from Japan	2021
	Meyer and Sérandour	Placing the intangible: Space, nuclear power and social sciences	2024
	Mignacca et al.,	Deeds not words: Barriers and remedies for Small Modular nuclear Reactors	2020
	Pieńkowski	Is nuclear energy sustainable? A critical analysis on the example of the Polish energy transition plan	2024
	Tassone et al.,	Economics and finance of lead fast reactors: A systematic literature review	2024
Uranium mining	Sovacool et al.,	Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions	2019
	Fegadel and Lynch	Native American victimization and resistance: an examination of uranium mining in the Northwest and Northern Plains	2023
	Kinsella	Extracting Uranium's futures: Nuclear wastes, toxic temporalities, and uncertain decisions	2020
	Malin and Alexis-Martin	Assessing the state of uranium research: Environmental justice, health, and extraction	2020
	Marsh and Green	First nations rights and colonising practices by the nuclear industry: An Australian battleground for environmental justice	2020
	Redvers et al.,	Uranium exposure in American Indian Communities: health policy and the way forward	2021
Nuclear power plant operation	Rock and Ingram	Traditional Ecological Knowledge Policy Considerations for Abandoned Uranium Mines on Navajo Nation	2020
	Hanaček and Martinec-Alier	Nuclear supply chain and environmental justice struggles in Soviet and Post-Soviet countries	2022
	Kaur	Nuclear necropower: The engineering of death conditions around a nuclear power plant in south India	2021
	Klingelhöfer et al.,	Global research on nuclear energy in the context of health and environmental risks, considering economic interests	2024
	Sovacool et al.,	Dispossessed by decarbonization: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways	2021
	Huang and Chen	Injustices in phasing out nuclear power? Exploring limited public participation and transparency in Taiwan's transition away from nuclear energy	2021
Decommissioning Spent nuclear fuel disposal siting	Hirose and McCauley	The risks and impacts of nuclear decommissioning: Stakeholder reflections on the UK nuclear industry	2022
	Vilhunen et al.,	Perceptions of justice influencing community acceptance of spent nuclear fuel disposal. A case study in two Finnish nuclear communities	2022
	Bell	The epistemic tensions of nuclear waste siting in a nuclear landscape	2023
	Cruz	Environmental justice considerations in siting spent nuclear fuel disposal	2023
	Richter et al.,	The process to find a process for governance: Nuclear waste management and consent-based siting in the United States	2022

Data availability

Data will be made available on request.

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Riguardo alla nocività delle radiazioni non ha senso parlare di una soglia di sicurezza: la complicazione dei meccanismi immunologici e dei meccanismi di concentrazione nei singoli «siti» cellulari o molecolari comporta innumerevoli fattori di incertezza. Gli effetti biologici e il fondo naturale

Radiazioni: una dose da overdose

di R. Cieri, E. Tiezzi, S. Ulgiati

La terza guerra punica fu un assedio durato tre anni. Quando ebbe inizio, dietro le fortificazioni si trovavano 700.000 persone. Quando ebbe termine, non ne rimanevano che 50.000. Si narra che, per ottenere i favori degli dei, i cartaginesi abbiano sacrificato tutti i figli primogeniti nati durante l'assedio. Consumata una lunga ed eroica resistenza, alla fine la città venne selvaggiamente saccheggiata.

Nelle società moderne molte cose sono cambiate, ma il bisogno di riti sacrificali alla divinità continua a essere radicato, sia pure sotto altre forme. È diventato luogo comune, infatti, pensare che il prezzo da pagare per il progresso tecnologico sia inevitabile. Ad esempio, l'inquinamento delle acque conseguente all'industrializzazione chimica è il prezzo necessario per disporre di numerosi beni di consumo ormai di uso corrente. I bambini del terzo mondo sterminati per fame sono il sacrificio umano sull'altare del benessere dei paesi industrializzati. Ma si può affermare che il sottosviluppo, lo scempio del territorio, la progressiva desertificazione, lo sfruttamento senza limiti delle risorse, gli investimenti per fini militari siano indici di progresso?

Anche il problema energetico è stato affrontato nello stesso modo: per far fronte alle esigenze di un

duzione cellulare, così da fornire anche le cellule figlie del rispettivo codice genetico. La divisione cellulare è dunque la fase più delicata della vita della cellula, perché eventuali errori di trascrizione possono generare alterazioni nelle basi delle triplette e conseguenti modifiche alla struttura e funzione delle proteine.

Esistono meccanismi di riparazione che provvedono ad assicurare la stabilità del materiale genetico sia nella fase della trascrizione sia nel caso di eventuali danni provocati da agenti esterni (radiazioni ultraviolette, radiazioni ionizzanti, composti chimici di varia natura).

Quando una cellula viene inve-

gresso internazionale di radioprotezione tenutosi nel 1980 in Israele ha messo in luce l'esistenza di individui in grado di riparare perfettamente il danno subito (Full repair capacity), ma anche di individui con parziale capacità di riparazione (Partial repair capacity) e di individui completamente privi di questa capacità (No repair capacity).

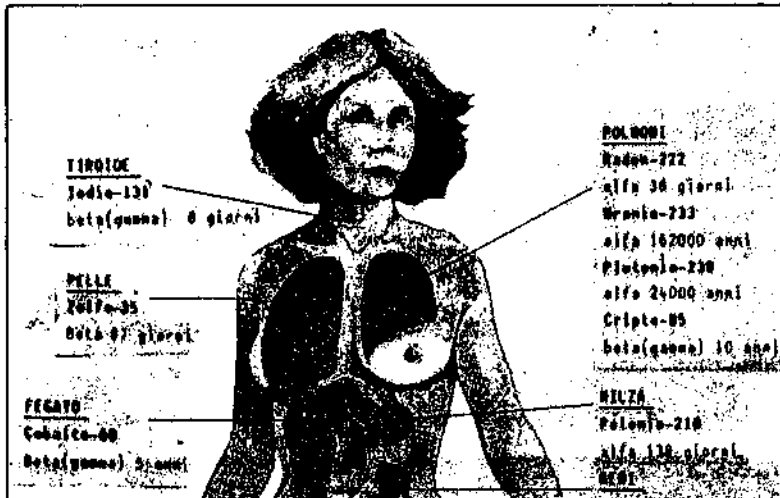
Una diminuita capacità di riparazione si traduce o in una mutazione o nella trasformazione di una cellula sana in una cellula cancerosa. Tali effetti possono rivelarsi direttamente sull'individuo irradiato dopo un periodo di latenza variabile fra i 5 e i 30 anni oppure

tervallo di tempo fra le singole frazioni comporta una sostanziale riduzione di efficacia, rispetto alla stessa dose impartita in seduta unica, per la maggior parte delle risposte biologiche, compresa la morte cellulare. Ciò è dovuto ai sistemi riparativi che, tra una frazione e la successiva, sono in grado di riparare parte dei danni introdotti dalla frazione precedente. Nel caso delle basse dosi, invece, quando il test biologico è quello della trasformazione, si ha l'effetto opposto. Questo fatto può essere spiegato con l'accumulo di danni riparati male, per intervento dei processi riparativi soggetti ad errore, a livelli di dosi in cui l'effetto più drammatico delle radiazioni, cioè la morte cellulare, è assente. Ammesso che esista una relazione tra trasformazione e mutazione e che tali processi abbiano a loro volta un rapporto con l'insorgenza di tumori a livello di individui, allora l'osservazione fatta a livello di cellule in coltura potrebbe avere importanti ripercussioni pratiche. In tal caso infatti non sarebbe corretta l'estrapolazione lineare, a fini protezionistici, basata sulle dosi singole per la stima del rischio radiobiologico. Più basse velocità di esposizione sono 10 volte più efficaci nel trasportare le cellule ad uno stato canceroso delle velocità più alte a causa dei processi riparativi soggetti ad errore.

a causa della elevata velocità di scambio fra le cellule. Se a concentrarsi è un radionuclide, il danno che ne può derivare sarà comunque elevato. La concentrazione momentanea di uno di questi («non naturali») elementi chimici radioattivi in un determinato sito biologico può essere decine di migliaia di volte superiore rispetto ad un altro sito anche vicinissimo (per esempio fuori e dentro una cellula).

Questa concentrazione inoltre dipende da moltissimi parametri chimici, fisici e biologici i quali possono variare con estrema rapidità (anche in frazioni di secondo).

Per quanto sia possibile fare un calcolo «a posteriori» o un dosaggio medio di concentrazione circa la presenza di un certo elemento in un determinato sistema (per esempio una pianta o un animale), il risultato riguarderà sempre una situazione statica media complessiva (che porterà poi al concetto, di nuovo mediato, di dose, non rilevante ai fini del nostro discorso) e nessuna informazione potrà essere ricavata sulla reale situazione «in vivo» in quel determinato istante, a meno di fare indagini mirate con particolari tecniche (esempio: tempi di rilassamento di spin nucleare), indagini che richiederebbero tempi infiniti e costi proibiti per seguire un solo ele-



vegetazione che assorbe direttamente scorie dal terreno e che poi nutre il bestiame, etc.). Sono queste piccole dosi che, sommandosi nel tempo, arrecano seri danni all'uomo.

La figura a pagina 9 mostra le sedi selettive dei vari elementi radioattivi arrivati nel corpo umano attraverso la catena alimentare. Questo schema evidenzia come elementi diversi, con periodo di dimezzamento radioattivo diverso, si concentrano nelle differenti parti del corpo umano. Lo iodio-131 si concentra nella tiroide (nei neonati ciò può portare alla morte), lo zolfo ha come sede selettiva la pelle, con conseguente possibilità di cancro in tale sede, il cobalto si concentra nel fegato, etc. Gli organi più delicati sono le ossa (dove lo stronzio sostituisce il calcio e irradia il midollo) e le ovaie, queste ultime importanti per la trasmissione ereditaria, per le conseguenze a livello genetico. Gli organi della riproduzione sono attaccati da tutti gli isotopi radioattivi che emettono radiazioni.

Il plutonio-239 si concentra nelle gonadi, portando a difetti di nascita e malformazioni nella prima e nelle future generazioni.

Riassumendo, ogni elemento (iodio-131, cobalto, cripton, rutenio, zinco, bario, potassio) ha un destino completamente diverso, cioè partecipa a reazioni chimico-biologiche diverse interagendo a diversi livelli con i vari organi. Esiste tutta una serie di possibili elementi radioattivi che hanno periodi di dimezzamento lunghissimi (cioè vite radioattive lunghissime fino a migliaia di anni) che si possono concentrare nei vari organi arrecando danni anche a grande distanza di tempo. Alcuni invece sono molto più labili, per esempio lo iodio ha una durata di radioattività soltanto di 8 giorni, e possono dare effetti in tempi brevi. Il fatto che gli elementi chimici radioattivi si accumulano in maniera diversa nei vari

organi e nei vari esseri viventi fa sì che non ha senso parlare di soglia.

I fattori del nucleare sostengono che il fondo naturale di radioattività (cioè la radioattività da cui siamo colpiti per cause naturali) è superiore a quella emessa dalle centrali. Quindi, il rischio di vivere in una zona ad alto fondo di radioattività o di spostarsi da una zona con fondo minore ad una con fondo maggiore è di per sé superiore al rischio di vivere vicino alla centrale.

Non esistono in proposito indagini sufficientemente approfondite: quel poco che esiste fa riferimento a studi condotti su campioni numericamente ridotti e quindi poco significativi; oppure si tratta di effetti delle alte dosi estrapolati alle piccole dosi con modelli matematici differenti e discutibili. In particolare, il prof. C. Land del National Cancer Institute

di Bethesda (Usa) ha dimostrato che le stime di rischio effettuate dipendono più dal modello matematico usato per valutarle che non dai dati stessi.

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Ferma restando la necessità di ulteriori e più approfonditi studi epidemiologici, è possibile trarre qualche indicazione da due ricerche condotte recentemente sugli effetti del fondo naturale di radioattività.

La prima riguarda alcune popo-

lazioni indios del Brasile in una zona (Minas Gerais e Goiaz) ad elevato tasso di radioattività naturale. È stato rilevato che in tale zona la mortalità per cancro è praticamente inesistente. La seconda indagine è stata condotta su alcuni villaggi della Bretagna (Francia) costruiti su graniti uranici o su graniti senza uranio. I risultati mostrano che la mortalità per cancro nei villaggi insediati su graniti uranici è più che doppia rispetto agli altri.

Come conciliare questi due dati apparentemente contraddittori? Se si tiene conto dei risultati del congresso di Israele (esistenza di individui con parziale o nulla capacità di riparazione enzimatica) è possibile avanzare un'ipotesi: nel caso degli indios brasiliani, popolazione insediata nella zona da millenni senza fenomeni migratori, si sarebbe realizzata una selezione naturale che ha eliminato gli individui più deboli. Ci sarebbe stata cioè una sorta di adattamento genetico

al fondo naturale di radioattività che ha premiato gli individui con sistema di riparazione enzimatico più efficiente. Nel caso, invece, dei villaggi della Bretagna, trattandosi di insediamenti più recenti, l'introduzione di radionuclidi di origine non naturale, dovuta a un impianto nucleare, può danneggiare individui non ancora geneticamente adattati. Mancano, del resto, in letteratura, dati su emigratori di massa. È probabile che un'emigrazione di 10 milioni di italiani nelle zone brasiliane e una di 10 milioni di indios nella nostra penisola porterebbe a una dram-

matica catastrofe di morti per cancro tra gli italiani e di morti per inquinamenti diversi tra gli indios.

Per finire la complicazione dei meccanismi immunologici (frontiera della scienza medico-biologica ancora in gran parte da investigare) e dei meccanismi di concentrazione nei singoli «siti» cellulari o molecolari porta tanti e tali fattori di incertezza che si può senz'altro concludere che non ha senso cercare una soglia di sicurezza su questo problema o comunque parlare di «dose». Del resto, come si è visto, le indagini epidemiologiche non ci sono di grande aiuto e le ultime scoperte sui meccanismi di riparazione gettano ulteriori ombre sulle «certezze» fino ad oggi dichiarate. Allora George Wald, premio Nobel per la biologia, aveva ragione: «Ogni dose di radiazione è un'overdose».

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Life-Span Carcinogenicity Studies on Sprague–Dawley Rats Exposed to γ -Radiation: Design of the Project and Report on the Tumor Occurrence After Post-Natal Radiation Exposure (6 Weeks of Age) Delivered in a Single Acute Exposure

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Background *Experimental long-term carcinogenicity bioassays conducted on rats and mice proved that ionizing radiation can induce a variety of tumor types. However few studies have been conducted on rats.*

Methods *This report deals with the effects of γ -radiation in groups of 416–1,051 6-weeks old Sprague–Dawley rats exposed to 0, 0.1, 1, or 3 Gy of γ -radiation delivered in a single acute exposure. The experiment lasted for the animals' lifespan and all were necropsied and underwent full histopathological evaluation.*

Results *The results confirm the dose-related carcinogenic effects of γ -radiation for several organs and tissues. Moreover they indicate that exposure to 0.1 Gy induces a statistically significant increased incidence in Zymbal gland carcinomas and pancreas islet cell carcinomas in females.*

Conclusions *Our data show that exposure to γ -radiation induces carcinogenic effects at all tested doses. Am. J. Ind. Med. 58:46–60, 2015. © 2014 Wiley Periodicals, Inc.*

KEY WORDS: *life-span bioassay; rat; carcinogenicity; γ -radiation; low-dose*

INTRODUCTION

Most of the recently reported epidemiological research on the relationship between ionizing radiation and cancer has concerned moderate-high-dose (0.5–1 Gy) whole-body exposure. However because low dose (defined as ≤ 0.1 Gy) or protracted exposure are of major interest when it comes to

protecting people from ionizing radiation, the research has started to be more focused on occupational cohorts, in particular workers at nuclear plants, or persons/patients exposed to multiple diagnostic radiological examination.

Epidemiological studies have shown that exposure to doses (>0.1 Gy) increased the risk of developing both solid cancers and leukemias among survivors of Hiroshima and Nagasaki [Preston et al., 2007], as well as among radiologists and physicians specialized in interventional medicine [Linet et al., 2010], workers in the nuclear industry [Cardis et al., 2007].

Some unresolved questions include: (1) differences in risk between acute and chronic exposure [Jacob et al., 2009]; (2) effects at low doses and the appropriateness of the linear no threshold model [Mullenders et al., 2009; Averbek, 2010]; (3) what cancer effects, if any, may be the result of

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preconception exposure or in utero exposure [Barber and Dubrova, 2006; Abouzeid Ali et al., 2012]; (4) identification of possible radio-sensitive subgroups in the population and how these subgroups can be identified [Jeggo, 2010]; (5) the possible interaction between ionizing radiation and other well-known carcinogenic agents or potential diffuse carcinogenic risks (e.g., chemical agents, extremely low frequency magnetic fields of power energy, or radiofrequency electromagnetic fields from cell phones).

To answer these questions, related in particular to the effects of low doses, more adequate data is still needed. To face this challenge, researchers use both epidemiological and experimental studies. However, it is quite understandable that when dealing with low-exposure scenarios (such as those of 0.1 Gy or less) with multiple confounding factors, epidemiological studies may lack sufficient statistical power to detect cancer risks. In these cases mechanistic and *in vivo* animal studies can help epidemiology to better evaluate the carcinogenic risk of low dose exposure.

Experimental studies conducted on mice and rats have proved that ionizing radiation can cause a variety of tumor types in both species. In a series of mouse studies [IARC, 2000, 2012] conducted using a large number of animals per group and sex exposed to either X-rays or to γ -rays with a range of doses and dose rates, it was observed an increased incidence of several types of neoplasms, including in particular myeloid leukemia and thymic lymphoma, ovarian, pituitary and Harderian gland tumors, lung and mammary carcinomas.

Despite the interest in the effects of ionizing radiation in mice, few studies were conducted on rats and, among them, the majority were focused on the study of mammary carcinogenesis. Rats are the most suitable animal species for studying mammary carcinogenesis by radiation since they are responsive and develop very similar tumors to their human counterpart. The responsiveness in developing mammary tumors depends on the strain and Sprague–Dawley rats are the most susceptible [Russo and Russo, 1996].

Studies conducted on female Sprague–Dawley rats showed an increased incidence of mammary cancers after exposure to X-ray dose over the range 0.25–6 Gy [Shellabarger et al., 1957, 1966; Bond et al., 1960]. It has been reported that in female Sprague–Dawley rats neutrons at a single dose as low as 0.1 Gy produced a significant increase in mammary tumors [Shellabarger et al., 1980]. Subsequent studies conducted on Sprague–Dawley rats and as well as other strains confirmed the strong carcinogenic effects of ionizing radiation on the mammary gland [Shellabarger et al., 1982; Broerse et al., 1986, 1987; Bartstra et al., 1998].

The experimental carcinogenic bioassays on rats conducted to date has their own limitations: the small size of animal groups, the duration of the study, which is all too often arbitrarily truncated, not to mention the lack of details of pathology. Indeed long-term carcinogenicity bioassays on rodents, when well-planned and conducted using adequate

animal models (as close as possible to the human equivalent tumor type incidences may provide better indications as to the carcinogenic effects which can be extrapolated to humans for risk assessment [Huff, 1999; Maltoni et al., 1999]).

Based on previous experience in conducting large-scale carcinogenicity bioassays, a project of long-term experiments on rats exposed to γ -radiation in different situations and at various dose levels have been conducted at the laboratories of the Cesare Maltoni Cancer Research Center of the Ramazzini Institute (CMCRC/RI) located in the province of Bologna, Italy, where this type of research has been performed since the early 1970s [Soffritti et al., 1999, 2002].

Overall, the project comprises four large scale experiments:

- (1) the main experiment which studies the effects at three dose levels (0.1, 1, and 3 Gy) plus controls, delivered in a single acute dose or in 10 doses (once every 4 weeks) to 4,016 six-week-old (starting age) male and female rats;
- (2) a second experiment, which studies the effects on male and female offspring of three doses at 0.1, 0.5, and 1 Gy delivered in one acute dose to pregnant dams, irradiated on the 12th day of pregnancy (2,799 rats);
- (3) a third experiment, which studies the effects on male and female offspring of three doses 0.1, 1, and 3 Gy delivered in a single acute dose to male breeders before mating (2,557 rats);
- (4) and finally a fourth experiment, which studies the effects of standard feed, administered after irradiation by 1 or 4 kGy, to pregnant dams from the 12th day of pregnancy, and then to their male and female offspring until spontaneous death (1,139 animals).

These four experiments started concurrently and the experimental animals were those born during the breeding of 4,000 rats (2,000 males plus 2,000 females).

The main experiment includes one control group which is common to all four experiments.

THE CARCINOGENIC EFFECTS OF EXPOSURE OF 6-WEEK-OLD SPRAGUE-DAWLEY RATS TO γ -RADIATION DELIVERED IN A SINGLE ACUTE EXPOSURE (MAIN EXPERIMENT)

This report deals with results in terms of overall carcinogenic effects in three groups of 416–1,046 male and female rats from the main experiment which exposed Sprague–Dawley rats at 6 weeks of age to three different dose levels of γ -radiation (0.1, 1, 3 Gy) delivered in a single acute exposure. One group of 1,051 males and females served as control. The highest dose level was selected on the basis of

data available in the literature. The lowest dose was chosen as representative of human scenarios of high exposure to ionizing radiation in various workplaces or during radiation therapy. Also 0.1 Gy is the lowest experimental dose in the mouse studies [Ullrich and Storer, 1979a,b].

MATERIALS AND METHODS

γ -Radiation Exposure Conditions and Facility

The irradiation facility consisted of a telecobalt therapy unit of the "Theratron 780" type (Fig. 1), that utilized Co60 as its radiation source, with an activity of about 56 TBq (1,500 Ci). The irradiation procedure was carried out inside a properly shielded irradiation room (bunker), constructed of reinforced concrete and was 5 m \times 4 m \times 3 m in size. The control board and exposure monitoring facilities were located in a room next to the bunker.

The "Theratron 780" unit was equipped with a turntable made of a 1 cm thick perspex sheet (size 48 cm \times 48 cm). The turntable has a pneumatic system for 180° rotation on its axis and is positioned 120 cm away from the radiation source. The system is controlled from outside the bunker and allows animals to be irradiated ventrally and dorsally at two different times. In order to obtain an evaluation of the irradiation beam

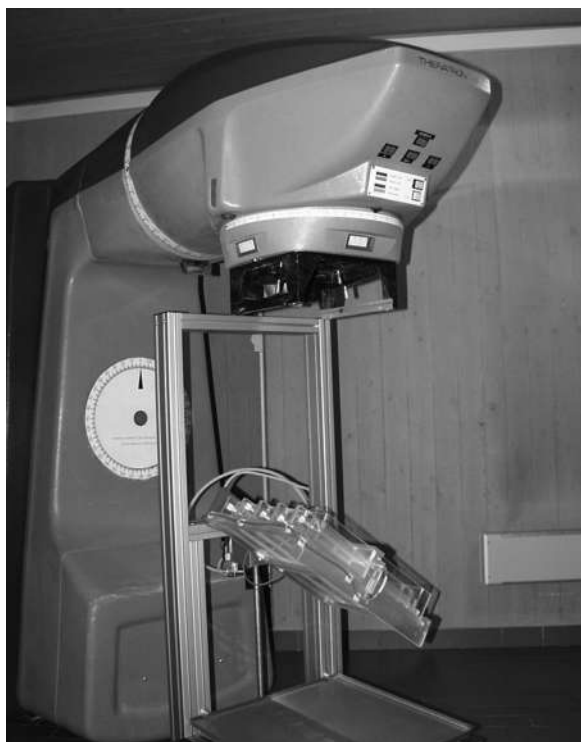


FIGURE 1. Exposure system.

effect on the whole body, it proved necessary to administer a uniform radiation dose inside the animal. This result was achieved by placing the animals in different positions relative to the source. To keep them from moving during exposure, animals were locked in special perspex holders, with 1 cm thick walls, 20.8 cm long \times 6.5 cm broad, placed on the turntable. The area used was 46 cm \times 46 cm in size and made it possible to radiate up to 10 animals at the same time, with an absorbed dose rate of about 0.21 Gy/min.

To measure the dose administered, a Nuclear Enterprise dosimeter type 2571A was used, with a 0.6 cc graphite ionization chamber, calibrated in terms of dose absorbed to water with 4% uncertainty. The dosimeter, irradiated together with the animals, was permanently fitted to the under-side of the turntable, located along the axis of the beam. The dose readings in the two positions (ventrally and dorsally) showed uniformity in the absorbed dose with the maximum differences between the various parts of the body in the order of a few percent (3–5%).

Possible sources of operator error in carrying out treatment may be incorrect selection of irradiation times, or non-rotation of the turntable after the first part of treatment. To ensure correct execution of the treatment, two checks were devised: (1) the dosimeter, irradiated together with the animals, was permanently fixed to the turntable; (2) this dosimeter was located along the axis of the beam, on the under-side of the turntable about 1 cm from its rotation axis, so that dose readings in the two positions must differ by more than 2%.

Animals

Strain

The animals used were Sprague–Dawley rats from the same colony as used for more than 40 years in the laboratories of the CMCRC/RI. The basic expected tumorigenesis and its fluctuations were based upon data deriving from more than 18,000 historical controls.

Generation of experimental animals

The generation of experimental animals took place as follows: (a) inbred breeders were distributed in four groups and the offspring of these were assigned to the respective groups; (b) randomization by body weight of the inbred brother and sister among the four breeder groups was as homogenous as possible; (c) mating of the breeders that generated the off-spring for the experiment was strictly out-bred (made possible by pedigree identification number of each animal) in each breeder group and lasted 72 hr; (d) the size of breeder groups was dictated by the number of offspring required; (e) in order to evaluate the family effect in the carcinogenic process, the experimental groups included

all the offspring of each litter; (f) all the male and female breeders were sacrificed 6 weeks after birth and 1 week after the weaning of the offspring, respectively.

The animals of all experiments were weaned, weighted, separated by sex and identified by ear punch at 5 weeks of age.

Conduct of the experiment

The animals were kept in highly standardized environmental conditions. They were housed 5 per cage, in makrolon cages with a solid top in stainless steel. A shallow layer of white wood fir-tree shavings served as bedding. The animals were kept in a temperature-controlled laboratory at 21–24°C, with relative humidity at 40–60% and 12-hr light/dark alternation. The experiment was conducted in accordance with Italian law regulating the use and human treatment of animals for scientific purposes [Decreto Legislativo, 1992].

After weaning, animals received food and water *ad libitum*. The food was purchased from “Mangimificio COMER” (Bologna), which is the same as used in the CMCRC/RI for more than 40 years, while the water came from the local water supply. Water and feed were periodically analyzed to monitor for the presence of possible contaminants.

Animals were kept under observation until natural death (life-span). The daily consumption of feed and water were measured in a sample of 100 animals (50 males and 50 females) from each group and each experiment from the age of 6 weeks every 4 weeks until 110 weeks of age. Body weight was recorded from the age of 6 weeks every 4 weeks until 110 weeks of age, then every 8 weeks until the end of the experiment. The health and behavior of the animals were controlled three times daily throughout the experiment. Checks for pathological lesions, including mammary tumors (the most frequent lesion in females), were performed every 2 weeks throughout the experiment. Animals with lumps greater than 3 cm in diameter were isolated from other animals and individually caged to avoid cannibalization. The development of the lumps/masses was monitored until spontaneous death. A systematic gross examination was performed and all pathological changes recorded.

For histopathological examination, in addition to macroscopically observed pathological lesions (with a margin of surrounding normal tissue), the following tissues and organs were taken: skin, subcutaneous tissue, mammary gland, brain, pituitary gland, Zymbal gland, salivary glands, Harderian glands, cranium, tongue, thyroid and parathyroid, pharynx, larynx, thymus, trachea, lung, heart, diaphragm, liver, spleen, pancreas, kidneys, adrenal glands, oesophagus, stomach (fore and glandular), intestine (four levels), bladder, prostate, uterus, ovaries, testes, interscapular fat pad and subcutaneous, mediastinal and mesenteric lymph nodes.

All specimens were fixed in 70% alcohol, except for bones and other tissues of a bone-like consistency which were fixed in 10% formalin. The trimming was performed

according to the CMCRC/RI Standard Operating Procedures (SOP). All pathological tissues were trimmed in order to maintain a border of normal tissue around the lesions. With regard to normal tissue and organs: (1) the decalcified cranium was trimmed at five levels from nose to occipital bone, including oral and nasal cavities and internal ear ducts; (2) parenchymal organs were dissected through the hilus to expose the widest surface; and (3) hollow organs were sectioned across the greatest diameter(s). Trimmed specimens were processed as paraffin blocks, and 3–5 μ m sections of every specimen were obtained. Sections were routinely stained with hematoxylin and eosin (H&E). Histopathological evaluation of the lesions, in particular benign and malignant tumors, was performed according to the National Toxicology Program criteria [Boorman et al., 1990]. The evaluation was performed by the same group of pathologists on all tissues and organs. The same supervisor reviewed all lesions of oncological interest. All pathologists used the same evaluation and classification criteria.

Statistical Analysis

Cox proportional hazard models were used to estimate the relative risk of malignant tumors as a function of dose. For benign tumors logistic regression was used with age as a covariate. The risk model used was:

$$\lambda(t, D) = \lambda(t, 0) \exp\{f(D)\}$$

where $\lambda(t, D)$ is the hazard rate, t is the age of the animal in days at death, D is the dose and $\exp\{f(D)\}$ is the relative risk. For estimating the relative risk of the individual dose group D_i ($i = 1, 2, \text{ or } 3$) we used $f(D) = \sum a_i D_i$ with D_i equal to 1 for group i and 0 for the other two. For modeling the relative risk as a function of dose the model used was:

$$\lambda(t, D) = \lambda(t, 0) \{1 + aD + bD^2\}$$

with the estimates of a and b restricted to being non-negative. The computer package used for the data analysis was Egret. In using the standard Cox proportional hazard analysis competing risks and differential survival were thus taken into account. A dose group with reduced survival may have a greater estimated hazard rate than controls yet a smaller incidence of cases. Details can be found in the biostatistical textbook of Hosmer and Lemeshow [1999].

RESULTS

During the experiment, no noticeable alteration of the behavior or health of the animals in the various groups was observed. Evaluation of the probability of survival in males

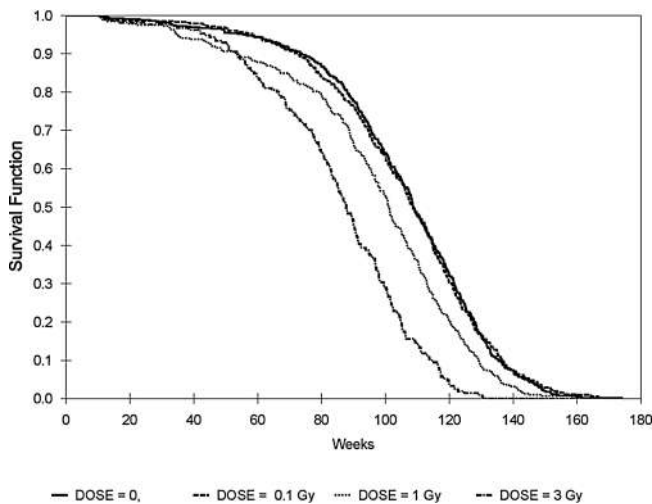


FIGURE 2. Survival male Sprague–Dawley rats.

and females exposed to γ -radiations compared to controls is shown as Kaplan–Meier curves (Figs. 2 and 3). The hazard ratios and median survival times in males and females are presented in Table I. The data showed that no change in survival for either sex was observed among animals exposed to 0.1 Gy compared to controls.

Multiple tumors of differing type and site, of differing type at the same site, of the same type in bilateral organs, of the same type in the skin, in subcutaneous tissue, in mammary glands, or at distant sites of diffuse tissue (e.g., bones and skeletal muscles) were counted as single/independent tumors. Multiple tumors of the same type in the same tissue and organ, apart from those listed above, were counted only once.

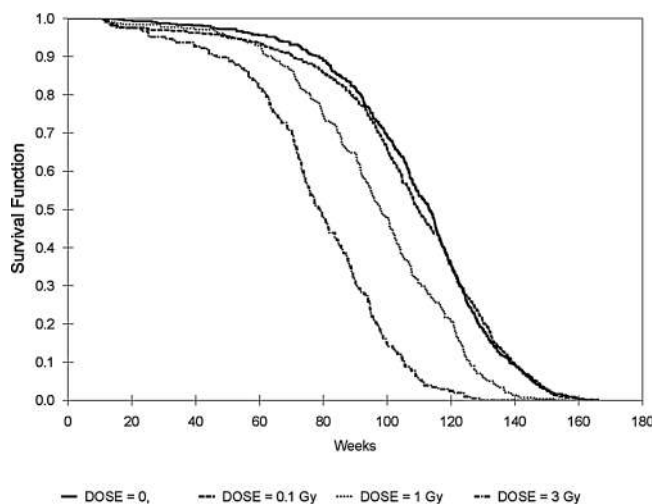


FIGURE 3. Survival female Sprague–Dawley rats.

TABLE I. Hazard Ratios and Median Survival Time in Male (M) and Female (F) Sprague–Dawley Rats

Group no. (Gy)	Animals ^a sex, no		Hazard ratio		Median survival (days)	
	M	F	M	F	M	F
I (0)	514	537	Reference		760	792
II (0.1)	524	522	0.99	1.01	760	767
III (1)	318	301	1.39**	1.74**	707	685
IV (3)	211	205	2.73**	4.38**	613	551

*Statistically significantly different from 1.00 at $P \leq 0.01$ by Cox Proportional Hazard analysis.

^aSix weeks old at the time of exposure.

Significant oncological results are reported in Tables II–VII. Because there were differences in survival between the control group and the 1 and 3 Gy exposure groups of males and females, statistical tests adjusted for differences in survival were applied to the pairwise and trend analysis. Historical control data on specific spontaneous tumor incidences regarding 2,180 and 2,189 male and female offspring recorded during the period 1984–1997 were also considered. Moreover, the large number of animals per sex and per group allowed us to express more sharply the variation effects and indeed to raise the accuracy and statistical sensitivity of the study, reducing the likelihood of getting false positive results.

Benign and Malignant Tumors

Overall benign and malignant tumor incidence is reported in Table II. A significant dose-related increased incidence of animals bearing benign tumors occurred both in males and females ($P \leq 0.01$). Significant increased incidences ($P \leq 0.01$) were observed in males and females exposed to 1 and 3 Gy compared to controls. An increased number of total benign tumors per 100 animals occurred in males and females exposed to 1 and 3 Gy compared to the controls and to the lowest treated group. A significant dose-related increased incidence ($P \leq 0.01$) of animals bearing malignant tumors occurred in males and females. Significant increased incidences were observed in males and females exposed to 3 Gy ($P \leq 0.01$) compared to the controls. A sharp increase in the total number of malignant tumors per 100 animals occurred in males and females treated at 3 Gy as compared to controls. The statistically significant differences in males and females bearing benign or malignant tumors exposed to 1 and 3 Gy, as compared to controls, are due to the reduced survival in the two treated groups. This explains the still statistically significant increased tumor incidences and the greater estimated cumulative hazard rate (Figs. 4 and 5)

TABLE II. Benign and Malignant Tumors in Male (M) and Female (F) Sprague–Dawley Rats

Group no. (Gy)	Animals ^a		Benign tumors				Malignant tumors			
			Tumor-bearing animals		Tumors ^b		Tumor-bearing animals		Tumors ^b	
	Sex	No.	No.	%	No.	Per 100 animals	No.	%	No.	Per 100 animals
I (0)	M	514	320	62.3 ^{##}	612	119.1	241	46.9 ^{##}	294	57.2
	F	537	439	81.7 ^{##}	1264	235.4	280	52.1 ^{##}	404	75.2
	M + F	1051	759	72.2 ^{##}	1876	178.5	521	49.6 ^{##}	698	66.4
II (0.1)	M	524	331	63.2	685	130.7	253	48.3	339	64.7
	F	522	420	80.5	1320	252.9	280	53.6	431	82.6
	M + F	1046	751	71.8	2005	191.7	533	51.0	770	73.6
III (1)	M	318	202	63.5 ^{**}	416	130.8	157	49.4 ^{**}	208	65.4
	F	301	253	84.0 ^{**}	851	282.7	142	47.2 ^{**}	229	76.1
	M + F	619	455	73.5 ^{**}	1267	204.7	299	48.3 ^{**}	437	70.6
IV (3)	M	211	142	67.3 ^{**}	366	173.5	156	73.9 ^{**}	225	106.6
	F	205	173	84.4 ^{**}	628	306.3	136	66.3 ^{**}	223	108.8
	M + F	416	315	75.7 ^{**}	994	238.9	292	70.2 ^{**}	448	107.7

^{**}Significantly greater than control ($P \leq 0.01$).

^{##}Near the control incidence are the P values ($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend.

^aSix weeks old at the time of exposure.

^bOne animal can bear more than one tumor.

in the two exposed groups in spite of their incidences being reduced.

Cancers of the Skin, Subcutis Liposarcomas, and Breast

The occurrence of malignant tumors of the skin, subcutis liposarcomas and breast are reported in Table III. A dose-related increased incidence ($P \leq 0.01$) of malignant tumors of the skin

was observed in males and females compared to controls. In males exposed to 3 Gy, the incidences of basocellular and squamous cell carcinomas were both significantly increased ($P \leq 0.01$) compared to male controls. A dose-related increased incidence of animals bearing subcutis liposarcomas was observed in males ($P \leq 0.01$) and in females ($P \leq 0.05$). Among the males exposed to 3 Gy the incidence was significantly increased ($P \leq 0.01$) compared to male controls.

The incidences of animals bearing breast adenocarcinomas and sarcomas (encompassing fibrosarcomas, liposarcomas, hemangiosarcomas, and osteosarcomas) show a significant dose-related increase ($P \leq 0.01$) in males and females for both adenocarcinomas and sarcomas. When compared to the untreated controls, the incidence of adenocarcinomas in males and females exposed to 1 or 3 Gy were significantly increased ($P \leq 0.01$) in both sexes. When compared to controls, the incidence of sarcomas of all types were significantly increased in males and females ($P \leq 0.01$) exposed to 3 Gy. At 1 Gy, the incidence of sarcomas was significantly increased in males ($P \leq 0.01$) and also in females ($P \leq 0.05$). When females bearing atypical lesions of mammary glands were aggregated with females bearing mammary adenocarcinomas, a significant increased incidence ($P < 0.05$) was also observed at 0.1 Gy, compared to controls (Table IV). The increase in mammary carcinomas plus their atypical precursor lesions was extremely marked and confirms our first results [Soffritti et al., 1999].

It is, of course, well known that intraductal atypical hyperplasia of the mammary gland is a precursor of carcinomas

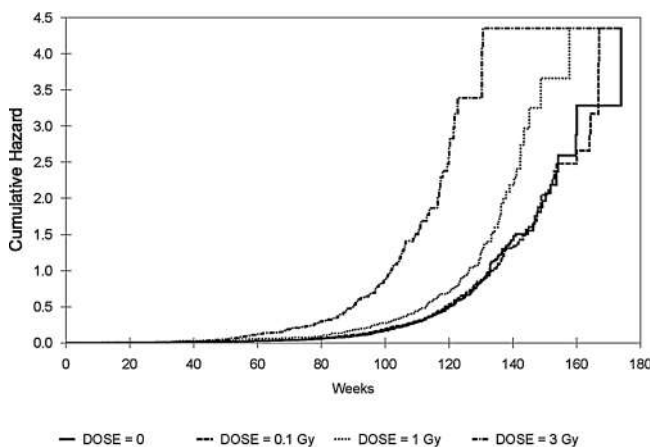


FIGURE 4. Cumulative hazard for total malignant tumors male Sprague–Dawley rats.

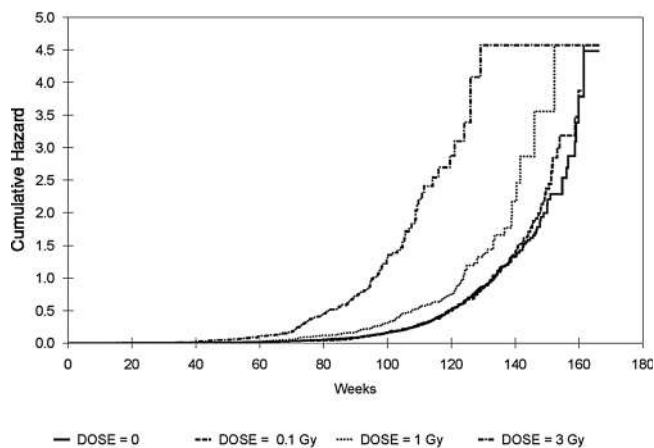


FIGURE 5. Cumulative hazard for total malignant tumors female Sprague–Dawley rats.

in rats [Russo and Russo, 2004]. As described by the WHO, this lesion is characterized by morphological changes that include altered architecture and abnormalities in cytology and differentiation [WHO—OMS—IARC, 2003]. The relative risk of developing a mammary cancer among patients with atypical ductal hyperplasia is 4–5 times higher, as reported by the Cancer Committee of the College of American Pathologists

[Fitzgibbons et al., 1998]. For these reasons the aggregation of animals bearing atypical mammary lesions with animals bearing carcinomas is justified to show the significant increased risk of mammary neoplasms in female rats exposed to 0.1 Gy.

Head and Neck, Thyroid Gland, and Parathyroid Tumors

The incidence of tumors of head and neck, including thyroid and parathyroid, are reported in Table V. In females a significant dose-related increased incidence ($P \leq 0.05$) of Zymbal gland carcinomas was observed; the incidence of carcinomas was significantly increased in females exposed to 3 Gy and in males exposed to 0.1 Gy ($P \leq 0.01$), the lowest exposure dose. When males and females were aggregated, the incidence of carcinomas increased significantly at 0.1 Gy ($P \leq 0.05$). Zymbal gland carcinomas are not frequent in Sprague–Dawley rats of our colony. Out of 2,180 untreated male historical controls, the overall incidence was 1.7% (range: 0.0–3.0%).

Significant increased incidence of ear duct carcinomas was observed in females exposed to 3 Gy ($P \leq 0.05$) compared to the controls.

A dose-related increased incidence of nasal cavities carcinomas was observed in males ($P \leq 0.01$) and specifically

TABLE III. Cancers of the Skin, Subcutis, and Breast in Male (M) and Female (F) Sprague–Dawley Rats

		Tumor-bearing animals								
		Animals ^a		Skin cancers		Subcutis liposarcomas		Breast cancers		
Group no. (Gy)	Sex	No.	No.	%	No.	%	No.	%	No.	%
I (0)	M	514	6	1.2 ^{##}	5	1.0 ^{##}	3	0.6 ^{##}	2	0.4 ^{##}
	F	537	2	0.4 ^{##}	0	— [#]	76	14.2 ^{##}	7	1.3 ^{##}
	M + F	1051	8	0.8 ^{##}	5	0.5 ^{##}	79	7.5 ^{##}	9	0.9 ^{##}
II (0.1)	M	524	6	1.1	9	1.7	3	0.6	8	1.5
	F	522	3	0.6	0	—	78	14.9	14	2.7
	M + F	1046	9	0.9	9	0.9	81	7.7	22	2.1*
III (1)	M	318	5	1.6	3	0.9	7	2.2**	14	4.4**
	F	301	4	1.3	1	0.3	86	28.6**	3	1.0*
	M + F	619	9	1.5	4	0.6**	93	15.0**	17	2.7**
IV (3)	M	211	9	4.3**	15	7.1**	7	3.3**	9	4.3**
	F	205	3	1.5**	2	1.0	91	44.4**	4	2.0**
	M + F	416	12	2.9**	17	4.1**	98	23.6**	13	3.1**

*Significantly greater than controls ($P \leq 0.05$), **($P \leq 0.01$). [#]Near the control incidence are the P values ($P \leq 0.05$) or ^{##}($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend.

^aSix weeks old at the time of exposure.

^bFibrosarcomas, liposarcomas, hemangiosarcomas, and osteosarcomas.

TABLE IV. Animals Bearing Mammary Adenocarcinomas or Their Atypical Precursors in Female (F) Sprague–Dawley Rats

Group no. (Gy)	Animals bearing mammary atypical precursors ^b or adenocarcinoma							
	Animals ^a		Atypical precursors		Adenocarcinomas		Total number of animals bearing atypical precursors or adenocarcinomas ^c	
	Sex	No.	No.	%	No.	%	No.	%
I (0)	F	537	40	7.4	76	14.2 ^{##}	116	21.6 ^{◆◆}
II (0.1)	F	522	68	13.0	78	14.9	146	28.0 [◆]
III (1)	F	301	27	9.0	86	28.6 ^{**}	113	37.5 ^{◆◆}
IV (3)	F	205	11	5.4	91	44.4 ^{**}	102	49.8 ^{◆◆}

^{**}Significantly greater than control ($P \leq 0.01$). ^{##}Near the control incidence is the P -value ($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend. [◆] P values ($P \leq 0.05$) and ^{◆◆} P values ($P \leq 0.01$) using Mantel–Haenszel Model for the analysis of combined lesions.

^aSix weeks old at the time of exposure.

^bAtypical hyperplasia in mammary gland or in fibroadenoma.

^cAnimals bearing more than one type of lesion are plotted only one according to the most severe lesion.

a significant increase ($P \leq 0.01$) was observed in males exposed to the highest dose.

The incidence of thyroid malignant tumors indicate a significant dose-related increase of follicular cell adenocarcinomas in females ($P \leq 0.01$). When compared to untreated females, the increased incidence of follicular cell adenocarcinomas was significant ($P \leq 0.01$) in females exposed to 3 Gy. A significant dose-related increased incidence of C-cell carcinomas was observed in females ($P \leq 0.01$). When compared to untreated male and female controls, a significant

increased incidence of C-cell carcinomas was observed in males and females exposed to 3 Gy ($P \leq 0.05$ and $P \leq 0.01$, respectively).

A dose-related increased incidence of parathyroid glands adenomas was observed both in males and females ($P \leq 0.01$). The incidence of adenomas was significantly increased ($P \leq 0.01$) in both males and females exposed to 1 and 3 Gy. No malignant tumors were observed among the treated and untreated males and females. Parathyroid glands adenomas are rare tumors in our rat colony. Among the

TABLE V. Tumors of Head, Neck, Thyroid, and Parathyroid Glands in Male (M) and Female (F) Sprague–Dawley Rats

Group no. (Gy)	Tumor-bearing animals													
	Animals ^a		Zymbal gland carcinomas		Ear ducts carcinomas		Nasal cavities carcinomas		Thyroid follicular cell carcinomas		Thyroid C-cell carcinomas		Parathyroid adenomas	
	Sex	No.	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
I (0)	M	514	9	1.8	32	6.2	2	0.4 ^{##}	3	0.6	6	1.2	8	1.6 ^{##}
	F	537	15	2.8 [#]	46	8.6	1	0.2	1	0.2 ^{##}	7	1.3 ^{##}	4	0.7 ^{##}
	M + F	1051	24	2.3 [#]	78	7.4	3	0.3 ^{##}	4	0.4 ^{##}	13	1.2 ^{##}	12	1.1 ^{##}
II (0.1)	M	524	25	4.8 ^{**}	45	8.6	1	0.2	3	0.6	13	2.5	13	2.5
	F	522	16	3.1	50	9.6	4	0.8	5	1.0	4	0.8	7	1.3
	M + F	1046	41	3.9 [*]	95	9.1	5	0.5	8	0.8	17	1.6	20	1.9
III (1)	M	318	6	1.9	12	3.8	2	0.6	1	0.3	3	0.9	14	4.4 ^{**}
	F	301	3	1.0	11	3.7	1	0.3	1	0.3	2	0.7	10	3.3 ^{**}
	M + F	619	9	1.5	23	3.7	3	0.5	2	0.3	5	0.8	24	3.9 ^{**}
IV (3)	M	211	3	1.4	4	1.9	4	1.9 ^{**}	0	—	2	0.9 [*]	8	3.8 ^{**}
	F	205	4	2.0 ^{**}	6	2.9 [*]	0	—	2	1.0 ^{**}	4	2.0 ^{**}	3	1.5 ^{**}
	M + F	416	7	1.7 ^{**}	10	2.4 [*]	4	1.0 ^{**}	2	0.5 ^{**}	6	1.4 ^{**}	11	2.6 ^{**}

^{*}Significantly greater than controls ($P \leq 0.05$), ^{**}($P \leq 0.01$). [#]Near the control incidence are the P values ($P \leq 0.05$) or ^{##}($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend.

^aSix weeks old at the time of exposure.

historical controls, during the period 1984–1997 (when the biophase of this study was conducted), the overall incidence of parathyroid glands adenomas was 0.5% (range: 0.0–1.6%) out of 2,180 males and 0.4% (range: 0.0–2.0%) out of 2,189 females. No malignant tumor was recorded.

Carcinomas of the Liver, Lung, Endocrine Pancreas, Kidneys, and Adrenal Glands

The incidence of malignant tumors of the liver, lung, endocrine pancreas, kidneys and adrenal glands are reported in Table VI. The data indicate a dose-related increased incidence ($P \leq 0.01$) of hepatocellular carcinoma (HCC) in males and females. When compared to untreated males and females, the incidence of HCC was significantly increased both in males and females exposed to 1 Gy ($P \leq 0.01$ in males and $P \leq 0.05$ in females), and to 3 Gy ($P \leq 0.01$).

Although not significant, a numerical increase in the incidence of animals bearing lung adenocarcinomas was observed in males exposed at 1 and 3 Gy (0.6% and 1.9%, respectively), as compared to 0.2% in male controls. Adenocarcinoma of the lung is a very uncommon malignant tumor among male Sprague–Dawley rats from our colony. Out of 2,180 males the overall incidence of lung adenocarcinomas was 0.10% (range: 0.0–1.1%).

Regarding the endocrine pancreas, the data indicate a significant dose-related increased incidence ($P \leq 0.01$) of

islet-cell carcinomas both in males and females. The incidence of islet-cell carcinomas in males exposed to 1 and 3 Gy were significantly increased ($P \leq 0.05$ and $P \leq 0.01$ respectively) compared to male controls. The incidence of islet-cell carcinomas in females exposed to 0.1, 1 and 3 Gy were significantly higher ($P \leq 0.01$) than in female controls. Islet-cell carcinoma of the pancreas is a very rare type of tumor among the Sprague–Dawley rats from our colony. Moreover, it is interesting to note that 80 weeks after X-ray irradiation, Watanabe and Kamiya [2008] observed a significant increased incidence of pancreas islet cell adenomas in rats. The overall incidence of islet-cell carcinomas in our historical controls was 0.2% (range: 0.0–0.8%) out of 2,180 males and 0.05% (range: 0.0–0.1%) out of 2,189 females.

The incidence of kidney adenocarcinoma-bearing animals occurred with a significant dose-related increase in males ($P \leq 0.01$) and females ($P \leq 0.05$). The incidence of malignant tumors was significantly increased in males exposed to 3 Gy ($P \leq 0.01$). Adenocarcinomas of the kidneys are very uncommon malignant tumors among Sprague–Dawley rats from our colony. Indeed, the overall incidence of kidney adenocarcinomas was 0.2% (range: 0.0–0.3%).

A significant dose-related increased incidence of cortical adenocarcinomas was observed in females ($P \leq 0.01$), in particular in females exposed to 1 Gy ($P \leq 0.05$) and 3 Gy ($P \leq 0.01$) compared to controls. The overall incidence of cortical adenocarcinomas of adrenal glands in our historical controls was 1.2% (range: 0.0–4.0%).

TABLE VI. Malignant Tumors of the Liver, Lung, Endocrine Pancreas, Kidneys, and Adrenal Glands in Male (M) and Female (F) Sprague–Dawley Rats

Group no. (Gy)	Animals ^a		Tumor-bearing animals									
			Hepatocellular carcinomas		Adenocarcinoma of the lung		Islet cell carcinoma of the pancreas		Adenocarcinoma of the kidneys		Cortical adenocarcinoma of the adrenal glands	
	Sex	No.	No.	%	No.	%	No.	%	No.	%	No.	%
I (0)	M	514	4	0.8 ^{##}	1	0.2	4	0.8 ^{##}	1	0.2 ^{##}	2	0.4
	F	537	1	0.2 ^{##}	0	—	0	— ^{◆◆}	2	0.4 [◆]	6	1.1 ^{##}
	M + F	1051	5	0.5 ^{##}	1	0.1	4	0.4 ^{##}	3	0.3 ^{##}	8	0.8 ^{##}
II (0.1)	M	524	4	0.8	0	—	8	1.5	1	0.2	2	0.4
	F	522	4	0.8	1	0.2	11	2.1 ^{◆◆}	1	0.2	7	1.3
	M + F	1046	8	0.8	1	0.1	19	1.8 ^{**}	2	0.2	9	0.9
III (1)	M	318	8	2.5 ^{**}	2	0.6	5	1.6 [*]	2	0.6	3	0.9
	F	301	3	1.0 [*]	0	—	7	2.3 ^{◆◆}	0	—	5	1.7 [*]
	M + F	619	11	1.8 ^{**}	2	0.3	12	1.9 ^{**}	2	0.3	8	1.3 ^{**}
IV (3)	M	211	6	2.8 ^{**}	4	1.9	25	11.8 ^{**}	7	3.3 ^{**}	0	—
	F	205	3	1.5 ^{**}	0	—	4	2.0 ^{◆◆}	3	1.5	5	2.4 ^{**}
	M + F	416	9	2.2 ^{**}	4	1.0	29	7.0 ^{**}	10	2.4 ^{**}	5	1.2 ^{**}

*Significantly greater than controls ($P \leq 0.05$), ** ($P \leq 0.01$). ^{##} Near the control incidence are the P values ($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend. [◆] P values ($P \leq 0.05$) and ^{◆◆} P values ($P \leq 0.01$) using Mantel–Haenszel Model for the analysis (insufficient data to use Cox model).

^aSix weeks old at the time of exposure.

Hemangiosarcomas of Circulatory System (All Sites) and Hemolymphoreticular Neoplasias

The incidences of hemangiosarcoma of all sites of the circulatory system and hemolymphoreticular neoplasias (HLRN) are reported in Table VII. The data indicate a significant dose-related increased incidence of hemangiosarcomas in males and females ($P \leq 0.01$). When compared to controls, the incidence of hemangiosarcoma was increased in males exposed to 0.1 Gy ($P = 0.06$), significantly increased at 1 Gy ($P \leq 0.01$), 3 Gy ($P < 0.01$) and in females exposed to 3 Gy ($P \leq 0.01$) and significantly increased at all tested doses when males and females are combined. In historical controls the overall incidence of hemangiosarcomas (all sites) in males was 0.5% (range 0.0–1.3%).

For HLRN the data show a significant dose-related increased incidence ($P \leq 0.01$) in males. When compared to male and female controls, the incidence of HLRN was significantly increased in males ($P \leq 0.01$) and females ($P \leq 0.05$) exposed to 3 Gy. The most frequent histotypes observed among the hemolymphoreticular neoplasias were lymphomas and leukemias. Both lymphomas and leukemias are neoplasias arising from hemolymphoreticular tissues and their aggregation is used because solid and circulating phases are present in many lymphoid neoplasms, and distinction between them is artificial [Harris et al., 2001].

TABLE VII. Hemangiosarcomas (All Sites) and Hemolymphoreticular Tumors in Male (M) and Female (F) Sprague–Dawley Rats

Group no. (Gy)	Animals ^a		Tumor-bearing animals			
			Hemangiosarcomas		Hemolymphoreticular tumors	
	Sex	No.	No.	%	No.	%
I (0)	M	514	0	—♦♦	120	23.3 ^{##}
	F	537	4	0.7 ^{##}	96	17.9
	M + F	1051	4	0.4 ^{##}	216	20.6 ^{##}
II (0.1)	M	524	5	1.0♦	118	22.5
	F	522	8	1.5	70	13.4
	M + F	1046	13	1.2*	188	18.0
III (1)	M	318	6	1.9♦♦	59	18.6
	F	301	3	1.0	22	7.3
	M + F	619	9	1.5**	81	13.1
IV (3)	M	211	16	7.6♦♦	55	26.1**
	F	205	11	5.4**	17	8.3*
	M + F	416	27	6.5**	72	17.3**

*Significantly greater than controls ($P \leq 0.05$), **($P \leq 0.01$). ^{##}Near the control incidence are the P values ($P \leq 0.01$) associated with Cox Proportional Hazard Model for the analysis of the trend; ♦ P values ($P \leq 0.05$) and ♦♦ P values ($P \leq 0.01$) using Mantel–Haenszel Model for the analysis (insufficient details to use Cox model).

^aSix weeks old at the time of exposure.

Cancer Risk Estimation

The Cox proportional hazard model used in the statistical testing of the various tumor types and sites also provides estimates of hazard ratios or relative risk estimates.

Hazard ratios were calculated for animal bearing malignant solid tumors, and for lymphomas and leukemias combined. For the solid tumors it is shown in Table VIII that statistically significant increases occur at 1 and 3 Gy. The increase rises rapidly and the data fit to a standard linear-quadratic dose response model. For lymphomas/leukemias, effects are not seen until 3 Gy and the dose–response is purely quadratic.

Finally for several of the cancer sites namely, mammary adenocarcinomas, Zymbal gland carcinomas, thyroid C-cell carcinomas, pancreas islet cell carcinomas and hemangiosarcomas (Table IX), the hazard ratios were estimated with the sexes combined but stratified in the analysis. Although the data are limited, it is useful to observe the risk ratios since the life shortening at the higher doses will underestimated the risk from simply observing the incidences of the tumors as is reported in the main tables. Interestingly the increase in pancreatic carcinomas has not been observed in the A-bomb survivors although it has been suggested that there is a possible association with pancreas cancer in Thorotrast patients [Travis et al., 2003].

DISCUSSION

The capacity of ionizing radiation to induce solid cancers and leukemias in humans at high exposure doses and also at low and very low doses (≤ 0.1 Gy) has been shown among the survivors of Nagasaki and Hiroshima atomic bombing [Preston et al., 2007].

The effects and mechanism of interaction between ionizing radiation and living matter is based on the biophysical theory of how ionizing radiation interacts with DNA, which is considered the major biological target. Thus, the extension of DNA damage to cells is related to the radiation dose delivered, with clear evidence of the relationship between DNA damage, mutation and cancer induction [Hanahan and Weinberg, 2000].

However in the last few decades, low doses and very low doses of ionizing radiation have been demonstrated to elicit effects on biological tissues that are independent of their direct interaction with DNA, namely the so-called non-targeted effects which include bystander effects, genomic instability, hormesis, adaptive and transgenerational radiation response [Tubiana et al., 2006]. These findings, as reviewed by Averbeck [2010] and Mullenders et al. [2009], suggest some differences in the biological responses to higher and low doses of ionizing radiation which may affect the evaluation of the risk at low exposures. Although the extent

TABLE VIII. Hazard Ratios for Male (M) and Female (F) Sprague–Dawley Rats Bearing Malignant Solid Tumors and Lymphomas/Leukemias

Group (Gy)	Animals ^a		Malignant solid tumors				Lymphomas/leukemias				
	M	F	Observed hazard ratio		Linear-quadratic		Observed hazard ratio		Linear-quadratic ^b		
			M	F	M	F	M	F	M	F	
I (0)	514	537	Reference								
II (0.1)	524	522	1.11	1.12	1.01	1.09	0.97	0.76	1.00	1.00	
III (1)	318	301	1.98**	2.10**	1.71	1.92	1.10	0.76	1.22	1.11	
IV (3)	211	205	7.53**	9.59**	7.35	9.34	2.91**	1.86*	2.94	1.98	

*Statistically significantly different from 1.00 at $P \leq 0.05$ and ** at $P \leq 0.001$.

^aSix weeks old at the time of exposure.

^bOnly a simple quadratic dose–response model fits the data.

to which these phenomena reflect different molecular mechanisms is not clear, experimental evidence may contribute to better defining the carcinogenic dose-response relationship at low exposure levels.

The capacity of ionizing radiation to induce various types of tumors in experimental animals has been well recognized for many years. In animals the carcinogenic effects can be affected by the total dose delivered (acute or fractionated), by the dose rate and type of radiation, by the responsiveness of the animal species and strain used, by the age at the time of irradiation, by hormonal factors and by the exposure to co-carcinogenic agents [Upton, 1968; IARC, 2012].

Over the years the interest of animal research in ionizing radiation has focused on quantitative aspects of the carcinogenic effects, in particular from low doses. We here summarize the results of some major studies on rats and mice.

Apart from the studies on the induction of mammary cancer in Sprague–Dawley rats by Shellabarger et al., few other studies have been performed on this species. Bartel-Friedrich et al. reported a significant increase in malignant

tumors of the head and neck in Wistar rats following exposure of the head region to X-radiation at a total dose of 60 Gy fractionated in 2 Gy per day [Bartel-Friedrich et al., 1999]. Watanabe and Kamiya [2008] reported a significant increase in islet cell adenomas of the pancreas in Long-Evans rats which are very susceptible to the induction of pancreas islet tumors. The rats were exposed to two doses of 10 Gy each to the gastric region with a 3-day interval, and sacrificed after 80 weeks (not sufficient time to develop carcinomas). In a 2-year study conducted by Lafuma et al. [1989] to compare the induction of lung carcinomas in male Sprague–Dawley rats by exposure at low doses to radon daughters, fission neutrons or γ -rays, it was shown that 3.6% out of 505 rats exposed to 1 Gy γ -radiation developed lung carcinomas. This incidence (0.6%) is little higher than we found in our experiment on males exposed to 1 Gy of γ -radiation. In rats generally, apart from the carcinogenic effects observed in the mammary gland, there are very few qualitative and quantitative data on dose–response carcinogenic effects for use in risk assessment.

Upton et al. [1970] examined the development of neoplasms in large groups of male and female mice (more

TABLE IX. Hazard Ratios for Several Cancer Sites in Sexes Combined (M + F) Sprague–Dawley Rats

Group (Gy)	Animals ^a		Cancer sites ^b				
	Sex combined, no		Mammary adenocarcinoma	Zymbal glands	Thyroid C-cell carcinomas	Pancreas islet cell carcinomas	Hemangiosarcomas
	M	F					
I (0)	1051		Reference				
II (0.1)	1046		1.05	1.71*	1.30	4.33**	3.18*
III (1)	619		3.94**	1.11	1.17	11.34**	6.51*
IV (3)	416		19.4**	4.04**	7.93***	205**	73.5**

* $P \leq 0.05$.

** $P \leq 0.01$.

*** $P \leq 0.001$.

^aSix weeks old at the time of exposure.

^bCox regression with stratification on gender.

than 4,000 in all). Whole-body irradiation started at 10 weeks of age, after which the animals were observed for the lifespan. All animals were fully necropsied, but only selected lesions were examined histopathologically, as and when needed to confirm diagnoses. The dose ranged from 0.25 Gy to 4.5 Gy for acute X-radiation and from \sim 1 to 98.75 Gy for chronic Co60 γ -irradiation. An increased incidence of various neoplasms was observed even at the lowest dose. Specifically, an increased incidence of myeloid leukemia and thymic lymphoma was observed in males and females, and an increased incidence of ovarian tumors in females.

A highly comprehensive series of studies on the induction of tumors by γ radiation in mice was performed by Ullrich and Storer [1979a,b,c]. A total of more than 19,000 male and female RFM mice (plus almost 5,200 controls) were exposed to doses from 0.1 to 3 Gy. More than 5,600 female BALB/C mice (plus 865 controls) were exposed to a range of doses from 0.5 to 2 Gy. An increased dose-related incidence of myeloid leukemia and thymic lymphoma was observed in male and female RFM mice. A dose-dependent increased incidence in ovarian, pituitary and Harderian gland tumors was observed in female RFM mice. At 0.25 Gy the incidence of ovarian cancer was increased by almost three times. An increased incidence of ovarian tumors and lung and mammary carcinomas in BALB/C mice was observed even at the lowest dose. These studies, with its large groups of animals and dose range (0.1–3 Gy), afforded a more complete analysis of the dose–response in mice.

More recently Di Majo et al. [2003] published a summary of several studies conducted over several years on the carcinogenic effects of ionizing radiation in mice. The aim of this summary was to evaluate the effects of the dose–response at low doses (4, 8, 16, and 32 cGy) of 250 KVpX-rays. The small sample size ($n = 52$ –97) provided limited evidence for an increase in cancer risks, apart from a significant increase in ovarian tumors at 8, 16, and 32 cGy.

A large study on the effects of low-dose γ rays was conducted by Tanaka et al. [2007] using 4,000 mice exposed over 400 days to a total dose of 2, 40, and 800 cGy. Compared to the controls, the incidence of myeloid leukemias in males, the incidence of soft tissue neoplasms and malignant granulosa cell tumors in females, and the incidence of hemangiosarcomas in both sexes, were significantly increased at the highest dose.

Taken together, these major experiments on rats and mice and others available in the literature suffer from limitations that could lead one to query the capacity of lifespan rodent bioassays to show the carcinogenic effects of ionizing radiation at low doses.

For this reason we planned a project with experimental groups of adequate size to evaluate the potential carcinogenic effects in rats at low doses of exposure, as well as the dose–response relationship.

In the present study, conducted on large groups of male and female Sprague–Dawley rats, exposed at 6 weeks of age to three different dose levels (0.1, 1, or 3 Gy) delivered in a single acute exposure, we found: (a) a significant dose-related increased incidence of males and females bearing malignant tumors in the groups exposed to 1 and 3 Gy; (b) in animals exposed to 3 Gy, we observed a specific significant increase in the incidences of skin cancers (males and females), subcutis liposarcomas (males), breast adenocarcinomas and sarcomas (males and females), Zymbal gland carcinomas (females), ear duct carcinomas (females), nasal cavity carcinomas (males), thyroid follicular cell carcinomas (males and females), hepatocellular carcinomas (males and females), pancreas islet cell carcinomas (males and females); kidney adenocarcinomas (males), cortical adrenal gland adenocarcinomas (females), hemangiosarcomas (all sites) (males and females), hemolymphoreticular neoplasias (males and females); (c) a significant increased incidence of breast adenocarcinomas and breast sarcomas (in males and females), hepatocellular carcinomas (males and females), pancreas islet cell carcinomas (males and females), cortical adrenal gland adenocarcinomas (females), and hemangiosarcomas (all sites) (in males) was also observed at the exposure of 1 Gy; (d) a significant increased incidence of Zymbal gland carcinomas (males), pancreas islet cell carcinomas (females) was also observed at 0.1 Gy. Concerning the significant increased incidence of carcinomas of the Zymbal glands and of the pancreas islet cell at 0.1 Gy, it is unlikely that these findings are due to chance if we consider that: (1) these malignant tumors are very rare among the historical control of our Sprague–Dawley rat colony; (2) the differences in absolute number between treated versus control groups is remarkable; (3) except for Zymbal gland carcinomas, which are significantly increased in males only at 0.1 Gy

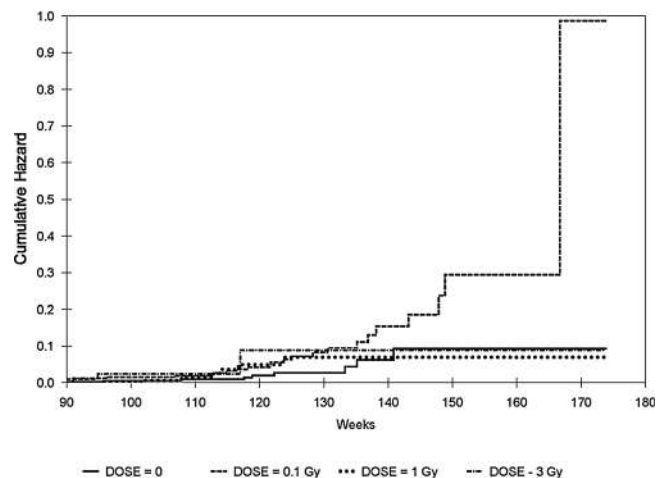


FIGURE 6. Cumulative hazard for Kaplan–Meier estimation: Zymbal glands carcinoma in male Sprague–Dawley rats.

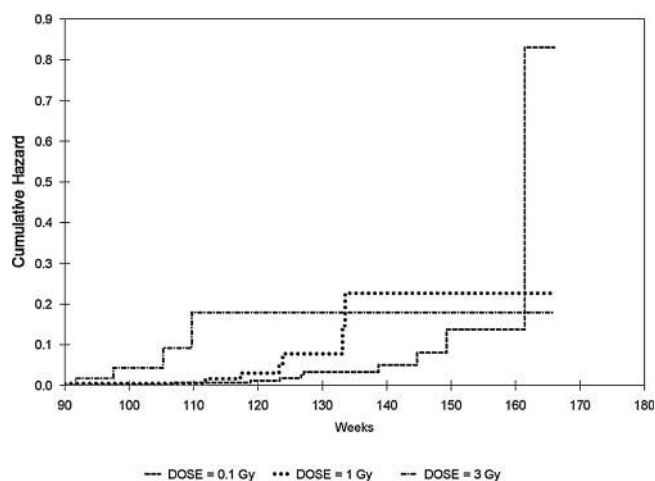


FIGURE 7. Cumulative hazard for Kaplan–Meier estimation: pancreatic islet cell carcinoma in female Sprague–Dawley rats.

(but with a significant dose-related relationship), islet cell carcinomas of the pancreas in females was in turn significantly increased at 1 and 3 Gy, with a significant dose-related relationship, as shown also by the cumulative hazard for Kaplan–Meier Estimation (Figs. 6 and 7).

Concerning the carcinogenic effects of exposures to 1 Gy, the results from the studies on A-bomb survivors showed that the relative risk for solid cancer mortality is about 1.4 [Ozasa et al., 2012] instead of 2 which is observed in Table VIII of this study. This relative risk of 1.4 is for an individual exposed at age 30 years. If the exposure were for an individual aged 10–15 years, then the relative risk would also be about 2, as we found for young exposed Sprague–Dawley rats. It is also interesting to note that in this study lymphoma and leukemia dose-response is resulted to be purely quadratic. The same has been observed for acute myeloid leukemia (the most common) among A-bomb survivors [Hsu et al., 2013].

CONCLUSIONS

Taken together, the experiments on rats available in the literature suffer from limitations depending on the dose levels, number of animals per group and duration of the studies.

For this reason we planned a project with experimental groups of adequate size to evaluate the potential carcinogenic effects in rats at low doses of exposure, as well as the dose-response relationship.

With this experiment we have shown that acute exposure to γ radiation causes a significant increase in the incidence of a few types of tumors in males and females at the dose of 0.1 Gy. These results confirm that our Sprague–Dawley rat colony is suitable to identify and quantify carcinogenic risks. They also show that large-scale experiments produce important new quantitative results, particularly in the area of low exposure. However, since the animals were randomized by breeders and since all the experimental groups include all the offspring of each litter, it may be possible to evaluate the synergism between familiar susceptibility and γ radiation exposure at the lowest dose.

The results call for attention to various human scenarios of low radiation exposure. Thus, one can hardly underestimate the fact that the dose to tissues absorbed from a whole body CT scan typically in the range of 0.05–0.1 Gy and this must be weighed all the more seriously if those examined are children or adolescents [Brenner, 2010].

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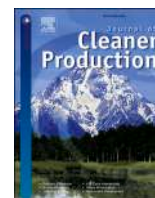
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Environmental assessment of multiple “cleaner electricity mix” scenarios within just energy and circular economy transitions, in Italy and Europe

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ABSTRACT

The current European context, affected by the dramatic conflict between Russia and Ukraine and the related energy and food shortages, is putting a strain on the natural gas availability of the European member states. The latter are forced to new negotiations with other potential energy suppliers, to urgent internal measures to reduce energy demand and, at the same time, to fulfil their commitments to internationally agreed climate targets, where the energy transition is a key strategy. A sustainable energy transition strategy is also essential in circular economy implementation (CE), requiring the replacement of fossil energies with renewable ones. In turn, the energy transition should meet the CE principles to reduce the consumption of natural resources and the contribution to climate change. In this context, this study assesses the environmental impacts of the Italian and EU electricity mixes under different governmental and research scenarios and perspectives, by means of the Life Cycle Assessment approach (Midpoint and Endpoint LCA). Results show that the shift from the BAU electricity mix (year 2021) to the emergency Government plan scenario (2021–2023) replacing 14% of Russian natural gas by means of 42% oil and coal and 58% renewables slightly reduces the contribution to Midpoint LCA impact indicators, including global warming and fossil resource scarcity, while still contributing to particulate matter formation, terrestrial acidification, eco-toxicity and water consumption. The contribution to global warming further decreases in the other modelled scenarios, where natural gas is assumed to decrease from 30% to a high 60% in favour of renewables (Governmental plan 2030 scenario). Other impacts, in particular terrestrial and human toxicity, are instead expected to worsen, calling for much needed improvement of renewable technologies. Further, the Endpoint LCA impact indicators, expressed as DALY (human health damage), lost species potential (biodiversity damage) and increased costs for the extraction of mineral and fossil resources, improve in the Governmental Plan 2030 scenario and other modelled options. LCA shows to be a key method for the energy transition, in order to identify hotspots of modelled electricity scenarios and suggest more environmentally, circular and socially just improvement solutions. The adoption of the concept of CE in energy transition entails the expansion of the boundaries of an LCA to include the end-of-life of renewable technologies (so-called “cradle to cradle” approach) and the assessment of the most successful options to mitigate the environmental and social impacts of energy transition.

1. Introduction

The start of the war between Russia and Ukraine has roiled all the world for its dramatic consequences on population and the environment (Smit et al., 2022). Moreover, the effects on energy markets have been very high as prices of natural gas have recorded higher values than ever in the last decade contributing in turn to record-high wholesale electricity prices (Tollefson, 2022).

The conflict has forced many European Union (EU) countries including Italy to reconsider their suppliers of energy beyond Russia as well as adopting urgent measures in order to meet the domestic demand of natural gas (European Commission, 2022a, b) and energy in general. Overall, the EU imported before the conflict about 40% of natural gas from Russia, but some member States had a even much higher dependence, as they imported their natural gas purchases 100% from Russia (Tollefson, 2022). Furthermore, what is perhaps even more troubling, is

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that ultimately, the conflict is also challenging the efforts of EU member states in their decarbonization path and commitments towards the climate goals (Dennison, 2022; Gatto, 2022; Pastore et al., 2022).

1.1. The EU energy policy context

In order to create a basis for energy policies, the so-called “European Union taxonomy” was proposed by the European Commission, which classifies certain fossil gas and nuclear energy processes as transitional activities useful to contribute to the EU climate goals. This taxonomy will become effective as of 1 January 2023 if both the European Parliament and the Council will finally approve it (European Parliament, 2022a).

If the scope of the energy problem is expanded to the entire European Union, an increasing awareness of the importance of the adoption of energy savings measures appears evident. For example, the French Government evidenced that “*the only way to avoid a crisis is to substantially reduce energy consumption for the next six months. Every business will be required to have an “energy sobriety” plan in place to cut consumption by this fall*”.¹

1.2. The Italian energy situation

In Italy, natural gas has a 38.5% share of gross domestic energy consumption, compared with the 35.5% of oil and 17.3% of renewables (Italian Ministry of Environment and Protection of Territory and Sea et al., 2021). Natural gas is almost entirely imported from abroad, since the domestic production is very low (3.34 billion cubic meters) compared to the demand (76.1 billion cubic meters). In the year 2020, Italian primary energy demand was 166.2 Mtoe (IEA, 2022) compared with about 107.5 Mtoe of final energy uses. Out of these final uses, electricity (from fossil fuels and renewables) was about 24 Mtoe, namely 22.32% of total final uses. Electricity production and consumption will be the main focus of the present study, to gradually replace electricity imports as well as production from fossil powered plants, mainly natural gas (IEA, 2022).

After the start of the conflict between Russia and Ukraine, the Italian Ministry for the Ecological Transition adopted a “National Plan for the containment of natural gas consumption” (Ministry of Ecological Transition, 2022) where the most urgent measures needed to cover the national stocks of natural gas for the country are summarised. Such measures aim to achieve the following goals: ensure a high level of filling of the stocks for the winter 2022–2023 as well as quickly diversify the supply of imported natural gas. In that, the Italian Government plans also aims to: a) widen the natural gas infrastructures by means of a new regasifier (still to be located and put in action); b) substitution of about 30 billion of natural gas from Russia by means of a diversification with other suppliers (25 billion cubic meters), c) further development of renewable sources along with the adoption of energy efficiency measures (5 billion cubic meters).

The Plan also promotes measures related to responsible and smart behaviours of citizens to decrease the consumption of natural gas and electricity. These measures include dissemination campaigns to suggest a set of virtuous behaviours by citizens, that could have immediate benefits in the reduction of the demand of natural gas and related

¹ The behaviors that the Government is promoting are about the reduction of the temperature and duration of showers, the use for winter heating of electric heat pumps used for summer air conditioning, lowering of the fire after boiling and the reduction of the oven ignition time, the use of a fully loaded dishwasher and washing machine, the disconnection of the powering of washing machine when not are not in use, the shutdown or insertion of the low-power function of the refrigerator when households are in vacation, the avoidance of the “stand by” mode for the TV, decoder, DVD, the reduction of the hours of switching on the bulbs.

economic costs, also contributing to the decarbonization policies.²

1.3. Planning just energy and circular economy transitions

The circular economy (CE) transition is a non-negligible challenge for the energy sector (Janik et al., 2020), strictly connected to the Green Deal and the EU climate goals (Pastore et al., 2022), via the promotion of a better use of natural resources and their diversification (Ghisellini et al., 2021). The CE transition integrates the renewable energy transition, considered as a necessary and useful step to promote more sustainable, resilient (Mulvaney et al., 2021; Ghisellini and Ulgiati, 2020) and hopefully just (Levenda et al., 2021; United Nations, Goal 7 Affordable and Clean Energy, 2022) economies and societies. Some scholars point out that the global crises of ecological degradation and social injustice are strictly interrelated and underline the importance to critically examine the values and narratives of the current economic and social systems and affirm the moral necessity of a socially just approach to the ecological crisis (Solomonian and Di Ruggiero, 2021; Carley and Konisky, 2020). In this regard, the innovative “doughnut economy” concept developed by Kate Raworth (2017) calls for a much needed “safe and just space for humanity”. Political leaders in the EU are also increasingly aware of the need for addressing the theme of environmental and social justice in energy (European Commission, 2021a) and CE transitions (European Commission, 2021b), in an attempt to ensure that the changes generated by both transitions in all the sub-systems of the society (cultural, legislative-political, economic-productive, technical-technological) are just for all the social groups and implemented through participative approaches without discriminations (Gebeyehu et al., 2019).

1.4. Goals and novelty of this research

The goal of this study is the assessment of energy costs and LCA environmental impacts of a real “Plan of the Italian Government” to face the present worldwide gas-shortage after the Russia-Ukraine war and the “Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions”, with reference to the total electricity generated per year. As a comparison, we also evaluated the environmental impacts of selected scenarios modelled by the Lappeenranta-Lahti University of Technology and Green European Free Alliance³ for Italy and EU countries (Ram et al., 2022). Evaluating Italian plans and EU level scenarios allows to focus on options that take into account the actual EU mixes and the existing (economic, political, technological) constraints that affect the viability of scenarios beyond theoretical and good will proposals, which most often disregard aspects that are not easy to overcome in a short time. One of the novelties of this study is applying the LCA and its well-known methodological framework in this situation of emergence in evaluating the environmental performances of the Italian Governmental scenario and its evolution to 2030 and comparing them with other research scenarios aligned with the European decarbonization targets. To the best of our knowledge, there are not LCA studies that performed this assessment for which we also think there is an academic and Governmental need of building assessment frameworks useful to face this situation but at the same time do not disregard the existing and urgent environmental and social challenges.

This study also considers and compares two different approaches to the electricity production and related environmental impacts.

² Green European Free Alliance is a political group in the European Parliament that aims to make Europe a global leader in environmental protection, peace and social justice, fair globalisation, protection of human rights, available at: <https://www.greens-efa.eu/en/who-we-are> (last accessed: 13/12/2022).

³ <https://www.gse.it/servizi-per-te/news/fotovoltai-co-pubblicato-il-rapporto-statistico-gse-2021>.

- (i) Assessment of energy cost and LCA environmental impacts of electric productions from single sources (e.g.: natural gas, nuclear, wind, etc, see Table 3, based on literature studies), in order to explicitly ascertain their energy efficiency (electric output/cumulative energy input) and the midpoint & endpoint impact efficiency, per unit of electricity generated (kWh). This single source assessment allows to identify the strengths (e.g.: less GHG emissions, less non-renewable energy input) and weaknesses (e.g.: more ionizing radiations, more toxicity) of each energy production technology, on the basis of a multidimensional set of indicators, in order to suggest potential improvements within the specific production pattern itself (e.g.: improving plant technology, using recycled materials, recycle waste heat into the plant itself, etc);
- (ii) Assessment of energy costs and LCA environmental impacts of BAU energy mix in Italy and for a set of virtual scenarios where fractions of BAU production mix are replaced by equivalent fractions of a different production source, in order to evidence the fraction of energy and environmental benefits achievable (and additional costs, if any) through replacement. In so doing, focus on mix changes allows to compare replacement solutions based on their real LCA benefits, without disregarding costs, and finally compare the virtual scenarios to the BAU energy mix, per unit of electricity generated (kWh). This answers to most often suggested single-benefit “solutions” (e.g., less GHG or country’s energy dependence upon abroad imports), by identifying a multi-dimensional performance of each proposed energy mix and the potential consequences of energy policy changes. This is one of the novelties of this study compared to the existing literature.

A further novelty, compared to the literature, is the inclusion in the research context of the LCA of the just energy and CE frameworks as briefly presented in sub-section 1.3. Therefore, the results of the LCA will be interpreted and discussed in the lights of these two frameworks.

As a consequence, this study is organised as follows: Section 2. Materials and Methods analyses the previous literature, the goal of the present research and its novelty in terms of contribution to fill the current research gaps as well as the LCA approach. In particular, Sub-section 2.1 provides a short overview of the literature, while sub-section 2.2 provides information about the annual electricity generated in the year 2021 in Italy and the share of each fuel used for such electricity (BAU, Business as Usual). Subsection 2.3 describes the features and assumptions of the alternative scenarios to the BAU current scenario (year 2021). Each scenario is based on a set of fuels that contribute to the generation of the two functional units selected for the present LCA: 1 kWh and total annual electricity.

In particular, the following two types of alternative scenarios to the BAU are evaluated.

- **Governmental Scenarios** based on the adopted Italian Government Plan for the years 2021–2023 (replacement by 14% of electricity from natural gas by means of renewables, coal and oil) and its projection to the year 2030;
- **Proposed Research-based Scenarios** with 30% of electricity from natural gas replacement by means of renewables, nuclear and energy efficiency measures, assuming the same electricity production as in the year 2021. As mentioned above, scenarios for Italy and the EU (referring to the years 2030, 2035, 2040) developed by the Lappeenranta-Lahti University of Technology (LUT) were also evaluated, all characterized by higher annual electricity generated and higher share of renewables.

All the modelled scenarios are structured as described in sub-section 2.4, while Subsection 2.5 provides details about the LCA approach. Section 3. Results presents the results in terms of environmental impacts in each Midpoint and Endpoint impact categories, according to the

RECIPE 2016 Impact Assessment method. Results are then discussed in detail in Section 4. Discussion. Subsection 4.1 analyses and compares the environmental performances of the different scenarios and whenever possible some results are compared with the available literature. In subsection 4.2, results are discussed taking into account their implications to the just energy and circular economy frameworks while Section 5. Conclusions and Policy Implications summarizes the main general achievements and the theoretical and practical implications of the study.

Table 1 presents the list of acronyms used throughout this study and their meaning.

2. Materials and methods

The sub-section 2.1 provides a short overview of literature about LCA use to study energy and circular economy transitions. The following subsections 2.2, 2.3 and 2.4 describe the data used for the evaluation of the current electricity production in Italy and other Italian and EU scenarios. Finally, sub-section 2.5 deals with the main stages and features of the LCA approach applied to the present study. LCA performances (efficiency and impacts) of one-source electricity generation processes (to be used for mix scenario calculations) are shown in Table 3.

Fig. 1 summarizes the flows of information and data used as Materials and the stages of the LCA (Methods section) and achieved results in terms of Midpoint and Endpoint Indicators, reflecting environmental and social impacts generated by the analysed Italian and European electricity mix scenarios.

2.1. A short literature overview of life cycle assessment use for the evaluation of environmental sustainability of energy and circular economy transitions

The LCA approach has been widely used to evaluate the environmental sustainability of electricity mixes of countries worldwide (Gargiulo et al., 2020; Murphy and Raugei, 2020; Ramirez et al., 2020; Raugei et al., 2020; San Miguel and Cerrato, 2020; Carvahlo et al., 2022; Meng and Asuka, 2022) contributing to measure quantitatively and according to a holistic approach their environmental soundness in the whole life cycle of electricity generation, also preventing environmental burden shifts from one stage to another (Ramirez et al., 2020). LCA is an essential tool, of course not the only one, to evaluate on a scientific basis (avoiding greenwashing) the transition to CE in production sectors (including electricity) and the successful adoption of its principles in the economy and society (Mannan and Al-Ghamdi, 2021; Barros et al., 2020; Longo et al., 2020; Ncube et al., 2021). The CE model redefines the concept of value of products starting from process design to the end-of-life of products, with the feedback of materials and components to a new production cycle, through a deep analysis of the environmental, economic and social sustainability of products (Mannan and Al-Ghamdi, 2021). Gargiulo et al. (2020) suggest the need for adequate LCA

Table 1
Acronyms and their full terms.

CE	Circular Economy
EU	European Union
LCA	Life Cycle Assessment
BAU	Business As Usual
S-LCA	Social Life Cycle Assessment
DALY	Disability Adjusted Life Years
LUT	Lappeenranta-Lahti University of Technology
GHGs	Greenhouse Gases (emissions)
INECP	Integrated National Energy Climate Plan of Italy (to the year 2030)
EUREF	European Union Reference (Scenario) 2016 for energy, transport and GHGs emissions with trends to 2050.
PV	Photovoltaic (Solar)
GWP	Global Warming Potential
LFI	Life Cycle Inventory
IEA	International Energy Agency

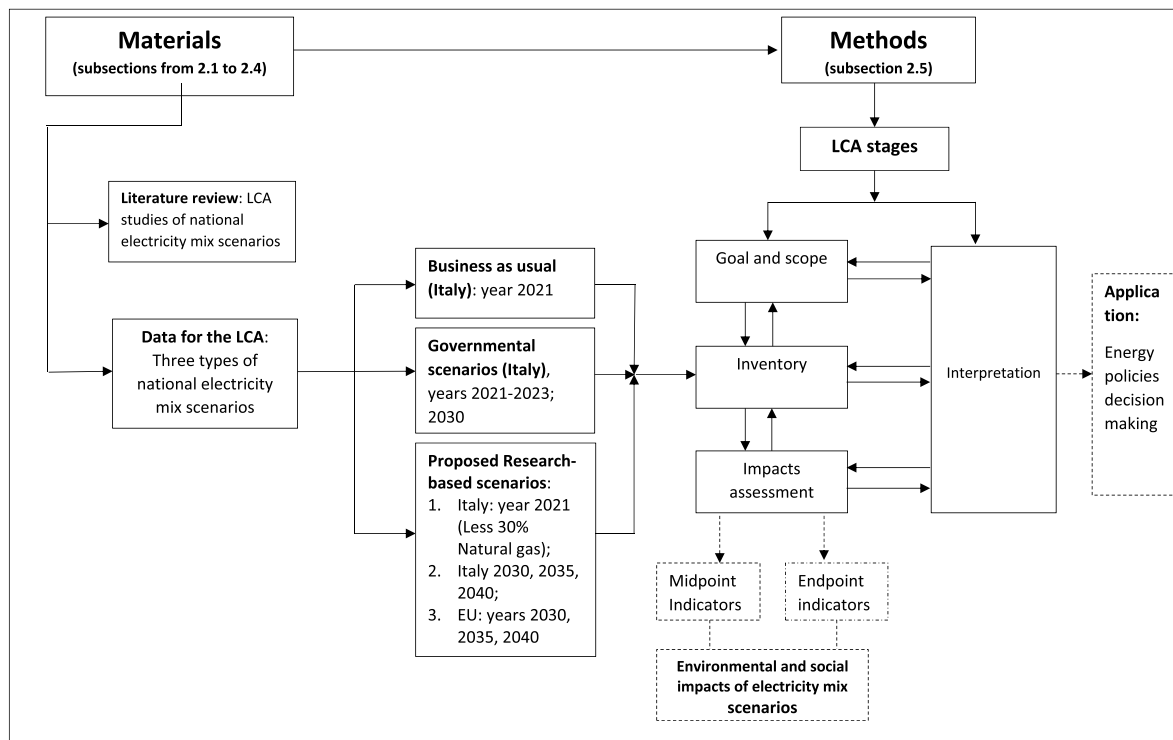


Fig. 1. Overview of the main content and stages of the materials and method sections of the present study.

accounting of the recycling scenarios in energy transition technologies, such as PV modules, in order to reduce the burdens on mineral resource depletion as well as improve the inventory data of their life cycle.

The LCA importance as a suggested key method for the assessment of environmental impacts of products or services in European legislations and policies increased over time since the first regulations (Sala et al., 2021), until recently with the development of the CE and the adoption of the Circular Economy Action Plan (European Commission, 2020). It is rather remarkable that one of the first applications is the Ecolabel Regulation where the life cycle thinking concept and LCA approach were suggested as suitable impact assessment framework for awarding the Eco-Label to processes and products. By identifying the main hotspots (local, regional and global) in the life cycle of a product or a service (Sala et al., 2021), LCA facilitates the link with the environmental dimension of products or services and their social dimension (Ingrao et al., 2021). When used in combination with s-LCA (social life cycle assessment, Kaiser et al., 2022) LCA reinforces the comprehensiveness of the analysis and the robustness of results (Ramirez et al., 2020). Within the CE framework, the Ellen MacArthur Foundation (2022) suggests the use of LCA in support to the CE transition for particular cases, by taking into account its limitations (e.g., LCA ignores impacts that are difficult to measure or not yet well known, may have the limited scope of the specific investigated system, and depends on the quality of the data and the assumptions made). Main LCA results may be the highlighting of hotspots and areas of improvement, testing against external factors changes (e.g., changes in the energy mix), comparison of environmental performances of two different materials packaging choices, later stages of the development of innovations when good and less uncertain data become available.

Several articles in the international LCA literature assessed the decreasing environmental impacts of the transition to electricity mix scenarios consistent with decarbonization plan and targets (Table 2). Most studies evidence the reduction of GHGs emissions and water footprint (Meng and Asuka, 2022) as well as water availability, in particular in the case of relevant share of hydroelectricity (Ramirez et al., 2020), in so confirming the need to consider the energy-water

nexus in energy policies. Other factors (population growth, increasing/decreasing energy demand by society, climate change uncertainties, future scarcity of oil sources, lack of change in the lifestyle, etc.) are also relevant and could affect the future decarbonization patterns and performances (San Miguel and Cerrato, 2020; Ramirez et al., 2020) and in some cases more than offset in a negative way the final results of national energy policies, leading to an increase of the contribution to GWP (Ramirez et al., 2020). Ambitious political commitment towards renewables is a key factor for the success of future decarbonization scenarios (Murphy and Rauegi, 2020; San Miguel and Cerrato, 2020).

Rauegi et al. (2020) assess the environmental impacts of the so-called "Future Energy Scenario - 2°" that is one of the decarbonization pathways to the year 2050 for United Kingdom that foresees electricity generation capacities for all the grid mix technologies and the associated annual electricity generation over the next 30 years. Their results show the importance of the adoption of a life cycle approach for the identification of the sources with the most relevant impacts in the production of electricity as well as the LCA usefulness for improving their environmental performances or alternatively encourage their replacement with other sources. Finally, concerning the share of nuclear in the mix, the authors point out that the continued and even increased share expected after 2030 poses challenges in the energy transition of UK increasing its energy dependence from abroad, given that UK lacks of domestic uranium ores.

With regard to Italy, two recent LCA studies (Gargiulo et al., 2020; Carvahlo et al., 2022) analysed the evolution of the energy mixes and impacts of the electricity Italian mix from baseline scenarios to 2030 scenarios. Gargiulo et al. (2020) point out that the generation of 1 kWh of electricity in the 2030 scenarios (base 2030, INECP 2030 and EUREF 2030) shows a reduction of the environmental impacts in all the selected impact categories with the lowest environmental impacts in the 2030 INECP scenario for almost all the impact categories. The contribution to climate change from the current scenario 2016 to the 2030 INECP scenario decreases by 46%. The results, show a decrease of ionizing radiation impacts in both 2030 scenarios (2030 BASE and 2030 INECP)

Table 2
Recent Life cycle assessment studies published in the international literature.

Author/s	Method/s	Goal of the study	Country	Further results	Functional Unit
Carvahlo et al., 2022	LCA	Comparison of the evolution of the environmental impacts of the Italian electricity mix from 2018 to 2030 with that of other European countries: Belgium, Denmark, Finland, France, Germany, Portugal and Spain.	Italy	<ul style="list-style-type: none"> • Average reduction of 42% of the impacts to climate change in European Union countries investigated; • Adoption of INECP scenario for Italy should reduce by 50% the impacts to Climate Change performing similarly well as France and Portugal. 	1 kWh of Gross National Consumption of electricity plus the net electricity foreign exchange (imports of electricity minus exports of electricity).
Meng and Asuka, 2022	Hybrid LCA	Evaluation of the impacts on carbon emissions and water consumption of the energy transition in Japan under the Sixth Strategic Energy Plan to 2030 compared to the year 2015.	Japan	<ul style="list-style-type: none"> • The energy transition will reduce the carbon emissions and increase the water consumption; • Decrease of acceptance of nuclear power after Fukushima accident; • The transition to 100% renewable electricity in Japan is possible. 	Total electricity generated
Gargiulo et al. (2020)	LCA	Evaluation of the environmental impacts of two current scenarios (years 2016 and 2017) and three scenarios at 2030 (2030 Base, 2030 EU reference scenario for Italy and 2030 INECP (Italian Integrated National Energy and Climate Plan).	Italy	<ul style="list-style-type: none"> • Reduction of the environmental impacts in all the selected impact categories for the generation of 1 kWh of electricity in the three 2030 scenarios; • 2030 INECP has the lower impacts than the other scenarios except for mineral, fossil & renewable resources depletion, due to the increase of solar PV share; • Normalized values of ionizing radiation and climate change decrease from the current scenario (2016) to the 2030 scenario, while the normalized values of mineral, fossil & renewable resources depletion increase from about 0.10 to about 0.18 in the 2030 INECP scenario. 	1 kWh of Gross National Consumption of electricity plus the net foreign exchange (imports of electricity minus exports of electricity).
Murphy and Raugei (2020)	LCA and Net Energy Analysis	Evaluation of the changes in net energy, life cycle energy and GHGs emissions of electricity generated in New York due to the energy transition. Calculation of the following indicators: EROI and net-to-gross energy ratios, CED and GWP. Clen Energy standard of New York set the target 70% renewable energies generation by 2030 and 100% by 2040.	US (New York)	<ul style="list-style-type: none"> • The achievement of a grid mix as per the target of 70% of electricity from renewables will strongly reduce the GHGs emission per kWh; • Renewable technologies have a lower CED than conventional thermal technologies (steam turbines, combined cycles and nuclear reactors). 	1 kWh of electricity generated by the grid mix.
Ramirez et al. (2020)	LCA	Assessment of Environmental impacts of electricity generation from year 2012–2018 and forecasting electricity scenarios from 2020 to 2050.	Ecuador	<ul style="list-style-type: none"> • Hydropower (and in particular run-on-river) has very low impact compared to electricity from fossils. Increasing hydro share in the mix strongly reduces the impacts; • The evolution of the impacts depends on the share of electricity from hydro; • The expected increase of the electricity demand to 2050 will more than offset the efforts in increasing the share of renewables in the electricity mix; • Water-energy nexus should be taken into account due to climate change effects on water availability for hydro; • Many factors beyond decarbonization affects the transition to sustainability. 	1 kWh of net electricity supplied to final consumers.
Raugei et al. (2020)	Net energy and LCA	Assessment of the environmental and energy impacts of energy transition scenarios for the UK and analysis of the evolution of the environmental impacts as well as the net energy delivery in the shift from the current United Kingdom grid mix (year 2019) to a future mix in the so-called UK National Grid's "2°" scenario (years 2035 and 2050).	United Kingdom	<ul style="list-style-type: none"> • The study further confirms that the UK National Grid's "2°" mix is effective for decarbonizing UK electricity even if not to the extent projected; • Biogas and biogas showed a low return on energy investment. Biogas and biomass show a high contribution for the generation of 1 kWh of electricity to acidification potential compared to the other sources; • Large-scale development of renewable energy generation (wind, solar PV, tidal) entails some trade-offs in terms of depletion of metal resources and toxicity potential impacts. 	1 kWh of electricity delivered by the UK grid, inclusive of energy storage and transmission.

(continued on next page)

Table 2 (continued)

Author/s	Method/s	Goal of the study	Country	Further results	Functional Unit
San Miguel and Cerrato, 2020	LCA, Levelized cost of electricity and direct life cycle employment generation (direct number of jobs)	Analysis of the evolution of sustainability of Spain's electricity system from 1990 to 2015 and future projections (2030 and 2050). The future scenarios consider the goals of the Spanish Renewable Energy Action Plan 2020, the European 2030 Climate and Energy Framework and the European 2050 long-term strategy. Analysed scenario are: current situation (2015) and four scenarios for the years 2030, 2050 (decarbonization, current policies, accelerated technology advance, stagnation).	Spain	<ul style="list-style-type: none"> The results are analysed across three time periods: 1990–2000: strong increase in the impacts from the electricity system in most of the environmental categories (CC, FDP, OLDP, TAP, HTP, PSP) due to economic growth and increase of energy demand and dependence on fossil sources in the mix; 2000–2008: less rapid increase of electricity demand mainly met by natural gas while the share of coal reduced, the effects of the change on economic costs and employment are low; 2008–2016: strong economic crises coupled with ambitious public strategies promoting the development of renewables. The factors lead to a reduction of GHG per kWh, a small increase of generations costs and a high increase of employment; The analysis of the future projected three scenarios (in particular in the year 2050) that have a higher share of renewables show a reduction of GHGs emissions per kWh, higher employment rates and lower economic costs. 	1 MWh; Cost (MM €); Number of Jobs

Table 3
LCA Midpoint impacts per 1 kWh of the production of electricity from different sources.

ReCiPe Midpoint (H) 2016	Reference unit/ kWh	Oil plant	Average Nuclear Plant ^a	Average Nat-GAS ^b	Average PV Plant ^c	Hard Coal	Hydro	Wind onshore	Geothermal
Fine particulate matter formation	kg PM2.5 eq	2.37E-03	4.77E-05	5.61E-04	1.59E-04	1.81E-03	1.07E-03	5.53E-05	1.57E-04
Fossil resource scarcity	kg oil eq	2.81E-01	4.04E-03	2.60E-01	1.67E-02	2.26E-01	2.69E-01	6.45E-03	1.76E-02
Freshwater ecotoxicity	kg 1,4-DCB	1.80E-03	1.17E-03	1.93E-03	1.75E-02	1.29E-02	7.41E-03	1.95E-02	2.42E-03
Freshwater eutrophication	kg P eq	1.56E-05	6.11E-06	2.86E-05	5.48E-05	4.16E-04	1.36E-04	1.55E-05	1.43E-05
Global warming	kg CO2 eq	9.02E-01	1.62E-02	6.84E-01	6.57E-02	1.14E+00	9.01E-01	2.58E-02	6.27E-02
Human carcinogenic toxicity	kg 1,4-DCB	4.36E-03	2.22E-03	3.94E-03	6.06E-03	2.60E-02	1.15E-02	8.47E-03	7.59E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	6.32E-02	3.10E-02	5.20E-02	2.47E-01	3.91E-01	1.63E-01	8.63E-02	5.68E-02
Ionizing radiation	kBq Co-60 eq	1.44E-02	1.17E+00	1.23E-02	1.02E-02	8.25E-03	1.45E-01	1.87E-03	2.76E-03
Land use	m2a crop eq	4.26E-04	1.47E-04	2.68E-04	3.90E-04	5.79E-03	1.78E-03	9.12E-04	2.69E-04
Marine ecotoxicity	kg 1,4-DCB	4.82E-03	1.72E-03	2.86E-03	2.30E-02	1.80E-02	1.04E-02	2.39E-02	3.23E-03
Marine eutrophication	kg N eq	5.00E-05	8.14E-06	1.76E-05	5.34E-05	4.45E-05	1.64E-03	1.06E-05	6.89E-06
Mineral resource scarcity	kg Cu eq	4.02E-04	8.84E-04	4.44E-04	1.37E-03	3.75E-04	1.42E-03	1.48E-03	1.62E-03
Ozone formation, Human health	kg NOx eq	2.86E-03	5.05E-05	1.03E-03	1.74E-04	2.20E-03	1.54E-03	7.58E-05	4.48E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.90E-03	5.15E-05	1.08E-03	1.81E-04	2.20E-03	1.57E-03	7.88E-05	4.57E-04
Stratospheric ozone depletion	kg CFC11 eq	6.21E-07	4.13E-08	3.26E-07	3.63E-08	2.77E-07	4.92E-07	1.08E-08	7.05E-08
Terrestrial acidification	kg SO2 eq	7.67E-03	8.08E-05	1.67E-03	4.04E-04	5.29E-03	3.08E-03	1.19E-04	3.09E-04
Terrestrial ecotoxicity	kg 1,4-DCB	3.13E+00	3.24E-01	1.13E-01	1.43E+00	3.25E-01	6.46E-01	2.44E-01	1.35E-01
Water consumption	m3	2.30E-03	3.13E-03	1.05E-03	1.84E-03	1.88E-03	6.30E-03	3.29E-04	1.32E-02

^a Average values from BWR-CH, BWR-IN, BWR-RU, PWR-CH, PWR-FR, PWR-RoW.

^b Average values from Nat Gas-IT Conventional Power Plant, Nat Gas-RoW Conventional Power Plant and Nat Gas-RoW Comb Cycles Power Plant.

^c Average values from PV-IT 570kWp open ground multi S; PV-RoW, 3kWp flat roof multi S; PV-RoW 3kWp slanted roof multi S.

compared to the baseline 2016 scenario, due to the reduction of the imports of electricity from countries that produce electricity from nuclear source. The normalized LCA results also show that ionizing radiations, climate change and mineral, fossil & renewable resources depletion are the most affected environmental impact categories within the electricity mix of Italy.

Carvahlo et al. (2022) evaluated the environmental impacts of two scenarios (current, year 2018 and future, year 2030) for Italy and some European countries: Belgium, Denmark, Finland, France, Germany, Portugal and Spain modelled on the basis of EUREF and INECP for Italy and EUREF for the other European countries.

The results of the energy mixes evolution from 2018 to 2030 shows that there is a small foreseen increase of the electricity consumed in the year 2030 with all countries widening their share of electricity from wind while nuclear increases only in Finland and decreases its share in Belgium and Germany in favour of natural gas due to the phase-out of some nuclear plants. Coal remains stable only in Germany and decreases in the other countries. The results of the LCA impact assessment are consistent with the decarbonization path of the seven EU countries. From 2018 to 2030, Climate change worsens only in Belgium following the expected phase out of nuclear plants, while mineral, fossil & renewable resource depletion impact category increases in all countries due to the consumption of resources for nuclear, wind and solar plants and the imports of nuclear and wind electricity.

2.2. Current electricity mix scenario

The data of the current scenario (business as usual, BAU) have been retrieved from the database by TERNA (that is the main operator in Italy for the transmission of electricity in the country) and refer to the net electricity production of Italy in the year 2021, amounting to 280,045.2 GWh. The latter has been added to the net foreign exchange equal to 42,793 GWh in the year 2021 to obtain a total electricity generation of 322,838 GWh (TERNA, 2021a, b). Fig. 2 shows the net electricity production by type of fuel in the year 2021 and in the first group of assumed alternative scenarios (of course, total yearly production is not the same in all scenarios, depending on the assumption). In the BAU scenario, natural gas had the highest share in the net production of electricity of the year 2021 (44.3% of total electricity) while hydro (19.5%), solar PV (8%), wind (7.1%), hard coal (4.4%), other solid fuels (5.1%), other gaseous fuels (2.3%), geothermal (1.7%), other sources (0.2%).

The electricity demand of the country in 2021 has been met by 86.6% with national production and the rest (13.6%) by means of imports of electricity from other countries (France, Switzerland, Slovenia, Montenegro, Greece and Austria) (TERNA, 2021a, b). At the end of the year 2021, the electricity produced from renewables amounted to 115 TWh with solar PV contributing with a share of about 22%, following hydro which is the main renewable source at 39% (GSE, 2022).⁴

Concerning wind energy, in the year 2021 Italy installed about 0.3 GW of new plants reaching a total capacity of 11.1 GW. Compared to some European countries Italy still performs worse in terms of wind power and installed capacity. In the same year, UK added a new capacity by 2.6 GW and Sweden increased by 2.2 GW.⁵ At worldwide level the new installations have increased by 13% in the year 2021 compared to the year 2020. Just as a comparison, although considering the different size and population, China added a new capacity from wind by 55.8 GW achieving a total of 344 GW at the end of the year 2021 (World Wind

⁴ Germany installed a new wind capacity by 1,7 GW (total wind capacity is 64 GW), France by 1,1 GW (total capacity is 19 GW), Denmark by 0,9 GW (total capacity is 7,1 GW), Spain by 0,7 GW (total capacity is 28,1 GW) while Greece installed 0.3 GW.

⁵ European Platform on Life Cycle Assessment, Life Cycle Assessment, available online at: <https://eplca.jrc.ec.europa.eu/lifecycleassessment.html> (last accessed: 29/12/2022).

Energy Association, 2022).

2.3. Governmental and proposed research-based electricity mix scenarios less dependent on natural gas

Besides the business-as-usual scenario (year 2021), the present study considers a further scenario modelled on the basis of the data of the electricity mix of the year 2021 and the measures of the “National Plan for the containment of natural gas consumption” (Ministry of Ecological Transition, 2022). The Plan of the Italian Government suggests the substitution of 2.1 cubic meters of natural gas in the period 1 August 2022–31 March 2023 for the production of electricity with other conventional fuels such as coal, oil and bioliquids. The Plan also forecasts an increase of the capacity of production of electricity from renewables (solar PV and wind) equal to 8 GW from 2023 onwards. The production of electricity with conventional fuels and the additional renewable power from 2023 (8 GW) should replace about 14.2% of the total amount of electricity produced from natural gas. For the sake of simplicity, we assumed a Government Plan scenario for the year 2023 based on the data of the total electricity generation (322,838 GWh) of the year 2021, with a reduction of 14.2% of electricity from natural gas and its substitution with coal, oil and renewables.

We also investigated further research-based scenarios where we assumed a replacement by 30% of the amount of electricity from natural gas with (i) only wind, (ii) only solar PV, (iii) only nuclear, (iv) only energy savings measures and finally (v) a scenario where these four options replace 30% of electricity from natural gas. The scenarios are more advanced in terms of natural gas substitution and allow to appreciate the environmental contribution due to the replacement of each one of the sources with natural gas. Moreover, one of these scenarios evaluates the environmental impacts due to the possible introduction of nuclear source in the electricity mix. Fig. 2 shows the electricity mix of Italy in all these described scenarios on the basis of the data of the year 2021. The total amount of electricity generated in scenarios 1, 2, 3 is the same as the BAU scenario and that of Government Plan (322,838 GWh). In scenario 4 the total amount of electricity is 280,159 GWh (due to the proposed substitution by 30% of electricity from natural gas with energy efficiency measures) while in scenario 5 is 312,168 GWh as 30% of electricity from natural gas is replaced by increasing the share of wind, solar PV, nuclear and energy efficiency measures of the same amount.

2.4. Governmental and proposed research-based scenarios for the years 2030, 2035 and 2040

The present study also modelled the scenario for the year 2030 of the “National Plan for the containment of natural gas consumption” of the Italian Government on basis of the BAU scenario described in the previous section. We assumed a constant net electricity production equal to the year 2021 (322,838.2 GWh) and the development of renewable energies of 8 GW per year from 2023 to 2030. This would add a new renewable capacity of 64 GW in the year 2030 distributed between solar PV (51.2 GW) and wind (12.8 GW). In the year 2030, a yearly electricity production from solar PV of 71,680 GWh and from wind of 22,211.76 GWh should be achieved on the basis of the current development of such two sources.

As a comparison, we also evaluated three proposed research-based scenarios both for Italy and EU (years 2030, 2035, 2040) modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). In these scenarios, solar PV and wind are considered the main sources for the production of electricity as can be seen from Fig. 3 both for Italy and EU.

The construction of new nuclear plants is not considered in all the scenarios due to high costs and long times that are not competitive to those of renewable sources. However, for the EU, the contribution of nuclear to the production of electricity remains until the phasing out of

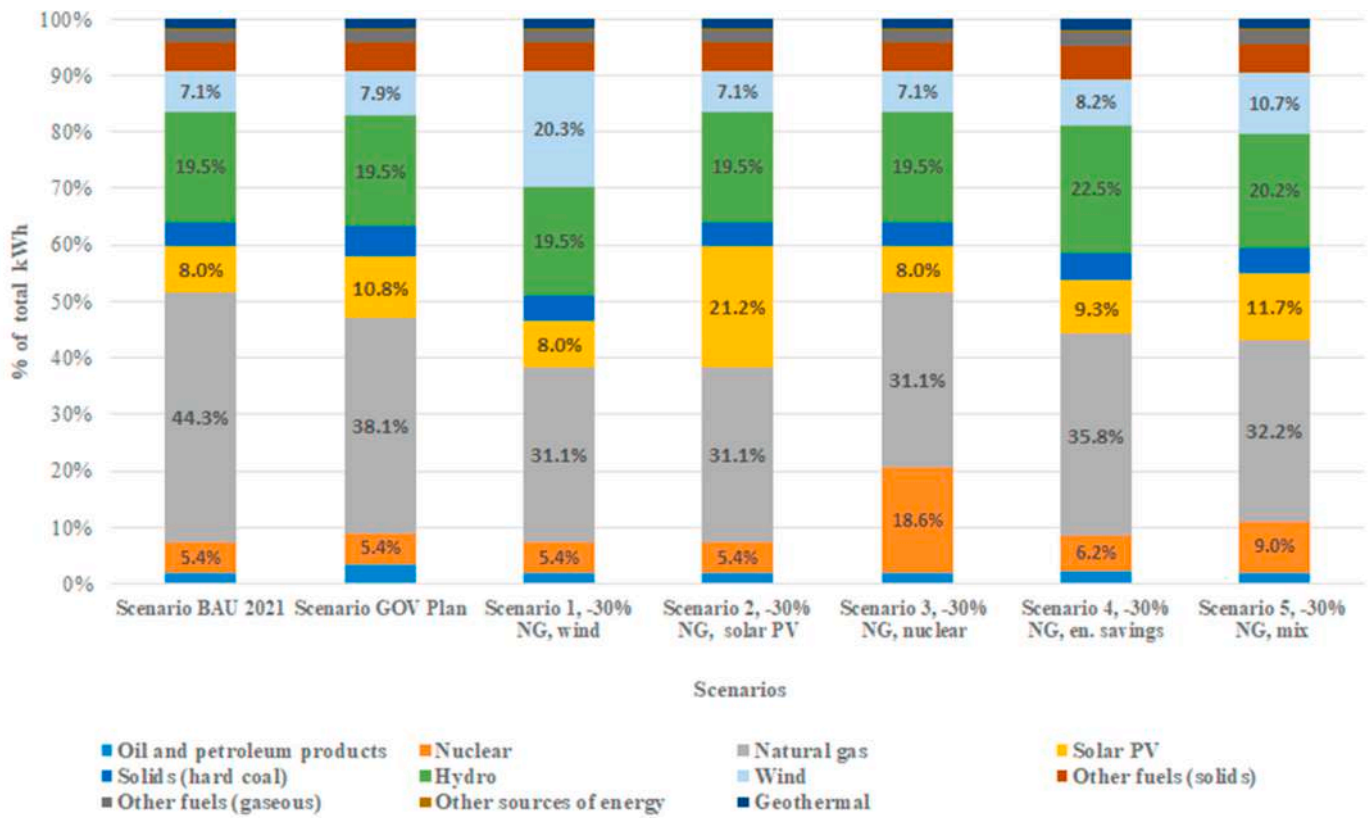


Fig. 2. Net electricity production by fuel in the BAU scenario, GOV Plan scenario and five proposed research-based scenarios. Elaboration of the authors with data by TERNA, 2021c. In BAU and GOV Plan scenarios and scenario 1, 2, 3 the total electricity generated is 322, 838 GWh. In scenario 4 the total electricity generated is 280,159 GWh while in scenario 5 the total electricity generated is 312,168 GWh.

the existing plants. These scenarios also characterize themselves for a high increase of electricity generation compared to the current BAU scenarios both for Italy (322.84 TWh) (TERNA, 2021a,b) and the whole EU (2664 TWh) (EUROSTAT, 2020). At the year 2030 the expected electricity generation for Italy would almost double achieving 432.39 TWh (scenario Italy 2030) and increasing to 694.13 TWh in the year 2035 (scenario Italy 2035) and reducing to 478.64 TWh in the year 2040 (scenario Italy 2040). About the EU, projected electricity generation to 2030 is 3746.1 TWh (scenario EU 2030), while 6361.52 in the year 2035 (scenario EU 2035) and 4237.71 TWh (scenario EU 2040) in the year 2040.

These scenarios, hereafter defined as “smarter”, align with the decarbonization goals of the EU to the year 2050 that aim to reduce the amount of Greenhouse Gas Emission by 80–100% compared to 1990 levels (European Union, 2021). In turn, these scenarios for Italy, are also in line with the “Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions” (hereinafter the Strategy) that is the proposed plan for decarbonization paths for Italy in order to reach, by 2050, the so-called “climate neutrality” (Ministry of Environment, Protection of Territory and the Sea et al., 2021). The latter is a condition of balance between emitting carbon and absorbing carbon from the atmosphere in carbon sinks with net GHGs emissions equal to zero that are counterbalanced by carbon sequestrations sources (European Parliament, 2022b). The Strategy takes as a reference the Integrated National Plan for Energy and Climate adopted to achieve the first step in the decarbonization path for Italy for the period 2021–2030. This plan has identified specific goals about the growth of renewable sources (30% in final consumption), the improvement of energy efficiency (−43% compared to the trend scenario) and the reduction of GHGs in the “Emission Trading System” and “non-Emission Trading System” sectors (respectively at least −43% and −33% compared to the amount of the

year 2005).

Finally, the Strategy also evidences that the emissions in terms of CO₂/kWh and CO₂ eq/kWh reduced over time by 40% compared to the year 2005 thanks to the contribution of renewables in the electricity mix. These latter have grown from 20 GW to 55 GW in the period 2004–2018 with a strong increase in particular from the year 2010 onwards. The projections to the year 2050 expect a radical transformation of the electricity system that would further expand its share in the whole energy consumption of the country, due to the use of electric energy for the production of hydrogen and electric fuels, the generation of heat without CO₂ emissions, the application of advanced system for direct capture of CO₂ from the atmosphere. In order to meet the decarbonization goals the Strategy expects an increase to the year 2050 of the electricity demand of about 650 TWh. In the year 2050, the electricity generation should almost be entirely sourced by renewables with a minimal share from natural gas integrated by capture and storage systems of CO₂. A high contribution is expected by solar PV power that should rise of about ten times the current levels while wind will grow up to 40–50 GW and geothermal, wave and tidal energy will contribute more than the current levels.

2.5. The life cycle assessment approach

Life cycle assessment, also called environmental LCA, is a well-known methodology regulated by the standards ISO 14040:2006/AmD 1:2020) that allows the quantification of the potential environmental impacts of a product, process, activities in all the life cycle stages from raw materials extraction to end of life including the reintroduction of the materials/components into a new production/consumption cycle (Muralikrishna and Manickam, 2017).

The LCA has been applied through its main four stages: goal and

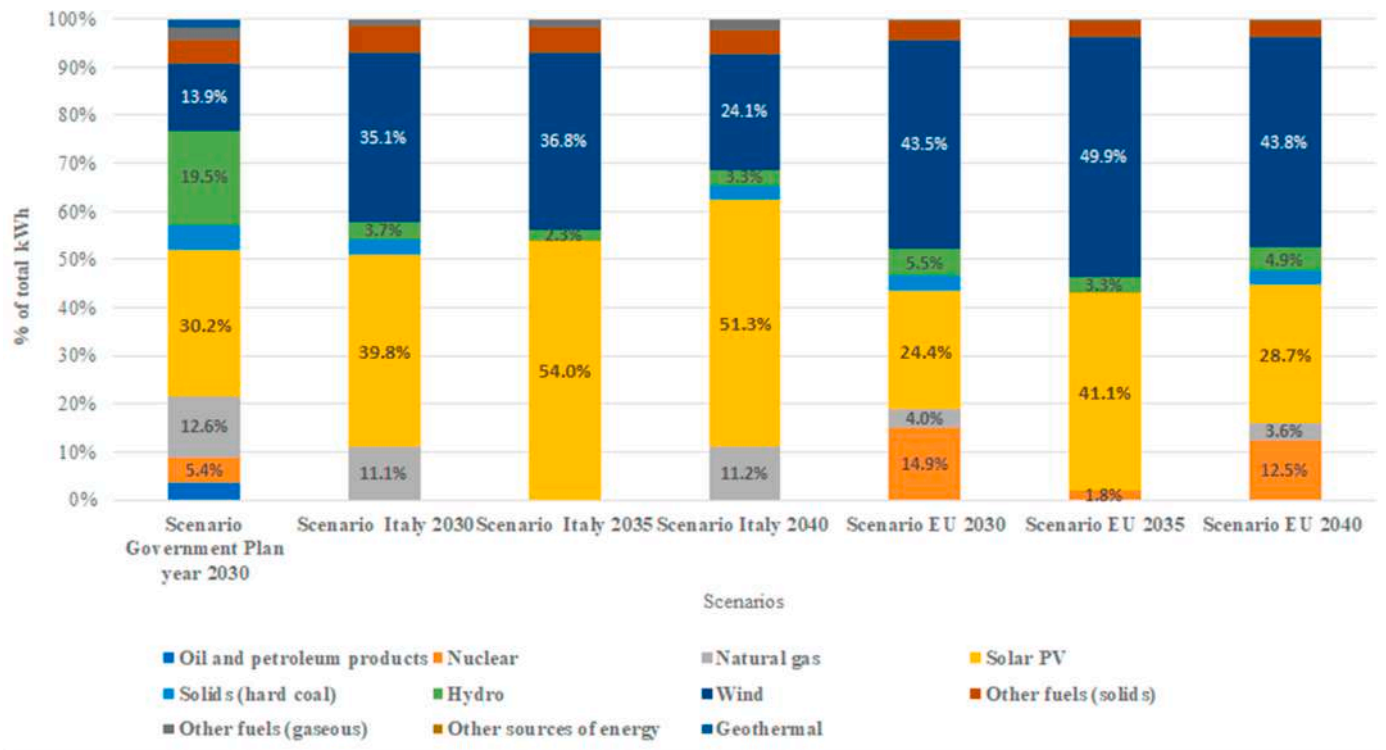


Fig. 3. Electricity generation by fuel in the Government Plan in the year 2030 and in proposed research-based scenarios for Italy and European Union modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). In the 2030 Government Plan scenario the total electricity generated is 322, 838 GWh. In the Italy 2030 scenario the total electricity amounts to 432, 403 GWh while in the scenarios Italy 2035 and Italy 2040 it is 694,126 GWh and 478,656 GWh respectively. In the EU 2030 scenario the total electricity produced is 3,746,112 GWh while in the EU 2035 and EU 2040 scenarios it is 6,361,536 GWh and 4,237,654 GWh respectively.

scope, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation (Fig. 1). These latter are described next in the light of the characteristics of the present study.

2.5.1. Goal and scope

This stage is fundamental in an LCA study, to clearly define goals, motivations, the intended application of results and the recipients to which the results will be communicated. The choices related to these aspects strongly affect the whole study and its level of detail in terms of boundaries of the system and processes to be included within such boundaries.⁶ This is why the Fig. 1 shows that some of the stages of the LCA (inventory, impacts assessment and interpretation) are highly interdependent with the first stage. This LCA has the following main goals.

- Evaluation and comparison of the potential environmental impacts of the different electricity production mix scenarios for Italy summarised in the previous sub-sections 2.2 and 2.3 as well as comparison with selected EU smarter electricity scenarios (sub-section 2.4);
- Identification of the potential environmental costs and benefits of each scenario;
- Evaluation and interpretation of the results of this study on the basis of a just energy and circular economy transition frameworks;

The results of this LCA are expected to provide useful scientific data in support of stakeholders and policy makers decisions, within the energy sector, the Italian Government and European Commission.

The functional units are, depending on the case, the production of 1

kWh of net electricity and the total net electricity use (kWh) in the year 2021 in Italy, also including the net foreign exchange in the same year. The scope includes boundaries, the present debate about different energy policy options, as well as the European energy mix and imports from outside Europe.

The system boundaries of this LCA are cradle to grave for the different electricity generation systems (thermoelectric, nuclear and renewable) and include raw materials extraction and fuels supply, construction and plant operation, end-of-life disposal for thermoelectric plants, hydroelectric, solar PV and wind power plants. About electricity from nuclear energy the end-of-life stage does not include the environmental impacts of the disposal of radioactive waste in temporary and final repositories (sometimes only including transport and storage site preparation). This is because in general the low and medium radioactive waste is stored in proximity of the power plant itself, while the highly radioactive waste is treated for different purposes (including military) and partially returned to temporary repositories (Ulgiati and Ghisellini, 2013). Actually, a permanent nuclear waste repository does not exist, after several failed options worldwide (Bell and Farlaine, 2022; O’Leary, 2022).

2.5.2. Life cycle inventory (LCI)

The second LCA stage accounts for the input and output flows of an investigated product-system from and to the natural environment. In the LCI, the input flows are about materials and energy extracted from the environment and then transformed in the system while outputs are the emissions and waste of the system released to the environment (Mohan, 2018).

This LCA uses primary data about the net electricity generation in Italy in the different scenarios (BAU, Government Plan, Scenarios 1 to 5 assuming a 30% reduction of electricity from natural gas), while secondary environmental data (that generally are previously published

⁶ LCIA: ReCiPe 2016 <https://www.rivm.nl/en/life-cycle-assessment-lca/recipe>.

data about the unit impacts generated by the processes) are derived from the Ecoinvent Database 3.1 (Table 3). The environmental data retrieved from the Ecoinvent Database 3.1 consider different type of plants (and reactors, in case of nuclear) for the production of electricity (thermal, nuclear and renewable), in order to represent all the types of available plants in Italy and abroad (e.g. imported nuclear electricity). Data from Table 3 provide a better picture of the performance (efficiency and impacts) of electricity production from each different source, in order to understand if a source is suitable to be part of the mix and what is its improvement potential. Table 3 reports the environmental data about the impacts of the production of 1 kWh, calculated as weighted averages of LCA midpoint impacts of individual sources from the Ecoinvent Database version 3.1 adjusted to the investigated countries. For example, in the case of nuclear electricity the weighted averages of LCA midpoint impacts derive from considering the individual midpoint impacts of six types of nuclear plants located in different areas (BWR-CH, BWR-IN, BWR-RU, PWR-CH, PWR-FR, PWR-RoW). The weighted average of LCA midpoint impacts related to each type of plant and source have been multiplied by the specific share in the electricity Italian or EU mixes in order to obtain the LCA impacts per FU: 1 kWh and total kWh produced annually. Here we report only Table 3 with the environmental data about the LCA midpoint impacts. We also collected the environmental data about the impacts of the production of 1 kWh from the Ecoinvent Database 3.1 and calculated the weighted averages of LCA endpoint impacts for each individual type of plant and source.

Secondary data have been also used for the electricity generation in Italy and EU to assess the impacts of 2030, 2035 and 2040 scenarios modelled by LUT University and Greens European Free Alliance (Ram et al., 2022). The associated environmental data have been retrieved from the Ecoinvent 3.1 Database.

For Biofuels and Biogas, the Ecoinvent database does not provide the impacts for these sources. Therefore, we have used the same impacts of fossil oil as conservative estimates.

2.5.3. Life cycle impact assessment and interpretation

In this stage, the secondary environmental data from the Ecoinvent Database 3.1 concerning the processes for the generation of electricity from the different types of fuels (natural gas, oil, coal, nuclear, wind, hydro, solar PV) have been elaborated by means of the software OpenLCA 1.10 (<https://www.openlca.org>) and the impact assessment methods Recipe Midpoint and Endpoint (H) 2016 in order to determine the contribution of each kWh and total country kWh produced from the different fuel types to the environmental impact categories. Fig. 4 shows the Midpoint impact categories considered in this study and their relation with the Endpoint impact categories. Midpoint impact categories are focused on single environmental impacts while Endpoint impact categories result from aggregating the environmental impacts within three areas of potential damage: damage to human health (unit of measure: DALY as Disability Adjusted Life Years (DALY) measuring the impact of premature death, disease or disability of population, due to environmental pollution; damage to ecosystems (unit of measure: Species richness lost per year) and damage to resource availability (unit of measure: US \$) as the increased costs due to the future extraction of minerals and fossil fuels.⁷ The secondary data from Ecoinvent Database 3.1 have been jointly processed with the primary data in order to obtain the environmental impacts of 1 kWh and total kWh produced on the basis of the Italian and EU electricity mix under the different scenarios. The results of the impact assessment stage are presented in the next Section 3 and interpreted and discussed in the light of the goal of this study in Section 4.

⁷ Disability Adjusted Life Years (DALY) quantifying the impact of premature death or disability that climate change has on the population.

3. Results

This study presents the results with reference to two Functional Units: 1 kWh of net electricity generated and total annual net electricity generated (total kWh) in Italy or EU. In the first case (1 kWh), the results point out the specific environmental performances (impact generation efficiency) of the investigated scenarios for electricity production, while, in the second case (total electricity), they help create a global relationship of each scenario with the size and characteristics of the system (namely population, economy, and surrounding environment as a whole), in order to understand if the system can afford the investigated electric production. Furthermore, some scenarios refer to the years 2021–2023 (BAU and Governmental) and others at 2030–2040 (Governmental and research scenarios), in order to ascertain how the energy situation in Italy could evolve over time, compared to that in Europe.

3.1. Environmental impacts per 1 kWh of net electricity generated

Table 4 shows the environmental impacts to the 18 midpoint impact categories generated by the production of 1 kWh of electricity in the seven scenarios for Italy 2021–2023, involving different shares of some fuels (natural gas, solar PV, wind) used for generating electricity in the mix. The scenarios are: business as usual (BAU, year 2021), the Governmental Plan scenario (year 2021–2023) decreasing by about 14% the electricity produced from natural gas, and five scenarios assuming a reduction of 30% of electricity from natural gas and its replacement by wind, solar PV, nuclear, energy savings measures and a mix of all these four options, as described in Fig. 1.

Table 4 indicates that the production of 1 kWh of electricity releases 0.62 kg CO₂ eq in the BAU scenario, not very different than 0.60 kg CO₂ eq expected in the Government Plan scenario. In the other scenarios (except scenario 4) the impacts to Global Warming are lower as 1 kWh generates 0.53 kg CO₂ eq (scenario 1 and 3), 0.54 kg CO₂ eq (scenario 2) and 0.55 kg CO₂ eq (scenario 5) respectively. With regard to the other impact categories, the contribution to terrestrial acidification worsens in the Government Plan scenario (2.30E-03 kg SO₂ eq/kWh) and Scenario 4 (2.30E-03 kg SO₂ eq/kWh) compared to the BAU scenario (2.22E-03 kg SO₂ eq/kWh), while it decreases in the others reaching the lower values in scenario 1 and 3 (2.01E-03 kg SO₂ eq/kWh). It is worth pointing out that the contribution to ionizing radiation in scenario 3 is the highest (0.25 kBq Co-60 eq/kWh) compared to the other scenarios (0.10 kBq Co-60 eq/kWh) including the BAU, the Government Plan, and scenarios 1 and 2.

The environmental impacts to the Endpoint impact categories of the analysed seven scenarios differ much for 1 kWh of net electricity produced shifting from the BAU and Government Plan scenarios to the others for the category DALY (Table 5) while in a lower extent for the other two categories (species*year and USD 2013). Scenario 3 resulted with the lower Endpoint impacts for the production of 1 kWh of electricity that affects human health by 9.72 E+07 DALY (Disability Adjusted Life Years) as well as species diversity by a potential 2.14E-09 Species*yr decrease and the economy by an increased cost equal to 5.82E-02 USD 2013.

Table 6 shows the midpoint impacts of the production of 1 kWh in the Government Plan 2030 scenario as well as in all the supposedly smarter scenarios for Italy and EU from 2030 to 2040. Overall, the impacts to many categories in the 2030 Government Plan scenario are higher than the other scenarios for Italy 2030 to 2040 as well as for the EU scenarios 2030 to 2040. Concerning the specific contribution to Global Warming, the 2030 Government Plan scenario releases 0.44 kg CO₂ eq/kWh while much less GHGs emissions are estimated in the smarter scenarios for Italy to 2030 (0.24 kg CO₂ eq/kWh), 2035 (0.12 kg CO₂ eq/kWh) and 2040 (0.24 kg CO₂ eq/kWh) as well as in EU 2030 (0.18 kg CO₂ eq/kWh), 2035 (0.10 kg CO₂ eq/kWh) and 2040 (0.16 kg CO₂ eq/kWh) scenarios. The ionizing radiation impacts are lower for

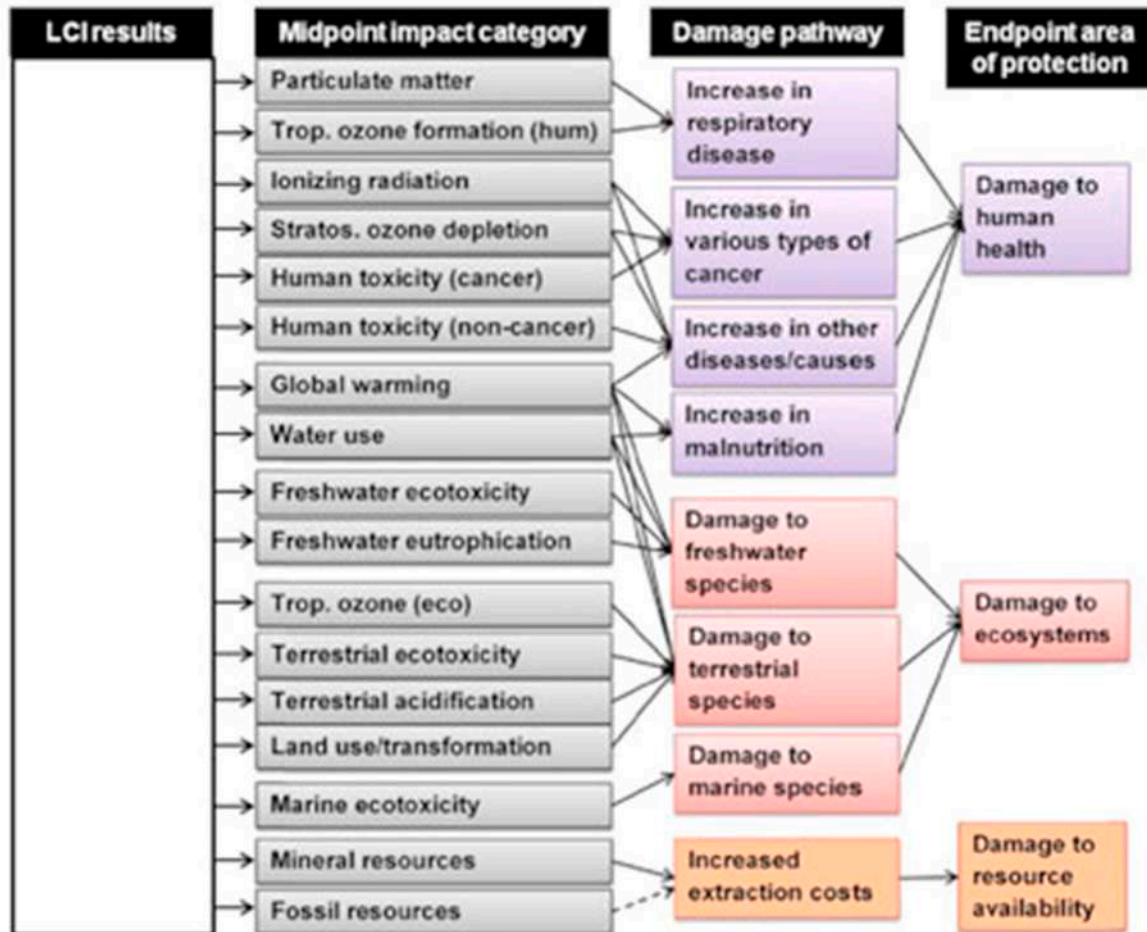


Fig. 4. Overview of the Midpoint impact categories and Endpoint Impact categories included in the Impact Assessment Method ReCiPe 2016. Source: <https://simapro.com/2017/updated-impact-assessment-methodology-recipe-2016/>.

Table 4
LCA characterized midpoint impacts associated to 1 kWh of net electricity generated in Italy according to different electricity mix assumptions.

ReCiPe Midpoint (H) 2016	Reference unit/kWh	Business as usual year 2021	Scenario GOV Plan less 14% NG, year 2021-2023	Scenario 1 Less 30% NG wind	Scenario 2 Less 30% NG solar PV	Scenario 3 Less 30% NG Nuclear	Scenario 4 Less 30% NG, en. sav.	Scenario 5 Less 30% and mix
Fine particulate matter formation	kg PM2.5 eq	7.44E-04	7.70E-04	6.77E-04	6.90E-04	6.76E-04	7.71E-04	7.01E-04
Fossil resource scarcity	kg oil eq	0.21	0.20	0.17	0.17	0.17	0.20	0.18
Freshwater ecotoxicity	kg 1,4-DCB	5.94E-03	6.64E-03	8.26E-03	8.00E-03	5.84E-03	6.55E-03	7.18E-03
Freshwater eutrophication	kg P eq	6.54E-05	6.98E-05	6.36E-05	6.88E-05	6.24E-05	7.10E-05	6.63E-05
Global warming	kg CO2 eq	0.62	0.60	0.53	0.54	0.53	0.61	0.55
Human carcinogenic toxicity	kg 1,4-DCB	6.87E-03	7.21E-03	7.47E-03	7.16E-03	6.65E-03	7.32E-03	7.14E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.07E-01	1.16E-01	1.11E-01	1.32E-01	1.04E-01	1.15E-01	1.16E-01
Ionizing radiation	kBq Co-60 eq	0.10	0.10	0.10	0.10	0.25	0.11	0.14
Land use	m2a crop eq	8.66E-04	9.35E-04	9.51E-04	8.82E-04	8.50E-04	9.57E-04	9.08E-04
Marine ecotoxicity	kg 1,4-DCB	8.18E-03	9.10E-03	1.10E-02	1.08E-02	8.03E-03	8.99E-03	9.72E-03
Marine eutrophication	kg N eq	3.40E-04	3.42E-04	3.39E-04	3.45E-04	3.39E-04	3.89E-04	3.52E-04
Mineral resource scarcity	kg Cu eq	8.21E-04	8.55E-04	9.59E-04	9.44E-04	8.80E-04	8.79E-04	9.16E-04
Ozone formation, Human health	kg NOx eq	1.12E-03	1.12E-03	9.89E-04	1.00E-03	9.86E-04	1.13E-03	1.02E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.15E-03	1.16E-03	1.02E-03	1.03E-03	1.01E-03	1.16E-03	1.05E-03
Stratospheric ozone depletion	kg CFC11 eq	3.12E-07	3.06E-07	2.71E-07	2.74E-07	2.75E-07	3.10E-07	2.81E-07
Terrestrial acidification	kg SO2 eq	2.22E-03	2.30E-03	2.01E-03	2.05E-03	2.01E-03	2.30E-03	2.09E-03
Terrestrial ecotoxicity	kg 1,4-DCB	0.57	0.66	0.59	0.74	0.60	0.64	0.64
Water consumption	m3	0.0025	0.0026	0.0024	0.0026	0.0028	0.0028	0.0027

Table 5
LCA endpoint impacts associated to 1 kWh of net electricity produced in Italy according to different electricity mix assumptions.

	Business as usual year 2021	Scenario Government Plan year 2021–2023	Scenario 1 Less 30% NG only wind	Scenario 2 Less 30% NG only PV solar	Scenario 3 Less 30% NG only Nuclear	Scenario 4 Less 30% NG only en. eff.	Scenario 5 Less 30% and mix
DALY	1.10E-06	1.10E-06	9.76E-07	9.94E-07	9.72E-07	1.11E-06	1.01E-06
Species*yr	2.45E-09	2.43E-09	2.15E-09	2.18E-09	2.14E-09	2.45E-09	2.22E-09
USD2013	7.01E-02	6.68E-02	5.83E-02	5.86E-02	5.82E-02	6.69E-02	6.03E-02

Italy than in the EU scenarios in the years 2030 and 2035 while they are a bit higher in the year 2040 (0.013 kBq Co-60 eq/kWh in the year 2040 versus 0.012 kBq Co-60 eq/kWh). The impacts of the EU Scenarios (2030, 2035 and 2040) are also lower than for Italy with regard to Terrestrial acidification, Terrestrial ecotoxicity, while they are higher for Land use.

Table 7 shows the endpoint impacts per 1 kWh of net electricity generated in the 2030 Government plan scenario and in the other estimated scenarios. The EU 2035 scenario resulted to be the one with the best environmental performances as the impacts to human health (2.93E-07 DALY/kWh), to species diversity (5.23E-10 species*year/kWh) and the economy (1.04E-02 USD, 2013/kWh) are lower than for the other scenarios.

3.2. Environmental impacts of the total annual electricity generated

When shifting from FU = 1 kWh to FU = total electricity production, it should be noted that the calculated impacts depend on the assumed total net yearly production. For the sake of clarity, a scenario that assumes a yearly doubling of electricity production will likely generate higher impacts in some categories than a scenario assuming 30% electricity savings thanks to increased use efficiency, also depending on the specific mix components. This makes comparison more difficult and

requires careful evaluation.

Results of the midpoint impacts related to the total electricity of the first group of scenarios are summarised in Table 8. They point out that the production of total electricity in the BAU scenario and the Government Plan scenario generate the highest impacts to the Global Warming, compared with the other scenarios. The global warming impacts in the two scenarios are 2.00E+11 kg CO2 eq/total kWh and 1.95E+11 kg CO2 eq/total kWh respectively while in the other scenarios ranges between 1.74 E+11 kg CO2 eq/total kWh (scenario 2) and 1.71E+11 kg CO2 eq/total kWh (scenarios 3 and 4). For the environmental category “ionizing radiation” the contribution of the scenario 3 (replacement of 30% of electricity from natural gas with nuclear fuel) is the highest, with 8.15E+10 kBq Co-60 eq/total kWh, while the lowest values can be found in the scenario 4, with a value of 3.16E+10 kBq Co-60 eq/total kWh, and the scenario 1 with 3.17E+10 kBq Co-60 eq/total kWh. Further, the Scenario 3 generates the highest contribution to the water consumption category: 9.07E+08 m³/total kWh, while scenario 1 and 4 generate the lowest environmental impacts: 7.88 E+08 m³ and 7.74 E+08 m³/total kWh. All in all, the scenario 4 is the best scenario for Italy 2021–2023, as it shows the lowest impacts compared to the others, for all categories. It is also interesting to note the worsening of the environmental performances shifting from the BAU scenario to the Government Plan scenario for several impact categories except fossil resource scarcity, Global

Table 6
LCA characterized impacts associated to 1 kWh of electricity produced in the smarter research scenarios.

ReCiPe Midpoint (H) 2016 Impact categories	Unit/kWh	Scenario GOV Plan 2030	Scenario Italy 2030	Scenario Italy 2035	Scenario Italy 2040	Scenario EU 2030	Scenario EU 2035	Scenario EU 2040
Fine particulate matter formation	kg PM2.5 eq	6.61E-04	3.83E-04	2.65E-04	3.76E-04	3.09E-04	2.13E-04	2.76E-04
Fossil resource scarcity	kg oil eq	0.13	0.07	0.04	0.07	0.05	0.03	0.05
Freshwater ecotoxicity	kg 1,4-DCB	1.07E-02	1.48E-02	1.69E-02	1.47E-02	1.39E-02	1.73E-02	1.44E-02
Freshwater eutrophication	kg P eq	7.41E-05	5.01E-05	3.97E-05	5.30E-05	4.39E-05	3.55E-05	4.27E-05
Global warming	kg CO2 eq	0.44	0.24	0.12	0.24	0.18	0.10	0.16
Human carcinogenic toxicity	kg 1,4-DCB	7.90E-03	7.38E-03	6.95E-03	7.03E-03	7.32E-03	7.31E-03	7.06E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.56E-01	1.57E-01	1.73E-01	1.74E-01	1.29E-01	1.53E-01	1.32E-01
Ionizing radiation	kBq Co-60 eq	0.098	0.013	0.010	0.013	0.187	0.032	0.012
Land use	m2a crop eq	9.97E-04	7.84E-04	6.14E-04	7.03E-04	8.29E-04	6.93E-04	7.89E-04
Marine ecotoxicity	kg 1,4-DCB	1.43E-02	1.91E-02	2.17E-02	1.90E-02	1.77E-02	2.19E-02	1.83E-02
Marine eutrophication	kg N eq	3.48E-04	9.16E-05	7.32E-05	9.04E-05	1.14E-04	8.35E-05	1.04E-04
Mineral resource scarcity	kg Cu eq	1.10E-03	1.21E-03	1.35E-03	1.20E-03	1.24E-03	1.38E-03	1.15E-03
Ozone formation, Human health	kg NOx eq	9.00E-04	5.13E-04	3.25E-04	5.03E-04	4.01E-04	2.64E-04	3.59E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.20E-04	5.27E-04	3.33E-04	5.17E-04	4.10E-04	2.71E-04	3.67E-04
Stratospheric ozone depletion	kg CFC11 eq	2.31E-07	1.21E-07	7.29E-08	1.20E-07	9.54E-08	5.99E-08	8.10E-08
Terrestrial acidification	kg SO2 eq	1.96E-03	1.12E-03	7.65E-04	1.10E-03	8.90E-04	6.00E-04	7.95E-04
Terrestrial ecotoxicity	kg 1,4-DCB	0.92	0.88	1.04	0.99	0.68	0.84	0.67
Water consumption	m3	0.0027	0.0014	0.0014	0.0015	0.0016	0.0013	0.0012

Table 7
LCA endpoint impacts associated to 1 kWh of electricity produced in the research smarter scenarios.

	Scenario GOV Plan year 2030	Scenario Italy 2030	Scenario Italy 2035	Scenario Italy 2040	Scenario EU 2030	Scenario EU 2035	Scenario EU 2040
DALY	8.97E-07	5.29E-07	3.48E-07	5.26E-07	4.11E-07	2.93E-07	3.92E-07
Species*yr	1.89E-09	1.06E-09	6.30E-10	1.06E-09	8.12E-10	5.23E-10	7.61E-10
USD2013	4.45E-02	2.50E-02	1.33E-02	2.48E-02	1.65E-02	1.04E-02	1.51E-02

Warming, ionizing radiation. Moreover, shifting from the BAU to scenario 1 some indicators show higher values: e.g. land use showing 3.07E+08 m²a crop eq/total kWh versus 2.80E+08 m²a crop eq/total kWh (BAU scenario), freshwater ecotoxicity that in scenario 1 achieves 2.67 E+09 kg 1,4-DCB and in scenario 2 achieves the value 2.58E+09 kg 1,4-DCB/total kWh versus the BAU scenario where the value is 1.92 E+09 kg 1,4-DCB/total kWh. In particular, with regard to Global Warming, a higher percent decrease of the Global Warming impact compared to the BAU scenario (Table 5) is calculated.

The contribution of the seven scenarios to the Endpoint impact categories is shown in Table 9. The Endpoint impacts are higher in the BAU (3.54 E+05 Daly; 7.91E+02 Species*yr; 2.26E+10 USD 2013), dominated by natural gas, while decrease in the other five scenarios where 30% natural gas is replaced by other options; however, these options also generate some impacts, although smaller, which explains the lower and different values in each scenario, reaching the best performance in the scenario 4 (3.10E+05 Daly; 6.86E+02 Species*yr; 1.87E+10 USD 2013), where no additional energy sources are foreseen.

Table 10 indicates the Midpoint impacts generated by the production of total net electricity in the 2030 Government plan scenario and in the smarter seven scenarios. These scenarios are characterized for much higher shares of electricity from renewables as shown in Fig. 3 and an increase of the amount of total electricity to 2030 and 2035 as underlined in the caption of Fig. 3.

The 2030 Government Plan scenario shows that e.g., for global warming (total electricity generated assumed to be constant from Government Plan, 2021–2023) the impacts decrease from 1.95E+11 kg CO₂ eq/total kWh to 1.44E+11 kg CO₂ eq/total kWh. The impacts are also

lower than for scenarios 1, 2 and 3 with less 30% natural gas group (Table 8). The analysis of the impacts of the smarter scenarios from 2030 to 2040 highlights that they decrease from 1.04 E+11 kg CO₂ eq/total kWh (Scenario Italy 2030) to 8.61E+10 kg CO₂ eq (Scenario 2035) and increase again to 1.15 E+11 kg CO₂ eq (Scenario Italy 2040).

The same path is shown in the EU scenarios where the impacts decrease for Global Warming from the EU scenario 2030 (6.84E+11 kg CO₂ eq/total kWh) to EU scenario 2035 (6.58 E+11 kg CO₂ eq/total kWh) and increase in the EU Scenario 2040 (7.04E+11 kg CO₂ eq/total kWh).

Table 11 summarizes the Endpoint impacts generated by the total electricity in the Governmental Plan to 2030 and in the smarter scenarios. It should be noted that, as in Table 9, results are not only affected by the mix of components sources but also by the different amounts of electricity produced.

4. Discussion

4.1. Evaluation and comparison of the potential environmental impacts of the different electricity production mix scenarios

Results show that the potential environmental impacts of the production of 1 kWh of electricity (or total electricity produced annually) in Italy (e.g., for global warming category), slightly decrease from the BaU scenarios to the Government plan scenario, that considers a reduction by 14% of electricity from natural gas and its replacement with coal, oil and renewables. However, also an increase of the contribution to terrestrial acidification and terrestrial ecotoxicity can be ascertained from BaU to

Table 8

LCA characterized midpoint impacts associated to the total annual electricity produced in the different mix scenarios (total kWh).

ReCiPe Midpoint (H) 2016	Unit	Business as usual year 2021	Scenario GOV Plan Less 14% NG	Scenario 1 Less 30% NG only wind	Scenario 2 Less 30% NG only PV solar	Scenario 3 Less 30% NG only Nuclear	Scenario 4 Less 30% NG only en. save	Scenario 5 Less 30% mix 4 options
Fine particulate matter formation	kg PM 2.5 eq	2.40E+08	2.49E+08	2.19E+08	2.23E+08	2.18E+08	2.16E+08	2.19E+08
Fossil resource scarcity	kg oil eq	6.67E+10	6.38E+10	5.59E+10	5.63E+10	5.58E+10	5.56E+10	5.59E+10
Freshwater ecotoxicity	kg 1,4-DCB	1.92E+09	2.14E+09	2.67E+09	2.58E+09	1.89E+09	1.84E+09	2.24E+09
Freshwater eutrophication	kg P eq	2.11E+07	2.26E+07	2.06E+07	2.22E+07	2.02E+07	1.99E+07	2.07E+07
Global warming	kg CO2 eq	2.00E+11	1.95E+11	1.72E+11	1.74E+11	1.71E+11	1.71E+11	1.72E+11
Human carcinogenic toxicity	kg 1,4-DCB	2.22E+09	2.33E+09	2.41E+09	2.31E+09	2.15E+09	2.05E+09	2.23E+09
Human non-carcinogenic toxicity	kg 1,4-DCB	3.44E+10	3.75E+10	3.59E+10	4.28E+10	3.35E+10	3.22E+10	3.61E+10
Ionizing radiation	kBq Co-60 eq	3.21E+10	3.20E+10	3.17E+10	3.20E+10	8.15E+10	3.16E+10	4.42E+10
Land use	m ² a crop eq	2.80E+08	3.02E+08	3.07E+08	2.85E+08	2.74E+08	2.68E+08	2.84E+08
Marine ecotoxicity	kg 1,4-DCB	2.64E+09	2.94E+09	3.54E+09	3.50E+09	2.59E+09	2.52E+09	3.04E+09
Marine eutrophication	kg N eq	1.10E+08	1.10E+08	1.10E+08	1.11E+08	1.09E+08	1.09E+08	1.10E+08
Mineral resource scarcity	kg Cu eq	2.65E+08	2.76E+08	3.10E+08	3.05E+08	2.84E+08	2.46E+08	2.86E+08
Ozone formation, Human health	kg NOx eq	3.61E+08	3.63E+08	3.20E+08	3.24E+08	3.19E+08	3.16E+08	3.20E+08
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.71E+08	3.73E+08	3.28E+08	3.33E+08	3.27E+08	3.25E+08	3.28E+08
Stratospheric ozone depletion	kg CFC11 eq	1.01E+05	9.88E+04	8.74E+04	8.85E+04	8.87E+04	8.70E+04	8.79E+04
Terrestrial acidification	kg SO2 eq	7.17E+08	7.44E+08	6.50E+08	6.62E+08	6.49E+08	6.45E+08	6.52E+08
Terrestrial ecotoxicity	kg 1,4-DCB	1.85E+11	2.13E+11	1.90E+11	2.41E+11	1.94E+11	1.80E+11	2.01E+11
Water consumption	m ³	8.19E+08	8.33E+08	7.88E+08	8.52E+08	9.07E+08	7.74E+08	8.30E+08

Table 9

LCA endpoint impacts associated to the total annual electricity produced in the different mix scenarios (total kWh).

	Business as usual (year 2021)	Scenario Government Plan less 14% NG	Scenario 1 Less 30% NG only wind	Scenario 2 Less 30% NG only PV solar	Scenario 3 Less 30% NG only Nuclear	Scenario 4 Less 30% NG only en. eff.	Scenario 5 Less 30% and mix
DALY	3.54E+05	3.56E+05	3.15E+05	3.21E+05	3.14E+05	3.10E+05	3.15E+05
Species*yr	7.91E+02	7.85E+02	6.93E+02	7.03E+02	6.91E+02	6.86E+02	6.93E+02
USD2013	2.26E+10	2.16E+10	1.88E+10	1.89E+10	1.88E+10	1.87E+10	1.88E+10

Governmental scenario. This is a well-known trade-off due to the development of solar energy, where the construction and decommissioning of PV modules involves the use of smaller amounts of higher toxicity chemicals (Karkour et al., 2020; Cusenza et al., 2020). However, the research in the field is looking at promising less impacting materials and technologies (e.g. perovskite solar cells, Jung and Park, 2014, Grätzel and Milić, 2019; Cali et al., 2022 and algae solar cells, LIFE SUNALGAE, 2022 and Greenfluidics, 2022). Moreover, solar PV materials have a low turnover time and their impacts could be reduced by designing PV panels for recycling and longer durability (Cali et al., 2022).

A much stronger reduction of Global Warming can be appreciated in the other scenarios (Table 4) where less 30% of electricity is generated from natural gas and is substituted with wind, solar PV, nuclear, energy efficiency and a mix of all these sources (Figure A1, Appendix). Scenario 1 and Scenario 3 show the lowest impacts per 1 kWh to Global Warming and Terrestrial Acidification while scenario 3 evidences lower impacts in Freshwater and Terrestrial Ecotoxicity. On the other hand, Scenario 1

and Government plan scenario perform better than Scenario 3 with regard to Ionizing Radiations (0.10 kBq Co-60/kWh eq versus 0.25kBq Co-60 eq/kWh in scenario 3) and Water Consumption (0.0024 m³/kWh versus 0.0028 m³/kWh). These aspects should be taken into account in Italy where some political leaders and stakeholders in energy sector support a possible return to nuclear energy. Nuclear scenarios are unlikely to be a solution to the current and medium period natural gas emergence due to the costs and time for the construction of nuclear plants (Rothwell, 2020; Ulgiati and Ghisellini, 2013) nor to climate goals, as showed in this study, given that other scenarios where solar PV or wind replace natural gas have similar Global warming performances but perform much better in the case of ionizing radiation and water consumption categories. It is worthwhile to remember that Italy is facing the worst drought of the last 70 years (Levantesi, 2020) of which the very low levels of water in the river Po (that is the most important river in Italy) is one of the symbols. The higher temperatures are causing a process of ‘Mediterraneanization’ to the river regime of Northern Italy where rivers increasingly become intermittent, as water can disappear from the

Table 10

LCA characterized midpoint impacts associated to the total electricity production (total kWh) in the Governmental plan 2030 scenario and in the smarter scenarios.

ReCiPe Midpoint (H) 2016 Impact categories	Unit/kWh	Scenario GOV Plan year 2030	Scenario Italy 2030	Scenario Italy 2035	Scenario Italy 2040	Scenario EU 2030	Scenario EU 2035	Scenario EU 2040
Fine particulate matter formation	kg PM2.5 eq	2.14E+08	1.66E+08	1.84E+08	1.80E+08	1.16E+09	1.36E+09	1.20E+09
Fossil resource scarcity	kg oil eq	4.36E+10	3.23E+10	2.54E+10	3.57E+10	1.96E+11	1.88E+11	2.01E+11
Freshwater ecotoxicity	kg 1,4-DCB	3.46E+09	6.42E+09	1.18E+10	7.01E+09	5.21E+10	1.10E+11	6.18E+10
Freshwater eutrophication	kg P eq	2.39E+07	2.16E+07	2.76E+07	2.54E+07	1.65E+08	2.26E+08	1.84E+08
Global warming	kg CO2 eq	1.44E+11	1.04E+11	8.61E+10	1.15E+11	6.84E+11	6.58E+11	7.04E+11
Human carcinogenic toxicity	kg 1,4-DCB	2.55E+09	3.19E+09	4.82E+09	3.36E+09	2.74E+10	4.65E+10	3.11E+10
Human non-carcinogenic toxicity	kg 1,4-DCB	5.04E+10	6.80E+10	1.20E+11	8.35E+10	4.84E+11	9.74E+11	5.76E+11
Ionizing radiation	kBq Co-60 eq	3.17E+10	5.48E+09	7.28E+09	6.27E+09	7.00E+11	2.04E+11	6.68E+11
Land use	m2a crop eq	3.22E+08	3.39E+08	4.26E+08	3.37E+08	3.11E+09	4.41E+09	3.42E+09
Marine ecotoxicity	kg 1,4-DCB	4.61E+09	8.26E+09	1.51E+10	9.10E+09	6.64E+10	1.39E+11	7.86E+10
Marine eutrophication	kg N eq	1.13E+08	3.96E+07	5.08E+07	4.33E+07	4.27E+08	5.31E+08	4.45E+08
Mineral resource scarcity	kg Cu eq	3.54E+08	5.23E+08	9.36E+08	5.74E+08	4.64E+09	8.80E+09	5.36E+09
Ozone formation, Human health	kg NOx eq	2.91E+08	2.22E+08	2.25E+08	2.41E+08	1.50E+09	1.68E+09	1.55E+09
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.97E+08	2.28E+08	2.31E+08	2.47E+08	1.53E+09	1.72E+09	1.58E+09
Stratospheric ozone depletion	kg CFC11 eq	7.45E+04	5.24E+04	5.06E+04	5.76E+04	3.57E+05	3.81E+05	3.65E+05
Terrestrial acidification	kg SO2 eq	6.34E+08	4.86E+08	5.31E+08	5.25E+08	3.33E+09	3.82E+09	3.41E+09
Terrestrial ecotoxicity	kg 1,4-DCB	2.98E+11	3.79E+11	7.24E+11	4.74E+11	2.55E+12	5.37E+12	3.00E+12
Water consumption	m3	8.69E+08	6.05E+08	9.69E+08	7.37E+08	6.02E+09	8.07E+09	6.53E+09

Table 11

Endpoint impacts of the total electricity produced (total kWh) in the Government plan 2030 scenario and in the smarter research scenarios.

	Scenario Government Plan year 2030	Scenario Reference Italy 2030	Scenario Italy 2035	Scenario Italy 2040	Scenario Reference EU 2030	Scenario EU 2035	Scenario EU 2040
DALY	2.90E+05	2.29E+05	2.42E+05	2.52E+05	1.58E+06	1.86E+06	1.66E+06
Species*yr	6.12E+02	4.60E+02	4.37E+02	5.05E+02	3.11E+03	3.33E+03	3.23E+03
USD2013	1.44E+10	1.08E+10	9.21E+09	1.19E+10	6.28E+10	6.64E+10	6.38E+10

riverbed for many months (Levantesi, 2020). Therefore, in the case of nuclear, the energy-water nexus should be taken into account in future political plans.

The improvement of the impacts to Global Warming from the Government plan scenario of 2021–2023 to the 2030 scenario (Figure A2, Appendix) should provide an incentive to the Government towards accelerating the development of renewable energies and replacing natural gas, coal and oil in the shortest possible time. It is rather meaningful what the Italian 2021 Nobel Prize winner Giorgio Parisi said in a recent interview, that it is easier to win the Nobel Prize than to install solar panels, due to the resistance of uninformed people and huge bureaucracy (La Repubblica, 2022).

In the smarter research scenarios for Italy to the years 2030, 2035 and 2040 the contribution to Global Warming per 1 kWh produced is about half of that in the scenarios with less 30% of electricity from natural gas (Figure A3, Appendix). The smarter scenarios assume a high share from renewables (from 75% to 90%) as also proposed in the Italian Long-Term Strategy for the Reduction of Greenhouse Gas Emissions that has been adopted to lead the country to the so-called “climate neutrality” (Ministry of Environment, protection of Territory and the Sea, 2021) and meet the goals of the European Green Deal. A decreasing trend can be also found for Terrestrial acidification while in the case of ionizing radiation the reduction is much stronger in the smarter research scenarios, as they did not include imported nuclear electricity nor the construction of new nuclear plants in Italy and Europe. Very interesting is the comparison of the Ionizing radiation indicator in the smarter scenarios of Italy and EU, where impacts of existing nuclear plants are

included until their phasing-out. The contribution in Italy is very low compared to EU, in particular in the scenarios of the years 2030 (0.013 kBq Co-60 eq/kWh versus 0.187 kBq Co-60 eq/kWh) and 2035 (0.010 kBq Co-60 eq/kWh versus 0.032 kBq Co-60 eq/kWh) while the impacts are similar for the year 2040 (0.013 kBq Co-60 eq/kWh versus 0.012 kBq Co-60 eq/kWh), presumably due to the phasing out of some existing plants.

Considering the smarter research scenarios for Italy generates an improvement of the impacts to the Fossil Resource Scarcity category per kWh produced, while there is a worsening to the Freshwater ecotoxicity due to the higher shares of solar PV and wind. In Table 6 it is possible to see that in the 2030 scenario of the Government Plan the production of 1 kWh releases 1.07E-02 kg 1,4-DCB, a Toxicity that is lower than the impacts of scenario Italy 2030 (1.48E-02 kg 1,4-DCB/kWh), Italy 2035 (1.69E-02 kg 1,4-DCB/kWh), and Italy 2040 (1.47E-02 kg 1,4-DCB/kWh).

The results of this study per kWh produced in Italy e.g. with regard to Global Warming category, are higher in the first group of seven scenarios compared to the previous literature (Carvalho et al., 2022; Gargiulo et al., 2020) discussed in section 2, while are similar in the case of the smarter scenarios. In Carvalho et al. (2022), the two evaluated scenarios for 2030 Italy the impact to Global Warming resulted 0.31 kg CO2 eq/kWh (EU-REF scenario for Italy) and 0.20 kg CO2 eq/kWh (Italy INECP scenario 2030). In Gargiulo et al. (2020) the contribution to Climate Change category was 0.226 kg CO2 eq/kWh in the INECP 2030 scenario, lower than the 2030 base scenario (0.357 kg CO2 eq/kWh) and the 2030 EU-REF scenario for Italy (3.14 kg CO2 eq/kWh).

Table 12

Evolution of the contribution to the investigated impact categories in the 2030 Government Plan Scenario.

ReCiPe Midpoint (H) 2016	Unit	Scenario Government Plan year 2021–2023	Scenario Government Plan year 2030
Fine particulate matter formation	kg PM2.5 eq	2.48E+08	2.14E+08
Fossil resource scarcity	kg oil eq	6.38E+10	4.36E+10
Freshwater ecotoxicity	kg 1,4-DCB	2.14E+09	3.46E+09
Freshwater eutrophication	kg P eq	2.26E+07	2.39E+07
Global warming	kg CO2 eq	1.95E+11	1.44E+11
Human carcinogenic toxicity	kg 1,4-DCB	2.33E+09	2.55E+09
Human non-carcinogenic toxicity	kg 1,4-DCB	3.74E+10	5.04E+10
Ionizing radiation	kBq Co-60 eq	3.20E+10	3.17E+10
Land use	m2a crop eq	3.02E+08	3.22E+08
Marine ecotoxicity	kg 1,4-DCB	2.94E+09	4.61E+09
Marine eutrophication	kg N eq	1.10E+08	1.13E+08
Mineral resource scarcity	kg Cu eq	2.76E+08	3.54E+08
Ozone formation, Human health	kg NOx eq	3.63E+08	2.91E+08
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.73E+08	2.97E+08
Stratospheric ozone depletion	kg CFC11 eq	9.87E+04	7.45E+04
Terrestrial acidification	kg SO2 eq	7.43E+08	6.34E+08
Terrestrial ecotoxicity	kg 1,4-DCB	2.12E+11	2.98E+11
Water consumption	m3	8.32E+08	8.69E+08

Table 13

Generation of the Italian electricity mix from different sources (year 2020), International energy agency-IEA.

Oil	3.5	Mtoe
Coal	3.6	Mtoe
Nat gas	24.2	Mtoe
Biowaste	6.4	Mtoe
Geo	5.2	Mtoe
Solar/tide/wind	3.8	Mtoe
Hydro	3.8	Mtoe
TOTAL	50.5	Mtoe
Electricity output, Italy, 2020	23.7	Mtoe
	2.76E+11	kWh
	275.6	TWh
Average efficiency (Output/Input)	46.9%	

Compared to the existing studies (Gargiulo et al., 2020; Carvahlo et al., 2022) we also assessed the environmental impacts per total kWh produced as well as that of the Governmental Plan scenario and their evolution to 2030. As pointed out in the previous section, the transition towards scenarios with increasing share of renewable sources for the production of total electricity such as, e.g., in the Government 2030 Plan provides the opportunity to further reduce the contribution to Global Warming in the life cycle of electricity as shown in Figure A2 (Appendix) but also to particulate matter formation with environmental and social benefits to the population in terms of lower pollution at the local level and health benefits measured by a reduction of the endpoint indicators (e.g. 2.90E+05 Daly⁸ in the Scenario Gov. Plan 2030 versus 3.56E+05 Daly in the Scenario Gov Plan, 2021–2023) (Tables 9 and 11), decreasing the external costs of total electricity generation. These are much lower for wind and solar compared to the fossils such as hard coal, lignite, natural gas and oil (Karkour et al., 2020). Further social benefits due to natural gas reduction are related to employment opportunities as calculated by Pastore et al. (2022). There are also trade-offs in the evolution from the Scenario Gov. Plan (2021–2013) to that of 2030, as

discussed previously for the results related to the production of 1 kWh. Table 12 shows the environmental benefits and costs of the shift to 2030 scenario and the consequent worsening of the contribution to some impact categories in the life cycle of electricity requiring an adequate monitoring and planning in order to mitigate the side-effects of the energy transition.

Moreover, a further replacement of natural gas and other fossil sources with renewables would promote a huge energy efficiency improvement for the whole mix. The IEA (2022) provides data and Sankey diagrams updated to the year 2020. According to these data, we can see that the total Italian production in the year 2020 was generated as shown in Table 13, by achieving an average production efficiency of about 0.47. Brown and Ulgiati (2002) calculated an average, LCA-based EROEI (Energy Return on Energy Investment, electric energy output/fossil energy input) of about 0.25 for a coal power plant, 0.30 for an oil power plant, 0.37 for a natural gas power plant, while much higher values can be calculated for wind (13.3), geothermal (4.9), hydro (31.5, gross average of alpine plant, river plant and pumping plant) and PV (5.2) processes based on the Ecoinvent 3.1 LCA Database, where the environmental energy sources are not accounted for and only the fossil input for plant manufacturing are included for EROEI calculation. The much higher EROEIs of renewables (in terms of lower fossil energy embodied per unit of electricity output) have a positive effect on the global efficiency calculation, raising the average efficiency value to the 0.47 indicated in Table 13, a bit higher than the efficiency which could be calculated for electricity mix scenarios in Tables 1 and 3, derived from less updated values from slightly less updated values of the Ecoinvent database 3.1 (Table 3).

4.2. Interpretation of the results of this study in the light of the just energy and circular economy transitions frameworks

Previous literature interpreted the results about the environmental profiles of the electricity mixes mainly in the light of decarbonization scenario plans and policies (Carvahlo et al., 2022) or country-specific electricity challenges (increasing demand, increasing population, need for changing lifestyle, etc.) and climate and natural resource constraints

⁸ <https://www.ecoem.it/servizio/gestione-fotovoltaico/>.

(Ramirez et al., 2020; Raugei et al., 2020). In that, e.g. Ramirez et al. (2020) pointed out the importance to take into account that decarbonization policies focused on climate change could have also negative side-effects in other geographical areas and for this reason they highlighted that decarbonization is only one of the aspects to consider for a transition to sustainability.

The transition to the smarter scenarios in the years 2030, 2035 and 2040 for Italy is characterized by a relevant increase of the shares of electricity from renewables (in particular solar PV and wind). These scenarios are in line with the decarbonization goals of European Union for the year 2030, named the Fit 55% package (European Parliament, 2022c) and carbon neutrality goals in the European Green Deal to be reached at 2050 (Perissi et al., 2022) and transposed in member states decarbonization plans such as the Italian long-term strategy for the reduction of the GHGs emissions adopted in the year 2021. The implementation of such scenarios will create an increasing demand for solar PV panels, wind power plants and related raw materials (Calvo and Valero, 2022), the extraction of which is likely to create further burdens in particular to the local communities living in the mining regions, exposed to increased levels of air and water pollution as well as other external negative costs (Mancini and Sala, 2018). For example, local communities living near wind farms may suffer of increased noise and loss of land (Levenda et al., 2021). In this way, the energy transition could become the source of different types of environmental and social impacts under distributional and procedural aspects, since there could be a disproportionate distribution of the costs of the energy transition and the risk of lack of engagement and participation in decision-making of local populations for the installations of new renewable infrastructures (Levenda et al., 2021). Small scale plants are much more preferable (Ottinger, 2013) and if designed and created for experimental purposes by means of reused materials offer an opportunity of raising public awareness about the importance of renewable energies in CE transition (Schoden et al., 2019). At the same time a growing quantity of solar PV panels (Malandrino et al., 2017) and wind power plants is expected to be decommissioned from the year 2028 onwards (Mendoza et al., 2022; Schoden et al., 2019). The recycling of both solar panels and wind turbines at the end-of-life still poses several challenges (Mulvaney et al., 2021). For example, wind turbines are made of steel, aluminium and copper that are likely to achieve functional recycling rates in the range 45%–60%. Other components contained in wind turbines such as electronics and electrical materials, are recycled at 50%, while other materials, such as polyvinyl chloride, fiberglass, lubricants, paints, adhesives, concrete may have much lower recycling rates or even be landfilled (Mendoza et al., 2022; Schoden et al., 2019; Alsaleh and Sattler, 2019). Solar panels are made in a large part of glass (more than 80%), but they also contain some potentially toxic materials (e.g. lead and cadmium), rare earths (e.g., tellurium and indium) and precious materials (e.g. silver and aluminium) (Malandrino et al., 2017). The recycling rates for these materials are higher for glass and aluminium, much lower for copper and tellurium as well as indium and gallium (Malandrino et al., 2017). In European Union, solar panels are considered Waste Electrical and Electronic Equipment (WEEE), within the large appliances category and regulated by the WEEE directive (2012/19/EU) and national transposing legislations (Malandrino et al., 2017; Graedel, 2011). Their end-of-life management in Italy is also performed by the consortia of producers (e.g. ECOEM, among others)

that have implemented a certified system for the collection, transport, treatment and recycling of the photovoltaic modules in compliance with the WEEE directive, technical regulations and specific economic incentives schemes of the National Energy Services Manager (GSE in Italian).⁹ The management of solar panels through such a certification scheme may provide several environmental and social benefits, due to the fact that their treatment is performed within standardized processes and adequate technologies and the recovery becomes an opportunity for social development (jobs), economic benefits (decreased demand for metals and other materials used in production) (Ghisellini et al., 2019). In this perspective, the full implementation of the concept of Circular Economy in all the stages of renewable technologies becomes crucial, in particular in their design for waste prevention (Schoden et al., 2019), disassembly, product life extension, and closed-loop recycling (Mendoza et al., 2022). To this purpose, the concept of life cycle and the use of LCA procedure are necessary (Mulvaney et al., 2021) and complementary to other assessment methods (e.g. social life cycle assessment, social impact assessment, SWOT Analysis, emergy accounting) (Bonilla-Alicea and Fu, 2022; Martinez and Komendantova, 2020; Guangul and Chala, 2019; Odum, 1996) to ensure that environmental and social hotspots and their justice implications are identified and effective solutions for improvement are considered within a systemic approach (Mulvaney et al., 2021).

4.2.1. Promoting sobriety in future energy transition

In the smarter 2030 to 2040 scenarios, it is also projected a relevant growth of electricity generated from renewables. This will have important environmental benefits in terms of reduction of GHGs emissions but other stages of the life cycle may worsen, indicating the importance of preventing the burden shift of impacts from one stage (production of electricity) to another one (e.g. extraction of the materials for solar PV). As a result, the promotion of a higher electrification that also entails a change in the habits of population (e.g. use of electricity as a fuel for cars) should occur very carefully in order to avoid the perception that electricity is 100% clean and generated without environmental costs (also think of batteries, which require materials and recycling). The limits of the natural environment in providing its functions (such as natural resources use and assimilation of waste) to the economy and society cannot be overcome and climate change is the proof of the unconstrained consumption of fossil fuels in particular in developed countries (Balzani, 2019). The ecological degradation of the Planet Earth is at an unprecedented level and is coupled to a social crisis due to the unjust distribution of resources among the worldwide population, requiring an integrated approach to fight poverty and social exclusion as well as to preserve the natural environment. Balzani (2019) underlines that the goals of social and environmental sustainability can be achieved by means of three transitions: from fossil fuels to renewables, from linear to circular economy and from consumerism to sobriety. The latter concept, in turn, acts on “things” to improve their efficiency (e.g., cars that consume less fuel and impact less) as well as on “people” to promote much virtuous behaviours, aimed to avoid the unnecessary use of energy and material resources (Balzani, 2019)¹⁰. As a result, in particular in developed countries, the energy transition towards renewable sources would lead to the implementation of “energy sobriety” with the aim of reducing energy use, inequalities among worldwide population and finally the associated environmental degradation (Hickel and

⁹ Swiss scientists have estimated that 2000 W (about 1,5 toeq/year per person) represents a sufficient amount of energy to live comfortably and the Swiss government has thus proposed a law to decrease to 2000 W the energy consumption per person (presently around 4700 W) by 2050–2100.19 Such a law, in the form of a referendum, has been approved on May 21, 2017 by Swiss citizens. Thus, for people living in rich nations reducing energy consumption is indeed possible without compromising the quality of life, which is good news.

Slamersak, 2022; Fleurbaey et al., 2014). This will not imply a reduction of the quality of life in wealthier nations since their energy use far exceeds what is required to meet human needs (Balzani, 2019), while more than 3 billion of people in poorer nations still live in energy poverty and do not have enough energy to achieve a decent quality of life (Hickel and Slamersak, 2022).

5. Conclusions and implications

This study has assessed by means of LCA the electricity generation mix of Italy under different scenarios, including the one modelled on the basis of the measures for the electricity sector adopted by the Government to face the current natural gas emergence. Two functional units have been considered in the LCA to assess both the environmental efficiency of each source per kWh of net electricity generated as well as the impacts of total electricity generated annually. Midpoint and Endpoint impact indicators have been used to measure and inform about the environmental and social benefits and costs of electricity mix generation. In Italy and other European countries, natural gas is one of the most important sources for the production of electricity. The main goal of this study has been evaluating and comparing the potential environmental impacts of the different electricity generation mix scenarios for Italy from the BAU (data of the year 2021) and Government Plan (data of the year 2021–2023) to 2030 as well as comparing them with selected EU smarter research electricity scenarios that capture the future orientation from 2030 to 2040 of the EU climate policy for the achievement of the so-called climate neutrality.

The results point out that.

- The impacts of the total electricity generated under the scenario of the Government Plan (which replaces 14% of electricity from natural gas with coal, oil and renewables) produce similar impacts to the BAU scenario in the case of Global Warming and a worsening of several impact categories such as particular matter formation, terrestrial acidification and eco-toxicity and water consumption.
- The transition towards scenarios with increasing levels of substitution of natural gas with renewable sources by 30%–60% as in the 2030 Government Plan scenario reduces the contribution to global warming and other categories while for worsening other aspects, such as terrestrial ecotoxicity, in so calling for additional technological improvements for PV and other renewables. However, the research for renewable energies (such as for solar panels and wind power) is progressing in order to find less toxic materials as well as designing them for a longer life and for an easy disassembly and recycling.
- The implementation of the concept of CE is critical and highly recommended for renewable energies plants. It is important to remind that the latter also have higher energy ratios (EROEIs) compared to electricity plants based on fossils, contributing to increase the overall efficiency of the electricity mix. This provides a further incentive for Italy and Europe to accelerate to the largest possible extent the energy transition to renewables and reduce the dependence on natural gas, while also abandoning the unsustainable idea of introducing nuclear power again, a solution unable to provide the needed fast and cheap solution to the natural gas emergence for electricity generation, not to mention the still lacking solution, locally and worldwide, for permanent disposal of nuclear waste.
- The energy transition to a higher share of renewables will provide environmental and social benefits as well as costs to be addressed

and removed, in the whole life cycle of electricity generation. The costs of the energy transition can be mitigated by the adoption of the CE principles in the design of renewable technologies. LCA is then important to evaluate the environmental soundness of circular solutions in energy transition, coupled to other approaches (e.g. social life cycle assessment). LCA is therefore fundamental in this stage toward 2030 and beyond in order to ensure that both transitions meet the three dimension of sustainability and that winners and losers in the life cycle of electricity generation and use are identified and better solutions promoted.

This paper contributes to knowledge building, by integrating the LCA evaluation of the Italian electricity mix with midpoint and endpoint indicators, two different functional units, net energy analysis, “new” concepts (just energy and CE transition). It reflects the need to develop theoretical and interpretative frameworks to advance knowledge on environmental and social impacts of the electricity mix under different political and research perspectives, in order to face the current complex environmental, energy and social challenges. With this in mind, the designed frameworks must be based on the adoption of integrated assessment methods (that also include LCA) and on the improvement of the information to be provided to all stakeholders in the energy sector.

Finally, in terms of practical implications, the electricity transition should also be combined with innovative lifestyles, in particular in wealthier nations, as suggested by the Italian Government but also in other European countries, leading to the adoption of an energy sobriety concept, driven by the awareness that even renewable electricity (as shown this study) has environmental and social costs and justice implications. Future research may certainly take advantage of expanded LCA frameworks and knowledge and further deepen the assessment of environmental impacts and costs generated by the electricity sector by means of social life cycle assessment and benefits from the identified hotspots and environmental midpoint and endpoint indicators.

Author contributions

Conceptualization: P.G., S.U.; Methodology: P.G., S.U.; Writing—original draft preparation: P.G.; Writing—review and editing: P.G., R.P., S.U.; Supervision: S.U.; Project administration: R.P.; Funding acquisition: R.P. All authors have read and agreed to the submitted revised version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study have been collected from public statistics and private database

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APPENDIX

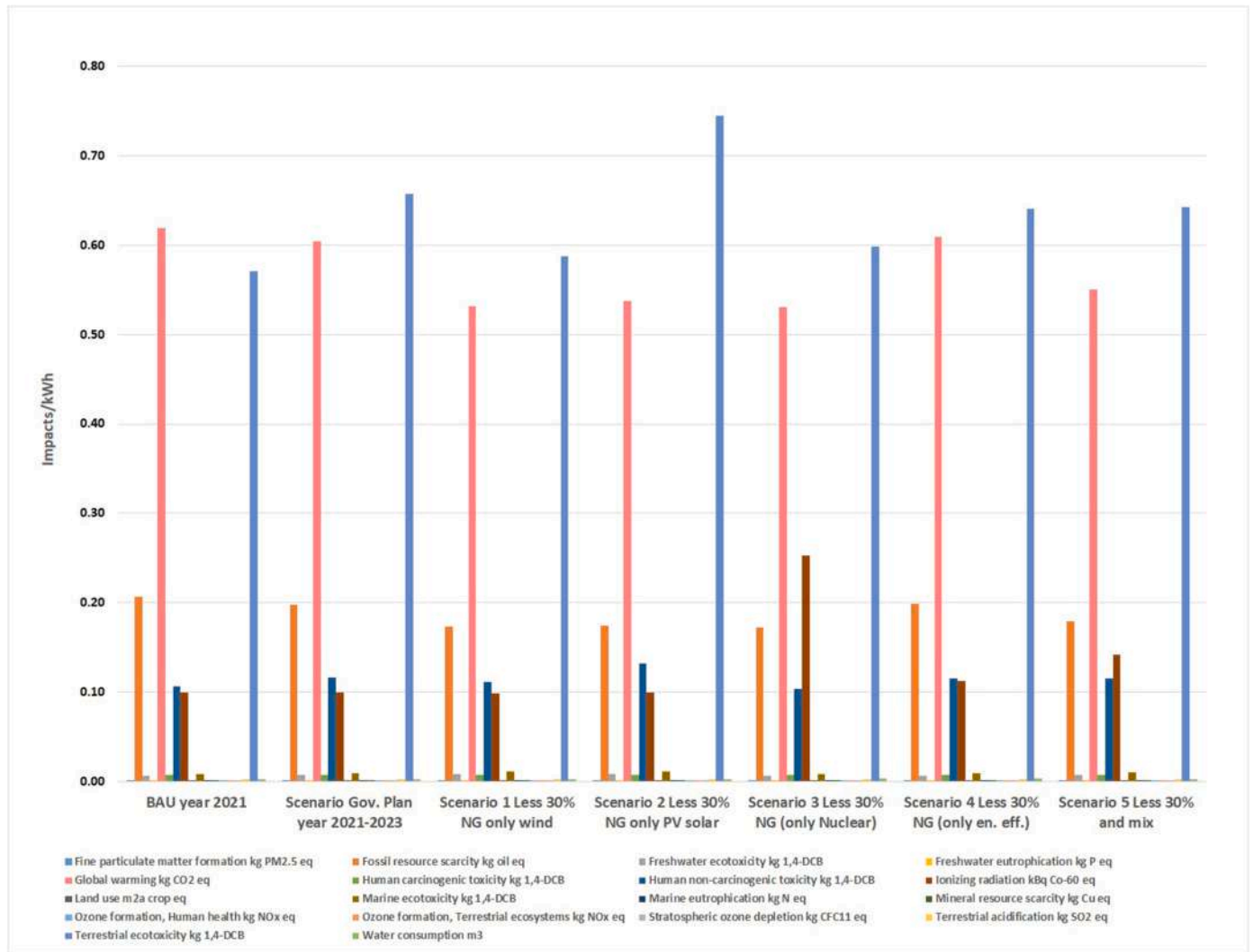


Fig. A1. LCA Environmental characterized midpoint impacts associated to 1 kWh of net electricity generated in the BAU and other scenarios with less natural gas from 14% (Government plan 2021–2023) to 30% (scenarios from 1 to 5). It should be noted that characterized impacts diagrams use different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

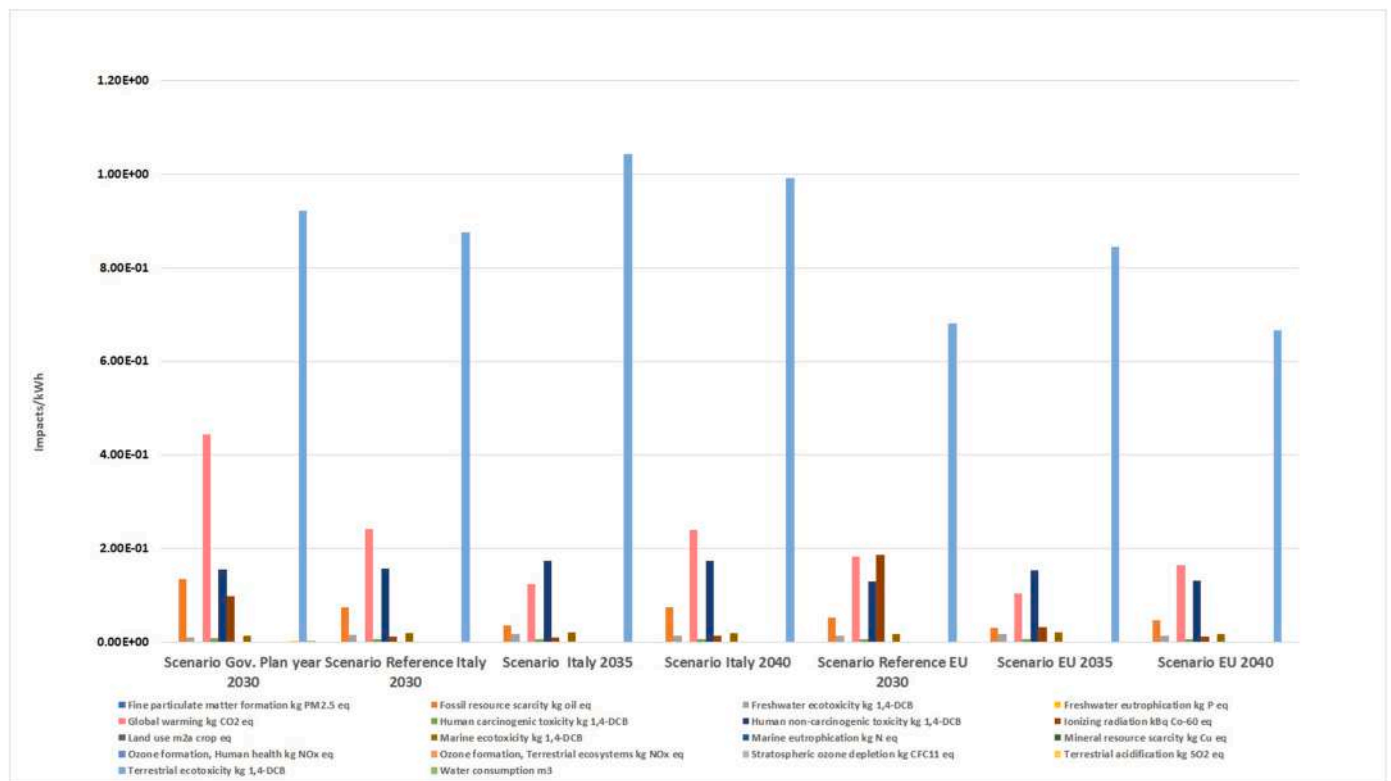


Fig. A2. LCA Environmental characterized midpoint impacts associated to 1 kWh of net electricity generated in the smarter scenarios. It should be noted that characterized impacts diagrams use different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

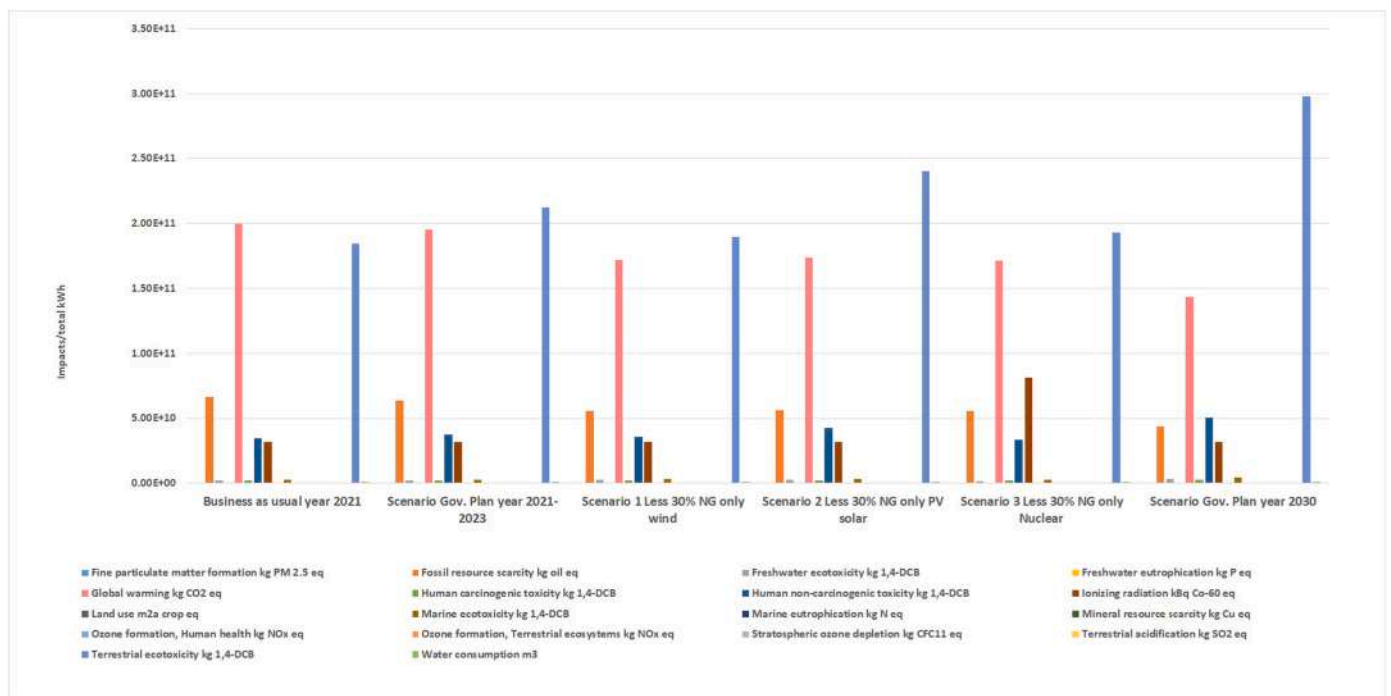


Fig. A3. LCA Environmental characterized midpoint impacts associated to net total annual electricity generated (322, 838 GWh) from the BAU (year 2021) to the 2030 Government Plan scenario (the total net electricity is assumed to be constant in these scenarios). It should be noted that characterized impacts diagrams use

different units per each impact category, which explain that some categories are represented by higher and more visible bars than others, not necessarily corresponding to higher impacts and potential damages.

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LAZARD LCOE+

LEVELIZED COST OF ENERGY+

June 2025

WITH SUPPORT FROM

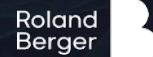


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LCOE

I

Executive Summary

Executive Summary—Selected Key Findings from Lazard’s 2025 LCOE+

Lazard’s 2025 LCOE+ Report is organized around three key areas: Energy Generation, Energy Storage and the Energy System

Energy Generation

Levelized Cost of Energy Version 18.0

- **Renewables Remain Competitive:** On an unsubsidized \$/MWh basis, renewable energy remains the most cost-competitive form of generation. As such, renewable energy will continue to play a key role in the buildout of new power generation in the U.S. This is particularly true in the current high power demand environment, where renewables stand out as both the lowest-cost and quickest-to-deploy generation resource
- **Increasing Competitiveness of Existing Gas Generation:** The gap between the LCOE of new wind and solar and the marginal cost of operating CCGTs has widened due to, among other things, persistent low gas prices, high energy demand and increasing renewable LCOEs
- **Significant Shifts Expected:** Unless otherwise indicated, Lazard’s LCOE is an LTM analysis focused on “today” and is not a forecasting tool. As such, the outcomes included herein are representative of current development and construction timelines, which vary by technology. For example, while this year’s analysis shows only a slight increase in the LCOE of CCGTs, turbine shortages, rising costs and long lead times are expected to drive steep LCOE increases for gas technologies in the near term, as illustrated herein. Additionally, cost declines across Vogtle units 3 and 4 indicate nuclear is poised to benefit from scale and development efficiencies

Energy Storage

Levelized Cost of Storage Version 10.0

- **Storage Cost Decline:** This year’s analysis shows notable declines in the LCOS of utility scale and C&I battery energy storage systems. Key drivers of such results include both market dynamics (e.g., lower-than-expected EV demand and the resulting oversupply of cells) and technological advancements (e.g., increased cell capacity and energy density)
- **Tariffs Increase Uncertainty:** While current pricing is further benefiting from aggressive competition, widening LCOS spreads indicate increased volatility as uncertainty related to the ultimate tariff regime is shaping market dynamics in real time. For example, supply chain relocation to Southeast Asia and India is well underway, and market participants are executing on forward procurement strategies to mitigate future pricing risk
- **Market Expansion Is Underway:** The LCOS value snapshots show increased returns reflecting the confluence of lower costs and higher prices in several regions. Energy storage adoption is expanding beyond ISO/RTO-driven wholesale markets and into states where municipal procurement and data center growth is prevalent (e.g., Arizona, Colorado, Florida). Lazard expects continued expansion as backup power and grid resilience become increasingly important in high-growth markets

Energy System

Cost of Firming Intermittency

- **Firming Value Rises as Renewable Penetration Increases:** The cost of firming helps grid operators evaluate resources based on a region’s existing generation mix and load characteristics, ensuring the right balance between reliability and affordability. The results of this year’s firming analysis show that as the penetration of low-cost intermittent generation increases, the value of firm capacity rises
- **ISO Approaches to System Analysis Are Evolving:** Several independent system operators are adjusting their capacity accreditation methodologies in ways that are generally increasing firming costs. Both CAISO and PJM have reduced capacity accreditation values for highly correlated resources (e.g., solar and shorter-duration storage). Continued development of more sophisticated capacity accreditation frameworks, such as incorporation of seasonal adjustments or diversity benefits, could have material impacts on future firming costs
- **Diverse Generation Sources and Innovation Are Needed:** The results of Lazard’s LCOE+ have consistently supported deploying a diverse mix of energy resources. Despite the sustained unsubsidized cost competitiveness of renewable energy, resource planning metrics indicate diverse generation fleets will be required over the long term to meet power needs, likely bolstered by now-emerging technologies such as long duration energy storage, geothermal, nuclear small modular reactors, pumped storage hydropower and carbon capture and storage, among others

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II

Energy Generation

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LCOE



A

Lazard's Levelized Cost of Energy Analysis—Version 18.0

Introduction

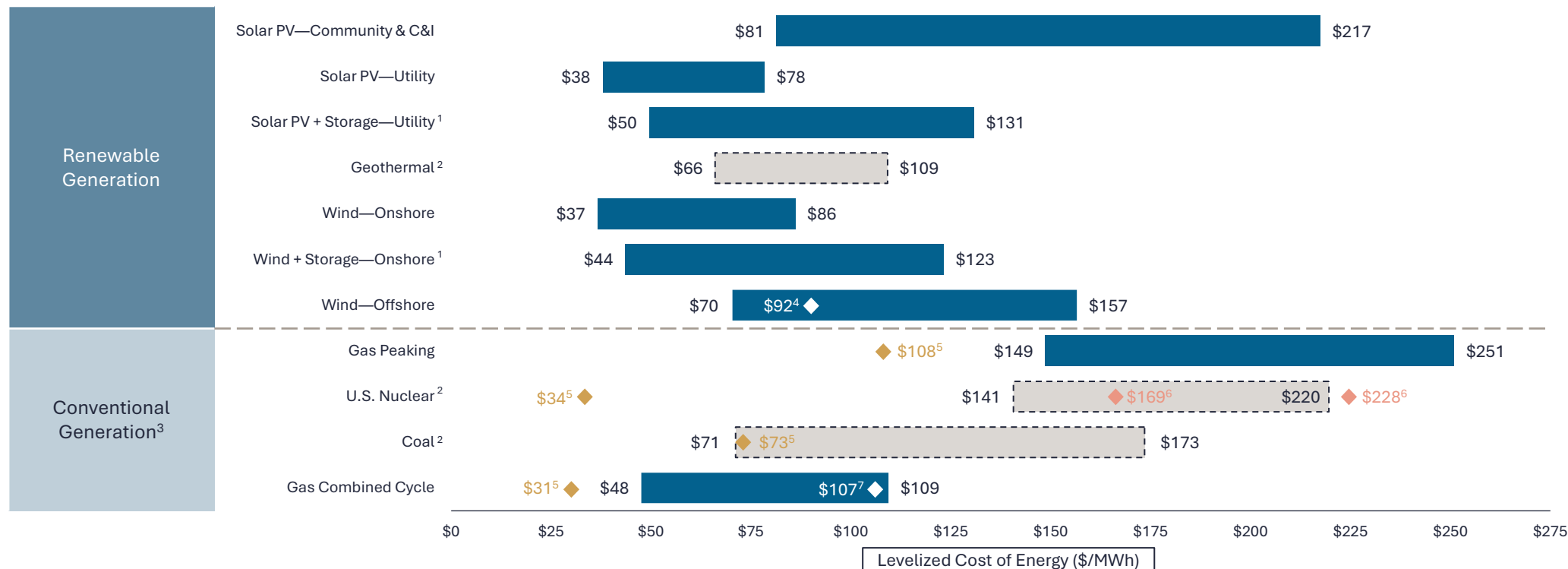
Lazard's Levelized Cost of Energy analysis addresses the following topics:

- Comparative LCOE analysis for various generation technologies on a \$/MWh basis, including sensitivities for U.S. federal tax subsidies, fuel prices, carbon pricing and cost of capital
- Illustration of how the LCOE of onshore wind, utility-scale solar and hybrid projects compare to the marginal cost of selected conventional generation technologies
- Historical LCOE comparison of various technologies
- Illustration of the historical LCOE declines for onshore wind and utility-scale solar
- Appendix materials, including:
 - An overview of the methodology utilized to prepare Lazard's LCOE analysis
 - A summary of the assumptions utilized in Lazard's LCOE analysis
 - Deconstruction of the LCOE for various generation technologies by capital cost, fixed operations and maintenance (“O&M”) expense, variable O&M expense and fuel cost

Other factors would also have a potentially significant effect on the results contained herein but have not been examined in the scope of this current analysis. These additional factors, among others, may include: recent tariff-related cost impacts; implementation and interpretation of the full scope of the IRA; economic policy, transmission queue reform, network upgrades and other transmission matters, congestion, curtailment or other integration-related costs; permitting or other development costs, unless otherwise noted; and costs of complying with various environmental regulations (e.g., carbon emissions offsets or emissions control systems). This analysis is intended to represent a snapshot in time and utilizes a wide, but not exhaustive, sample set of Industry data. As such, we recognize and acknowledge the likelihood of results outside of our ranges. Therefore, this analysis is not a forecasting tool and should not be used as such given the complexities of our evolving Industry, grid and resource needs. Except as illustratively sensitized herein, this analysis does not consider the intermittent nature of selected renewables energy technologies or the related grid impacts of incremental renewable energy deployment. This analysis also does not address potential social and environmental externalities including, for example, the social costs and rate consequences for those who cannot afford distributed generation solutions as well as the long-term residual and societal consequences of various conventional generation technologies that are difficult to measure (e.g., airborne pollutants, greenhouse gases, etc.).

Levelized Cost of Energy Comparison—Version 18.0

Selected renewable energy generation technologies remain cost-competitive with conventional generation technologies under certain circumstances

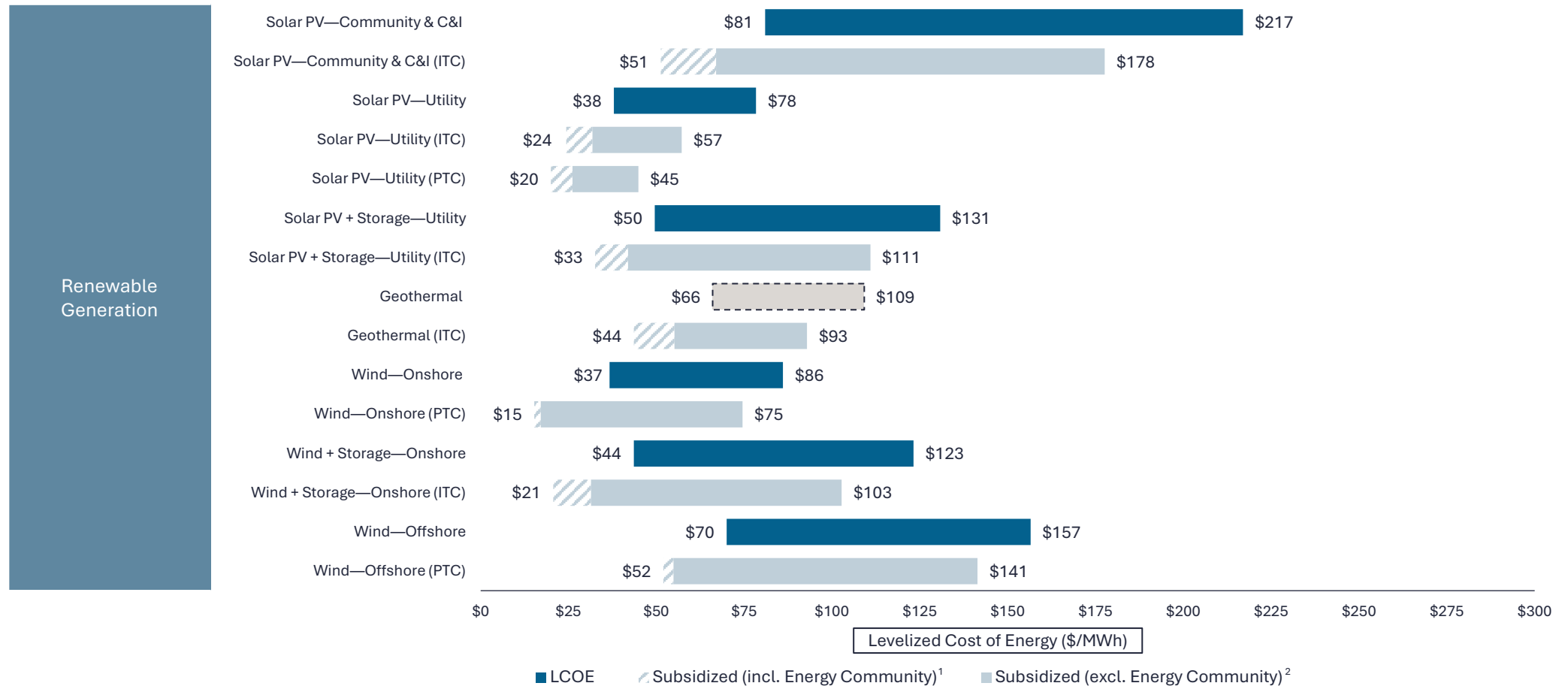


Source: Lazard estimates and publicly available information.
 Note: Here and throughout this analysis, unless otherwise indicated, the analysis assumes 60% debt at an 8% interest rate and 40% equity at a 12% cost. See page titled “Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital” for cost of capital sensitivities.

- 1 Reflects the LCOE for a system composed of standalone generation plus standalone storage less the combined system-level synergies (assumed to be 10% of storage capital costs and 25% of inverter costs). The synergies capture potential cost reductions or efficiency gains from integrating generation and storage, such as shared interconnection infrastructure, improved energy dispatch, enhanced capacity utilization and operational efficiencies.
- 2 Given the limited public and/or observable data available for new-build geothermal, coal and nuclear projects, the LCOE presented herein reflects Lazard’s LCOE v14.0 results adjusted for inflation and, for nuclear, are based on then-estimated costs of the Vogtle Plant. Coal LCOE does not include cost of transportation and storage.
- 3 The fuel cost assumptions for Lazard’s LCOE analysis of gas-fired generation, coal-fired generation and nuclear generation resources are \$3.45/MMBTU, \$1.47/MMBTU and \$0.85/MMBTU, respectively, for year-over-year comparison purposes. See page titled “Levelized Cost of Energy Comparison—Sensitivity to Fuel Prices” for fuel price sensitivities.
- 4 Represents the illustrative midpoint LCOE for Dominion’s Coastal Virginia Offshore Wind (“CVOW”) project, based on the publicly disclosed capital cost of ~\$8.7 billion (excluding onshore transmission costs) and offshore wind estimates from Lazard. Dominion’s projected LCOE for CVOW as of February 2025 is \$91/MWh in 2027 dollars, with an expected COD in 4Q 2026.
- 5 Reflects the average of the high and low LCOE marginal cost of operating fully depreciated gas peaking, gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard’s research. See page titled “Levelized Cost of Energy Comparison—New Build Renewable Generation vs. Marginal Cost of Conventional Generation” for additional details.
- 6 Represents illustrative LCOE values for Vogtle nuclear plant’s units 3 and 4. The analysis is based on publicly available estimates and suggestions from selected industry experts, indicating a cost “learning curve” of ~30% between Vogtle units 3 and 4. Analysis assumes total operating capacity of ~2.2 GW, total capital cost of ~\$32.3 billion, capacity factor of ~97%, operating life of 70 years and other operating parameters estimated by Lazard’s LCOE v14.0 results, adjusted for inflation.
- 7 Illustrative high case reflects elevated capital costs (\$2,400/kW – \$2,600/kW) based on recently observed market quotes for CCGT projects in early stages of development (post-2028 COD).

Levelized Cost of Energy Comparison—Sensitivity to U.S. Federal Tax Subsidies

The Investment Tax Credit (“ITC”), Production Tax Credit (“PTC”) and Energy Community adder, among other provisions in the IRA, are important components of the LCOE for renewable energy technologies



Source: Lazard estimates and publicly available information.

Note: Unless otherwise indicated, this analysis does not include other state or federal subsidies (e.g., domestic content adder, etc.). The IRA is a comprehensive and evolving piece of legislation that is still being implemented and remains subject to interpretation—important elements of the IRA are not included in our analysis and could impact outcomes. Lazard’s LCOE analysis assumes, for year-over-year reference purposes, 60% debt at an 8% interest rate and 40% equity at a 12% cost (together implying an after-tax IRR/WACC of 7.7%).

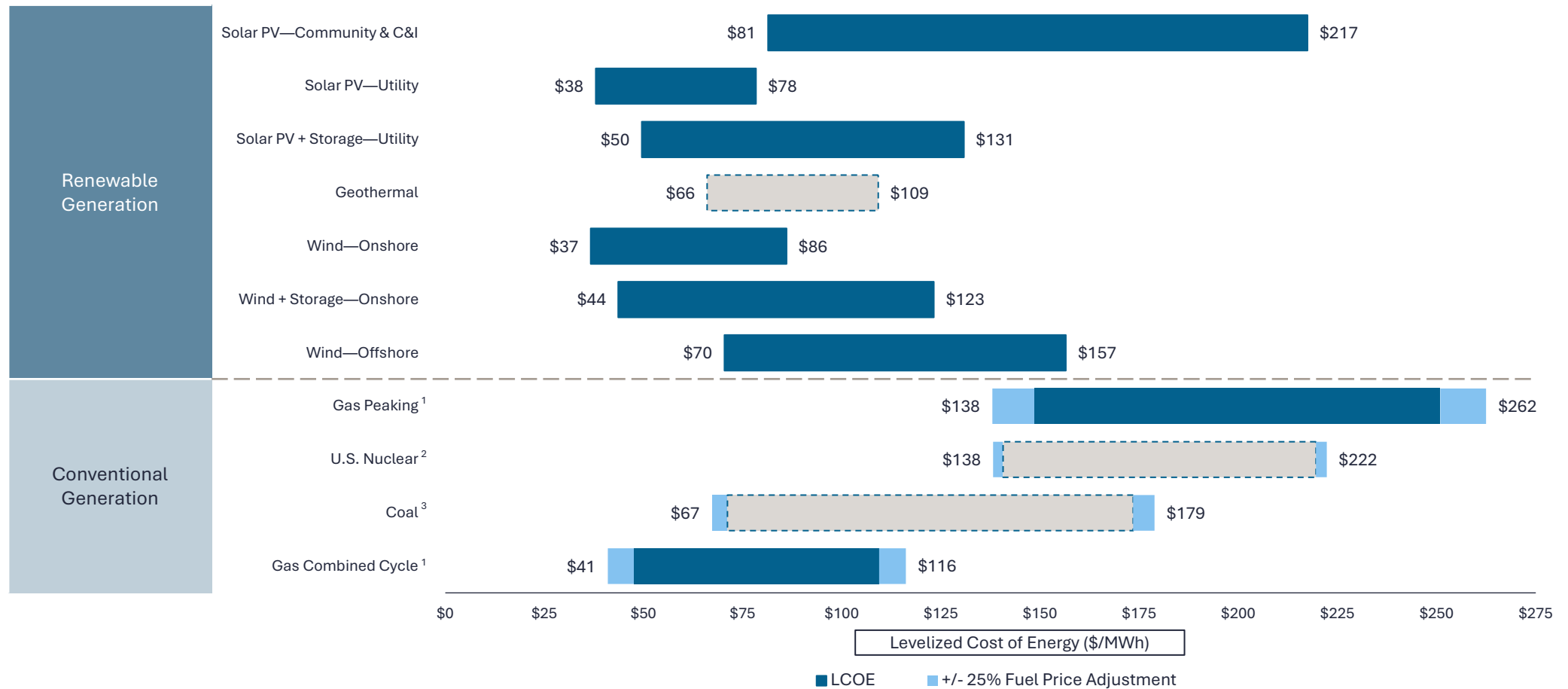
¹ This sensitivity analysis assumes that projects qualify for the full ITC/PTC, have a capital structure that includes sponsor equity, debt and tax equity and assumes the equity owner has taxable income to monetize the tax credits and also includes an Energy Community adder of 10% for ITC projects and \$3/MWh for PTC projects.

² This sensitivity analysis assumes that projects qualify for the full ITC/PTC, have a capital structure that includes sponsor equity, debt and tax equity and assumes the equity owner has taxable income to monetize the tax credits.

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Levelized Cost of Energy Comparison—Sensitivity to Fuel Prices

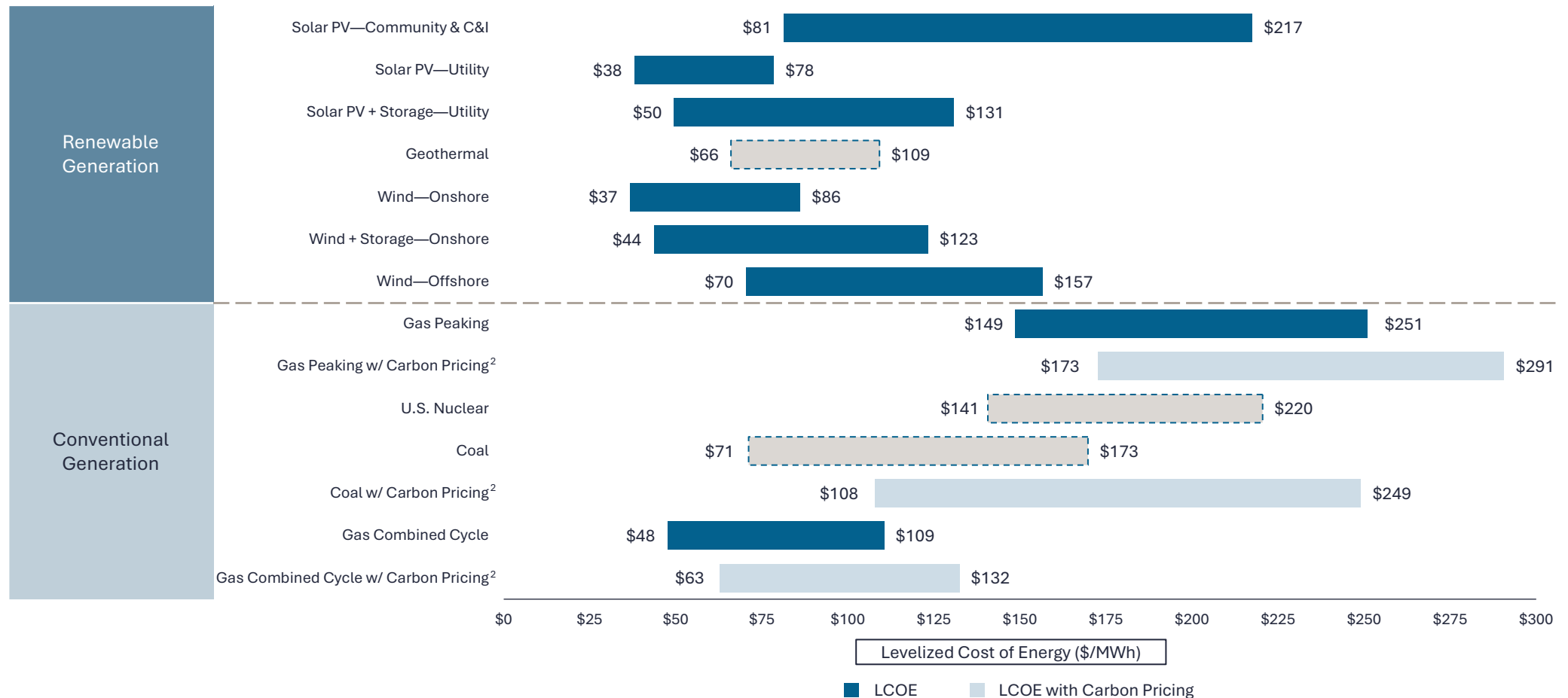
Variations in fuel prices can materially impact the LCOE of conventional generation technologies



Source: Lazard estimates and publicly available information.
 Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used in the LCOE analysis as presented on the page titled "Levelized Cost of Energy Comparison—Version 18.0".
 1 Assumes a fuel cost range for gas-fired generation resources of \$2.59/MMBTU – \$4.31/MMBTU (representing a sensitivity range of ± 25% of the \$3.45/MMBTU used in the LCOE).
 2 Assumes a fuel cost range for nuclear generation resources of \$0.64/MMBTU – \$1.06/MMBTU (representing a sensitivity range of ± 25% of the \$0.85/MMBTU used in the LCOE).
 3 Assumes a fuel cost range for coal-fired generation resources of \$1.10/MMBTU – \$1.84/MMBTU (representing a sensitivity range of ± 25% of the \$1.47/MMBTU used in the LCOE).

Levelized Cost of Energy Comparison—Sensitivity to Carbon Pricing

Carbon pricing is one avenue for policymakers to address carbon emissions; a carbon price range of \$40 – \$60/Ton¹ of carbon would increase the LCOE for certain conventional generation technologies, as indicated below



Source: Lazard estimates and publicly available information.

Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used in the LCOE analysis as presented on the page titled "Levelized Cost of Energy Comparison—Version 18.0". LCOE with Carbon Pricing is limited to carbon emissions directly related to generation and does not include the impacts of carbon pricing on embodied carbon.

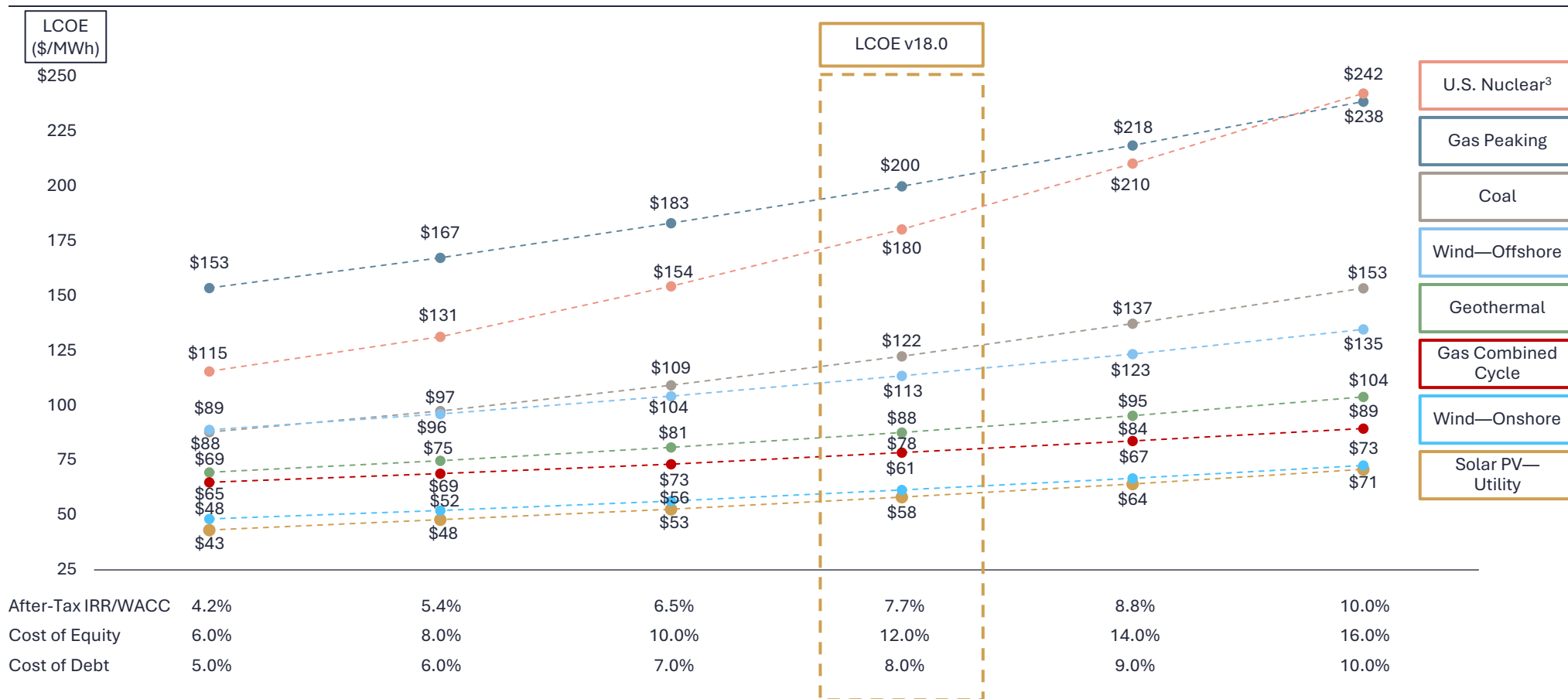
¹ The current administration no longer maintains an estimate of the monetized impacts of greenhouse gas emissions. Previous administrations estimated the social cost of carbon to range from \$5/Ton (first Trump Administration) to over \$200/Ton (Biden Administration).

² The low and high ranges reflect the LCOE of selected conventional generation technologies including an illustrative carbon price of \$40/Ton and \$60/Ton, respectively.

Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital¹

A key consideration in determining the LCOE for utility-scale generation technologies is the cost, and availability, of capital¹. In practice, this dynamic is particularly significant because the cost of capital for each asset is related to its specific operational characteristics and the resulting risk/return profile

Average LCOE²

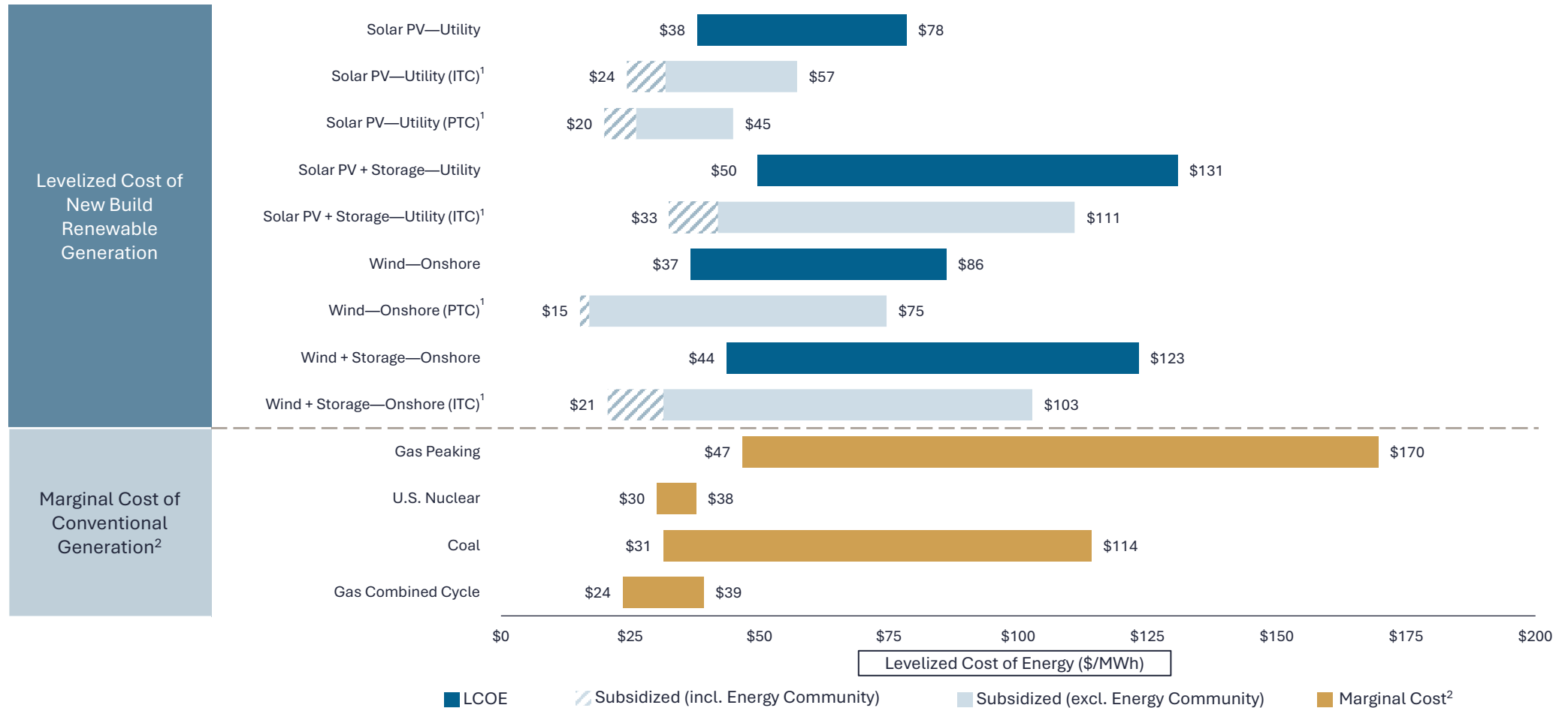


After-Tax IRR/WACC	4.2%	5.4%	6.5%	7.7%	8.8%	10.0%
Cost of Equity	6.0%	8.0%	10.0%	12.0%	14.0%	16.0%
Cost of Debt	5.0%	6.0%	7.0%	8.0%	9.0%	10.0%

Source: Lazard estimates and publicly available information.
 Note: Analysis assumes 60% debt and 40% equity. Unless otherwise noted, the assumptions used in this sensitivity correspond to those used on the page titled "Levelized Cost of Energy Comparison—Version 18.0".
 1 Cost of capital as used herein indicates the cost of capital applicable to the asset/plant and not the cost of capital of a particular investor/owner.
 2 Reflects the average of the high and low LCOE for each respective cost of capital assumption.
 3 Given the limited public and/or observable data available for new-build nuclear projects, the LCOE presented herein reflects Lazard's LCOE v14.0 results adjusted for inflation and are based on then-estimated costs of the Vogtle Plant.

Levelized Cost of Energy Comparison—New Build Renewable Generation vs. Marginal Cost of Conventional Generation

Certain renewable energy generation technologies have an LCOE that is competitive with the marginal cost of selected conventional generation technologies—notably, as incremental, intermittent renewable energy capacity is deployed and baseload gas-fired generation utilization rates increase, this gap closes, particularly in low gas pricing and high energy demand environments



Source: Lazard estimates and publicly available information.

Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used on page titled “Levelized Cost of Energy Comparison—Version 18.0”.

1 See page titled “Levelized Cost of Energy Comparison—Sensitivity to U.S. Federal Tax Subsidies” for additional details.

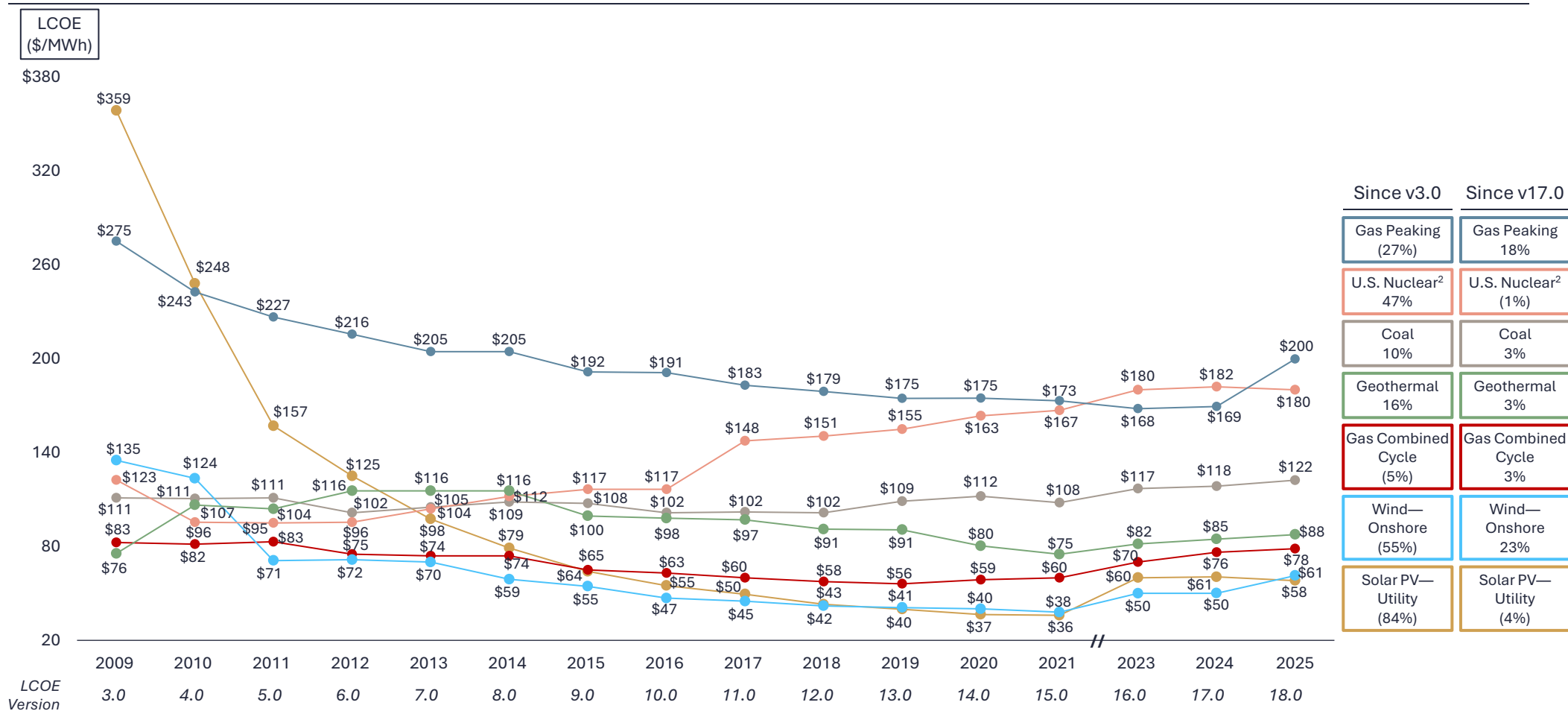
2 Reflects the marginal cost of operating fully depreciated gas, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed O&M are based on upper- and lower-quartile estimates derived from Lazard’s research.

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Levelized Cost of Energy Comparison—Historical LCOE Comparison

Lazard's LCOE analysis indicates significant historical cost declines for utility-scale renewable energy generation technologies, which has begun to level out and even slightly increase in recent years

Selected Historical Average LCOE Values¹

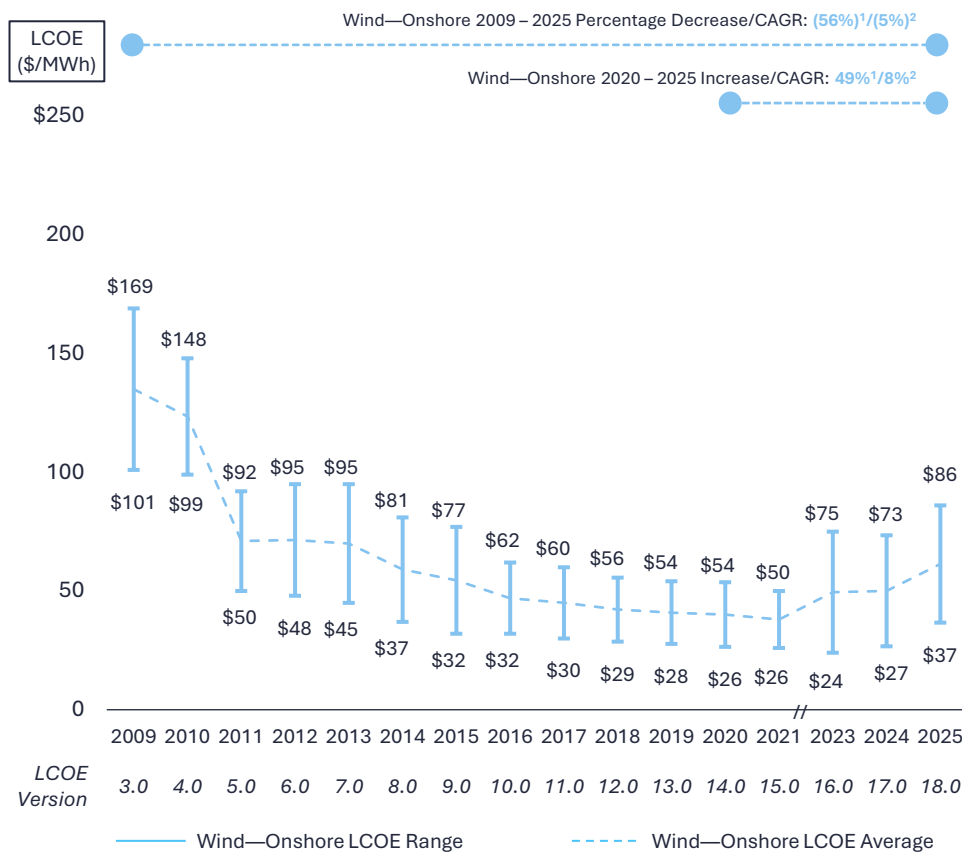


Source: Lazard estimates and publicly available information.
 1 Reflects the average of the high and low LCOE for each respective technology in each respective year. Percentages represent the total change in the average LCOE since Lazard's LCOE v3.0 and LCOE v17.0, respectively.
 2 Given the limited public and/or observable data available for new-build nuclear projects, the LCOE presented herein reflects Lazard's LCOE v14.0 results adjusted for inflation and are based on then-estimated costs of the Vogtle Plant.

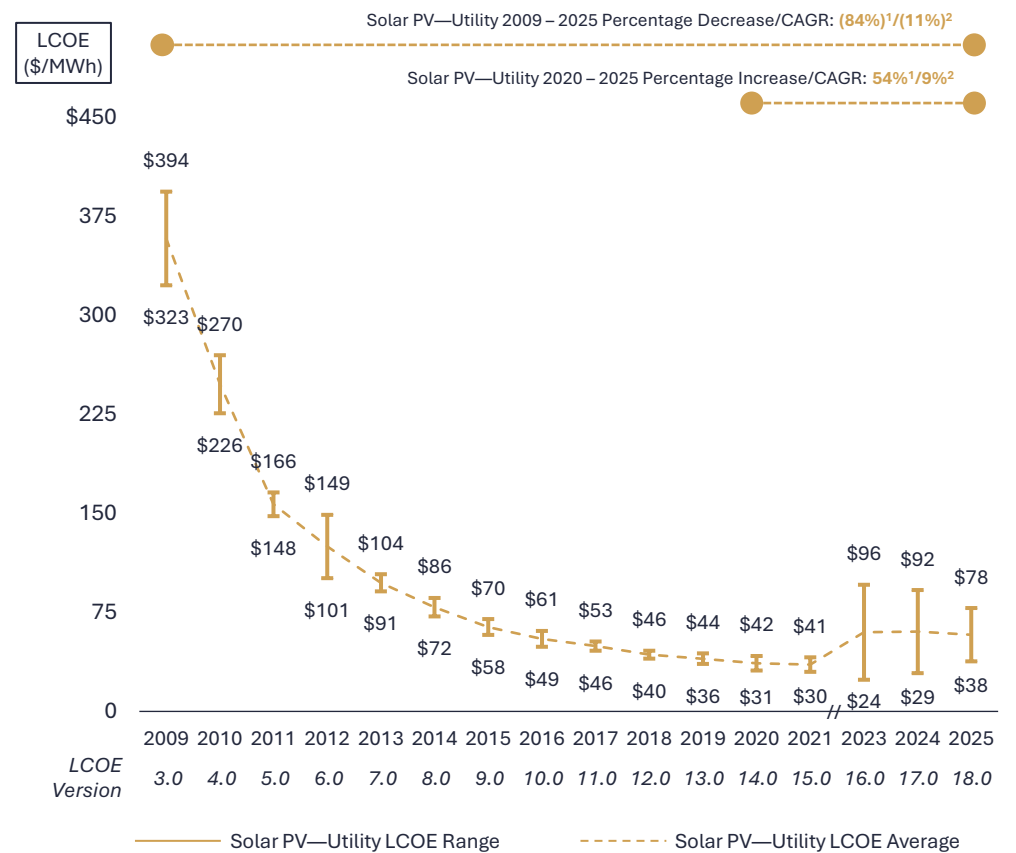
Levelized Cost of Energy Comparison—Historical Renewable Energy LCOE

This year's analysis shows a divergence in trends between wind and solar with solar costs declining slightly and wind costs increasing, likely reflecting the difference in supply chain conditions across each technology

Wind—Onshore



Solar PV—Utility



Source: Lazard estimates and publicly available information.
 1 Reflects the average percentage increase/(decrease) of the high end and low end of the LCOE range.
 2 Reflects the average compounded annual growth rate of the high end and low end of the LCOE range.



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Energy Storage

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Lazard's Levelized Cost of Storage Analysis—Version 10.0

Introduction

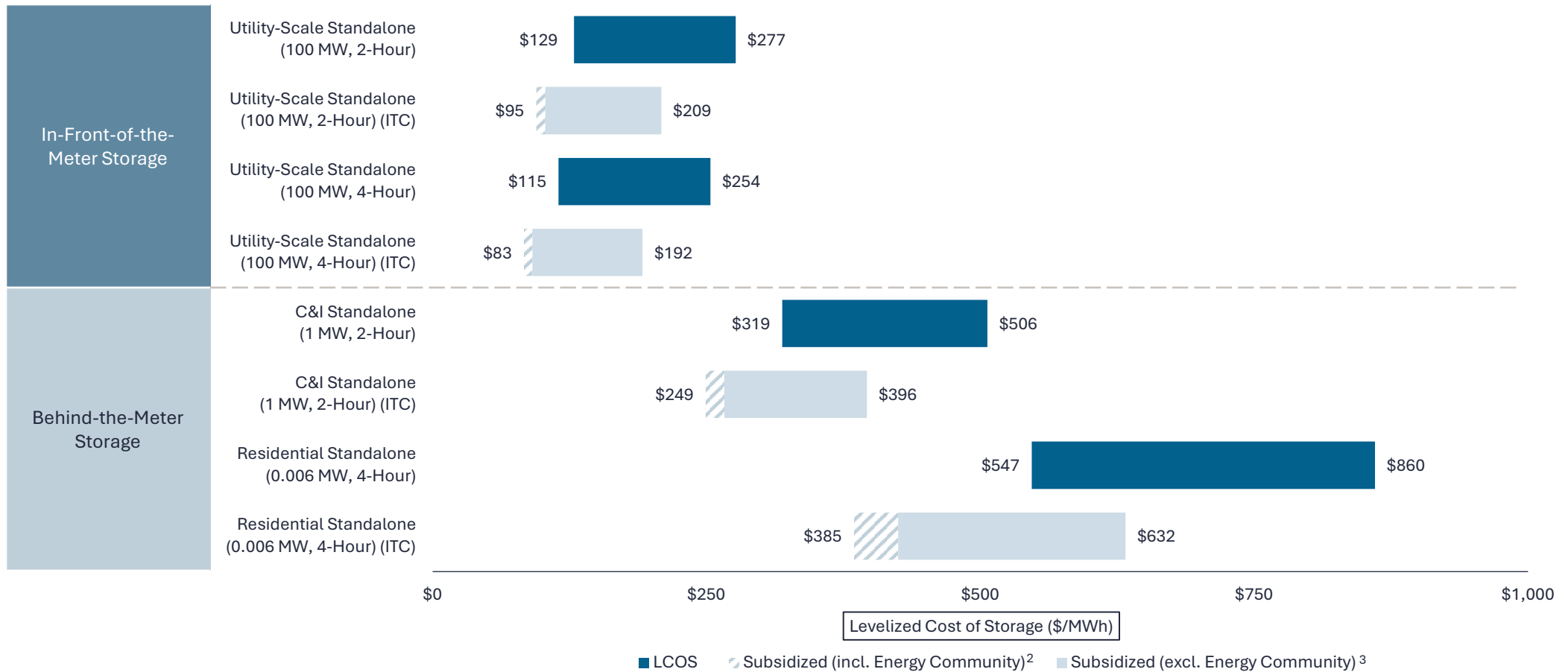
Lazard's Levelized Cost of Storage analysis addresses the following topics:

- LCOS Analysis:
 - Comparative LCOS analysis for various energy storage systems on a \$/MWh basis
 - Comparative LCOS analysis for various energy storage systems on a \$/kW-year basis
- Storage Value Snapshot Case Studies:
 - Overview of potential revenue applications for various energy storage systems
 - Overview of the Storage Value Snapshot Case Studies analysis and identification of selected geographies for each use case analyzed
 - Results from the Storage Value Snapshot Case Studies analysis
- Appendix Materials, including:
 - An overview of the use cases and operational parameters of selected energy storage systems for each use case analyzed
 - An overview of the methodology utilized to prepare Lazard's LCOS analysis
 - A summary of the assumptions utilized in Lazard's LCOS analysis
 - Deconstruction of the LCOS for various generation technologies by capital cost, fixed operations and maintenance (“O&M”) expense and charging cost

Other factors would also have a potentially significant effect on the results contained herein but have not been examined in the scope of this current analysis. These additional factors, among others, may include: recent tariff-related cost impacts; implementation and interpretation of the full scope of the IRA; economic policy, transmission queue reform, network upgrades and other transmission matters; congestion, curtailment or other integration-related costs; permitting or other development costs, unless otherwise noted; and costs of complying with various regulations (e.g., federal import tariffs or labor requirements). This analysis also does not address potential social and environmental externalities as well as the long-term residual and societal consequences of various energy storage system technologies that are difficult to measure (e.g., resource extraction, end-of-life disposal, lithium-ion-related safety hazards, etc.). This analysis is intended to represent a snapshot in time and utilizes a wide, but not exhaustive, sample set of Industry data. As such, we recognize and acknowledge the likelihood of results outside of our ranges. Therefore, this analysis is not a forecasting tool and should not be used as such given the complexities of our evolving Industry, grid and resource needs.

Levelized Cost of Storage Comparison—Version 10.0 (\$/MWh)

Lazard's LCOS analysis evaluates standalone energy storage systems on a levelized basis to derive cost metrics across energy storage use cases and configurations¹



Source: Lazard estimates and publicly available information.

Note: Here and throughout this section, unless otherwise indicated, the analysis assumes 20% debt at an 8% interest rate and 80% equity at a 12% cost, which is a different capital structure than Lazard's LCOE analysis. Capital costs include the storage module, balance of system and power conversion equipment, collectively referred to as the energy storage system, equipment (where applicable) and EPC costs. Augmentation costs are not included in capital costs in this analysis and vary across use cases due to usage profiles and lifespans. Charging costs are assessed at the weighted average hourly pricing (wholesale energy prices) across an optimized annual charging profile of the asset. See Appendix B for charging cost assumptions and additional details. The projects are assumed to use a 5-year MACRS depreciation schedule.

¹ See Appendix B for a detailed overview of the use cases and operational parameters analyzed in the LCOS.

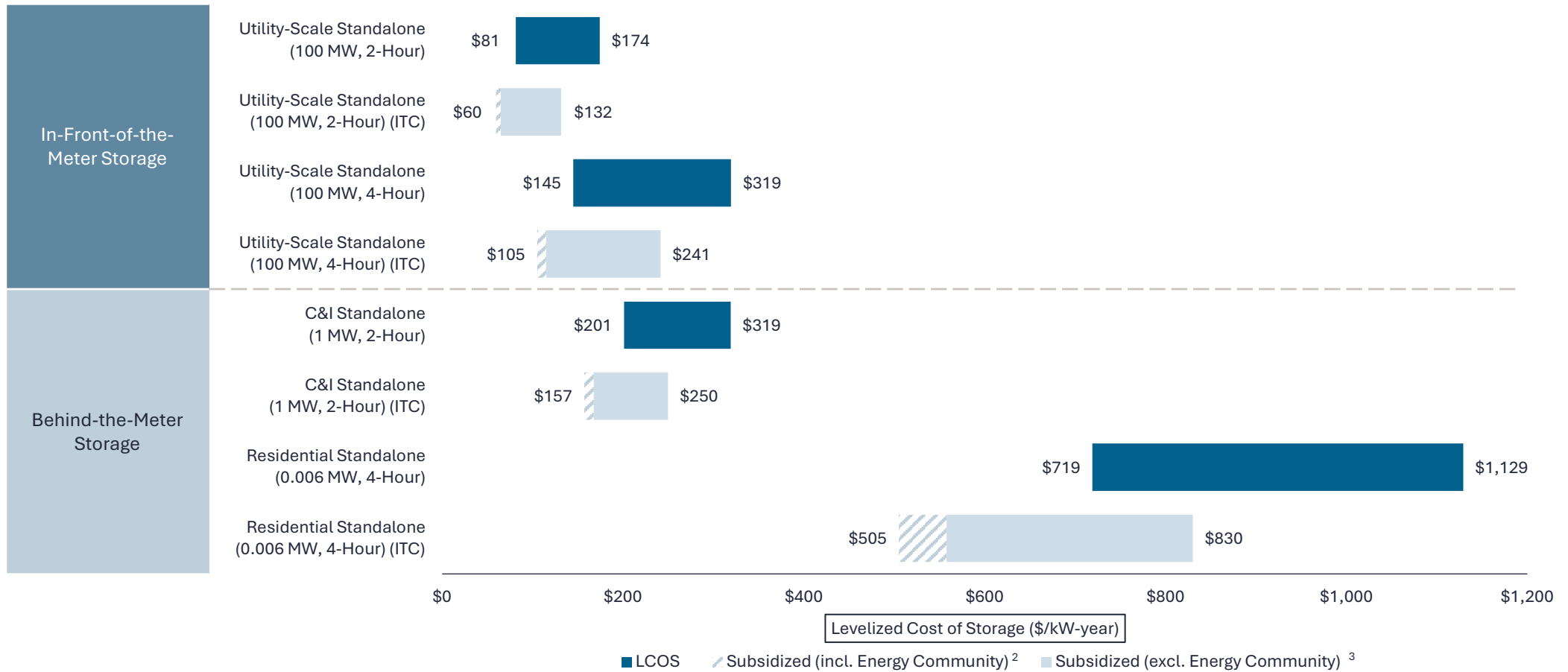
² This sensitivity analysis assumes that projects qualify for the full ITC and have a capital structure that includes sponsor equity, debt and tax equity and also includes a 10% Energy Community adder.

³ This sensitivity analysis assumes that projects qualify for the full ITC and have a capital structure that includes sponsor equity, debt and tax equity.



Levelized Cost of Storage Comparison—Version 10.0 (\$/kW-year)

Lazard's LCOS analysis evaluates standalone energy storage systems on a levelized basis to derive cost metrics across energy storage use cases and configurations¹



Source: Lazard estimates and publicly available information.

¹ See Appendix B for a detailed overview of the use cases and operation parameters analyzed in the LCOS.

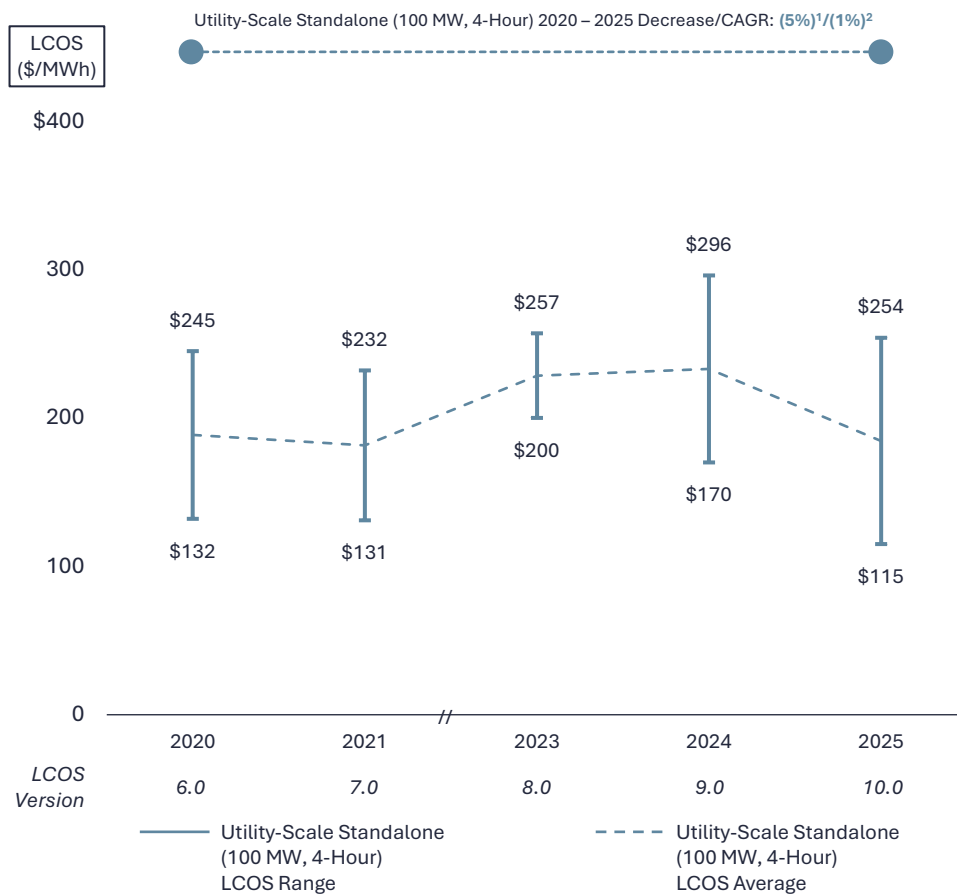
² This sensitivity analysis assumes that projects qualify for the full ITC and have a capital structure that includes sponsor equity, debt and tax equity and also includes a 10% Energy Community adder.

³ This sensitivity analysis assumes that projects qualify for the full ITC and have a capital structure that includes sponsor equity, debt and tax equity.

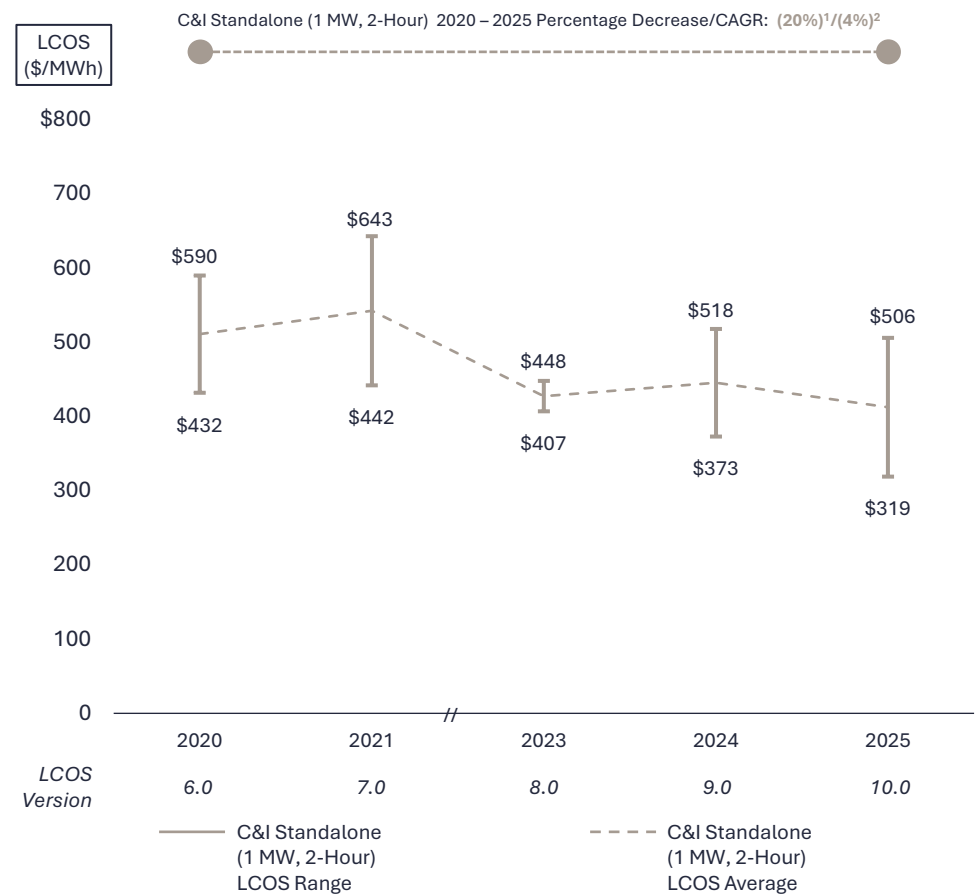
Levelized Cost of Storage Comparison—Historical LCOS Comparison

This year's analysis shows notable declines in the LCOS of utility scale and C&I battery energy storage systems. Key drivers include both market dynamics—slower-than-expected EV demand and the resulting oversupply of cells—and technological advancements, including increased cell capacity and energy density

Utility-Scale Standalone (100 MW, 4-Hour)



C&I Standalone (1 MW, 2-Hour)



Source: Lazard estimates and publicly available information.
 Note: The methodology for the Levelized Cost of Storage has evolved between v1.0 and v10.0 given technological advances and data availability. Page presents the most comparable Utility-Scale and C&I Standalone storage technologies included in the Levelized Cost of Storage report for that year.
 1 Reflects the average percentage increase/(decrease) of the high end and low end of the LCOS range.
 2 Reflects the average compounded annual growth rate of the high end and low end of the LCOS range.

Storage Value Snapshot Case Studies—Revenue Potential for Selected Use Cases

The numerous potential sources of revenue available to energy storage systems reflect the benefits provided to customers and the grid

- The scope of revenue sources is limited to those captured by existing or soon-to-be commissioned projects—revenue sources that are not clearly identifiable or without publicly available data have not been analyzed

	Description	Use Cases ¹				
		Utility-Scale Standalone	Utility-Scale PV + Storage	Utility-Scale Wind + Storage	Commercial & Industrial Standalone	Commercial & Industrial PV + Storage
Wholesale	Demand Response—Wholesale				✓	✓
	Energy Arbitrage	✓	✓	✓		
	Frequency Regulation	✓	✓	✓		
	Resource Adequacy	✓	✓	✓		
	Spinning/Non-Spinning Reserves	✓	✓	✓		
Utility	Demand Response—Utility				✓	✓
Customer	Bill Management				✓	✓
	Incentives				✓	✓

Storage Value Snapshot Case Studies—Overview

Lazard's Storage Value Snapshots analyze the financial viability of illustrative energy storage systems designed for selected use cases and geographies

		Location	Description	Storage (MW)	Generation (MW)	Storage Duration (hours)	Revenue Streams
In-Front-of-the-Meter Storage	1	CAISO ¹ (SP-15)	Large-scale energy storage system	100	–	4	<ul style="list-style-type: none"> • Energy Arbitrage
	2	ERCOT ² (South Texas)	Energy storage system designed to be paired with large solar PV facilities	50	100	4	<ul style="list-style-type: none"> • Frequency Regulation • Resource Adequacy
	3	ERCOT ² (South Texas)	Energy storage system designed to be paired with large wind generation facilities	50	100	4	<ul style="list-style-type: none"> • Spinning/Non-Spinning Reserves
Behind-the-Meter Storage	4	PG&E ³ (California)	Energy storage system designed for behind-the-meter peak shaving and demand charge reduction for C&I energy users	1	–	2	<ul style="list-style-type: none"> • Demand Response—Utility • Bill Management • Incentives
	5	PG&E ³ (California)	Energy storage system designed for behind-the-meter peak shaving and demand charge reduction services for C&I energy users	0.5	1	4	<ul style="list-style-type: none"> • Tariff Settlement, Demand Response Participation, Avoided Costs to Commercial Customer and Local Capacity Resource Programs

Source: Lazard estimates and publicly available information.

Note: Actual project returns may vary due to differences in location-specific costs, revenue streams and owner/developer risk preferences.

1 Refers to the California Independent System Operator.

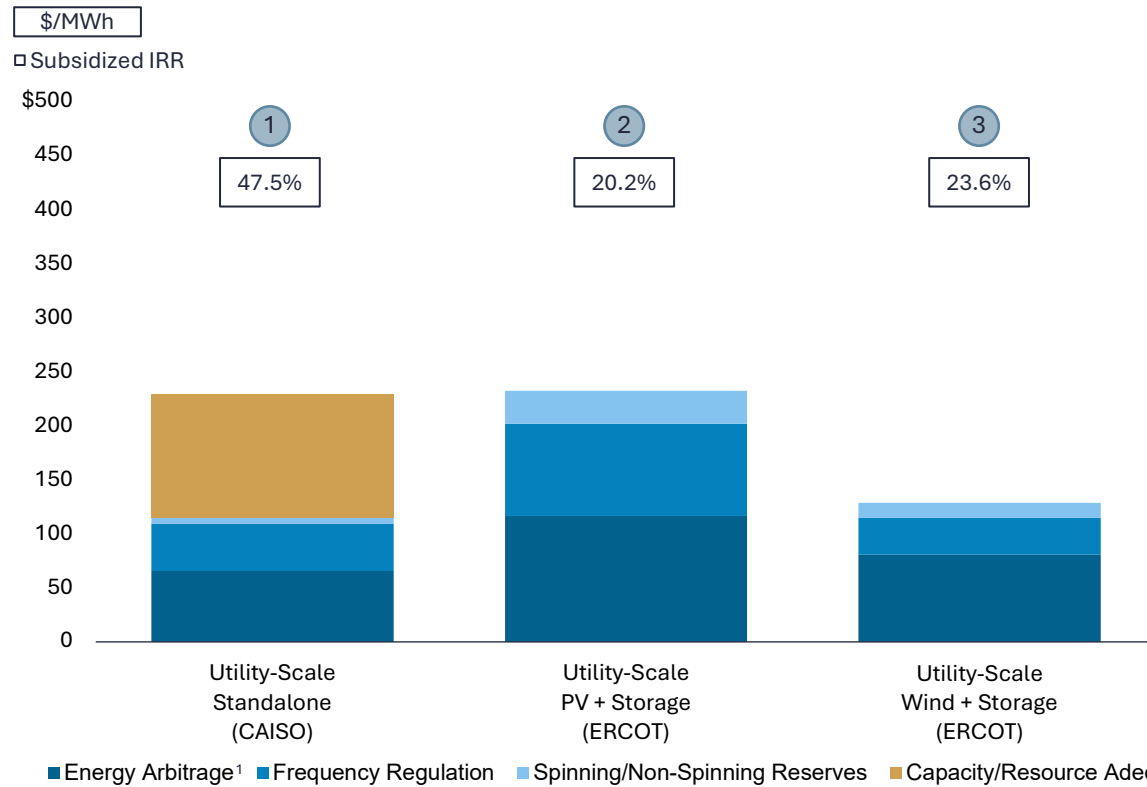
2 Refers to the Electricity Reliability Council of Texas.

3 Refers to the Pacific Gas & Electric Company.

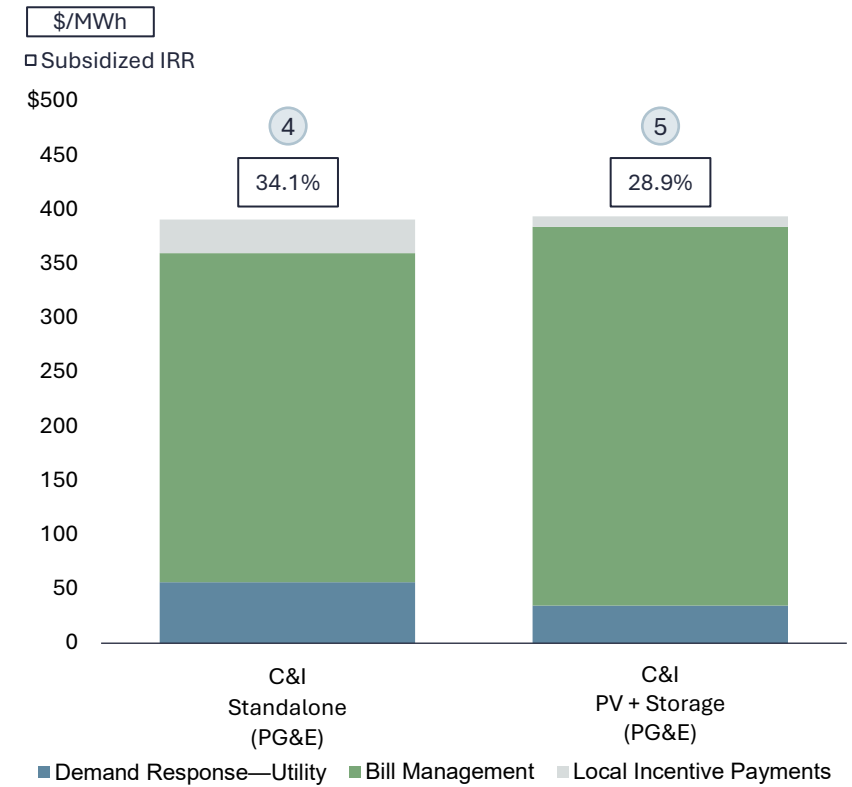
Storage Value Snapshot Case Studies—Results

Project economics evaluated in the Storage Value Snapshot Case Studies continue to evolve year-over-year as costs change and the value of revenue streams adjust to reflect underlying market conditions, utility rate structures and policy developments. Notably, this year capacity/resource adequacy payments nearly doubled which, combined with LCOS declines, significantly increased project returns

In-Front-of-the-Meter Storage



Behind-the-Meter Storage



Source: Lazard estimates and publicly available information.
 Note: Levelized costs presented for each Value Snapshot reflect local market and operating conditions (including installed costs, market prices, charging costs and incentives) and are different in certain cases from the LCOS results for the equivalent use case on the page titled "Levelized Cost of Storage Comparison—Version 10.0 (\$/MWh)", which are more broadly representative of U.S. storage market conditions as opposed to location-specific conditions. Levelized revenues in all cases are gross revenues (not including charging costs). Subsidized levelized cost for each Value Snapshot reflects: (1) average cost structure for storage, solar and wind capital costs, (2) charging costs based on local wholesale prices or utility tariff rates and (3) all applicable state and federal tax incentives, including 30% federal ITC for solar and/or storage and \$27.50/MWh federal PTC for wind. Value Snapshots do not include cash payments from state or utility incentive programs. Revenues for Value Snapshots (1) – (3) are based on hourly wholesale prices from the 365 days prior to December 31, 2024. Revenues for Value Snapshots (4) – (5) are based on the most recent tariffs, programs and incentives available as of February 1, 2025.
 In previous versions of this analysis, Energy Arbitrage was referred to as Wholesale Energy Sales.

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IV

Energy System

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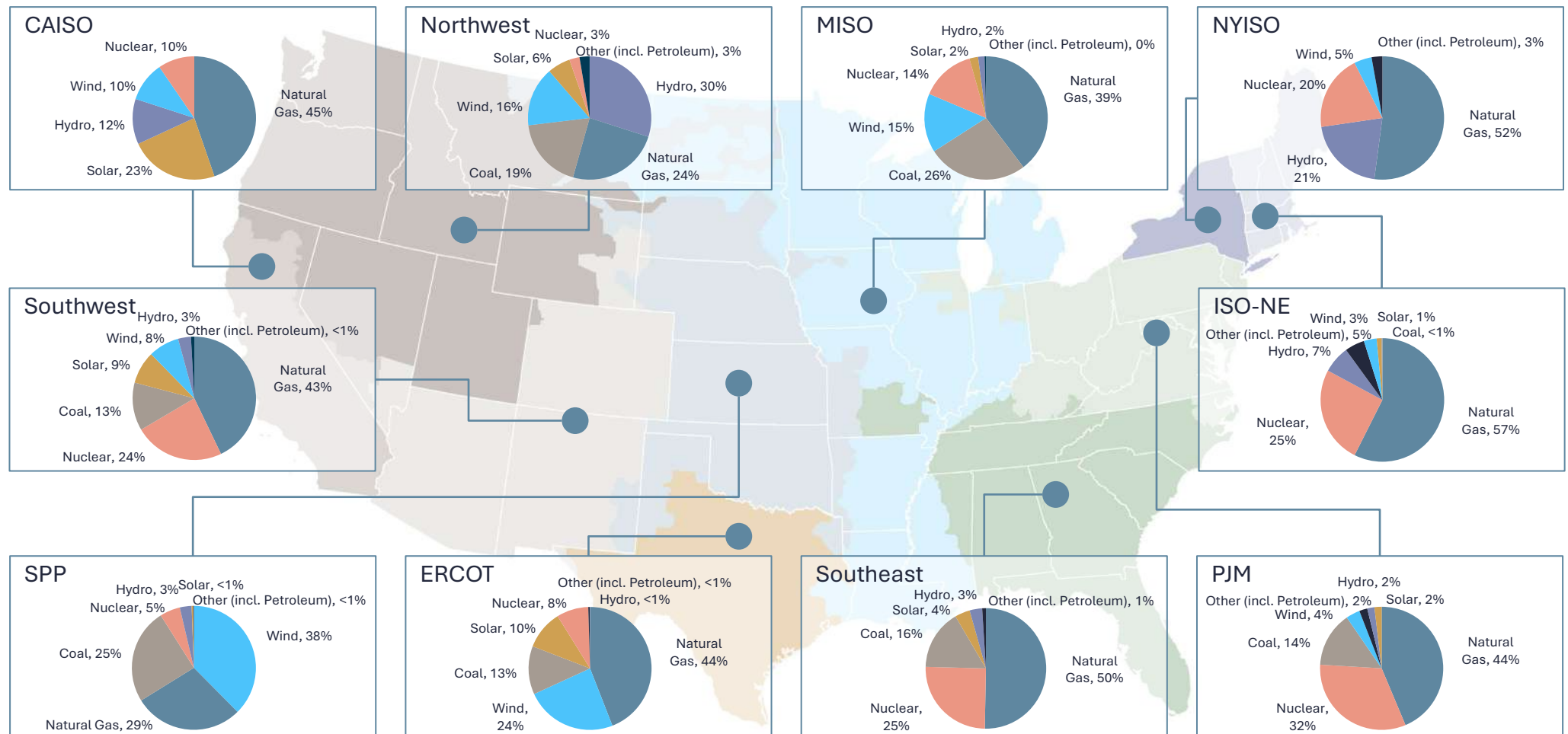
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Cost of Firming Intermittency

Market Overview—Current Generation Mix

The current generation mix across the U.S. varies significantly by market—resource availability, operational constraints, load profiles, transmission infrastructure, seasonal weather patterns and regulatory constructs, among other factors, are key drivers of such variation

2024 Generation Mix by Region



Market Overview—Current Firming Cost Frameworks

Many grid operators and utilities use effective load-carrying capability (“ELCC”) to measure the reliability of new power generation resources to contribute to the electricity grid at key periods of demand, particularly intermittent ones like wind and solar. Combined with the net cost of new entry (“Net CONE”)¹, as determined by the grid operator, ELCC helps to guide decisions on resource planning, capacity adequacy and system reliability. Balancing authorities (“BA”s) such as MISO, CAISO, SPP, PJM and ERCOT have adopted ELCC accreditation frameworks to ensure a reliable and efficient grid

- ELCC measures the performance of a resource at times of greatest “capacity need” for the system, where capacity need is a function of electricity demand patterns and the generation mix in each region—in general, the higher the renewable resource penetration, the lower the ELCC accreditation for each additional renewable resource

	BA-Specified “Firming” Source	ELCC Values ²	Net CONE ¹ (\$/kW-month)	Selected Market Commentary
MISO	Natural Gas Peaker	Solar: 39% Wind: 26%	\$10.03	<ul style="list-style-type: none"> • In March 2024, MISO adopted the FERC Reliability Availability and Need (“RAN”) seasonal capacity construct for wind and solar resources • Seasonal wind accredited capacity values are 18.1% for summer, 18.6% for fall, 53.1% for winter and 18.0% for spring • Solar capacity values are 50% for all seasons except winter, which is 5%
CAISO	4-Hour Lithium-Ion Battery	Solar: 7% PV + Storage ³ : 41% Wind: 12%	\$18.92	<ul style="list-style-type: none"> • Increasing levels of solar penetration in CAISO have shifted peak demand later in the day, reducing the ELCC value for solar • CAISO significantly reduced ELCC values for 4-hour battery storage systems, driven by significant growth in 4-hour storage capacity
SPP	Natural Gas Peaker	Solar: 51% Wind: 20%	\$8.38	<ul style="list-style-type: none"> • SPP published seasonal accreditation values based on 2024, assigning separate values to resources for summer and winter seasons • Summer wind and solar contributions are 15.2% and 25.5%, respectively, whereas winter values shift to 39.1% for wind and 62.2% for solar
PJM	Natural Gas Peaker	Solar: 12% PV + Storage ³ : 33% Wind: 38%	\$10.29	<ul style="list-style-type: none"> • PJM adopted a new, marginal ELCC methodology to begin in the 2025/2026 delivery year that reduces the reliability value of highly correlated resources, such as solar and short-duration storage⁴ • The update is expected to better capture expected resource performance during system peak
ERCOT	Natural Gas Peaker	Solar: 38% Wind: 25%	\$9.92	<ul style="list-style-type: none"> • ERCOT maintains notably high ELCC values despite having the highest renewable penetration by capacity of the U.S. regulatory markets • ERCOT updates its capacity scheme every three years; the most recent publication was December 2022

Source: Publicly available information.

¹ Net “CONE” is defined as capital and operating costs less expected market revenues for a new, firm resource (e.g., gas peaker or battery storage). Net CONE is established by the respective balancing authority.

² ELCC values are calculated by the respective balancing authority. ELCC is an indicator of the incremental reliability contribution of a given resource to the electricity grid based on its contribution to meeting peak electricity demand. For example, a 1 MW wind resource with a 15% ELCC provides 0.15 MW of capacity contribution and would need to be supplemented by 0.85 MW of additional firm capacity to represent the addition of 1 MW of firm system capacity. Where seasonal accreditation values exist, values have been annualized.

³ For PV + Storage cases, the effective ELCC value is represented. CAISO and PJM assess ELCC values separately for the PV and storage components of a system. Storage ELCC value is provided only for the capacity that can be charged directly by the accompanying resource up to the energy required for a 4-hour discharge during peak load. Any capacity available in excess of the 4-hour maximum discharge is attributed to the system at the solar ELCC. ELCC values for storage range from 55% to 75% for PJM and CAISO, respectively.

⁴ This year’s analysis does not reflect this future methodology.

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Cost of Firming Intermittency—Methodology

Lazard’s Cost of Firming Intermittency analysis builds on the LCOE results by evaluating system-level costs associated with supplementing intermittent renewable energy on the grid with firm capacity to ensure reliable electricity delivery during peak demand periods. The analysis utilizes ELCC and Net CONE values assessed and published by grid operators for each regional market to determine these costs

- The firm capacity value of a new resource is calculated as Nameplate Capacity × ELCC %, where:
 - Nameplate Capacity of a resource refers to its maximum potential energy output, and
 - ELCC measures the performance of a resource at times of greatest “capacity need” for the system, where capacity need is a function of electricity demand patterns and the generation mix in each region
- Over time, increased renewable penetration or changes in demand patterns can shift the timing of the capacity need, impacting ELCC
- The remaining non-firm capacity (Nameplate Capacity × (1 – (ELCC %))) is “firmed” at the Net CONE, a \$/kW-month figure which is intended to reflect capital and operating costs less expected market revenues for a new, firm resource (e.g., gas peaker or battery storage)
 - Net CONE is assessed and published by grid operators for each regional market

In the following analysis, the Levelized Firming Cost is defined as the additional capacity payment, priced at Net CONE, required to bring the ELCC of the combined system (intermittent and firming resource) to 100%. The LCOE plus Levelized Firming Cost varies between ISOs, due to (1) the standalone LCOE in the region based on regional capacity factor for wind or solar, (2) the ELCC value of the standalone renewable resource and (3) the region’s Net CONE

$$\frac{\text{Nameplate Capacity (kW)} \times (1 - \text{ELCC (\%)}) \times \text{Net CONE (\$/kW-month)} \times 12 \text{ Months}}{\text{Nameplate Capacity (MW)} \times \text{Regional Capacity Factor (\%)} \times 8,760 \text{ Hours}}$$

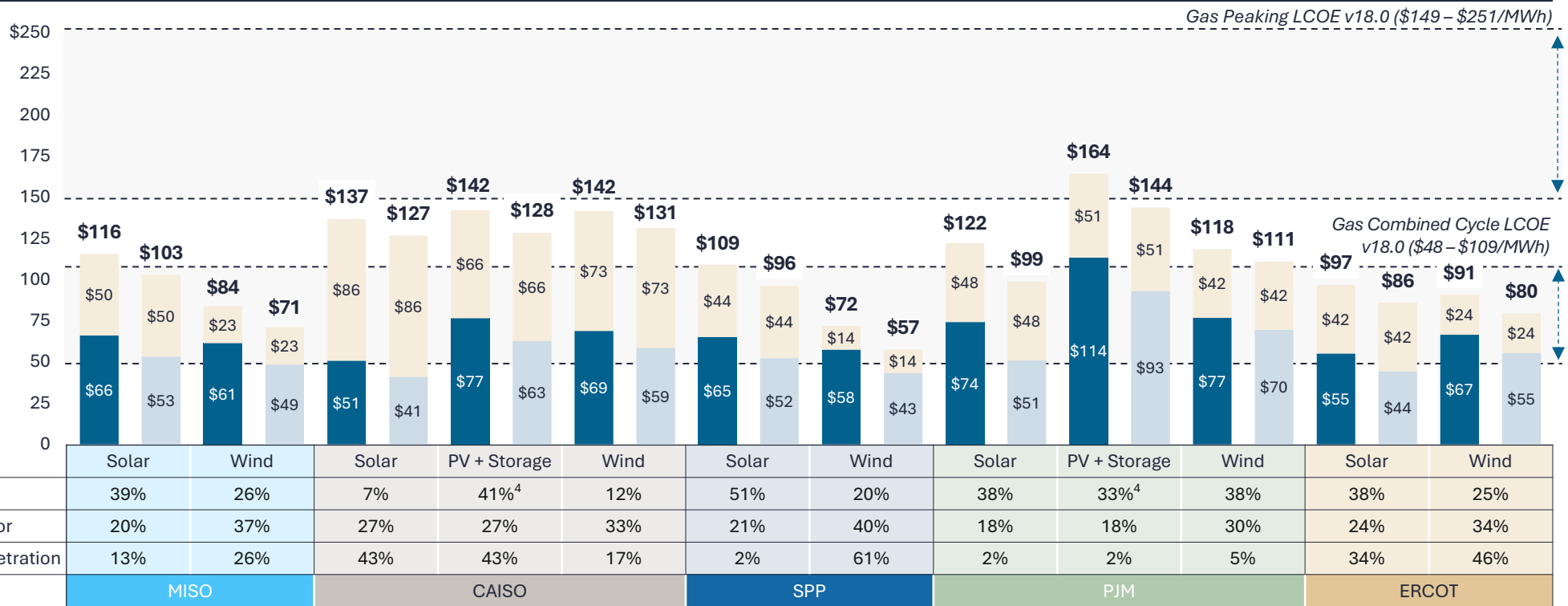


**Levelized Firming Cost
(\$/MWh)**

Cost of Firming Intermittency—Results

The Cost of Firming Intermittency or “firming cost” is the incremental cost to firm¹ solar, solar + storage or wind resources through additional monthly capacity payments to a firming resource under current regional system planning constructs

LCOE plus Levelized Firming Cost (\$/MWh)²



ELCC ³	39%	26%	7%	41% ⁴	12%	51%	20%	38%	33% ⁴	38%	38%	25%
Capacity Factor	20%	37%	27%	27%	33%	21%	40%	18%	18%	30%	24%	34%
Resource Penetration	13%	26%	43%	43%	17%	2%	61%	2%	2%	5%	34%	46%
	MISO		CAISO			SPP		PJM		ERCOT		

Source: Lazard estimates and publicly available information.

Note: Total, including firming cost, does not represent the cost of building a 24/7 firm resource on a single project site but, instead, the LCOE of a renewable resource and the additional capacity costs required to achieve the resource adequacy requirement in the relevant reliability region based on the net cost of new entry (“Net CONE”). ISO ELCC data as of April 2025 and representative of annualized ELCC values.

1 Firming costs reflect the cost of additional capacity required to supplement the net capacity of the renewable resource (nameplate capacity * (1 - ELCC)) and the Net CONE of a new firm resource (capital and operating costs, less expected market revenues). Net CONE is assessed and published by grid operators for each regional market. Grid operators use a natural gas peaker as the assumed new resource in MISO (\$10.03/kW-mo), SPP (\$8.38/kW-mo), PJM (\$10.29/kW-mo) and ERCOT (\$9.92/kW-mo). In CAISO, the assumed new resource is a 4-hour lithium-ion battery storage system (\$18.92/kW-mo). For the PV + Storage cases in CAISO and PJM, assumed storage configuration is 50% of PV capacity and 4-hour duration.

2 Reflects the average of the high and low of Lazard’s LCOE v18.0 for each technology using the regional capacity factor, as indicated, to demonstrate the regional differences in project costs.

3 ELCC is an indicator of the incremental reliability contribution of a given resource to the electricity grid based on its contribution to meeting peak electricity demand. For example, a 1 MW wind resource with a 15% ELCC provides 0.15 MW of capacity contribution and would need to be supplemented by 0.85 MW of additional firm capacity in order to represent the addition of 1 MW of firm system capacity.

4 For PV + Storage cases, the effective ELCC value is represented. CAISO and PJM assess ELCC values separately for the PV and storage components of a system. Storage ELCC value is provided only for the capacity that can be charged directly by the accompanying resource up to the energy required for a 4-hour discharge during peak load. Any capacity available in excess of the 4-hour maximum discharge is attributed to the system at the solar ELCC. ELCC values for storage range from 55% to 75% for PJM and CAISO, respectively.

5 This sensitivity analysis assumes that projects qualify for the full ITC, have a capital structure that includes sponsor equity, debt and tax equity and assumes the equity owner has taxable income to monetize the tax credits.



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LCOE

Appendix



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LCOE+

A

LCOE v18.0

Levelized Cost of Energy Comparison—Methodology

(\$ in millions, unless otherwise noted)

Lazard’s LCOE analysis consists of creating a power plant model representing an illustrative project for each relevant technology and solving for the \$/MWh value that results in a levered IRR equal to the assumed cost of equity (see subsequent “Key Assumptions” pages for detailed assumptions by technology)

Unsubsidized Onshore Wind — Low Case Sample Illustrative Calculations

Year ¹		0	1	2	3	4	5	30
Capacity (MW)	(A)		300	300	300	300	300	300
Capacity Factor	(B)		55%	55%	55%	55%	55%	55%
Total Generation ('000 MWh)	(C)* = (A) x (B)		1,445	1,445	1,445	1,445	1,445	1,445
Levelized Energy Cost (\$/MWh)	(D)		\$36.7	\$36.7	\$36.7	\$36.7	\$36.7	\$36.7
Total Revenues	(E)* = (C) x (D)		\$53.0	\$53.0	\$53.0	\$53.0	\$53.0	\$53.0
Total Fuel Cost	(F)		--	--	--	--	--	--
Total O&M	(G)*		7.4	7.5	7.7	7.9	8.0	14.0
Total Operating Costs	(H) = (F) + (G)		\$7.4	\$7.5	\$7.7	\$7.9	\$8.0	\$14.0
EBITDA	(I) = (E) - (H)		\$45.7	\$45.5	\$45.3	\$45.1	\$45.0	\$39.0
Debt Outstanding - Beginning of Period	(J)		\$342.0 ²	\$339.0	\$335.7	\$332.2	\$328.4	\$28.1
Debt - Interest Expense	(K)		(27.4)	(27.1)	(26.9)	(26.6)	(26.3)	(2.3)
Debt - Principal Payment	(L)		(3.0)	(3.3)	(3.5)	(3.8)	(4.1)	(28.1)
Levelized Debt Service	(M) = (K) + (L)		(\$30.4)	(\$30.4)	(\$30.4)	(\$30.4)	(\$30.4)	(\$30.4)
EBITDA	(I)		\$45.7	\$45.5	\$45.3	\$45.1	\$45.0	\$39.0
Depreciation (MACRS)	(N)		(114.0)	(182.4)	(109.4)	(65.7)	(65.7)	0.0
Interest Expense	(K)		(27.4)	(27.1)	(26.9)	(26.6)	(26.3)	39.0
Taxable Income	(O) = (I) + (N) + (K)		(\$95.7)	(\$164.0)	(\$91.0)	(\$47.1)	(\$47.0)	(\$2.3)
Tax Benefit (Liability)³	(P) = (O) x (tax rate)		\$38.5	\$65.9	\$36.6	\$18.9	\$18.9	(\$14.8)
After-Tax Net Equity Cash Flow	(Q) = (I) + (M) + (P)	(\$228.0)⁴	\$53.7	\$81.0	\$51.5	\$33.7	\$33.5	(\$6.2)
IRR For Equity Investors			12%					

Key Assumptions ⁵	
Capacity (MW)	300
Capacity Factor	55%
Fuel Cost (\$/MMBtu)	\$0.00
Heat Rate (Btu/kWh)	0
Fixed O&M (\$/kW-year)	\$24.5
Variable O&M (\$/MWh)	\$0.0
O&M Escalation Rate	2.25%
Capital Structure	
Debt	60.0%
Cost of Debt	8.0%
Equity	40.0%
Cost of Equity	12.0%
Taxes and Tax Incentives:	
Combined Tax Rate	40%
Economic Life (years) ⁶	30
MACRS Depreciation (Year Schedule)	5
Capex	
EPC Costs (\$/kW)	\$1,900
Additional Owner's Costs (\$/kW)	\$0
Transmission Costs (\$/kW)	\$0
Total Capital Costs (\$/kW)	\$1,900
Total Capex (\$m)	\$570

Source: Lazard estimates and publicly available information.
 Note: Numbers presented for illustrative purposes only.
 * Denotes unit conversion.
 1 Assumes half-year convention for discounting purposes.
 2 Reflects initial debt financing to fund capex.
 3 Assumes full monetization of tax benefits or losses immediately.
 4 Reflects initial cash outflow from equity investors to fund capex.
 5 Reflects a “key” subset of all assumptions for methodology illustration purposes only. Does not reflect all assumptions.
 6 Economic life sets debt amortization schedule.

■ Technology-Dependent
 ■ Consistent Across Versions/Technologies

Levelized Cost of Energy—Key Assumptions

Renewable Energy: Solar PV

	Units	Renewable Energy: Solar PV			
		Community and C&I		Utility	
		Low	High	Low	High
Net Facility Output	MW	2.0		150	
Total Capital Cost	\$/kW	\$1,600	– \$3,300	\$1,150	– \$1,600
Fixed O&M	\$/kW-yr	\$13.00	– \$20.00	\$11.00	– \$14.00
Variable O&M	\$/MWh	—		—	
Heat Rate	Btu/kWh	—		—	
Capacity Factor	%	20%	– 15%	30%	– 20%
Fuel Price	\$/MMBTU	—		—	
Construction Time	Months	6		15	
Facility Life	Years	30		35	
Levelized Cost of Energy	\$/MWh	\$81	– \$217	\$38	– \$78

Levelized Cost of Energy—Key Assumptions (cont'd)

	Units	Renewable Energy					
		Geothermal		Wind—Onshore		Wind—Offshore	
		Low	High	Low	High	Low	High
Net Facility Output	MW	250		300		900	
Total Capital Cost	\$/kW	\$5,000	– \$6,460	\$1,900	– \$2,300	\$3,450	– \$6,550
Fixed O&M	\$/kW-yr	\$14.50	– \$15.75	\$24.50	– \$40.00	\$60.00	– \$91.50
Variable O&M	\$/MWh	\$9.05	– \$24.80	—	—	—	—
Heat Rate	Btu/kWh	—	—	—	—	—	—
Capacity Factor	%	90%	– 80%	55%	– 30%	55%	– 45%
Fuel Price	\$/MMBTU	—	—	—	—	—	—
Construction Time	Months	36		18		24	
Facility Life	Years	25		30		30	
Levelized Cost of Energy	\$/MWh	\$66	– \$109	\$37	– \$86	\$70	– \$157

Levelized Cost of Energy—Key Assumptions (cont'd)

		Renewable Energy: Hybrid Generation + Storage					
		Solar PV + Storage—Utility			Wind + Storage—Onshore		
Units		Low	High		Low	High	
Storage							
Power Rating	MW	50			50		
Duration	Hours	4			4		
Usable Energy	MWh	200			200		
90% Depth of Discharge Cycles/Year	%	350			350		
Roundtrip Efficiency	%	92%			92%		
Inverter Cost	\$/kW	\$19	–	\$50	\$19	–	\$50
Total Capital Cost (excl. Inverter)	\$/kWh	\$122	–	\$313	\$122	–	\$313
Storage O&M	\$/kWh	\$3.00	–	\$8.02	\$3.00	–	\$8.02
Generation							
Capacity	MW	100			100		
Capacity Factor	%	30.0%	–	20.0%	55.0%	–	30.0%
Project Life	Years	35			30		
Total Capital Cost	\$/kW	\$1,150	–	\$1,600	\$1,900	–	\$2,300
Fixed O&M	\$/kW	\$11.00	–	\$14.00	\$24.50	–	\$40.00
Extended Warranty Start	Year	3			3		
Warranty Expense % of Capital Costs	%	0.7%	–	1.9%	0.7%	–	1.9%
Charging Cost	\$/MWh	\$0.00			\$0.00		
Unsubsidized LCOE	\$/MWh	\$50	–	\$131	\$44	–	\$123

Levelized Cost of Energy—Key Assumptions (cont'd)

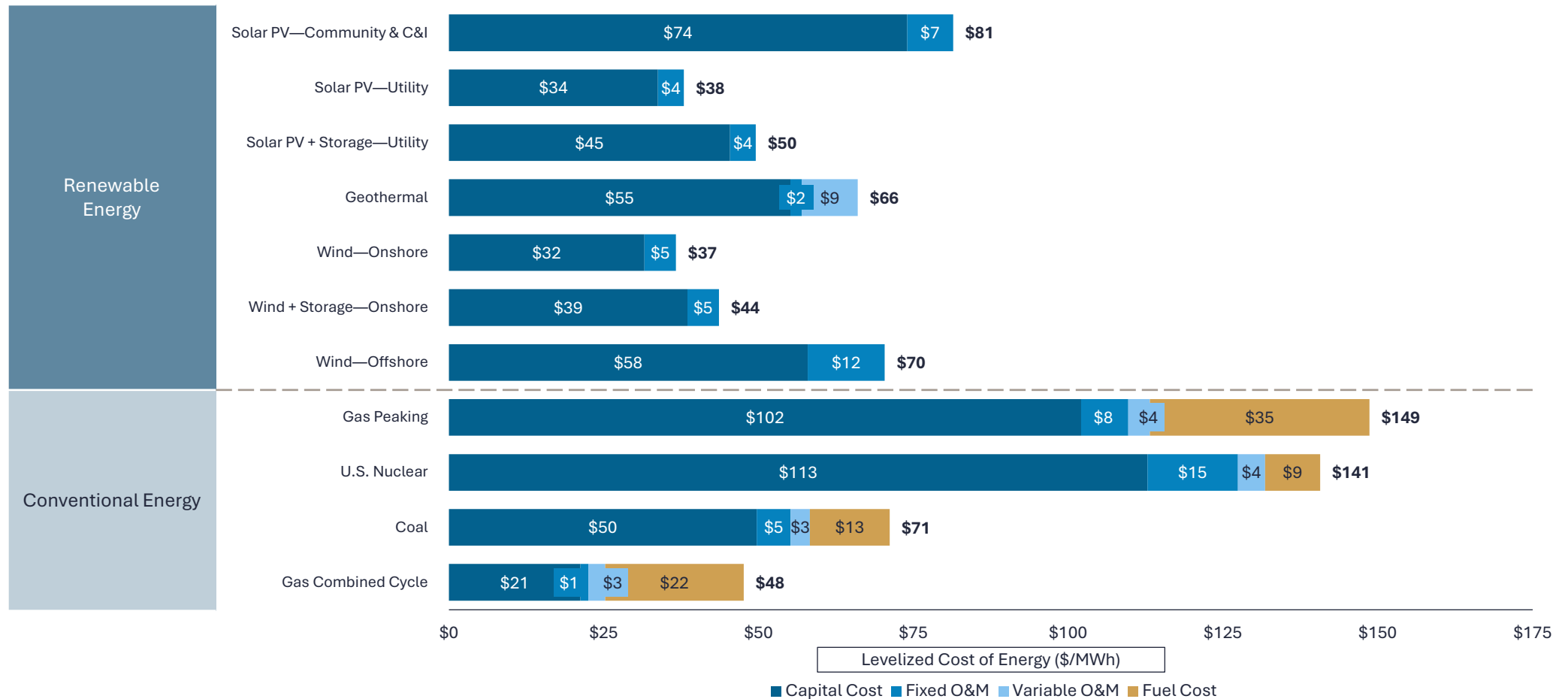
	Units	Conventional Energy							
		Gas Peaking (New Build)		U.S. Nuclear (New Build)		Coal (New Build)		Gas Combined Cycle (New Build)	
		Low	High	Low	High	Low	High	Low	High
Net Facility Output	MW	550	– 175	2,200		600		1,225	– 750
Total Capital Cost	\$/kW	\$1,150	– \$1,450	\$9,020	– \$14,820	\$3,405	– \$7,210	\$1,200	– \$1,600
Fixed O&M	\$/kW-yr	\$10.00	– \$17.00	\$136.00	– \$158.00	\$40.85	– \$94.35	\$10.00	– \$25.50
Variable O&M	\$/MWh	\$3.50	– \$5.00	\$4.40	– \$5.15	\$3.10	– \$5.70	\$2.75	– \$5.00
Heat Rate	Btu/kWh	10,275	– 11,175	10,450		8,750	– 12,000	6,475	– 6,550
Capacity Factor	%	15%	– 10%	92%	– 89%	85%	– 65%	90%	– 30%
Fuel Price	\$/MMBTU	\$3.45		\$0.85		\$1.47		\$3.45	
Construction Time	Months	24		84		60	– 66	24	
Facility Life	Years	30		70		40		30	
Levelized Cost of Energy	\$/MWh	\$149	– \$251	\$141	– \$220	\$71	– \$173	\$48	– \$109

Levelized Cost of Energy—Key Assumptions (cont'd)

		Marginal Cost of Selected Existing Conventional Generation							
	Units	Gas Peaking (Operating)		U.S. Nuclear (Operating)		Coal (Operating)		Gas Combined Cycle (Operating)	
		Low	High	Low	High	Low	High	Low	High
Net Facility Output	MW	240	– 50	2,200		600		550	
Total Capital Cost	\$/kW	\$0		\$0		\$0		\$0	
Fixed O&M	\$/kW-yr	\$4.00	– \$6.10	\$89.00	– \$121.60	\$21.70	– \$33.80	\$8.90	– \$13.60
Variable O&M	\$/MWh	\$2.70	– \$9.30	\$2.70	– \$3.90	\$3.20	– \$7.20	\$0.80	– \$1.80
Heat Rate	Btu/kWh	10,900	– 12,550	10,400	– 10,400	10,250	– 11,800	6,950	– 7,475
Capacity Factor	%	5%	– 1%	91%	– 87%	49%	– 7%	62%	– 17%
Fuel Price	\$/MMBtu	\$2.50	– \$2.90	\$0.80	– \$0.80	\$1.70	– \$2.40	\$2.50	– \$2.90
Construction Time	Months	24		84		60		24	
Facility Life	Years	30		70		40		30	
Levelized Cost of Energy	\$/MWh	\$47	– \$170	\$30	– \$38	\$31	– \$114	\$24	– \$39

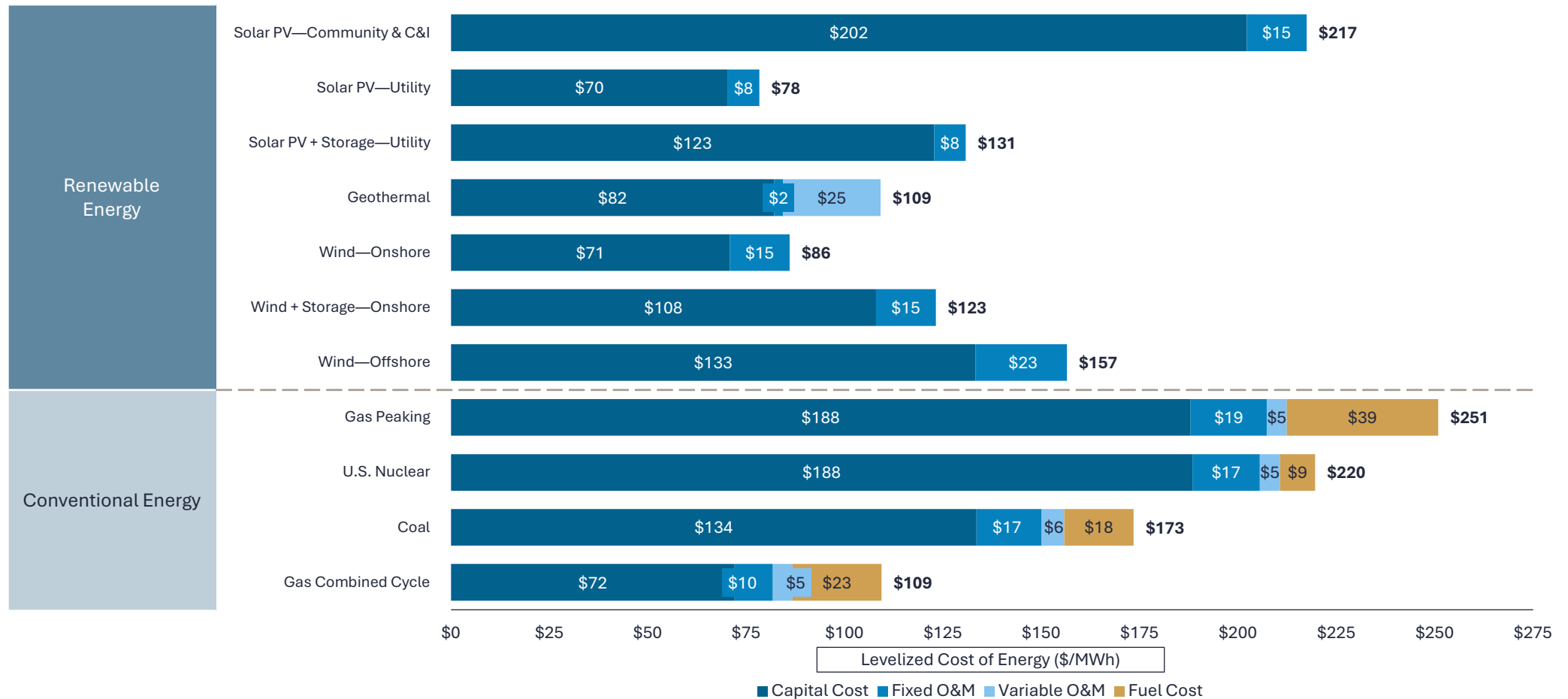
Levelized Cost of Energy Components—Low End (\$/MWh)

Certain renewable energy generation technologies are already cost-competitive with conventional generation technologies; key factors regarding the continued cost decline of renewable energy generation technologies are the ability of technological development and industry scale to continue lowering operating expenses and capital costs for renewable energy generation technologies



Levelized Cost of Energy Components—High End (\$/MWh)

Certain renewable energy generation technologies are already cost-competitive with conventional generation technologies; key factors regarding the continued cost decline of renewable energy generation technologies are the ability of technological development and industry scale to continue lowering operating expenses and capital costs for renewable energy generation technologies





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LCOE

B

LCOS v10.0

Levelized Cost of Storage Comparison—Methodology

(\$ in millions, unless otherwise noted)

Lazard’s LCOS analysis consists of creating a power plant model representing an illustrative project for each relevant technology and solving for the \$/MWh value that results in a levered IRR equal to the assumed cost of equity (see subsequent “Key Assumptions” page for detailed assumptions by technology)

Subsidized Utility-Scale Standalone (100 MW/200 MWh)—Low Case Sample Calculations

Year ¹		0	1	2	3	4	5	20
Capacity (MW)	(A)		100	100	100	100	100	100
Available Capacity (MW)		110	109	107	104	102	110	110
Total Generation ('000 MWh) ²	(B)*		63	63	63	63	63	63
Levelized Storage Cost (\$/MWh)	(C)		\$95	\$95	\$95	\$95	\$95	\$95
Total Revenues	(D)* = (B) x (C)		\$6.0	\$6.0	\$6.0	\$6.0	\$6.0	\$6.0
Total Charging Cost ³	(E)		(2.3)	(2.3)	(2.4)	(2.4)	(2.5)	(3.3)
Total O&M, Warranty, & Augmentation ⁴	(F)*		(0.6)	(0.6)	(0.8)	(0.8)	(2.6)	(1.1)
Total Operating Costs	(G) = (E) + (F)		(\$2.9)	(\$2.9)	(\$3.2)	(\$3.3)	(\$5.1)	(\$4.5)
EBITDA	(H) = (D) - (G)		\$3.1	\$3.0	\$2.8	\$2.7	\$0.9	\$1.5
Debt Outstanding - Beginning of Period	(I)		\$6.8 ⁵	\$6.6	\$6.4	\$6.3	\$6.1	\$0.6
Debt - Interest Expense	(J)		(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.1)
Debt - Principal Payment	(K)		(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.6)
Levelized Debt Service	(L) = (J) + (K)		(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
EBITDA	(H)		\$3.1	\$3.0	\$2.8	\$2.7	\$0.9	\$1.5
Depreciation (MACRS)	(M)		(5.4)	(8.6)	(5.2)	(3.1)	(3.1)	0.0
Interest Expense	(J)		(0.5)	1.7	0.0	0.0	0.0	(0.5)
Taxable Income	(N) = (H) + (M) + (J)		(\$2.9)	(\$3.9)	(\$2.4)	(\$0.4)	(\$2.2)	\$1.1
Tax Benefit (Liability)	(O) = (N) x (Tax Rate)		\$1.2	\$1.6	\$1.0	\$0.2	\$0.9	(\$0.4)
Federal Investment Tax Credit (ITC)	(P)		\$13.5	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0
After-Tax Net Equity Cash Flow	(Q) = (H) + (L) + (O) + (P)		(\$27.0)⁶	\$17.0	\$3.9	\$3.1	\$2.2	\$1.1
IRR For Equity Investors			12.0%					

Key Assumptions ⁷	
Power Rating (MW)	100
Duration (Hours)	2
Usable Energy (MWh)	200
90% Depth of Discharge Cycles/Day	1
Operating Days/Year	350
Charging Cost (\$/kWh)	\$0.033
Fixed O&M Cost (\$/kWh)	\$3.00
Fixed O&M Escalator (%)	2.5%
Charging Cost Escalator (%)	1.97%
Efficiency (%)	91%
Capital Structure	
Debt	20.0%
Cost of Debt	8.0%
Equity	20.0%
Cost of Equity	12.0%
Taxes	
Combined Tax Rate	40.2%
Economic Life (years)	20
MACRS (Year Schedule)	5 Years
Federal ITC - BESS	40%
Capex	
Total Initial Installed Cost (\$/kWh) ⁸	\$169
Extended Warranty (% of Capital Cost)	0.7%
Extended Warranty Start Year	3
Total Capex (\$m)	\$34

Source: Lazard estimates and publicly available information.
 Note: Numbers presented for illustrative purposes only.
 * Denotes unit conversion.
 1 Assumes half-year convention for discounting purposes.
 2 Total Generation reflects (Cycles) x (Available Capacity) x (Depth of Discharge) x (Duration). Note for the purpose of this analysis, Lazard accounts for degradation in the available capacity calculation.
 3 Charging Cost reflects (Total Generation) / [(Efficiency) x (Charging Cost) x (1 + Charging Cost Escalator)].
 4 O&M costs include general O&M (BESS plus any relevant Solar PV or Wind O&M, escalating annually at 2.5%), augmentation costs (incurred in years needed to maintain usable energy at original storage module cost) and warranty costs starting in year 3.
 5 Reflects initial debt financing to fund capex.
 6 Reflects initial cash outflow from equity sponsor.
 7 Reflects a “key” subset of all assumptions for methodology and illustration purposes only. Does not reflect all assumptions.
 8 Initial Installed Cost includes inverter cost, module cost, balance-of-system cost and EPC cost.

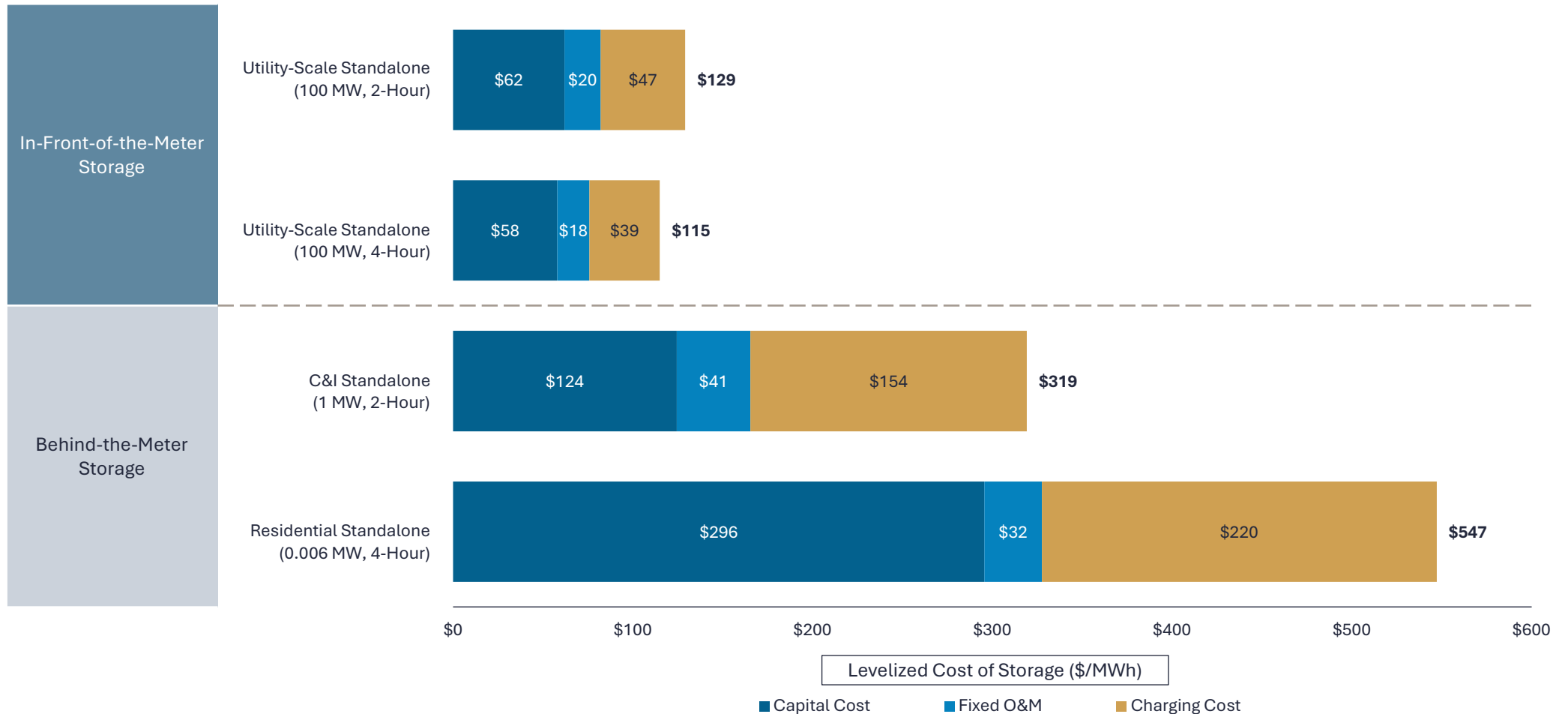
■ Technology-Dependent
 ■ Consistent Across Versions/Technologies

Levelized Cost of Storage—Key Assumptions

	Units	Utility-Scale Standalone			C&I Standalone			Residential Standalone					
		(100 MW/200 MWh)			(100 MW/400 MWh)			(1 MW/2 MWh)			(0.006 MW/0.025 MWh)		
Power Rating	MW	100			100			1			0.006		
Duration	Hours	2.0			4.0			2.0			4.2		
Usable Energy	MWh	200			400			2			0.025		
90% Depth of Discharge Cycles/Day	#	1			1			1			1		
Operating Days/Year	#	350			350			350			350		
Solar/Wind Capacity	MW	0.00			0.00			0.00			0.000		
Annual Solar/Wind Generation	MWh	0			0			0			0		
Project Life	Years	20			20			20			20		
Annual Storage Output	MWh	63,000			126,000			630			8		
Lifetime Storage Output	MWh	1,260,000			2,520,000			12,600			158		
Initial Capital Cost—DC	\$/kWh	\$113	–	\$244	\$107	–	\$232	\$238	–	\$445	\$721	–	\$1,338
Initial Capital Cost—AC	\$/kW	\$26	–	\$70	\$25	–	\$67	\$40	–	\$80	\$0	–	\$0
EPC Costs	\$/kWh	\$29	–	\$122	\$28	–	\$116	\$56	–	\$168	\$0	–	\$0
Solar/Wind Capital Cost	\$/kW	\$0	–	\$0	\$0	–	\$0	\$0	–	\$0	\$0	–	\$0
Total Initial Installed Cost	M \$	\$31	–	\$80	\$56	–	\$146	\$1	–	\$1	\$0	–	\$0
Storage O&M	\$/kWh	\$3.0	–	\$8.2	\$3.0	–	\$8.0	\$7.3	–	\$9.1	\$0.0	–	\$0.0
Extended Warranty Start	Year	3			3			3			3		
Warranty Expense % of Capital Costs	%	0.65%	–	1.50%	0.66%	–	1.85%	0.50%	–	1.30%	0.00%	–	0.00%
Investment Tax Credit (Solar)	%		0%			0%			0%			0%	
Investment Tax Credit (Storage)	%	30.00%	–	40.00%	30.00%	–	40.00%	30.00%	–	40.00%	30.00%	–	40.00%
Production Tax Credit	\$/MWh	\$0			\$0			\$0			\$0		
Charging Cost	\$/MWh	\$33			\$27			\$111			\$152		
Charging Cost Escalator	%	1.97%			1.97%			1.97%			1.97%		
Efficiency of Storage Technology	%	91%	–	87%	92%	–	86%	92%	–	88%	91%	–	88%
Unsubsidized LCOS	\$/MWh	\$129	–	\$277	\$115	–	\$254	\$319	–	\$506	\$547	–	\$860

Levelized Cost of Storage Components—Low End (\$/MWh)

Capital costs, fixed operating costs and charging costs contribute to the all-in cost in varying proportions depending on the specific energy storage use case and configuration



Levelized Cost of Storage Components—High End (\$/MWh)

Capital costs, fixed operating costs and charging costs contribute to the all-in cost in varying proportions depending on the specific energy storage use case and configuration



Energy Storage Use Cases—Overview

By identifying and evaluating selected energy storage applications, Lazard’s LCOS analyzes the cost of energy storage for in-front-of-the-meter and behind-the-meter use cases

		Use Case Description	Technologies Assessed
In-Front-of-the-Meter Storage	Utility-Scale Standalone	<ul style="list-style-type: none"> • Large-scale energy storage system designed for rapid start and precise following of dispatch signal • Variations in system discharge duration are designed to meet varying system needs (i.e., short-duration frequency regulation, longer-duration energy arbitrage¹ or capacity, etc.) <ul style="list-style-type: none"> – To better reflect current market trends, this analysis analyzes 2- and 4-hour durations² 	<ul style="list-style-type: none"> • Lithium Iron Phosphate (LFP) • Lithium Nickel Manganese Cobalt Oxide (NMC)
Behind-the-Meter Storage	Commercial & Industrial Standalone	<ul style="list-style-type: none"> • Energy storage system designed for behind-the-meter peak shaving and demand charge reduction for C&I users <ul style="list-style-type: none"> – Units are often configured to support multiple commercial energy management strategies and provide optionality for the system to provide grid services to a utility or the wholesale market, as appropriate, in a given region 	<ul style="list-style-type: none"> • Lithium Iron Phosphate (LFP) • Lithium Nickel Manganese Cobalt Oxide (NMC)
	Residential Standalone	<ul style="list-style-type: none"> • Energy storage system designed for behind-the-meter residential home use—provides backup power and power quality improvements <ul style="list-style-type: none"> – Depending on geography, can arbitrage residential time-of-use (“TOU”) rates and/or participate in utility demand response programs 	<ul style="list-style-type: none"> • Lithium Iron Phosphate (LFP) • Lithium Nickel Manganese Cobalt Oxide (NMC)

Source: Lazard estimates and publicly available information.
 1 For the purposes of this analysis, “energy arbitrage” in the context of storage systems paired with solar PV includes revenue streams associated with the sale of excess generation from the solar PV system, as appropriate, for a given use case.
 2 The Value Snapshot Case Studies only evaluate the 4-hour utility-scale use case.

Energy Storage Use Cases—Illustrative Operational Parameters

Lazard’s LCOS evaluates selected energy storage applications and use cases by identifying illustrative operational parameters ¹

- Energy storage systems may also be configured to support combined/“stacked” use cases

		A	B			C	B x C = D	E	F	D x E x F = G	A x G = H
		Project Life (Years)	Storage (MW) ²	Solar/Wind (MW)	Battery Degradation (per annum)	Storage Duration (Hours)	Nameplate Capacity (MWh) ³	90% DOD Cycles/Day ⁴	Days/Year ⁵	Annual MWh ⁶	Project MWh
In-Front-of-the-Meter Storage	Utility-Scale Standalone	20	100	–	2.6%	2	200	1	350	63,000	1,260,000
		20	100	–	2.6%	4	400	1	350	126,000	2,520,000
Behind-the-Meter Storage	Commercial & Industrial Standalone	20	1	–	2.6%	2	2	1	350	630	12,600
	Residential Standalone	20	0.006	–	1.9%	4	0.025	1	350	8	158

 = “Usable Energy”⁷

Source: Lazard estimates and publicly available information.
 Note: Operational parameters presented herein are applied to Value Snapshot and LCOS calculations. Annual and Project MWh in the Value Snapshot analysis may vary from the representative project.
 1 The use cases herein represent illustrative current and contemplated energy storage applications.
 2 Indicates power rating of system (i.e., system size).
 3 Indicates total battery energy content on a single, 100% charge or “usable energy”. Usable energy divided by power rating (in MW) reflects hourly duration of system. This analysis reflects common practice in the market whereby batteries are upsized in year one to 110% of nameplate capacity (e.g., a 100 MWh battery actually begins project life with 110 MWh).
 4 “DOD” denotes depth of battery discharge (i.e., the percent of the battery’s energy content that is discharged). A 90% DOD indicates that a fully charged battery discharges 90% of its energy. To preserve battery longevity, this analysis assumes that the battery never charges over 95%, or discharges below 5%, of its usable energy.
 5 Indicates number of days of system operation per calendar year.
 6 Augmented to nameplate MWh capacity as needed to ensure usable energy is maintained at the nameplate capacity, based on Year 1 storage module cost.
 7 Usable energy indicates energy stored and available to be dispatched from the battery.

LAZARD LCOE+

LCOS V10.0

Lazard's LCOE+ will continue to evolve over time, and we appreciate that there can, and will be, varied views regarding the specifics of our analyses. Accordingly, we would be happy to discuss any of our underlying assumptions and analyses in further detail—and, to be clear, we welcome these discussions as we try to improve our studies over time. In that regard, the studies remain our attempt to contribute in a differentiated and impactful manner to the Industry.

More generally, Lazard remains committed to our Power, Energy & Infrastructure Group clients, who remain our highest priority. In that regard, we believe that we have the greatest allocation of resources and effort devoted to this sector of any investment bank. Further, we have an ongoing and intense focus on strategic issues that require long-term commitment and planning. Accordingly, Lazard strives to maintain its preeminent position as a thought leader and leading advisor to clients on their most important matters, especially in this Industry.

If you have any questions regarding this memorandum or Lazard's LCOE+, please feel free to contact any member of the Lazard Power, Energy & Infrastructure Group, including those listed below.

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