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On the impact of nuclear fusion power plants deployment on selected critical materials consumption

D.N. Dongiovanni [a,b,*], Y. Melese [c], F. Gracceva [d], C. Bustreo [e], A. von Müller [f]

[a] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Frascati, Italy
[b] NUClear Department, Via Enrico Fermi, 45 Frascati, Rome, 00044, Italy
[c] ABB E-mobility, Delft, Netherlands
[d] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Lungotevere Thaon di Revel 76, Rome, 00196, Italy
[e] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4, 35127, Padova, Italy
[f] Max Planck Institute for Plasma Physics, Boltzmann Str. 2, Garching, 85748, Germany

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ABSTRACT

Nuclear fusion is one of the possible energy supply technologies that can meet the demand of low-carbon energy. In fact, as an energy technology, it has the potential to supply significant amounts of energy from small fuel quantities without any emission of greenhouse gases. Fusion technology development efforts are currently ongoing in Europe within a roadmap oriented towards fusion adoption and global market integration in the second half of the century.

Nuclear fusion is commonly considered a sustainable technology in terms of resources, given the abundance of raw materials to be used as "fuel" (namely, deuterium and lithium). However, beside lithium which is indeed experiencing a phase of great exploitation in the electric vehicle sector, other key materials are deemed crucial for the deployment at large scale of such technology. Specifically, they are beryllium and lead, required for tritium breeding process; tungsten for plasma facing material; tantalum for functional impurities in steel; niobium for Superconducting Magnets; helium for cooling and for fuel cycle. All these materials have been selected in literature as "critical raw materials" for fusion.

An analysis of the possible impact of nuclear fusion power plants penetration in the energy market in terms of material resources consumption is proposed in this paper. With this goal, an estimation of the demand of fusion critical materials for building and operating a fusion power plant (FPP) based on the European baseline fusion reactor concept is presented. The possible role of fusion critical material demand by concurrent technology is also addressed as well as the potential role of material re-use/recycling in support of primary production to cover the corresponding material demand. The estimates of FPP material demand based on recent fusion EU DEMO reactor design are projected over time according to a plausible range of energy market fusion shares. Finally, projections of long-term global demand for non-fusion applications are presented for comparison and coupling with fusion-driven material demand. Criticalities emerge mostly on Be and Li with respect to FPP deployment. The first is scarce and primary production is low with respect to FPP expected demand. Criticalities on lithium emerge from the expected high concurrent demand from non-fusion applications and the need of enrichment in 6Li.

1. Introduction

Anthropogenic greenhouse gas emissions (mainly CO_2) are the main cause of global warming observed since the second half of the 20th century according to the Intergovernmental Panel for Climate Change (IPCC) [1]. As a risk minimization strategy, 195 countries have committed themselves to reduce such emissions (COP21) to limit global average temperature raise well-below 2 °C. Europe itself is committed to reach within few years a "climate-neutral" economy. In practice, this translates into a huge and urgent change in the energy supply system, providing to replace fossil-based energy technologies (Coal, oil, natural gas, etc.) with carbon-free technologies. At the same time, the global

* Corresponding author. Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Frascati, Italy.
E-mail address: danilo.dongiovanni@enea.it (D.N. Dongiovanni).

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demand for energy is foreseen to rise, driven by socio-economic factors such as growth in world population or GDP per capita in developing countries. So, against this backdrop, sustainable energy generation technologies both in terms of resource exploitation and environmental impact (carbon-free, implying no burdens for future generations) are needed. The evident challenges in the pathway towards a 100 % renewable electricity generation system [2], open chances for other technologies to enter the energy mix. Nuclear fusion is among the candidates to possibly contribute to the mix of electricity supply technologies fulfilling a future low-carbon energy demand. In fact, as energy technology it has the potential to supply significant amounts of energy from small fuel quantities with no greenhouse gases emissions during operational phase. Despite the mentioned promising features as energy source, several factors will contribute to the penetration of nuclear fusion technology into the energy market [3]. Both knowledge gaps for the full control of burning fusion plasmas and technological challenges [4–8] still prevent near-term deployment of fusion power. ITER, currently under construction in the Southern France [9] is the largest existing magnetic confinement fusion experiment and it is expected to enter in operation in a decade. ITER is meant to increase the knowledge about magnetically confined burning deuterium-tritium plasmas with the goal of achieving a net energy gain,[1] improving the knowledge on components/materials operating in a very challenging environment and testing tritium breeding capability thanks to the Test Blanket Module program [10]. The ITER timeline, that initially foresaw a first plasma around 2025, is currently being reviewed and the first plasma is expected by 2035. In parallel with ITER construction, a new generation of DEMOnstration power plants (DEMO) are entering the conceptual design phase with the purpose of demonstrating the commercial exploitability of fusion by addressing technological issues in an integrated manner and considering all relevant technology challenges besides the achievement of stable burning plasma. Among the most urging challenges, we mention: the development of materials able to withstand fusion loads (nuclear, thermal, magnetic) for the expected lifetime, tritium breeding and self-sufficiency [11,12,13], balance of plant and connection to the electric grid, plant availability [14,15]. Several DEMO plants are under design e.g. in Europe [16], China [17], Korea [18] and currently planned to start operations in the mid-40s.

Besides public sector investments, a significant effort on fusion research is emerging from the private sector with a variety of approaches to fusion energy exploitation, ranging from evolution of tokamak concepts based on breakthrough technologies (e.g. magnets technology in Ref. [19]) or proposing alternative ones (e.g. Ref. [20]). These efforts might accelerate technological advancements and anticipate fusion energy commercial availability [21]. So, there is currently great uncertainty about which fusion plant concept will emerge as a technologically feasible solution to produce electricity and when it will actually be available as an economically viable supplier in the energy market.

A near-term extrapolation from EUROfusion DEMO tokamak concept is here considered as reference FPP. In such context, the assumed roadmap for such FPP availability is targeting for mid-2050s, followed by more advanced and efficient generation expected for mid-2070s [22]. With an expected plant lifetime of around 40 years, the resulting time horizon considered for the present analysis is 2055–2100.

EUROfusion socio-economic studies (SES) project [23] is currently focusing on the understanding of socio-economic conditions favoring nuclear fusion penetration in the energy market. The SES project is aimed at assessing the conditions for economic viability of fusion as a power source [22,24] while highlighting potential limiting factors.

The present study focuses on sustainability of fusion as an energy source in terms of material needs and related material supply issues. Previous most complete assessments on fusion plants material consumption [25–27,95] have focused on the definition of “material needs” for a fusion power plant and compared the material requirements to the actual estimated availability. These analyses neglect the possible role of critical material demand by concurrent markets as well as the potential role of material re-use/recycling in supporting primary production to cover the final demand. Also, these analyses do not assess the potential supply of fusion material as a function of the fusion might enter the energy market. This aspect is partially addressed in Ref. [28] with a focus on tritium and breeder blanket materials. Projection of cumulated demand scaled with energy demand of two generic small and large size fusion plants are presented. Instead, in the present study the estimate of FPP material demand is based on recent fusion EU DEMO reactor baseline design. The fusion-driven material demand is then projected over time to match with two alternative (pessimistic and optimistic) fusion plant deployment scenarios. Projections of long-term global demand for non-fusion applications are also presented for each fusion critical material for comparison and coupling with material demand for FPPs. The global demand is also compared to primary and secondary production projections to highlight possible criticalities in the supply chain.

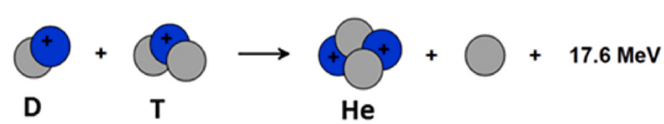
The first part of the document discusses material needs for a FPP, with estimates based on the EUROFusion DEMO material inventory derived from the available design datasheets (Section 2). Note that the EUROfusion DEMO design will be considered whenever DEMO is mentioned.

A list of potentially critical elements for FPPs construction and operation is then derived from the previous assessment and, for a selected subset of fusion relevant material elements, non-fusion usage estimates are derived. Such estimates are based on the current world reserve estimates and perspective usage. Future material demand is estimated on the basis of current trends taking into account consumption increase in drivers such as population growth or the role of recycling in limiting material production increase (Section 3).

Finally, in the last section, projections of fusion and non-fusion usage are compared to gain insights on the impact of FPP deployment on materials demand, at the same time, check whether some materials could potentially limit fusion installed capacity increase or whether a depletion issue may emerge from fusion deployment.

2. Estimation of nuclear fusion plant material needs

The basic principle of nuclear fusion is that the combination of two light atomic nuclei can result in a larger nucleus accompanied by release of energy. The nuclei of the hydrogen isotopes Deuterium and Tritium are considered as preferred reactor “fuel” in currently developed magnetic confinement fusion reactor concepts, exploiting the Deuteron – Tritium nuclear reaction.



Such reactions do not occur spontaneously though, so energy shall be actively provided to create a confined plasma achieving fusion conditions. The Lawson criterion [29] and its triple-product derivation, states the required condition for plasma density (n), temperature (T) and energy confinement time (τ_E) to achieve a self-sustaining process. The criterion identifies the self-sustainable process conditions by imposing net energy production after compensating for losses without external energy supply. In particular, fusion reactions generate an amount of power, P_{fus}, partly remaining available in the plasma as alfa particle kinetic energy to sustain the reaction. A breakeven point is achieved when the gain $Q = P_{fus}/P_{heat}$ equals 1. At same time part of plasma energy, P_{loss}, is lost through a variety of mechanisms such as convection of the fuel to the walls of the reactor chamber and various forms of

[1] ITER is designed to yield in its plasma a ten-fold return on power, or 500 MW of fusion power from 50 MW of input heating power.

radiation and cannot be captured within the plasma fuel (self-heating). To keep the reaction going additional heating energy, P_{heat}, must be then provided. This means that, in practice, higher Q values are needed to get to ignition, the condition where self-heating eventually removes the need for external heating.

Plasmas exploiting D-T reactions have the highest maximum reactivity occurring at the lowest temperature compared to the other possible fusion reactions such as Deuteron-Deuteron, Deuteron -3Helium, or the aneutronic proton −11Boron [30] reaction. In the D-T case, the minimal value for achieving ignition condition is reached with $nT\tau_E \geq 5 \times 10^{21}$ m^{-3} s KeV at about T = 14 KeV.

Several concepts have been proposed to achieve such conditions by exploiting either magnetic fields in various configurations to achieve plasma confinement or by heating and compressing a fuel target as in inertial fusion e.g. by means of laser beams [31]. Also, alternative confinement techniques such as Z-Pinch confinement or inertial electrostatic confinement or combined techniques have been proposed in the past and/or are object of current research, as summarized in Ref. [7]. In the present assessment, we will focus on magnetic confinement fusion based on the Tokamak concept. In particular, the European DEMO [32] design will be used as baseline for the assessment in terms of material needs. To estimate material inventory needed for the construction and operation of a single DEMO plant the material requirements from the whole foreseen 40-years' operating lifecycle is taken into account. The decommissioning phase is not considered.

The plant construction phase accounts for the material required to build the tokamak machine, hosting fusion specific systems based on tokamak technology, and the conventional power plant part, including balance of plant (BoP) and systems devoted to the conversion of heat into electricity and connection to the grid (e.g., steam generators, turbines, etc.). The plant operation phase considers material requirements in terms of fuel cycle and supplies (cooling, power, etc.). Finally, plant maintenance includes periodic replacement of components and possible material recycling and reuse.

2.1. Tokamak plant systems and components

Fig. 1 illustrates the main components of a magnetic confinement fusion reactor based on tokamak technology considered in the present assessment: the reaction chamber vacuum vessel which is surrounded by the cryostat chamber; the magnet system; the main in vessel components namely, breeding blanket and divertor. Other fusion-specific systems (e.g. plasma heating systems, fuel cycle processing systems, etc.) are not considered here due to the lack of detailed information concerning material usage.

2.1.1. Vacuum vessel and cryostat

Nuclear fusion reactions occur within a sealed toroidal chamber kept under ultra-high vacuum atmosphere (order of 10^{-5} Pa), hence called Vacuum Vessel (VV). Besides acting as a reaction chamber, the VV implements the safety function of confining radionuclides, namely tritium and activated dust deriving from wall material erosion. It is actively cooled and during plasma shutdowns or in case of accidental conditions, actively removes decay heat. Given its functions, the VV is designed as a double wall structure [33] to allow for cooling and confinement. Similarly to theITER VV, it will be mainly composed of austenitic steel 316L (N)-IG[2] with lower content of certain impurities (e.g. cobalt), to reduce activation. Due to diagnostics required for plasma control, the need for in-vessel components active cooling and their periodic replacement as well as the need for vacuum pumping and fuel refilling, the VV design requires several penetrations, ports and extensions. The VV is finally required to last for the entire operational lifetime of the plant without the need for replacement. This also results in a requirement for in-vessel components to shield the VV from nuclear loads.

To minimize the power requirement of the cryoplant and to shield thermal radiation at ambient temperature, both the magnetic coils and the VV are surrounded by a cryostat [34]. The cryostat is a pressurized vessel holding off the external air pressure and working at cryogenic temperature. The cryostat then provides a low emissivity ambient temperature surface thus enabling a thermally insulated vacuum around the cryogenic circuits. To estimate the material inventory for both VV and Cryostat the values provided by PROCESS reactor systems code [35] were exploited. PROCESS assesses the engineering and economic viability of a hypothetical fusion power station using simple models of all parts of a reactor system, from the basic plasma physics to the generation of electricity. PROCESS performs an optimization over a wide set of parameters under either physics or engineering constraints. In this specific case, the model referring to power plant conceptual studies [36] PPCS-AB was adopted as reference for VV and Cryostat size.[3] The PPCS-ABmodel is a near-term extrapolation concept with similar performances as those of models A (water-cooled lithium-lead breeder concept) and B (helium-cooled pebble bed breeder concept) (ref. to section 2.3). PPCS-AB presents helium-cooled lithium-lead blanket concept and it is used as reference for EUROFusion Times studies [23].

2.1.2. Magnetic field coils

The tokamak concept uses magnetic fields for plasma confinement and control. The magnetic fields are generated by several types of coils placed between the VV chamber and the cryostat. Very intense magnetic fields (peak value up to 16 T in DEMO) extending over large volumes (>1000 m^3) and acting stably for several hours are needed for plasma confinement. Traditional copper coils would pose a limitation in terms of sustainable current and heat losses, so that superconducting magnets are the only viable solution for FPP operating conditions.

We consider three main contributors [37] in terms of material inventory for the magnetic coils of a tokamak configuration. Superconducting cables are commonly laid within a steel jacket case along with helium cooling channels and copper-based channels for stabilization purposes (Fig. 1). The superconducting material currently used for the toroidal field coils (TF) is Nb_3Sn. NbTi is used for the Poloidal Field (PF) coils, that are needed for plasma shaping and control. Finally, the superconducting material in the Central Solenoid (CS) which is placed at the center of the toroidal chamber and is used at plasma start-up is Nb_3Sn.

The choice of superconducting material depends on different considerations [38] concerning for example critical field at the foreseen operation temperature around 4.5K (generally higher for Nb3Sn) and manufacturability (which is easier for NbTi).

NbTi and Nb_3Sn materials are Low Temperature Superconductors (LTS), hence requiring as mentioned around 4.5 K with a <3 K margin for temperature fluctuation. This small margin implies efficient and robust cooling by means of liquid helium and safety provisions to avoid/control possible release of associated magnetic energy and quick dissipation of significant currents. High Temperature Superconductors (HTS) offer an alternative to NbTi and Nb3Sn, as for example REBCO (Re-123) tapes can be used. These HTS are expected to extend the temperature domain over which they present superconducting properties, relaxing the constraints on temperature to keep the equipment within safe operational domain. Also, HTS superconducting magnets require less cooling energy for cooling and provide higher current density, despite being more expensive and harder to manufacture. In EU-DEMO, HTS technology has been proposed for central solenoid coils. Some preliminary studies on the feasibility of TF coils with HTS have been proposed in Ref. [37], though presenting some issues e.g. critical current

[2] A specific type of ultra-low carbon Cr-Ni-Mo austenitic steel – ITER GRADE (IG).

[3] Specifically, the total mass of Cryostat and VV were derived from PROCESS-PPCS-AB - dewmkg variable [102].

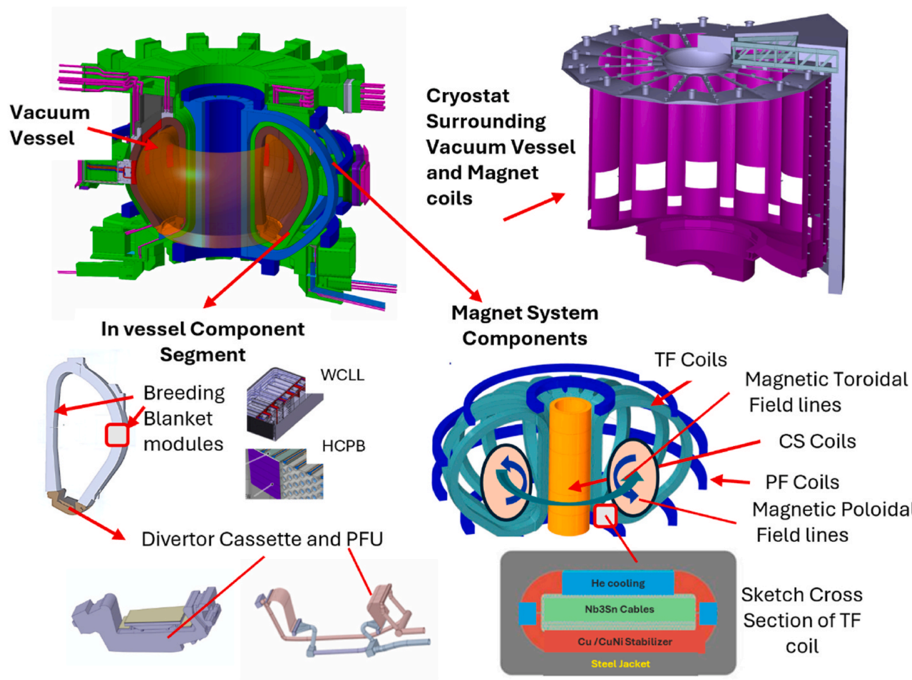


Fig. 1. Tokamak systems (image adapted from DEMO EFDA_D_2KVWQZ - PDD - Plant Description Document).

(Ic) degradation on neutron high fluence [39]. The scaling to DEMO size TF magnets currently appears challenging though HTS can possibly provide a mitigation strategy for Nb scarcity, especially in smaller size tokamak.

For the realization of the HTS superconductor, Rare Earth elements are used as well as other elements such as Barium, Copper and Oxygen. For the manufacturing of the tape, additional materials are used, such as Silver, Hastelloy and SnPb. Each Re-123 tape is made of Re-123 (~1 %), Hastelloy (~41 %), silver (~1 %) and SnPb solder (~57 %). For the material inventory assessment regarding the magnetic field coils, the densities used are the following: $\rho_{Cu} = 8960\ kg/m^3$, $\rho_{Nb3Sn} = 8950\ kg/m^3$, $\rho_{NbTi} = 6000\ kg/m^3$, $\rho_{Re\text{-}123} = 5000\ kg/m^3$, $\rho_{Steel} = 7860\ kg/m^3$.

As mentioned before, the baseline design coils are operated within superconducting regime for selected materials at about 4K so liquid Helium cooling is required. Copper is also foreseen to manage the event of possible abrupt losses of superconducting regime (quenches) and provide alternative paths for the electric current to quickly dissipate heat.

2.1.3. *Breeding blanket*

The breeding blanket (Fig. 1) is one of the main in-vessel components in a magnetic confinement fusion reactor. It is modular and is located inside the VV. It covers most of the internal surface area of the plasma chamber. The blanket modules have three main functions: i) to withstand and extract the heat originating from both the plasma and fusion neutrons ii) to breed tritium; iii) to provide a plasma interface material that can minimize plasma pollution by impurities and tritium trapping. Besides these functions, like all other plasma facing components, the blanket shall also shield the VV walls and the magnetic field coils from fusion neutrons. The second and most important function of the blanket, namely tritium breeding, arises from the fact that tritium is a rare element.[4] So, the fuel supply strategy adopted in tokamaks is to reach self-sufficiency [40] by continuously and efficiently breeding tritium by means of reactions occurring in the blanket modules among Lithium and neutrons generated by fusion reactions (Lithium: 6Li(n,α)3H, 7Li(n,n α) 3H). The 7Li(n,n α)3H reaction needs high energy neutrons to occur and absorbs energy. On the other hand, the 6Li(n,α)3H reaction requires slower neutrons to occur and releases energy. For this reason, the use of enriched lithium[5] (6Li) is required for properly breed tritium.

Despite the tritium breeding capability, an initial tritium inventory is required to start-up the plant and the breeding cycle. Currently, this start-up inventory is mainly foreseen to be obtained by HWRs (e.g. CANDU reactors), but surplus production in blanket modules shall ensure tritium start-up inventory for further FPPs. Alternative D-D start-up scenarios which avoid initial external tritium supply have been also proposed in Ref. [41], however highlighting that hundreds of discharges would be required before saturating the fueling systems with enough Tritium for a proper D-T operation.

Blanket modules are then filled with a breeding material comprising Lithium (from 60 % to 90 % enriched in Li_6). When estimating Lithium raw material needs, a multiplication factor shall be considered to account for 90 % and 60 % Li_6 enrichment from natural lithium isotope distribution.

In fact, the plant operation is initially started with a supplied tritium start-up inventory and subsequently relying on the neutron released by the D + T - > n + He reaction in the plasma to trigger 6Li(n,α)3H, 7Li(n,n α)3H reactions in order to be self-sufficient.

Due to unavoidable losses, to increase the breeding efficiency, elements providing neutron multiplication reactions such as lead (reaction 208 Pb(n,2n)) and beryllium (reaction 9Be(n,2n)) are needed.

Two main breeding blanket concepts are currently considered for the European DEMO: Water Cooled Lithium Lead (WCLL) [96] and Helium Cooled Pebble Beds (HCPB) [42,43]. The WCLL concept considers lithium in liquid phase withing an eutectic alloy with PB, while HCPB is commonly categorized among the solid lithium concepts.

The WCLL concept exploits an eutectic alloy made of liquid Lithium

[4] Tritium is not stable as it decays into Helium by means of beta decay – with approximately 12 years half-life. Tritium is naturally present on earth only in very small quantities due to 17N reactions in the upper atmosphere with cosmic rays. Tritium can be artificially produced by means of nuclear reactions with Deuterons in HWR (Heavy Water Reactor) fission reactors [104].

[5] Lithium isotopes average natural abundance is about 92.4 % and 7.6 % for 7Li and 6Li respectively.

and Lead (Li16Pb84) flowing into the breeding zone and acting both as breeding material and neutron multiplier. WCLL structures are actively cooled by water, while Helium is used to extract tritium from the LiPb alloy.

The HCPB concept uses pebbles out of BeTi as neutron multiplier and the so-called *KALOS-ACB* pebbles [65 %Mol-Li4SiO4 35 %Mol-Li2TiO3] as breeding material. Helium is exploited both as cooling fluid for structures and for purging of tritium.

For both the HCPB and WCLL concepts, a fusion specific reduced activation ferritic martensitic steel [44], EUROFER [45], is currently considered the preferred structural material.

2.1.4. Divertor

The so-called divertor is another key tokamak in-vessel component. It implements the following functions: i) to exhaust most of the plasma ions thermal power ii) to allow for exhaust neutral particle pumping in a region far from the plasma core to ensure and, at the same time, control an acceptable level of impurities in the plasma iii) to shieldthe VV walls in order to extend its lifetime to the expected lifetime of the plant. The current EU DEMO design [46,47] foresees the divertor as a modular assembly system composed by Plasma Facing Units (PFU) and a supporting cassette structure anchored to the tokamak vessel. PFUs include a W armour and CuCrZr cooling channels, while the supporting cassettes are mainly composed of EUROFER apart from a thin W layer covering the cassette surface exposed to plasma (liner and reflector plates). The current divertor concept is water-cooled.

Other than tokamak core components, FPP will be provided with a balance of plant (BoP) system to convert the heat removed from in-vessel components by means of heat transfer systems (HTSs) into electrical power thorough steam generators and turbines connected to the grid. Fusion plant would require the harmonization of BoP concept and conventional turbine to manage typical FPP pulsed operation. Some additional systems acting as energy buffer e.g., molten salts energy storage systems are under study for this purpose. Despite these issues the material inventory related to BoP and buildings is expected not to impact on demand of scares materials, so the related inventory has been derived from Ref. [48].

2.2. Estimation of inventory requirements for planned components replacement

To get a full estimation of the inventory needed throughout the whole expected plant lifetime (40 years), the contribution of planned components replacement and possible material recycling shall also be considered because of its relevant impact. It is worth specifying that in the present assessment the material inventory needed for component replacement due to unplanned failures is not estimated. As said, the vacuum vessel, the cryostat and the magnetic coils are components expected to last for the whole reactor lifetime, so the related material inventory equals the initial inventory needed for plant construction. Despite the possible effects of radiation on such components, and the uncertainty on radiation resistance behavior, e.g. for superconducting magnets [49], preventative replacements of such a component are not planned for EU-DEMO.

In-vessel components, namely the BB and divertor, are indeed subject to high nuclear and thermal loads and the number of replacements (**R**) will depend on specific capability to withstand the foreseen operational loads. In DEMO, a full replacement of divertor modules (cassette and PFU) is foreseen every 1.5 Full Power Year (FPY), while after a first replacement the BB is expected to last twice as long as the divertor [50].

The full replacement of divertor and BB modules would require about half a year. Note that different estimates are provided in literature for the time required for in-vessel component replacements. 20 months are reported in Ref. [51]; parametric studies [52,53] estimate a full replacement duration from 4 to 22 months. To match the FPP requirement of high availability (80 %), we assume a six-month replacement period taken from [Crofts 2014], using four remote handling systems.

An operating schedule interleaving campaigns and maintenance days [50], about 5 and 9 full replacements are respectively foreseen for BB and divertor components over 40 calendar years of plant operation. In Ref. [36] the divertor is expected to be replaced every two FPY for any PPCS model because of erosion, whilst the blanket every five FPY, corresponding to 150 dpa of neutron damage in steel.

Note that qualification studies on the actual ability of the steel structural material to withstand fusion-related phenomena (corrosion, activation, helium embrittlement etc.) are still ongoing and the assumed number of needed replacements is assumed as a balance between operational availability of the plant and load-withstanding requirements on in-Vessel components.

This is of course a source of uncertainty on the actual expected life for in Vessel components. In case the lifetime of material is found to be less than expected, the frequency of replacement would increase, and the 10-yrs average material refurbishment inventory increase accordingly.

Part of the materials of the in-vessel components can potentially be refurbished (i.e., promptly available for reuse) or recycled (i.e., become available for reuse in nuclear facility after on-site storage/treatments) because they are not fully degraded. The feasibility of reuse/recycling will depend on radiological and technological factors. In particular, key variables impacting on actual recycling feasibility and required time are: i) material contamination by tritium; ii) material activation and resulting contact dose rate [54], Gilbert [97], [55]; iii) decay heat [56] and iv) availability of processing technologies for segregation of radioactive species and reuse of the non-active component when required.

Tritium recovery is mandatory due to its high cost, its scarcity and the impact it can have on disposal (contact dose by beta-emitters). Tritium recovery is promoted by heat so that materials to be recycled should undergo heat treatments for the release of tritium within shielded hot cells.

Some radiological criteria to assess material availability for recycling processes have been proposed by Ref. [57,58] based on contact dose rate levels and decay heat. In particular, 2 mSv h^{-1} is considered as a reference limit for contact dose[6] above which maintenance must be performed on-site and by remote handling [54]. report on the same contact dose limit also for remote handling manipulation in view of the damage to electronic equipment. Concerning the impact of decay heat, a 2 kW/m^3 decay heat limit is considered for recycling operations by remote handling as active cooling would be required otherwise [59].

By combining the recycling process requirements together with the decay time needed before above-mentioned conditions for handling are achieved, an estimate of the actual possibility of material recycling for component refurbishment during the plant lifetime can be derived.

In particular, the ratio between the recycling time Tr (i.e. the time needed to treat the specific material so that it can be used for refurbishment) and the plant lifetime L (assumed to be 40 years long) is considered in a first approximation to characterize the fraction of initial inventory available for re-use. Considering a 6-month long term maintenance operation (LTM) for in-vessel component replacement (Divertor and Blanket) and given that a minimal Tr of 2 years is assumed[7] for recycling, at least 1 spare set of components for refurbishment shall be considered.

[6] Limit for dose rate at any point on the external surface of a package or overpack transportation [105].

[7] The assumption is also reported in Ref. [106]. Note that in absence of clear definition of recycling process, this period of time emerges from the minimal time needed for: i) extraction of components from inVV; ii) transport to on-site facility for preliminary detritiation treatment; iii) elapse of minimal time for contact dose/decay heat for cooling iv) segregation of components into homogeneous materials to recycle v) process the material to enable it to be recycled into new components.

As part of the EUROfusion program [60–62] the possibility to exploit currently available industrial processes for the recycling of fusion materials has been explored. EUROFER would satisfy the <2 kW/m^3 decay heat criterion within 10–20 years depending on the component, the blanket concept, and the position. The latter value would result into a *Tr*/L of 0.5. According to decay heat trends in Ref. [56], <2 kW/m^3 decay heat criterion is achievable for Be or Lithium within 2 years (*Tr*/L = 0.05). Lead and Lithium show different activation characteristics within the plant lifetime scale so that Lithium and Lead materials separation would be a requirement for Lithium recycling. So, Tr/L = 1 has been defined for Lead, while in the WCLL concept Lithium Tr/L ratio might range from 0.05 to 1 depending on the viability/efficiency of Lithium and Lead alloy segregation. Tungsten activity reaches contact dose acceptable levels within 10 years after shutdown [54,63]. Assuming a Tr of about 8 years would give for Tungsten a Tr/L = 8/40 = 0.2. Note that the amount of W included as alloying element within EUROFER (about 1 %) is of the same order of magnitude as the amount foreseen in PFCs, but W in PFC has lower Tr/L recycling time. Tantalum inventory is in the form of impurities in Steel, EUROFER, concrete. Recycling Tr/L = 1 impacts only on the number of elements in EUROFER. Other components characterized by large quantities of low activated material (e.g., Vacuum Vessel and magnets) will have good potential for being recycled considering that they are expected to last for the whole plant lifetime. AISI 316 needs some decades (about 80–100year, Tr/L = 2.5) but the choice for recycling (after interim storage ~ for 80 years, as currently occurring in fission power plants) will depend on other important aspects such as the economic viability of such recycling. Note that material recycling from plant decommissioning after 2100 is not considered in the present analysis. In summary, taking into account the initial inventory (I), the number of expected component replacements (R), and the ratio of minimal recycling time to plant lifetime Tr/L the total inventory **Q** per component/material in a FPP can be obtained as **Q= [1+ ((R + I)/I)T$_r$/L] *I** [Ward 2000]. Considering no direct reuse of materials from just extracted components (e.g. blanket modules), the multiplication factor to get the total inventory is I_f = max{2,[1+ ((R + I)/I)Tr/L]}. The 10-yrs averaged material needs are obtained as 10-yrsAMN=(Q- StartUp Inventory)/L*10.

Table 1 reports materials inventory for tokamak FPP core components meant to last for the plant lifetime. Materials for such components shall be available at the time of plant commissioning. They can be possibly recycled for other plants after the plant is decommissioned.

Table 2 reports materials inventory for EU-DEMO tokamak system core components for which one or multiple replacements discussed in Section 2.1) during plant lifetime are foreseen. For these components a start-up inventory is required at the time of plant commissioning and some refurbishment inventory is provided at later stages.

Note that given the considered time span of the analysis (2055–2100) and the plant lifetime (40 years), FPP plant material reuse/recycling to build other FPPs cannot be considered in the present work.

Conventional materials for plant construction were taken from Ref. [48]: 1.98E+05 tons of Steel SS316, 8.76E+05 and 8.07E+05 tons of ordinary and nuclear reinforced Concrete, respectively.

Table 3 aggregates the inventories reported for in-vessel components per material type for a single EU-DEMO plant as in Table 2, along with figures for conventional structures in a FPP (concrete, steel).

Table 4 shows the inventory aggregated per elements as resulting from Table 3. Such a list of elements is derived according to supply criticality, as elements both i) are required in significant amounts for a tokamak DEMO plant and ii) fall in the list of critical raw materials according to Ref. [64,65], namely: Li, Pb, He, W, Nb, Be, Ta.

Note that.

- The estimated amount of W as alloying impurity in EUROFER (about 1 %) is of the same order of magnitude as the amount foreseen in PFCs, but W in PFC has lower Tr/L recycling time;
- Ta contribution is in form of impurities in steel, EUROFER, concrete. Recycling Tr/L = 1 impacts only the amount within EUROFER, being the other component not replaced during the plant lifetime;
- Total Li wt% in KALOS-ACB is about 18.5 % leading to 30 tons of Li, enriched at 60 % in Li6;
- Be accounts for about 69 % of wt% of $Be_{12}Ti$;
- Multiplication estimated factors have been applied to the Lithium inventory resulting from breeding material estimated in Table 3 to account for 90 % and 60 % enrichment for WCLL and HCPB concepts. Specifically: EF_WCLL = 13.6: indeed a 90 % ^{6}Li enrichment requires approximately 13.6 times the amount of natural Lithium (kg) per WCLL grade Li (kg); EF_HCPB = 9: indeed, 60 % 6Li enrichment requires approximatively 9 times the amount of natural Lithium (kg) per HCPB grade Li (kg).

Table 1
Main components and materials inventory for a tokamak core for which no replacement over plant lifetime is planned. Figures derived from the current EUROfusion DEMO design.

Component	Subcomponent	Main materials	Start-Up Inventory [t]
Cryostat		ASME SA-240 Type 304L	5980
Vacuum Vessel	Double-wall In-wall shielding Port stubs Supports for in-vessel components	316L(N)-IG	7430
Coils	Toroidal Field Coils	Nb3Sn (t)	399
		Copper (t)	1161
		Steel Conduit (t)	2114
		Steel Case + Inter coil structures (t)	8206
	Poloidal Field Coils	NbTi (t)	47
		Copper (t)	293
		Steel Conduit (t)	3593
	Central Solenoid	REBCO (Re-123) (t)	6
		NbTi (t)	16
		Nb3Sn (t)*	[7–89]
		Copper (t)	290
		Steel Conduit (t)[a]	[1070–1463]
	Coolant	He	22
	Thermal shields coolant	He	0.39

[a] Inventory estimates from alternative design concepts. For the purpose of depletion analysis, the most conservative material supply need will be considered.

2.3. FPP driven material demand

Once the material inventory per FPP is defined (note that the focus of this study is on tokamak core components), the following step is to derive figures for the future growth rate of fusion energy supply during the considered time frame so to estimate the size of the operating FPP fleet. When considering the growth rates for new energy supply technologies (e.g. wind, PV and fission), an exponential pattern with a doubling time[8] of typically 3–5 years can be observed [66,67]. When considering the historical pattern of nuclear fission technology, fission energy production reached 2500 TWh [68] within about 40 years (1965–2005), with a doubling time of about 4.6 years before reaching a plateau.

Scenario analyses are also performed by means of the EUROfusion Times model to gain insights into the different parameters affecting FPP energy market penetration [Cabal 2016]. For the purpose of the present

[8] Defined here as the time needed to double the installed capacity for a given technology.

Table 2
Main components and materials inventory for an EU DEMO tokamak core for which one or more replacements over the plant lifetime are planned.

Component	Subcomponent	Main materials	Start-Up Inventory [t]	Replacements (R)	Recycling Time/Plant Lifetime (Tr/L)	Inventory Factor max{2,[1+ ((R + I)/I)Tr/L]}	10-yrs averaged material needs [t]	TOTAL Inventory over Plant lifetime Q [t]
Blanket WCLL concept	Armour	W	63	5	0.2	2.2	19	140
	First wall/ Structural	Eurofer	5890		0.5	4	4417	23559
	Breeder	Li (15.8) [90 % enrichment 6Li]	52		0.05	2	13	104
	Neutron Multiplier	Pb (84.2)	9413		1	7	14120	65892
	Coolant	Water	82					
Blanket HCPB concept	Armour	W	56	5	0.25	2.5	21	140
	First wall/ Structural	Eurofer	3052		0.5	4	2289	12206
	Breeder	KALOS-ACB [65 %Mol-Li4SiO4 35 %Mol-Li2TiO3] - [60 % enrichment 6Li]	160		0.05	2	40	320
	Neutron Multiplier	NMP- Be12Ti	613		0.05	2	153	1225
	Coolant	He	14		Leak Refilling			
	Purging gas	He	0.04					
Divertor	Cassette	Eurofer	271	9	0.5	6	339	1627
	Liner +	Eurofer	63		0.5	6	79	378
	Reflector Plates	W	5		0.2	3	2	15
	PFC	CuCrZr	2		1	11	5	22
		W	20		0.2	3	10	61

Table 3
Summary of material inventory of a Tokamak (estimated on the base of EUROfusion DEMO conceptual design).

	STARTUP		10-yrs avg. refurbishment	
	WCLL [t]	HCPB [t]	WCLL [t]	HCPB [t]
EUROFER	6224	3386	4835	2706
STEEL SS316, IG	7430		–	
Other Steel	21208		–	
CuCrZr	2		5	
Copper	1745		–	–
W	159	118	88	63
Li15.8/Pb	9483		14132	
KALOS-ACB [65 %Mol-Li4SiO4 35 %Mol-Li2TiO3]		160		40
BeTi		613		153
NbTi	63			
Nb3Sn	447			
Helium	23	59		
Concrete ordinary[a]	611			
Concrete Nuclear[b]	80			

[a] Data derived from [48].
[b] Data derived from [48].

Table 4
Critical elements requirements for a EU-DEMO like plant.

	START-UP		10-yrs avg. refurbishment	
	WCLL [t]	HCPB [t]	WCLL [t]	HCPB [t]
Lithium	705	272	176	68
Lead	9413		14120	
Helium	23	59		
Tungsten[a]	159	118	88	63
Niobium[b]	458	373	15	19
Beryllium		425		106
Tantalum[c]	8	5	6	3

[a] W is also present as 1.1 wt% of EUROFER and 0.02 wt% in Li16Pb84.
[b] Nb is also present as 0.005 wt% of EUROFER; 0.001 wt% of W; 0.01 wt% of SS316 IG steel; 0.001 wt% of Li16Pb84; 0.1 of CuCrZr.
[c] Ta is also present as 0.12 wt% of EUROFER; 0,002 wt% of W; 0.01 wt% of SS316 IG steel; 0.0001 wt% of CuCrZr.

Table 5
Fusion power deployment scenarios s compared to historical fission deployment.

Year	FUSION - FAST		FUSION - SLOW		*Nuclear FISSION Energy production*	
	Installed capacity [GW]	*Energy Production [TWh]*	*Installed capacity [GW]*	*Energy Production [TWh]*	Year	TWh
2050	3	18	1	7	**1965**	26
2060	11	74	4	28	**1975**	364
2070	38	264	14	101	**1985**	1.489
2080	152	1.067	27	192	**1995**	2.322
2090	395	2.768	71	498	**2005**	2.769
2100	1.024	7.179	184	1.293		

work that aims at understanding the potential impact of a fusion-driven demand on materials, the adopted approach is to consider upper and lower bounding patterns for the future FPP installed capacity. *Fusion slow* and *fusion fast* FPP deployment patterns were then assumed and defined by a curve of installed capacity as in Table 5. *Fusion fast* scenario is based on the best historical fission capacity growth pattern which is modified so to have a sustained capacity growth at 12 % after the first 2 decades (i.e. as if fission capacity growth had not been stopped by the occurrence of severe accidents in late 1970s–80s). The *fusion slow* scenario is limited by initial start-up tritium availability [40], requiring a tritium doubling time of 5 years for producing additional tritium for a new FPP to be started up. Recent scenario analyses on possible FPP energy market penetration [23] are all defined within the fusion fast/-fusion slow resulting capacity domain. Therefore, these two scenarios are assumed as bounding scenarios to estimate the fusion related material demand enabling FPP deployment rates over time.

To derive the annual demand from the above-mentioned installed capacity patterns the following additional assumptions were made.

Table 6
Start-Up Inventory materials considered for fusion power plants.

	START-UP		10-yrs avg. refurbishment	
	WCLL [t]	HCPB [t]	WCLL [t]	HCPB [t]
Lithium	1814	504	454	126
Lead	24223		36336	
Helium	23	59		
Tungsten	159	118	88	63
Niobium	458	373	15	19
Beryllium		787		196
Tantalum	8	5	6	3

- Supply Time: required material supply for a FPP to be started at year y0 has been spread over 5 years before y0. This considers the following:
  - o 12–18 month are needed from material order to material actual availability in common mineral extraction processes;
  - o FPP plant construction is assumed as long as for nuclear fission power plants, i.e. 5-7 years from commissioning [Shykinov 2016];
- Each new FPP requires an additional start-up inventory in the 5 years following its deployment to refurbish the in-vessel components (Blanket/Divertor) for first replacements;
- An average 80 % FPP availability is assumed. First generation FPPs are expected to achieve 75 % availability then improving up to 85 % availability over the following decades [Cabal 2016];
- Each FPP in operation requires an additional annual supply as large as the enriched Lithium consumption to be refurbished. With 80 % annual availability, ^{6}Li consumption $= 374\ \mathrm{g\ d^{-1}} * 365\ \mathrm{d\ y^{-1}} * 0.8 \sim \mathbf{110\ kg\ y^{-1}}$ per GWth.

Estimates of fusion material needs were performed with start-up inventories as reported in Table 6, partly modified from Table 4 to account for fusion power scaling from a DEMO reactor to a power plant.[9] Note that this scaling brings to a unit reactor size of 1.33 GWe (HCPB) −1.55 GWe (WCLL). This implies a lower material demand per GWe in the following figures to meet expected the required installed capacity. In fact, the PPCS/DEMO ratio in fusion power (e.g. PPCS A/DEMO-WCLL: 5GWth/1.943GWth) is lower than the electric power ratio (e.g. PPCS A/DEMO-WCLL 1.55GWe/0.5 GWe) for materials related to breeding (Lithium, Lead and Beryllium), while other materials are not scaled linearly since being comparable in size[10] (e.g. magnet materials).

The material annual demand driven by FPPs construction is reported in Fig. 2 for both Fusion Fast and Fusion Slow scenarios, considering unit plant material demands for each element considered in Table 6 and each breeding blanket concepts (WCLL, HCPB).

To visualize at glance the impact on materials of fusion power plant, one can consider material needs to for the production of a 1 PWh fusion electricity (with a fleet of about 152 GWe size, that can be achieved about 30 years after the initial commercialization with the Fission-like historical penetration rate) and relate it to currently estimated Reserves (dated 2022) and mine production for each material as shown in Fig. 3. Current reserves look sufficient to match fusion demand, except for Beryllium for which currently reserves appear insufficient (Fig. 3 – left). Fusion demand will impact on the annual mine production of lithium and more significantly of Beryllium (Fig. 3 – right).

It should be noted that considering *fusion fast* deployment scenario is conservative from the material demand perspective, since several factors could possibly reduce fusion technology penetration in the energy market, such as.

- Delays in raw material supply;
- Unavailability of material processing supply chain able to cope with required throughput. Consider as an example, the current uncertainty in selecting a both environmentally sustainable and industrially scalable ^{6}Li enrichment process [69];
- Regional effects in material provision, processing and delivery.

All these aspects might push the actual FPP penetration pattern in the energy market from *fusion fast* towards *fusion slow* scenario.

Another source of uncertainty resides in actual needs for spare sets of equipment for in-vessel components. The short time window currently foreseen (6–8 months) for in-vessel components replacements appears challenging to allow for immediate material re-use/recycling. This implies the requirement of at least one spare set of equipment. In case the re-use/recycling of in-vessel component materials would prove not economically viable, assuming only one spare equipment could then greatly underestimate the resulting material demand. Note in fact that divertor and blanket components would require about 9 and 5 replacements respectively.

Another uncertain aspect that should be mentioned is the possible differences arising in the material inventory in case a different power plant concept emerges from private sector. In [FIA 2024] different concepts are reported to be currently under investigation, with a median size around 200Mwe and operational dates distributed around the early mid-2030. The material demand in that case would be anticipated with possible differences in material supply due to differences on tons/MWe ratio and energy market penetration pattern.

3. Long term perspectives of fusion critical material supply

The future availability of materials is contingent upon the following factors: the current reserve[12] estimates and the rate at which materials can be produced and recycled.

Known resources and reserves of materials are reported for several countries. Data from the [70] is largely referenced and is the main source of data in the present study. Table 7 shows the resource and reserve levels as reported for the year 2020 for the elements shortlisted as critical in fusion (Table 4). All units are in metric tons, except for Helium, which is in cubic meters. Resource figures are reported to give context on material availability.

Other key drivers used in long-term projections scenarios available in the literature regarding material demand and supply are: i) population growth and world GDP increase on the demand side and ii) recycling dynamic and material reserves/depletion on the supply side. According to Ref. [71], global materials use is projected to more than double from 79 Gt in 2011 to 167 Gt in 2060, while GDP is projected to grow on

[9] Lithium, Beryllium and Lead start-up inventories in Table 4 were scaled by fusion power with respect to Power Plant Conceptual Studies (PPCS) [36].

- fusion power scaling for WCLL concept: PPCS WCLL fusion Power 5.0 GWth/DEMO POWER 1.943 GWth = 2.57
- fusion power scaling for HCPB concept = HCPB fusion Power 3.6 GWth/DEMO POWER 1.943 GWth = 1.85

[10] The major radius of the tokamak for DEMO, PPCS A and PPCS B are 9m, 9.55m, 8.6m respectively.

[12] Reserves: "That part of the reserve base which could be economically extracted or produced at the time of determination. Reserves include only recoverable materials ....''Reserve Base: "That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the .... resource from which reserves are estimated ... The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). Resources: A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible." [USGS].

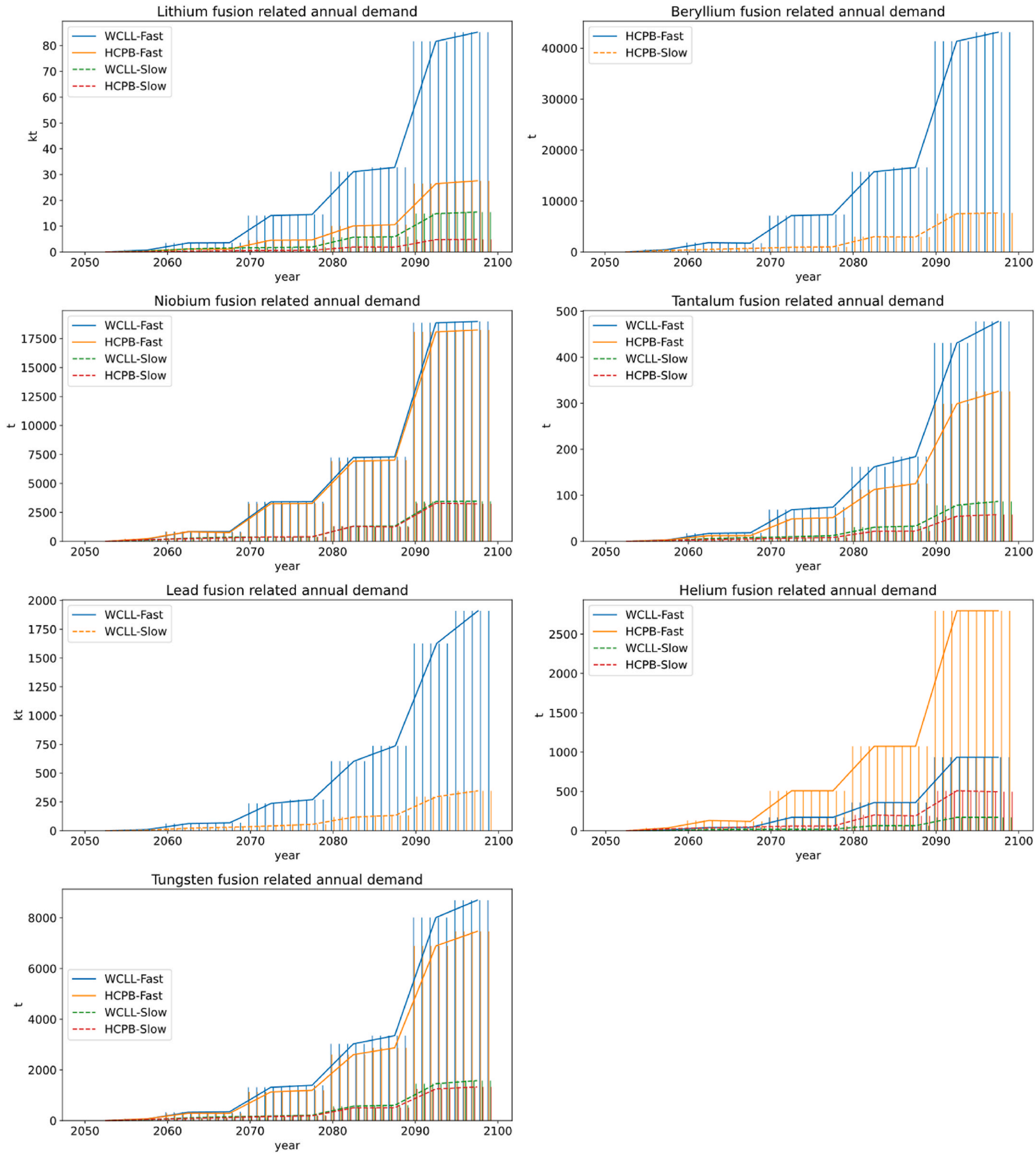


Fig. 2. Fusion usage projections for Fast and Slow fusion deployment scenario for the considered elements.[11][1].

average by 2.8 % annually between 2011 and 2060. When considering the coupled dynamics of material intensity[13] and GDP, materials intensity of the global economy is projected to decline more rapidly than in recent decades — at a rate of 1.3 % per year on average — implying a relative decoupling with global materials use increases, but not as fast as GDP. This can be possibly modeled by an increasing efficiency in material exploitation. In fact [72], suggested that with each passing generation, an increase in efficiency in mineral use can reasonably be expected, whether that be in the form of new technology less material demanding or advances in processing efficiency or simply by producing

[13] Quantity of materials used/manufacturing value added (at constant prices, international dollars).

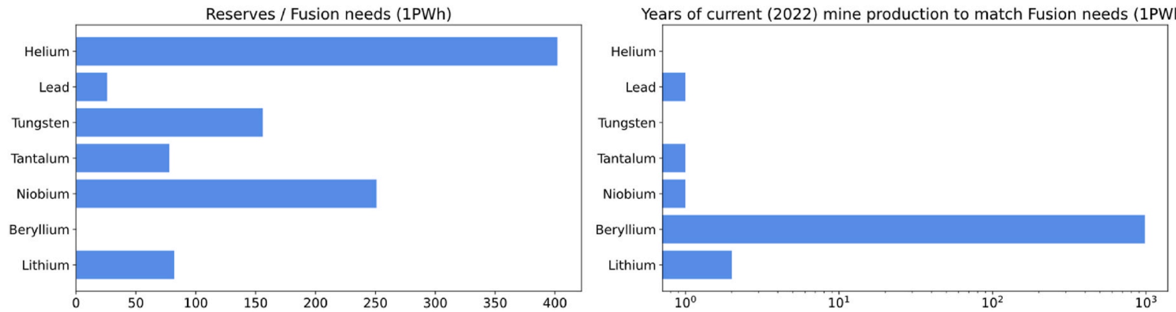


Fig. 3. Ratio between material reserves (2022 estimate) and cumulated material inventory for a fusion plant fleet generating 1 PWh per year (left). Ratio between fusion plant able to annually produce 1 PWh and current (2022 estimate) mine production (right).

Table 7
Materials facts: global resource and reserve level data for 2022 (USGS, 2024). Data in metric tons except Helium (cubic meters). W resources taken from Ref. [73].

Element	Resources	Reserves	[Resources]/[Reserves]	Mine production 2022	Reserves/Production 2022 ratio [years]
Lithium	8.90E+07	2.20E+07	4	1.32E+05	>100
Lead	2.00E+09	9.00E+07	22	4.38E+03	>1000
Helium	3.98E+10	8.50E+09	5	1.60E+02	>1000
Tungsten	7.00E+06	3.70E+06	2	7.84E+04	<100
Niobium	1.80E+07	1.70E+07	1	6.77E+04	>100
Beryllium	1.00E+05	2.00E+04	5	1.65E+02	>100
Tantalum	2.20E+05	9.40E+04	2	2.10E+03	<100

less mineral waste.

On the supply side, recycling is projected to become more competitive as compared to the extraction of primary materials. The strong increase in demand for materials implies that both primary and secondary materials use increases at roughly the same pace.

For simplicity we here define material usage (*U*) as the part of demand satisfied by production supply, hence disregarding material annual stocks. Production supply accounts for primary raw material production (i.e., mine production, *MP*) and secondary raw material production (i.e., material recovered from post-consumer scrap, recycling *R*). Then we can write:

$$U_i \sim P_{bas} = \mathrm{MP} + R_i \tag{1}$$

With the goal of deriving estimates for future material production concurrent to fusion driven usage for the considered materials, the proposed approach is to extrapolate future production by analyzing historical production data series to derive a baseline production projection (P_{bas}). A common modeling approach for production projections exploits a logistic function fit Hook [74] to extrapolate from historical production data series. This type of function enables the inclusion of Ultimate Recoverable Resources (URR) boundary information [75] in the production projection. In particular, the cumulative production at year i, $MP_{cum}(i)$, is then given by:

$$\mathrm{MPcum}(\mathrm{i}) = \frac{URR}{\left(1 + e^{-c(i-d)}\right)} + b \tag{2}$$

with.

b = offset value; c = logistic growth rate; d is the *i* value of the sigmoid midpoint.

Hence, given an estimation for URR for each material, the logistic parameters (*b, c, d*), are fitted to match historical trends for cumulative production. For this purpose, historical mine production data were taken from the United States Geological Survey (USGS) Mineral Commodities Summaries [76]. Fig. 4 shows the logistic fit on historical mine production data exploiting URR = Material Resources estimation provided in Table 7.

A baseline yearly production estimate (P_{bas}) is then derived from cumulative production in eq-1 as

$$MP_{bas}(i) = MP_{cum}(i+1) - P_{cum}(i). \tag{3}$$

This approach has the advantage of considering material depletion when approaching the URR. Fig. 5 shows Mine Production projections according to eq. (3). and related cumulative production model fitting (eq. (2)) when assuming URR equals the Resources/Reserves estimation provided in Table 7. As reference an [77] curve has been also shown, derived by applying to USGS 2020 mine production starting value an average annual growth rate for primary material extraction for metals of 0,72 % from 2020 and2060,[14] to USGS 2020 mine production.

Fig. 5 shows a significant dependency of the model on the bound introduced from the URR parameters. Mine production for Be, Nb, Ta and W starts decreasing under the effect of resource relative scarcity. Moreover, being based on historical data series information, it is poorly sensitive to recent increases in the material demand to satisfy, such as the new material demand emerging from technology changes opening new sectors of exploitation for mineral commodities (e.g. Electric Vehicles (EV) Lithium batteries) (ref Table A1-1).

Note that, given the intrinsic variability in the outcomes of logistic projections that depend on the assumptions on the set of parameters and related scenarios, the purpose of Fig. 5 is to compare such models including URR information with OECD models moving from socio-economic drivers and consistent as for the econometric perspective.

It is interesting to note that the energy transition for a net-zero climate impact is expected to drive additional demand for some materials, which in turn will have a not negligible environmental impact [78]. Focusing on the material demand projections [79], projects that Lithium production will increase by more than 450 % by 2050 due to the additional demand for energy transition, where Lithium demand is driven by energy storage technology. The fact that Lithium is intensively exploited for a single technology also increases uncertainty in the projections.

[14] Fig. 5.4 in Ref. [77]. Primary material extraction for metals is expected to growth of 10 % (2020 on 2017), 38 % (2030 on 2017), 126 % (2060 on 2017) respectively, with an annual growth rate of 0,72 % from 2020 to 2060. Primary material extraction for metals extrapolated from data https://doi.org/10.1787/888933884992.

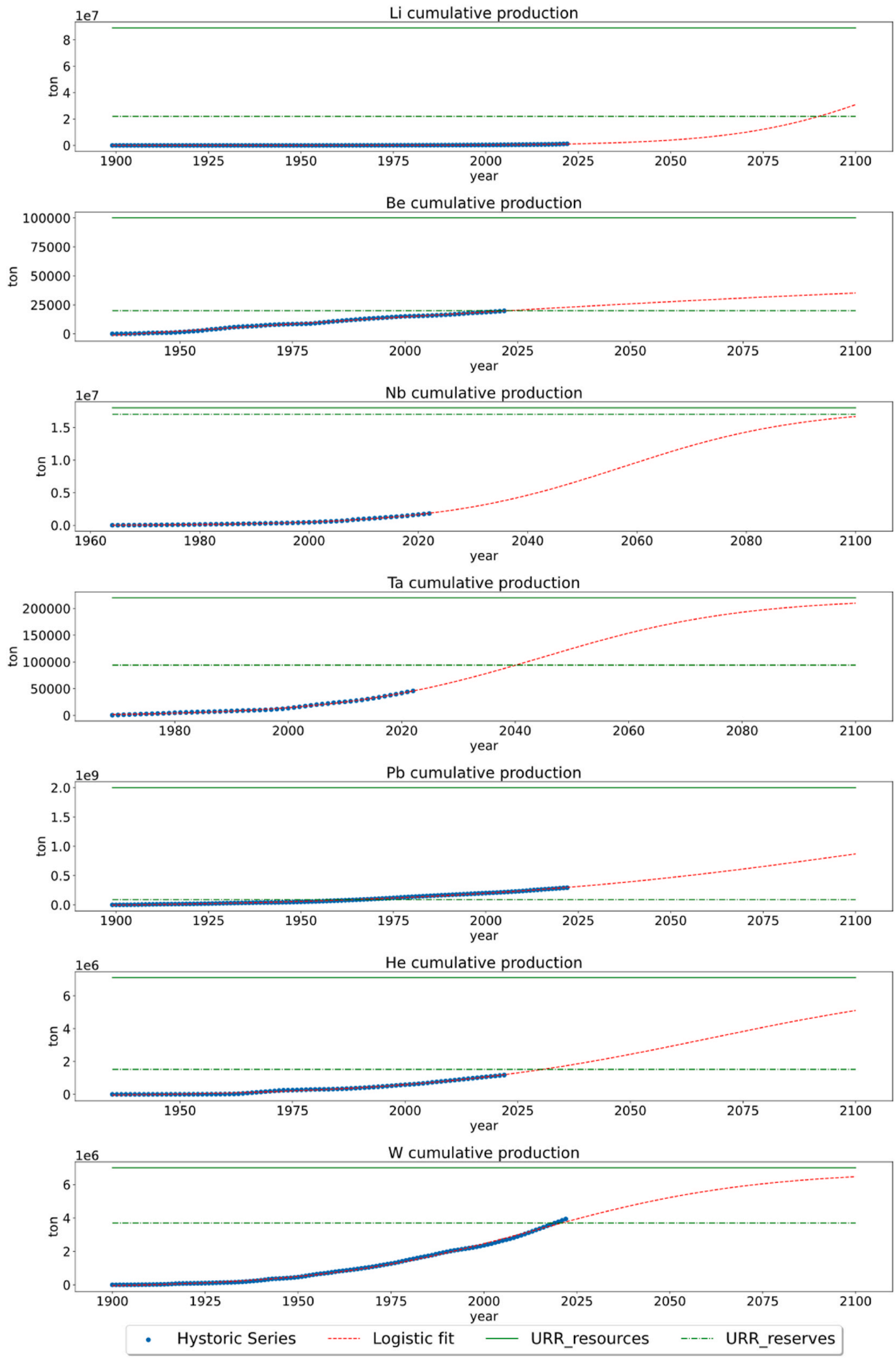


Fig. 4. For the materials considered in this study, the URR reference value and cumulative Mine Production logistic fit are shown. URR is assumed to be as high as the amount of material resources. Future figures are derived from cumulative mine production time series up to the year 2022.

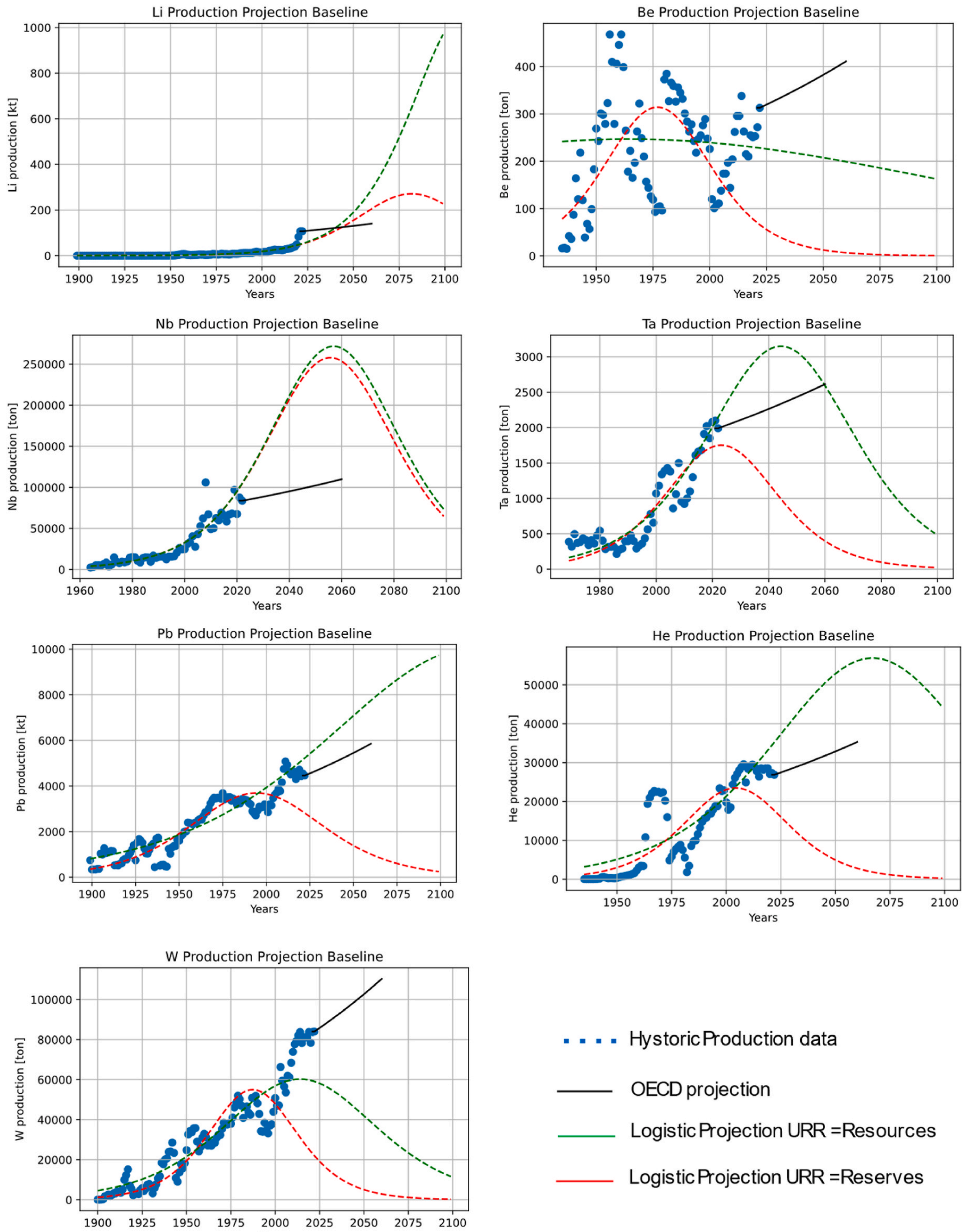


Fig. 5. Projections of mine production for considered materials. Logistic URR_Reserves and URR_Resources are assumed to be as high as URR Reserve and Resources in cumulative production modeling, respectively. OECD 2060 material outlook projection is also shown for comparison.

Lead usage is reported [79] as related to multiple technologies, related to energy transition as well (e.g. Wind, Solar, Energy Storage, nuclear) while Nb is reported in Ref. [80] as related to carbon capture and storage (CCS) technology. Besides a baseline growth from light steel applications, the Nb market is expected to potentially grow driven by nanocrystalline materials (ferroniobium used to magnetically convert and control electricity) and Lithium-ion batteries [Project Blue [119]]. Such demand increase patterns cannot be captured from a regression on historical series, being driven by a recent environmental policies and consequential technology paradigm change in mobility.

Table A1-1 summarizes some current usage facts on considered materials as well as a literature review on demand/production projections (also graphically highlighted in Fig. 6).

Also, other socioeconomic factors are only implicitly accounted for, as for example increases in the portion of population that will consume these mineral commodities and the standard of living that will determine just how much each person consumes on average [72]. The general assumption is that population increases, and life standard improvements drive the demand for materials. Population increase estimates can be derived from the UN World Population Prospects 2019 [81]. The UN population projections (UNpp) consist of a base, low population and high population scenarios. By considering historical production trends, the baseline yearly production estimate (MPbas) in (eq-2) is assumed to be consistent with a base population projection scenario. Conversely, low and high population scenarios will respectively reduce or increase the material demand and require additional production. Note that by examining trends in the intensity of use (IoU) rather than looking at total consumption trends, socioeconomic factors that lie at the heart of changes in per capita consumption of minerals (e.g., growth of GDP and standards of living) are implicitly included in the projections. According to [OECD-2060], exploiting a UNpp MEDIUM, global materials use per capita is projected to keep increasing over time at an annual rate of about 1.12 %[15] for metals (material group consistent with herein considered materials). Table A1-1 also reports the demand characteristics of materials and reports recent trend in Intensity of Usage (IoU_{avginc}), the average increase rate in usage intensity (kg/1000 person) for the material derived from historical data series on consumption [70].

Secondary material production from recycling can partially fulfill material demand, hence reducing the need for mines production. According to [77]-(OECD 2060 Figure 6.4), the recycling sector is projected to more than triple in size between 2017 and 2060. The principal recycling indicator adopted in this study is the so-called end-of-life recycling input rate (EOL_RIR), which is defined as the ratio of secondary raw materials obtained through recycling of products, which reached end-of-life, divided by the overall quantity of raw materials fed into the economy [82].

The amount of recycled material at year i (*Ri*) is commonly expressed with respect to usage, Ri = EOL_RIRi*Ui at year *i*.

Literature review regarding EOL_RIR of the selected fusion critical materials indicates that information is scarce as there are few comprehensive studies except for Lithium. As a result, existing studies extrapolate available historical data by considering policies that promote sustainability and material use efficiency. However, in many cases, recycling can be done if it is financially feasible. For recycling to be a major part of the material use cycle, the value of recycled material should exceed the recycling cost. The expectation is that material scarcity coupled with policies that promote sustainability will increase recycling in the coming decades.

Regarding the recovery of materials for recycling [83,84], 90 % upper recovery limit is a common assumption, given that some material is likely to be lost in landfills, transportation, stored waste in houses/facilities, etc. The rate for Li, Pb [85] and W [86,87] saturates at 90 % as there exists already a well-established recycling industry which can be expected to keep growing and be prioritized, and for the rest of the metals (except He), saturate at 80 % within 2100. Among these materials, Lithium is the one with more margin for increasing recycling. Both collection of used equipment (e.g. batteries) and recycling industry for Lithium recycling is currently increasing and projected to reach 80 % within 2060 [88,75,89,99] as well as collection. The other metals keep rising and saturate at 50 %, which is a metric threshold used in literature between medium and high recycling rates. Morevore, there is a higher likelihood of these metals (e.g. Be, Nb, Ta)[90–92]) to be lost within the recycling chain of other materials such as Copper or steel. Niobium is already at 50 % of the recycling rate. Note that in this approach, available recycled materials are assumed to be all exploited regardless of their cost-effectiveness [93] with respect to new mine-production. Table A1-2 summarizes literature data about considered material recycling, other than the assumed saturation values for recycling.

Fig. 7 shows projections of possible contributions to supply by secondary production (from recycling) for the selected materials. In particular, for each considered material, projections in the following two scenarios are presented.[16]

- OECD recycling scenario: derived by applying a growth scaling index (2060–2017) from [77]-(OECD 2060 Figure 6.4)
- ECO recycling scenario: derived by defining $R_i = EOLRIR{\cdot}U_i$ and approximating apparent usage $U_i = P_i + R_i$, Leading to the approximated figure for $R_i = \frac{EOLRIR}{1-EOLRIR}P_i$. In this scenario EOLRIR is assumed to reach 80 % by 2060 for Li, Pb and W, while a 50 % saturation in 2060 is assumed for Be, Ta and Nb. A linear increase trend starting from 2020 EOLRIR estimates reported in Table A1-2- the assumption of achieving saturation in 2060 holds. In this approach material recycling is assumed to growth regardless of the cost-effectiveness [93] with respect to new mine-production.

4. Impact of nuclear fusion on projections of critical material resources consumption

To investigate the impact on materials consumption of the two assumed bounding deployment scenarios for FPP (ref section 2.3), we need to link projections of fusion and non-fusion usage. Section 2 has provided an estimate of material demand in fusion for selected elements. Section 3 has provided an estimation of non-fusion usage up to 2060 for the same elements.

In this section we merge the two pieces of information to derive possible limitations originating from material depletions issues to FPP penetration into the market as an energy generating technology or, similarly, the impact of FPP penetration on material depletion.

Note that FPP driven material demand is expected to start in the long term, as a result of an intense research program according to the public sector roadmaps (e.g. EUROfusion roadmap [94]) mentioned in section 2. Here, we assume 2050 as a starting year for FPP driven material demand. Nonetheless, the recent growth of private sector initiatives [21] might anticipate the commercial availability of FPPs, with claims of electricity generation from 2035 and commercial fusion power on the market from 2040.

Also note that in the presented projections price dynamics are not considered. This might be a relevant aspect in actual future production rates. As an example, the scarcity of specific material approaching the URR limit might induce a price rise resulting in some production demand disappearing depending on the technology or sector. Despite the mentioned importance of price dynamic aspects, the complexity and uncertainty of the subject would require a specific analysis, and it is therefore left out of present scope.

The following graphs merge the information on production and fusion and non-fusion driven demand for each material. Note that the demand to satisfy either a full set of WCLL-FPP or HCPB-FPP (namely the most demanding concept in terms of material, depending on the specific material) matching the required installed capacity is reported, so the two demands are alternative even though scenarios with FPP from both concepts deployed are possible. Also, it should be noted that energy transition related demand projections available in literature extend up to 2050 only.

In the case of **Lithium**, Fig. 8 – Lithium box shows projections for both fusion and non-fusion related productions in the case of the fusion Fast deployment scenario, the most demanding one. By the end of the century, fusion driven demand in WCLL case would match about 44 % of projected production (which would become about 76 % if commercial availability were anticipated 20 years in advance). This percentage of

[15] Source data https://doi.org/10.1787/888933885106.

[16] Source data OECD-2060 https://doi.org/10.1787/888933885258.

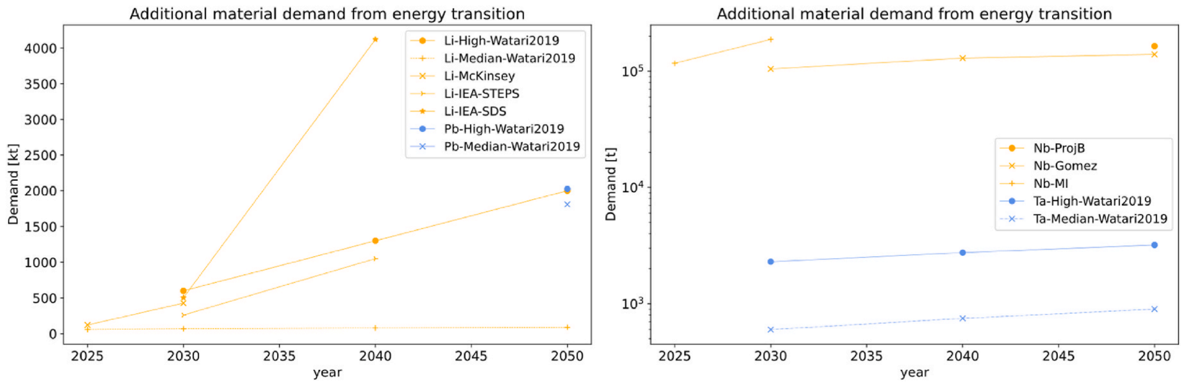


Fig. 6. Additional material demand driven by energy transition.

production might be reduced in case of an early significant increase in the production capability to supply the 2030–2050 expected additional demand driven by the energy transition (median case from Fig. 6 is considered in Fig. 8). Note that the annual increase rate of production would then go above 5 % (commonly assumed as a literature limit in production increase). Only a significant increase in secondary production from recycling (Fig. 5 – Lithium) could impact on reducing the pressure on mine production exerted by the mentioned demand. As material depletion is concerned, it is worth to note that the cumulated production projections (from model Logistic URR_Resources in Fig. 4) account for 114 % and 28 % of currently estimated reserves and resources (from Table 7) respectively, posing pressure on the need to extend the current Lithium reserves[17] exploiting resources as well. FPP cumulated demand would in turn account for <2 % of available resources.

Note that in case of concurrent usage (fusion vs non-fusion usage), in a regime of reserve scarcity, fusion might be able to accept higher prices of raw Lithium, because of its limited impact with respect to the cost of processing to reach fusion-grade. As an example, raw Lithium cost is in the order of k$43 per ton (2021 Lithium carbonate price), while refined ^{6}Li-enriched Lithium[18] is estimated to cost 1M$/ton in EUROfusion TIMES model. Note that despite the relevant amount of Lithium required for the deployment of FPP plants, only about 2 % of this Lithium stock is burnt as fuel for plant operation, providing a reserve for future usage within fusion industry in case suitable recycling processes are technologically feasible and realized. Another aspect to mention is that the natural lithium FPP demand is required to extract mostly 6Li (at percentages varying from 60 % to 90 %). A significant amount of 7Li enriched lithium is therefore left available for other usage. This could significantly reduce the conflicting demand and pressure on the supply chain.

Lead fusion driven demand is mainly related to WCLL concept (Fig. 2 - Pb box). fusion related demand would not require a significant increase in production (Fig. 8 – Pb box) in the first decades while approaching 40 % of projected production in 2100. Similarly, to the Lithium case, fusion related demand at the highest installed capacity (fusion Fast deployment scenario after 40 years from initial commercial availability) is like the estimate of additional demand coming from energy transition in 2030–2050 (Pb from Fig. 6).

Concerning material depletion, the cumulated production projections (from model Logistic URR_Resources in Fig. 4) significantly exceed the available reserves and account for 43 % of the current estimated resources (from Table 7) posing pressure on the need to extend the current Lead reserve base. A further increase in the already relevant secondary production of Lead from recycling (Fig. 7 – Lead) could mitigate depletion issues on mine production exerted by the above-mentioned demand.

FPP cumulated Lead demand would in turn account for <1 % of available resources. In the first case demand/supply and price dynamic could favor fusion industry (that is likely to be able to pay higher price) with respect to fusion concurrent usage.

Helium fusion demand is higher in HCPB concept, but not greater than non-fusion demand (Fig. 8 – He box), accounting for about 10 % of projected production by the end of the considered time horizon. Note that no recycling nor recovery has been considered for Helium which also presents a relatively low resources/reserve ratio (which is 5 as from Table 7). Concerning material depletion, the cumulated production projections (from model Logistic URR_Resources in Fig. 4) significantly exceed available reserves and account for 72 % of currently estimated resources (from Table 7) posing pressure on the need to extend the current Helium reserve base.

Beryllium presents a peculiar case given that the FPP start-up inventory (for the HCPB concept only) is of same order of the estimated production in year 2050. Therefore, an initial significant increase in production would be required to sustain FPP penetration in the 2050–2070 decades (Fig. 8 – Be box). Moreover, as shown in (Fig. 3 – Be box), the impact of fusion driven demand for Beryllium depletion is relevant (~7 % of available resources, ~34 % of available reserves), posing a possible concern for deployment, also considering the relatively low resources/reserve ratio (which is 5 as from Table 7). A significant increase in recycling (Fig. 7 – Be) could mitigate but not solve the related depletion issue.

Tungsten fusion demand (Fig. 8 – W) is not expected to require significant increases in production although fusion demand would appear during a phase of decreasing production due to approaching of URR (Fig. 4 Mine Production – W box). Concerning material depletion, fusion related cumulated demand is in the order of 2 % of the resources

[17] The issue of new reserve discoveries has been studied in the oil and gas sector. The concept of "peak production", originally developed for oil by M. Hubbert and applied to other natural resources such as metals and minerals. But the concept has received increasingly more criticism Meiner, Robinson, Nassar [107]. All these criticisms focus on the difference between "reserves" and "resources", whereby most 'peak' predictions focus on the depletion of the former. Yet, these authors argue, the true mineral resources on earth are vast, with elements occurring throughout the Earth's crust in proportions of several (tens of) parts per million. Of course, most of these minerals occur in forms too dispersed to economically mine. Yet, any time demand for a specific material grows the boundaries of what becomes economic to mine shifts and reserves grow along with the demand. Additionally, advancements in mining and refining technology, too, push the boundaries of reserves further and further into what was previously considered resources. Nevertheless, no one can know for sure when in the future new reserves can be added to the existing reserve stock. This depends on technological development, market dynamics, and demand growth. One thing is sure we cannot extract all resources. But for all materials, we can assume that a certain percentage of the resources potentially can be exploited in the future although the specific percentage would likely vary from one material to another.

[18] 6Li-enriched 2021 market price is in the order of $600/g.

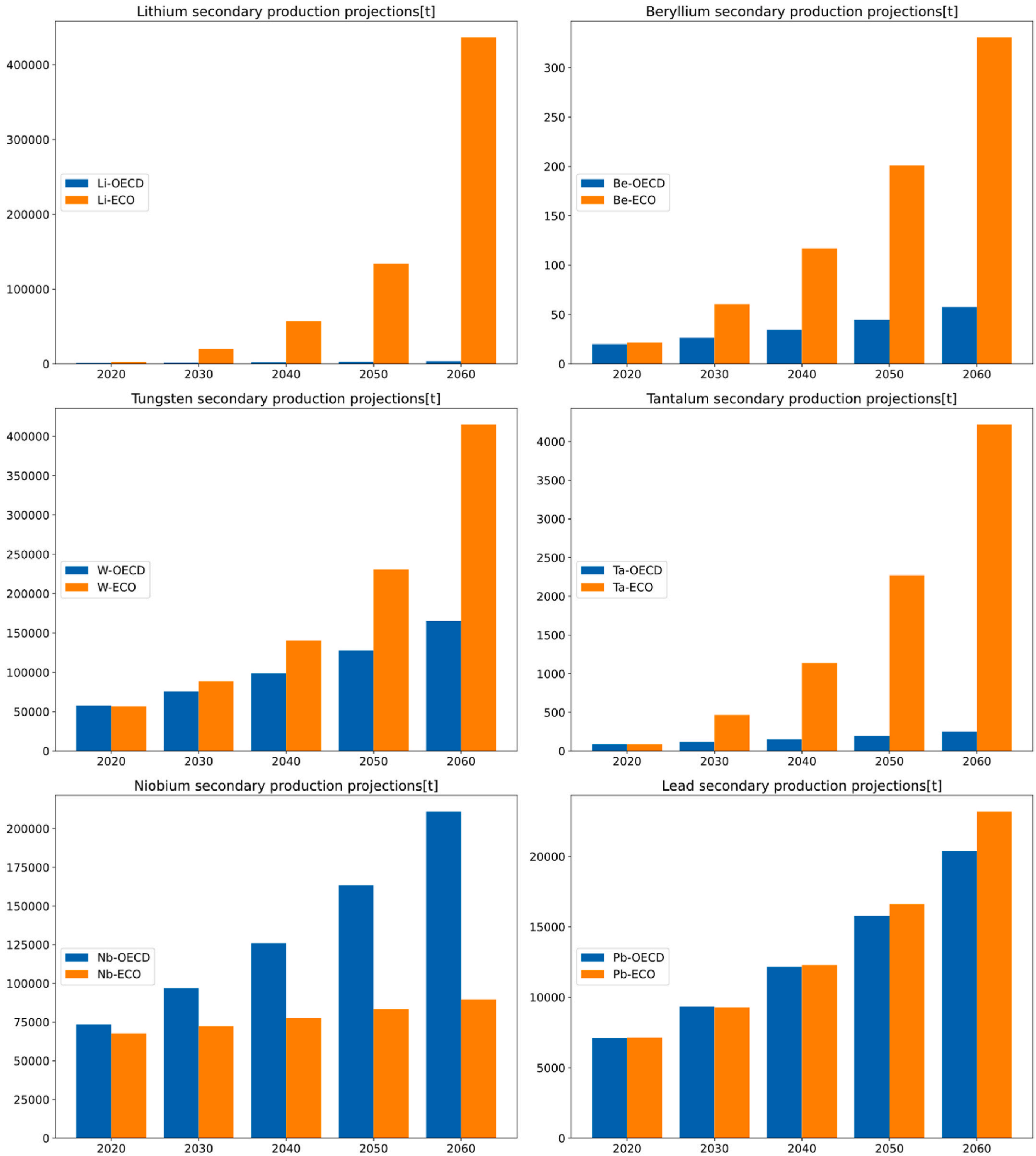


Fig. 7. Material secondary production projections for considered materials.
Note that when comparing *ECO recycling scenario* and *OECD* projections the former appear systematically higher than the latter except for Nb and Pb.

while the cumulated production projections (from model Logistic URR_Resources in Fig. 4) exceed available reserves and account for 92 % of currently estimated resources (from Table 7) posing pressure on the need to extend the current Tungsten reserve base. A further increase in the already relevant Tungsten secondary production from recycling (Fig. 7 – Tungsten) could mitigate depletion issues on mine production exerted by the above-mentioned demand.

Niobium (Fig. 8 – Nb**)** and **Tantalum (**Fig. 8 – Ta**)** show a similar pattern and are not expected to require a significant increase in production driven by fusion demand. Similarly, Niobium and Tantalum show a peak in production around year 2060 (Fig. 5 – Nb and Ta box) limited by resources depletion concerns. Note that additional demand

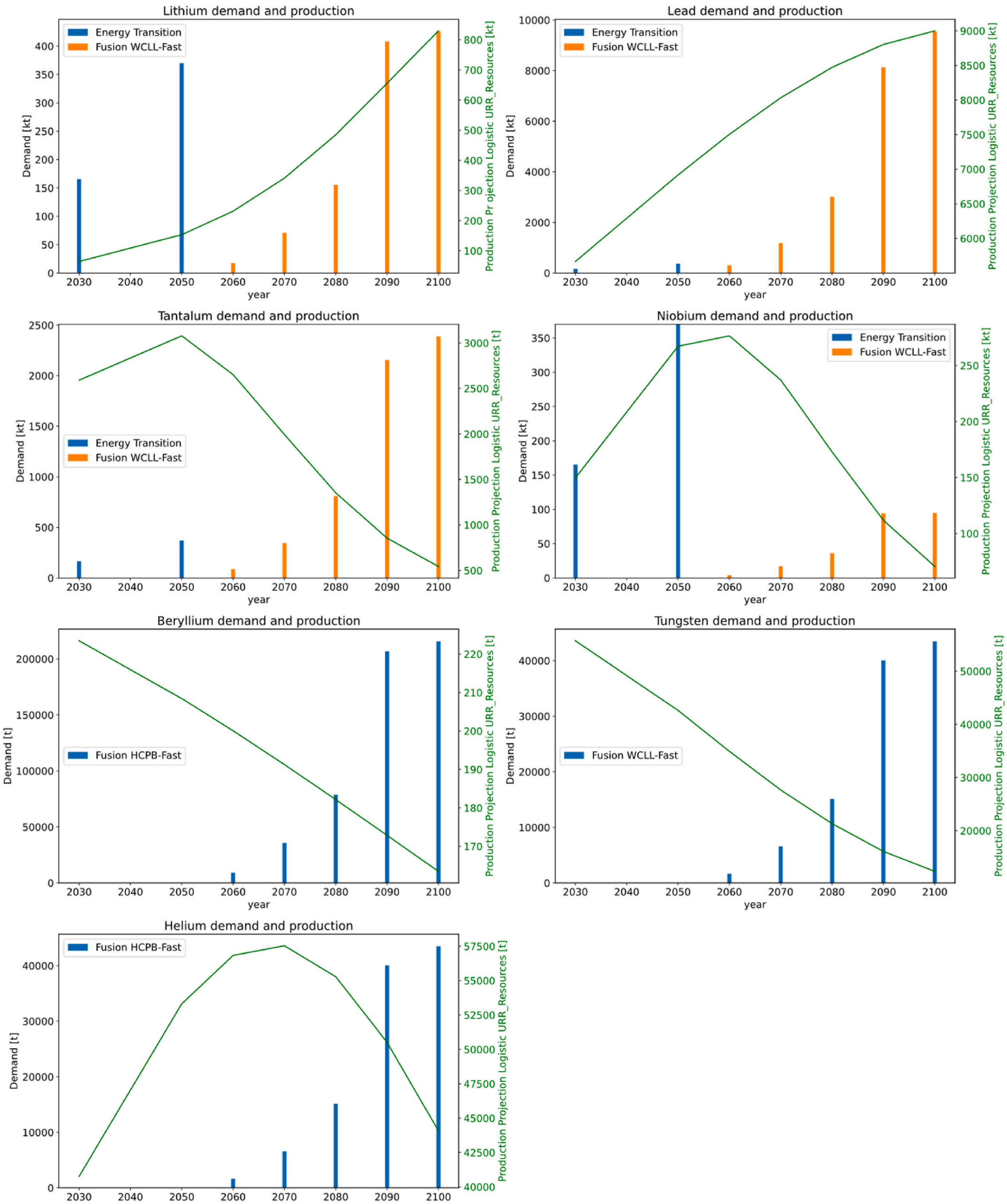


Fig. 8. Mine production projections based on logistic model fitted on historical demand (right axis in each box) and demand from fusion (left axis in each box). For Lithium, Lead, Niobium and Tantalum, also the additional demand due to energy transition is shown (left axis in each box). Note that fusion related demand is assumed to start in 2050 while literature estimates for energy transition demand are available up to the year 2050 only.

driven by the energy transition (Fig. 6) is expected to further increase production in 2030–2050 as anticipated by the significant increase in intensity of usage IoUavgInc [2008–2019] (Table A1-2). Secondary production from recycling (Fig. 7 – Nb/Ta) could mitigate depletion issues on mine production exerted by the mentioned demand, though less margin of improvement is expected for Niobium, already at about 50 % of EOL_RIR, considered to be a possible upper limit for recycling in some literature (as mentioned in section 3.

It should be noted that the figures reported are subject to great uncertainty and should be regarded as possible future realization of different scenarios. Fig. 6 reproduces a summary of different estimates found in literature regarding the expected increase in material demand driven by currently ongoing energy transition. These estimates span over a wide range and rather than prediction of actual demand shall be regarded as possible source of material supply issues emerging from concurrent usage with respect to fusion driven demand. To highlight this aspect such estimates have been presented in Fig. 8 together with estimated fusion-driven. In Fig. 8 also production projections considering the constraint of known available resources have been reported. These projections are based on logistic fit on historic production data and therefore not able to capture future trends. Despite this fact the relevant information conveyed is that the approaching of URR limit will put additional pressure on production, so that a possible mismatch of demand-production could occur. The information in Fig. 7 regarding secondary production shows a big difference between a economic-consideration-driven projection (OECD) and a linear projection from today's EOL_RER to a saturation value. The information therein conveyed is that the pressure on material supply coming from aggregated fusion/non-fusion demand, could also push for secondary production increase either in search for recycling technical solutions or making known recycling solutions economically viable.

5. Conclusion

Nuclear fusion has the potential to play a relevant role as a future sustainable and low-carbon emission energy supply technology. It is expected to become commercially available around the middle of the century or even earlier depending on the successful impact of private enterprises on fusion exploitation as an energy source.

The present work has focused on the possible impact of energy market adoption and integration of fusion power on fusion material availability. An estimate of the possible impact on materials demand driven by FPP penetration into the energy market up to 2100 has been provided. The study scope has been limited to a set of elements that emerged as potentially critical either because of their natural scarcity or because of the high non-fusion concurrent usage. The following elements have been considered: Li, Nb, Pb, W, Ta, He.

FPP material usage has been estimated based on available design documents for a European DEMOnstration power plant while key figures are scaled up to FPP size. An optimistic energy market penetration pattern like that experienced by nuclear fission in1960–80 (section 2.3) has been assumed to derive conservative figures in terms of materials exploitation. Such FPP-driven material usage estimates have been summarized in section 2 for the subset of chemical elements considered. Due to the long-term time horizon (2050–2100), materials usage from concurrent technologies (labeled as non-fusion usage) has been estimated by means of logistic regression models and compared to OECD derived projections (presented in section 3). Also estimates on material recycling have been derived to evaluate the potential mitigation effect of recycling on such materials depletion.

In some cases, the fusion-driven demand for critical material (Li, Nb, Pb, Ta ref. Fig. 8) will superpose to the demand pressure expected in consequence of the energy transition occurring in the 2030–2050. This is particularly the case when most demanding scenarios for fusion penetration are considered, namely fusion fast penetration.

Lithium, one of the two fuel cycle elements in a power plant (Deuterium being the other and not considering the start-up tritium inventory) as well as the most strategically relevant material for FPPs, is not expected to present depletion issues given the potential exploitation of known resources as URR. The steep pattern in production increase experienced in recent years (mainly due to the demand driven by the transition to EV mobility) might require technological improvements needed to transform estimated resources into economically viable reserves, although possibly at higher costs. Note, however, that due to the high costs of Lithium post-production refinement required by fusion industry to meet both purity and ^{6}Li enrichment requirements, electric cars con-current usage might be overcome by the fusion possibility of paying higher price for raw Lithium resource. Another aspect to consider is the fact that the ^{6}Li enrichment process required to get FPP grade lithium will leave significant quantities of ^{7}Li available for other uses, possibly relaxing pressure on lithium production coming from concurrent non fusion demand. On the other hand, the establishment of a Li^{6} enrichment industry might slow down FPP penetration in the short term as well as further increasing supply costs.

Among the materials discussed in this study, neutron multipliers supply might raise some concerns. Beryllium will require an initial significant increase in mine production given that the start-up inventory (in the HCPB concept only) is of same order as the estimated production in 2050. Moreover, the impact of fusion driven demand on Beryllium depletion is relevant, posing a possible concern for fusion deployment, also considering the relatively low resources/reserve ratio. Also, the fast reserve depletion of Lead is likely to be linked to the growing consumption projection. However, the global resources of Lead are much bigger than reserves (24 times the reserves). So, to meet the growing demand for Lead, technological achievements will be needed to make more resources exploitable as reserves with consequent impact on prices. Beryllium apart, fusion driven demand for neutron multipliers is not expected to significantly change the industrial production levels in the short term. Niobium and Tantalum show a similar pattern and are not expected to require a significant increase in production driven by fusion demand. Both Niobium and Tantalum are expected to have an increase in demand driven from energy transition.

Finally, Lead, Tantalum, Tungsten and Helium are characterized by low reserves with respect to projected needs. Hence, additional efforts on the expansion of known reserves and improvement in secondary production are necessary. Although secondary production could possibly mitigate the demand increase, it is already at saturation for some materials (e.g. Lead) or not at all performed yet. Great efforts are therefore needed to establish a secondary production supply chain (e.g. for lithium)

Concerning the limitations of the presented study, these might impact three main aspects: i) uncertainty on the definition of FPP material inventory, ii) uncertainty on timeline and intensity of fusion energy penetration pattern in the energy market and iii) uncertainties on concurrent material usage demand projections. As for the first point, it should be noted that the projections of FPP demands are based on EU-DEMO design material needs for which detailed inventory per material was available. Different figures per material could emerge when exploiting other design concepts despite the difference is expected to be more significant across different types of confinement concept (e.g. inertial fusion vs magnetic tokamak) than in terms of material per GWth when varying the design (e.g. across different mentioned DEMO plants). To provide a significant range, projections for two main breeding concepts (WCLL and HCPB) were provided. As for the second point, the considered timeline expects a commercially viable fusion plant to be available from mid-2050s. Two different deployment scenarios (Fast and Slow respectively) have been considered to cover a plausible range of fusion share in the future energy market. As for the timeline, the success of private sectors' initiative could anticipate the material demand making. The same considerations on pressure on primary production for materials apply to this last case, especially for the materials for which an increase in demand for net-zero emission energy transition is expected. As for the last point of non-fusion material demand projections, the proposed logistic model for material primary production based on historic production and URR has the purpose of introducing the limit coming from scarcity of resources in the projections based on expected demand. Material demand projections from different literature sources are indeed reported for sake of comparability. This information should be regarded from the perspective of highlighting possible criticalities rather than providing an estimate of material usage in the long term.

CRediT authorship contribution statement

D.N. Dongiovanni: Conceptualization, Software, Formal analysis, Methodology, Roles, Writing – original draft, Writing – review & editing, Visualization. **Y. Melese:** Non fusion driven material usage analysis, Conceptualization, Methodology, Roles, Writing – original draft. **F. Gracceva:** Methodology, on fusion power plant projection estimation, Validation, Supervision. **C. Bustreo:** Methodology, on fusion power plant projection estimation, Validation, Supervision. **A. von Müller:** Fusion material Re-Use /Recycling conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Danilo Nicola Dongiovanni reports financial support was provided by ENEA National Agency for New Technologies Energy and Economic Sustainable Development. Danilo Nicola Dongiovanni reports a relationship with European Consortium for the Development of Fusion Energy that includes: funding grants.

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LIST OF ABBREVIATIONS

ACB	Advanced Ceramic Breeder
BB	Breeding Blanket
BoP	Balance of Plant
BZ	Breeder Zone
COP	Conference of the Parties
DEMO	DEMOnstration fusion reactor
DIV	Divertor
EF	EUROFER
EV	Electric Vehicle
FPP	fusion Power Plant
FW	First Wall
GDP	Gross Domestic Product
HCPB	Helium Cooled Pebble Bed
HTS	High Temperature Superconductor
HTSs	Heat Transfer System
IPCC	Panel for Climate Change
LTS	Low Temperature Superconductor
PPCS	Power Plant Conceptual Studies
VV	Vacuum Vessel
WCLL	Water Cooled Lithium Lead

APPENDIX A. Material data

Table A1-1
Materials summary facts: literature overview on type of demand for the considered materials.

Material	Current use characteristics	Demand/Supply projection	Demand/Supply projections driven by energy transition
Lithium	Until 2010s bulk of demand was split between ceramics and glasses (35 percent) and greases, metallurgical powders, polymers, and other industrial uses (35-plus percent). Currently Most of the Lithium is used in (Li-ion) batteries. Batteries accounted for less than 35 percent of Lithium demand in 2016 [93], 71 % in 2019 [Source U.S. Geological Survey, Mineral Commodity Summaries, January 2021]. With the advent of the EV industry, demand for Lithium has shown an exponential increase in recent years. This trend is expected to continue	[Vikström 2013 [75]- Figs. . 6 and 8] project Lithium production in year 2050 of about 250 kt. In [108] several demand/supply scenarios are discussed. A low reserves scenario considering 26 Mt Li, comparable with assumptions in present paper, Li productions peaks at 1300 kt at 2037 [108] - Supplementary figure 12]. When considering logistic regression parameters for scenario production constrained model low and scenario production potential model low [Greim 2020 - Supplementary Table 8], Production (2050) is projected to be 23 Mt and 33 Mt respectively.	[Vikström 2013 [75]] estimates a range of about +50/+170 tons Electric Vehicle (EV) IEA blue map scenario at 2050 reports about +280 tons Lithium from EV demand [71] [100]. [103] reports from literature a range of projections for global demand in a Low Carbon constraint scenario spanning from 15 to 600 kt at year 2030 and from 400 up to 2000 kt at year 2050. [109] reports the demands for base and niche minerals to help build clean energy technologies are expected to rise substantially in the medium-long term projecting Lithium demand at year 2050 at

(*continued on next page*)

Table A1-1 (*continued*)

Material	Current use characteristics	Demand/Supply projection	Demand/Supply projections driven by energy transition
	through the energy transition in the coming 30 years. $IoU_{avginc[2011-2019]}$=9.39 % [USGS 2022]	[103] collects literature estimates from several studies, projecting global demand at year 2030 (for all uses) from a minimum of 60 kt up to 700 kt Lithium (median value across considered studies at 170 kt), increasing up to min 200 kt – max 1630 kt (median value across considered studies at 570 kt) at year 2050 (for all uses).	about 415 kt. [McKinsey- EV Lithium[116]] By 2030, batteries are expected to account for 95 percent of Lithium demand. A +20 % annual increase in Lithium (LCE) production between 2020 and 2030 is expected. IEA The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report [IEA–ENERGY] acknowledges that demand projections are subject to large variations, which lead to a wide range of possible futures. According to their analysis of the scenarios and alternative cases, lithium demand in 2040 may be 13 times higher (if vanadium redox flow batteries rapidly penetrate the market in the STEPS) or 51 times higher (if all-solid-state batteries commercialize faster than expected in the SDS) than today's levels."Two scenarios: SDS – sustainable development scenario & STEPS – Stated Policies Scenario.
Lead	Approximately 85 % of total global Lead consumption is used to produce Lead-acid batteries. Trends in the automotive industry are therefore one of the most significant incentives for future demand. Currently, more than half of the demand is met through recycling.It is expected that a major part of possible future increases in demand will be met by recycling [110]. $IoU_{avginc[2007-2019]}$=1.72 % [USGS 2022]	Current trends in consumption and production of Lead suggest that its production will remain around current levels in the coming decade or may experience only moderate growth [111]. [103] reports projections for global demand at year 2050 ranging from 7.653 kt to 7.463 kt	Demand at 2050 of 1435 kt is reported in [103] as related to Wind energy sector, while Solar PV and Nuclear would drive an additional 1435–2026 kt demand.
Helium	Helium is an important element for applications requiring very cold temperatures, and currently, 20 % of Helium consumption is used in Magnetic Resonance Imaging (MRI) scanners. It is also used for welding, controlled atmospheres and other uses, such as lifting gas. $IoU_{avginc[2007-2019]}$ = -1.39 %	Helium is expected to become very expensive as natural gas resources deplete and extraction from the atmosphere becomes necessary [112]. proposes two long-term scenarios for the World production: (a) regular growth peaking around 2100 at about 87 kt and (b) low weigh growth, peaking around 2075 at about 120 kt. He production around 2050 is in the range 60000–75000 tons He (estimations from Fig. 5)	
Tungsten	Tungsten has significant use in the military and several other industrial applications. Therefore, Tungsten demand is influenced by the developments of the world economy and the occurrence of war events. Much of the literature refers to the balance of Tungsten supply and demand. From 2007 onwards, Tungsten has been showing an increasing linear consumption trend. $IoU_{avginc[2008-2019]}$=2.69 %	[113] reports two projections respectively considering high (7 Mt) and low (3.4 Mt) URR scenarios: with peak production year at 2017 and 2039 respectively. Production at 2050 is projected as 47926t and 69922t respectively.	
Niobium	Over the past 25 years, the production of Niobium has followed a linear increasing trend. More than 90 % of Niobium is used in the production of high-grade structural steel. $IoU_{avginc[1997-2019]}$=6.68 %	Steel production is not expected to experience rapid growth in the (near) future and other uses of Niobium have of small influence on the total production [98, 101].	Nb is reported in [Moss 2013] as related to carbon capture and storage technology, CSS. Besides a baseline growth from light steel applications, Nb market is expected to grow also potentially driven by nanocrystalline materials (ferroNiobium used to magnetically convert and control electricity) and Lithium-ion batteries [Project Blue]. Additional demand is estimated [Project Blue] for about 165 kt.
Beryllium	Beryllium is used in aerospace, mechanical structure enhancement, specific scientific and medical applications, nuclear and specialized electronics applications. $IoU_{avginc[1997-2019]}$ = -0.40	None of these industries is expected to experience any major exponential growth during the next 30 years.	
Tantalum	The major use of Tantalum is in Tantalum capacitors widely used for consumer electronics such as mobile phones, laptops, and automotive electronics. $IoU_{avginc[1997-2019]}$ = 9.80	The mentioned markets are expected to continue their rapid growth in the coming years. [103]: global demand at year 2030 (for all uses) from a minimum of 15 kt up to 47 kt (median value 15 kt), increasing up to min 18 kt – max 66 kt (median value across considered studies at 22 kt) at year 2050 (for all uses).	[103] projecting global demand at year 2030 (for low carbon uses) from a minimum of 0.3 kt up to 2.3 kt (median value 0.6 kt), increasing up to minimum 0.65 kt – max 3.2 kt (median value across considered studies at 0.9 kt) in year 2050 (for all uses).

Table A1-2
Materials facts: recycling projection model data and assumptions

Material	Current estimates EOL-RIR 2020	EOL_RIR trends	Assumed saturation max EOL-RIR
Lithium	3 % [93]	1 % [UNEP, 2013] Scrap Collection trend increasing About 50 % of Lithium Batteries collected for recycling in EU [114]	Saturation value: 90 %

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Table A1-2 (*continued*)

Material	Current estimates EOL-RIR 2020	EOL_RIR trends	Assumed saturation max EOL-RIR
		10 % estimated value in 2017 [115]. Depending on the recycling process employed, it is possible to recover between zero and 80 percent of the Lithium contained in end-of-life batteries. By 2030, such secondary supply is expected to account for slightly more than 6 percent of total Lithium production [116].	
Lead	62 % [USGS, 2019]	1.1 % average annual increase 2010–2020 [USGS, 2010–2020] >50 % [UNEP, 2013] 65 % estimated value in 2017 [115]	Saturation value: 90 %
Helium	No recovery/recycling assumed	N.A.	N.A.
Tungsten	35 % [117] 37 %–42 % [USGS, 2020]	1 % average annual increase 2010–2020 [USGS, 2010–2020] 40 % estimated value in 2017 [115]	Saturation value: 90 %
Niobium	>50 % [84] ~20 % [USGS,2020]	60 % estimated value in 2017 [115]	Saturation value: 50 %
Beryllium	8 % [JRC, 2018] 20 %–25 % [USGS,2020]		Saturation value: 50 %
Tantalum	4 % [JRC, 2018] 10 % [USGS,2020]	Recycling rate in US 21 %[118] 25 % [115]	Saturation value: 50 %

Table A1-3
Materials facts: historic series for mine production [source USGS- Data140]

year	Li [t]	Pb [t]	He [t]	W [t]	Nb [t]	Be [t]	Ta [t]
1899	40	749000					
1900	50	1090000		77,3			
1901	35	342000		79,4			
1902	60	685000		205,4			
1903	23	367000		319			
1904	36	733000		2019			
1905	2	1040000		1900			
1906	10	2033000		4500			
1907	11	1280000		1800			
1908	15	2340000		4300			
1909	4	1100000		3300			
1910	9	2210000		6500			
1911	10	1160000		4200			
1912	17	2310000		8100			
1913	11	524000		3500			
1914	22	1068000		8700			
1915	10	517000		10000			
1916	22	1114000		22300			
1917	41	611000		15200			
1918	159	1375000		22200			
1919	126	804000		5500			
1920	360	1587000		7800			
1921	37	972000		3000			
1922	81	2052000		6300			
1923	46	1220000		2900			
1924	106	2630000		7800			
1925	84	744000		5800			
1926	181	2284000		10200			
1927	114	1680000		5500			
1928	239	3290000		13000			
1929	54	1520000		7900			
1930	121	2780000		14300			
1931	15	1050000		3200			
1932	30	2090000		9100			
1933	17	1200000		7800			
1934	45	2580000		18500			
1935	38	1470000	49	11800		16	
1936	63	1917000	71,4	30300		33	
1937	78	1700000	23,1	17800		15	
1938	150	3440000	52,3	37900		57	
1939	87	508000	30,1	20700		36	
1940	184	1059000	75,4	44600		123	
1941	119	558000	77,5	24100		164	
1942	287	1039000	236,5	52700		284	
1943	280	470000	558	23400		218	
1944	765	1720000	1166	34300		336	
1945	162	1030000	454	9040		39	

(*continued on next page*)

Table A1-3 (*continued*)

year	Li [t]	Pb [t]	He [t]	W [t]	Nb [t]	Be [t]	Ta [t]
1946	365	2340000	733	22740		107	
1947	187	1380000	337	17800		57	
1948	376	2750000	640	33600		156	
1949	270	1640000	264	18300		183	
1950	933	3240000	654	43100		452	
1951	886	1810000	537	32700		243	
1952	1746	3680000	1230	67100		544	
1953	1807	2000000	772	33800		298	
1954	4871	4010000	1686	69500		577	
1955	4360	2400000	1060	35800		323	
1956	10762	4780000	2230	64900		791	
1957	7170	2350000	1400	24200		410	
1958	13822	4670000	3000	50600		689	
1959	3957	2390000	2290	31200		406	
1960	7390	4780000	5370	64200		852	
1961	2460	2510000	3490	31300		468	
1962	5405	5070000	6910	58400		867	
1963	3160	2530000	10800	28100		265	
1964	6682	5230000	30200	55100	2480	443	
1965	4109	2850000	21000	28600	3120	222	
1966	9364	5720000	43100	57100	8180	387	
1967	4867	3010000	22700	31000	5150	197	
1968	9858	6250000	45200	63500	10100	460	
1969	3514	3390000	22500	32400	6610	322	388
1970	7184	6880000	44700	67800	15070	571	706
1971	4710	3450000	22400	38500	3740	210	496
1972	9480	6940000	42600	76400	9690	367	867
1973	7384	3490000	16000	37600	14700	144	384
1974	14345	6930000	20900	75900	24040	270	820
1975	6686	3690000	5870	38000	7860	119	411
1976	12042	7100000	12990	79100	17330	212	750
1977	6601	3460000	7830	46100	8800	103	409
1978	15122	6970000	16230	94700	18470	208	771
1979	6991	3520000	8890	52000	14400	96	476
1980	13944	6870000	16450	102300	29500	469	1020
1981	6761	3450000	5580	47000	14800	385	403
1982	12280	6800000	7410	87900	25400	712	687
1983	6858	3200000	3480	46200	8580	366	313
1984	15119	6590000	12050	92800	22480	725	628
1985	8193	3240000	9750	43500	14800	326	315
1986	16020	6670000	19750	86000	29400	682	530
1987	8271	3420000	11600	50900	9360	345	275
1988	18312	6820000	24900	101900	26260	677	567
1989	11233	3370000	14800	51900	14100	301	395
1990	23141	6630000	30400	100100	29400	585	791
1991	12030	3200000	15900	42900	15700	263	477
1992	23778	6100000	32800	77200	31000	541	876
1993	11692	2800000	16900	34000	12400	243	292
1994	23762	5510000	34800	72500	28100	461	625
1995	12252	2920000	18800	34700	15600	247	361
1996	27706	6020000	37600	67900	31800	502	797
1997	16966	3060000	23400	37000	20500	276	562
1998	32372	6140000	46100	74700	46700	565	1341
1999	14264	3200000	22900	44000	24600	248	656
2000	28674	6320000	42700	94800	49400	474	1726
2001	15913	2850000	17900	47000	31100	120	1180
2002	31835	6050000	36400	94200	64400	221	2520
2003	15877	3150000	24400	66300	40400	107	1390
2004	36831	6620000	50500	125800	68000	218	2820
2005	21303	3630000	27100	56600	43100	138	1380
2006	45648	7340000	55200	110200	95900	312	2239
2007	26603	3880000	28900	61900	62200	174	1060
2008	51739	7660000	58500	123100	168200	371	2560
2009	25136	4160000	24900	68400	67100	144	956
2010	50272	8910000	53300	142300	116200	348	1878
2011	23500	5080000	29100	77700	50200	262	1000
2012	49100	10010000	58600	157100	112900	558	2100
2013	28300	4630000	28900	82100	59700	296	1300
2014	58300	9140000	56700	165900	128900	634	2910
2015	31000	4640000	26400	78300	65700	263	1660
2016	64300	9270000	54960	159500	124100	478	3340
2017	36700	4300000	28203	81100	66800	210	1910
2018	76400	8860000	56763	162200	135000	465	3930
2019	49100	4720000	28560	83800	97000	251	1850
2020	131800	4747100	4458560	162200	164500	2331	2103

Data availability

Data for figure production have been added to the manuscript

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