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Assessing urban green roofs for CO_2 removal via enhanced rock weathering in Europe

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ABSTRACT

Green roofs represent a novel and promising platform for integrating enhanced rock weathering (ERW) as a carbon dioxide removal (CDR) strategy within urban environments. By utilising underused rooftop spaces, rock (feedstock)-amended green roofs for ERW could contribute meaningfully to climate mitigation targets while fitting within existing markets and policy frameworks. Despite this, a comprehensive assessment of opportunities and barriers to deployment is missing. Here, we provide a conceptual assessment, serving as a benchmark for the potential for large-scale ERW green roof deployment in Europe, examining literature from similar applications and estimating theoretical CDR potential at European and global scales, and identifying key opportunities and challenges. Our estimates suggest that, under conditions where 100% reactivity is achieved, green roofs in Europe could theoretically remove tens of millions of tonnes of CO_2 via ERW (in addition to plant uptake) by 2060, assuming expanded rooftop coverage. However, these findings are based on maximum geochemical capacities rather than empirical data from real-world conditions. Globally, theoretical removal potential ranges from tens to hundreds of millions of tonnes CO_2 per year, with major contributions from Central Asia, North America, Latin America and the Pacific. Beyond CDR benefits, ERW green roofs can enhance photovoltaic performance by improving energy efficiency and reducing evaporation, although weight capacity of each rooftop must be evaluated. This approach offers a promising pilot-scale research opportunity, bridging the gap between laboratory experiments and potential field-scale applications, but the feasibility and effectiveness of large-scale deployment will require further empirical investigation, especially concerning climatic conditions, infrastructure, costs and policy support.

1. Introduction

The IPCC Climate Change 2023 Synthesis Report highlights that meeting global climate goals, such as limiting warming to 1.5 °C, will require not only deep, rapid and sustained reductions in greenhouse gas (GHG) emissions across all sectors, but also the large-scale deployment of carbon dioxide removal (CDR) technologies (IPCC, 2023). CDR encompasses both nature-based approaches, such as afforestation and peatland restoration, and engineered solutions, including direct air capture (DAC) (Brack and King, 2021; Butnar et al., 2024; IPCC, 2022, 2023; Terlouw et al., 2021). Achieving net negative emissions by 2050 is expected to require the removal of CO_2 at the gigatonne scale (NASEM, 2019; Smith et al., 2024), positioning both conventional and emerging CDR methods as essential complements to emissions reductions in global mitigation strategies.

Geochemical CDR is an emerging and promising approach that involves processes to extract CO_2 from the atmosphere and store it in stable forms (Campbell et al., 2022, 2023; Renforth, 2024). These

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approaches rely on alkaline materials, such as calcium- and magnesium-rich rocks, minerals and industrial by-products (collectively known as feedstocks), to transform CO_2 into stable bicarbonate (HCO_3^-), or alkalinity, in solution and/or solid carbonate minerals (e.g., calcite; $CaCO_3$). A key pathway involves the weathering of silicate minerals to release base cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) that react with atmospheric CO_2 to form dissolved cation-stabilised alkalinity or precipitated carbonates.

While natural weathering removes up to ~1.1 Gt of CO_2 from the atmosphere each year (Ciais et al., 2013), this rate is too slow to counterbalance current fossil fuel emissions or keep pace with the urgent need to reduce atmospheric CO_2 concentrations. One method gaining increasing recognition for its potential to deliver high-volume, timescale-relevant CDR is enhanced rock weathering (ERW), a scalable hybrid approach that combines natural processes with human intervention by exposing reactive materials to the atmosphere to promote CDR through weathering. Key reactions for CDR are accelerated, or enhanced, through the application of fine-grained (ground and milled) materials, spread across large surface areas for increased exposure to the atmosphere. The increased material surface area and greater exposure to the atmosphere enhance mineral dissolution, alkalinity generation and carbonate precipitation, thereby increasing CDR and accelerating carbon uptake from timescales of thousands of years to human-relevant timescales of decades or faster.

To date, ERW activities have centred on spreading of materials such as basalt, dunite or wollastonite feedstocks on rural agricultural land (e.g., Beerling et al., 2018, 2020, 2025; Haque et al., 2020; Reershemius et al., 2023; Rinder and von Hagke, 2021; Schuiling and Krijgsman, 2006). This is due to the inherent advantages of using existing agricultural infrastructure to apply materials over large land areas globally, leveraging current spreading equipment and practices. Furthermore, incorporating fine-grained feedstocks into soils can not only reduce operational costs and benefit crop yield and health (Beerling et al., 2020, 2025; Gillman et al., 2002; Rinder and von Hagke, 2021; Vienne et al., 2022), but also accelerate CDR by taking advantage of higher CO_2 concentrations and biologically active conditions in the root zone, which enhance weathering rates compared to the slower reactions of larger rocks exposed to ambient air (Wen et al., 2021). Similar ERW approaches have been explored in other rural and semi-rural areas, including forest systems and plantations (e.g., Lafleur et al., 2013; Larkin et al., 2022; Van Der Bauwhede et al., 2025), mine sites (e.g., tailings ponds; Bullock et al., 2021, 2022; Power et al., 2020; Stubbs et al., 2022; Wilson et al., 2014), coastal areas (e.g., Flipkens et al., 2023; Foteinis et al., 2023; Meysman and Montserrat, 2017; Montserrat et al., 2017), along railway lines (e.g., Movares, 2013) and in greenhouses (e.g., Myers and Nakagaki, 2020). Successful and scalable ERW projects depend on the cooperation of operators and landowners, with co-benefits (e.g., economic, environmental or agronomic efficiency gains) likely to increase participation in feasibility studies, pilot schemes and full-scale deployments.

The justified focus on rural and semi-rural areas of ERW deployments has meant limited consideration to urban areas as a geochemical CDR host setting (Rodriguez Mendez et al., 2024). While rural areas offer many advantages for CDR, urban areas may seem less suitable due to limited space, low soil or microbial activity and complex land ownership. Despite the apparent challenges to ERW deployment in urban areas, limited studies have proposed potential approaches involving urban soils and available surface areas (e.g., Haque et al., 2021; Washbourne et al., 2015). These studies highlight how current land management practices in urban areas could be revised to permit ERW or other CDR approaches (e.g., mineral carbonation) to take place, making use of the millions of square km (and growing) of global urban land. Haque et al. (2021) draw attention to possibilities of implementing urban farming approaches, with the incorporation of ERW, that target municipal areas such as rooftops and balconies. These areas are already partially utilised for solar photovoltaic (PV) systems in Europe (Bódis et al., 2019; Gernaat et al., 2020), and green roof settings have been proposed for crop production potential (Xie et al., 2024).

Green roofs, also known as green rooftops or living roofs, are becoming increasingly common on buildings across European cities (Aboulnaga and Fouad, 2022). Their primary purposes are to enhance water retention capacity, provide thermal and sound insulation, extend roof life and increase biodiversity within urban areas, helping to meet European Union (EU) goals (e.g., Green City Accord initiative to make cities greener, cleaner and healthier; European Commission, 2025) and United Nations sustainability goals (e.g., Sustainable Development Goal (SDG) 9: Industry, Innovation and Infrastructure, and SDG 11: Sustainable Cities and Communities; and SDG 13: Climate Action; UN, 2023). Beyond stand-alone green roofs, hybrid systems integrating other established techniques offer significant potential (Vijayaraghavan, 2016), including incorporation of microbes (e.g., fungal additions; John et al., 2017; Metzler et al., 2024; Rumble et al., 2022) and biochar (Chen et al., 2021; Petreje et al., 2025) to further improve plant health, soil quality and overall ecosystem resilience. However, current designs are not optimised to maximise additional CDR benefits, partly due to limited research on key aspects of green roof performance and hesitancy to introduce new products prematurely into the market. This underscores the urgent need for further research in this field. By incorporating ERW, thereby increasing carbon sequestration rates in addition to those from rooftop vegetation, green roofs could further contribute to national and international climate goals, making effective use of an as-yet underexploited area for carbon removal.

In this study, we explore the potential of harnessing urban green roofs for ERW deployments in Europe, and provide a preliminary assessment of opportunities and barriers to deployment. We aim to highlight the types of green roof configurations into which ERW can be incorporated, emphasising the associated benefits, potential coverage across Europe, regional variability, opportunities, constraints and future directions. By focusing on these aspects, green roofs could be positioned as effective means for CDR in urban environments, while serving as pilot-scale demonstrators for large-scale rural ERW projects. Amended green roofs may serve as demonstrators for larger-scale rural projects in complex natural environments, bridging the gap between fully controlled laboratory studies and monitoring, reporting and verification (MRV) testing in rural agricultural lands. Alternatively, they have the capacity to function as standalone tools for urban CDR deployments, delivering negative emissions at a meaningful scale. These findings have implications for the future co-use and integrated deployment of ERW rooftop installations at European or global urban scales, offering intrinsic environmental benefits beyond CDR, such as improved energy efficiency, mitigation of urban heat islands, enhanced stormwater management and support for urban biodiversity. With sufficient promise for CDR, this study establishes the benchmark for future novel pilot-scale investigations, focused on the quantification of achievable carbon removal under actual rooftop conditions, with studies tailored to specific weathering kinetics and operational timescales to refine the potential of urban green roofs as a viable CDR solution.

2. Green roofs and their ERW practicalities

Green roofs are primarily used to enhance water retention, provide thermal and sound insulation, extend the lifespan of roofs, boost biodiversity in urban areas and add aesthetic value to buildings, benefiting urban planners, occupants and municipalities. Standard green roofs are generally classified into three main types - extensive, semi-intensive and intensive, primarily distinguished by soil depth (typically an engineered growing substrate medium). Substrate depth in turn influences vegetation type, maintenance requirements and structural demands (Getter and Rowe, 2006; Karteris et al., 2016; Oberndorfer et al., 2007; Raji et al., 2015; Shahmohammad et al., 2022; Vijayaraghavan, 2016). Extensive green roofs are the simplest and most widely implemented design due to their low weight, cost-effectiveness and minimal maintenance requirements. For instance, installation costs can typically range from ~25-140 €/m^2 for extensive roofs compared to ~50-362 €/m^2 for intensive roofs, depending on system and location (e.g., Manso et al., 2021; Perini and Rosasco, 2016). They often feature a thin substrate layer (≤15 cm), which limits plant diversity to drought-tolerant species such as grasses, mosses and succulents like *Sedum* (Getter and Rowe, 2006; Karteris et al., 2016; Vijayaraghavan, 2016). Extensive green roofs are generally used for environmental benefits such as stormwater management, temperature regulation and biodiversity enhancement. Their lightweight nature allows them to be installed on buildings with structural constraints, including sloped roofs.

Semi-intensive green roofs represent an intermediate system with a moderately thick (~10-20 cm) substrate, allowing for a wider range of vegetation, including small herbaceous plants, groundcovers and small shrubs. These systems require periodic irrigation and fertilisation, making them more resource-intensive than extensive green roofs (Vijayaraghavan, 2016). While offering enhanced biodiversity and aesthetic appeal, semi-intensive systems must balance increased plant diversity with structural load limitations and installation costs.

Intensive green roofs feature deep substrate layers exceeding 15 cm (e.g., up to 1 m), which enable the growth of a diverse array of plants, including small trees and shrubs. These systems require significant structural support due to their substantial weight and necessitate high maintenance, including regular irrigation, fertilisation and landscape management (Getter and Rowe, 2006; Karteris et al., 2016). Unlike extensive green roofs, intensive systems are often designed for human interaction and recreational use, making them common in urban developments with dedicated accessible rooftop spaces.

Despite variations in design, green roofs generally share essential components, including a root barrier, drainage layer, filter fabric, optional water retention layer, substrate layer and vegetation (Getter and Rowe, 2006; Vijayaraghavan, 2016) (Fig. 1). The configuration of these components depends on factors such as geographic location, building capacity, supplier preference and the intended function of the green roof. ERW on green roofs can tap into an existing market without imposing additional spatial footprint, making it an attractive, low-impact solution for urban environments. Furthermore, integrating ERW into green roofs can complement their existing benefits, such as improving air quality (Xu et al., 2020) and mitigating the urban heat island effect (Susca et al., 2011), whilst adding to existing carbon sequestration pathways (Karteris et al., 2016; Shahmohammad et al., 2022). It may also complement ongoing research into microbial and biochar amendments (Chen et al., 2025; Metzler et al., 2024). The controlled environment of green roofs may also allow for easier MRV of weathering processes compared to conventional rural-based deployments, as the configuration of the roofs and the outflow of weathering products can be tightly managed, providing valuable insights for future deployment in broader, more variable environments.

Incorporating ERW involves amending the substrate layer with finely ground silicate or alkaline feedstock materials, such as wollastonite, basalt or dunite, to accelerate natural CDR. Fig. 1 demonstrates how ERW can be integrated into existing standard green roof systems by amending the substrate with crushed silicate feedstocks. The principal processes are comparable to standard ERW deployment, with CO_2 from the air and dissolved in rainwater (carbonic acid; H_2CO_3) reacting with the feedstock in the substrate, releasing calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions and forming alkalinity. Resultant alkalinity percolates downwards to the drainage layer, permitting controlled outflow of weathering products. The presence of plant roots and microbial activity can enhance reaction rates (Wen et al., 2021), while CDR may be further accelerated by increased water retention and temperature regulation. Additionally, urban landscapes are typically warmer than nearby rural areas due to the urban heat island effect driven by anthropogenic activities (Monteiro et al., 2017; Oke, 1982). Elevated temperatures, combined with higher atmospheric CO_2 concentrations in urban areas from transport, industry and other human activities, can promote conditions favourable for ERW and associated alkalinity generation or carbonate precipitation.

Considering green roofs are fed almost exclusively by rainfall (with individual exceptions where standard building practices may include irrigation of rooftop plants), runoff will typically follow the same pathways as rainwater on urban buildings. However, the rainwater drainage practices may vary from city-to-city or country-to-country, with the responsibilities held by different authorities, initiatives and sewage plans. The general pathways are indicated here in Fig. 2. There is a necessity to drain rainwaters away from urban areas to prevent flooding and infiltration of waters into buildings. Rainwater that falls onto the green roofs will ultimately percolate downwards, and the weathering products will exit the bottom to the roof surface and drainage system infrastructure. Many modern European urban developments and housing areas use improved dual systems to rapidly discharge rainwaters through storm drains, avoiding sewerage systems

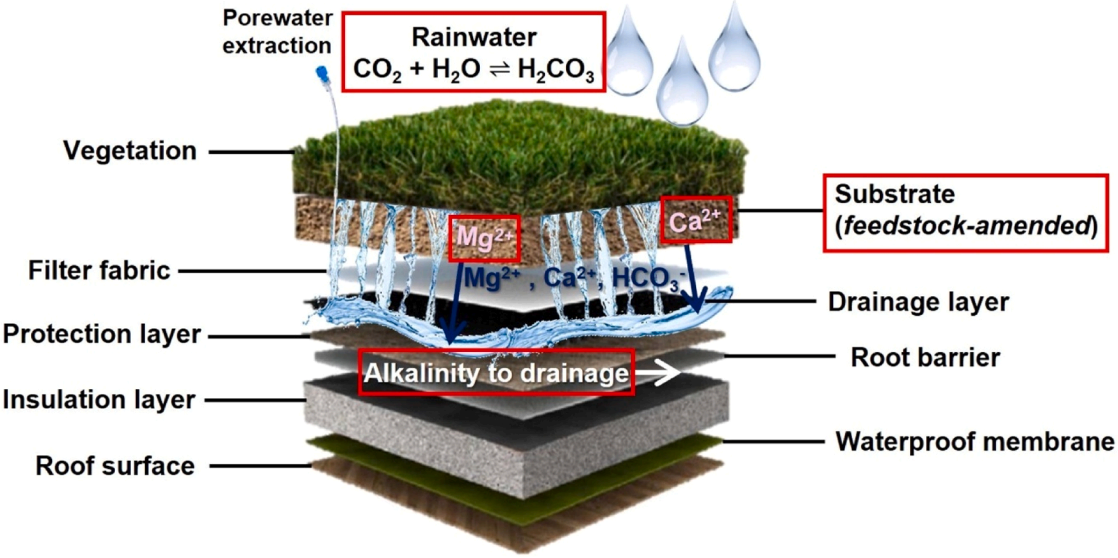

Fig. 1. Schematic of a representative green roof system, illustrating its typical layers and the integration of CDR through ERW (red boxes). Atmospheric CO_2 is captured via air and rainwater, leading to the weathering of alkaline feedstock within the substrate. This process releases alkalinity, which percolates through the lower layers and exits via drainage outlets, contributing to long-term CDR.

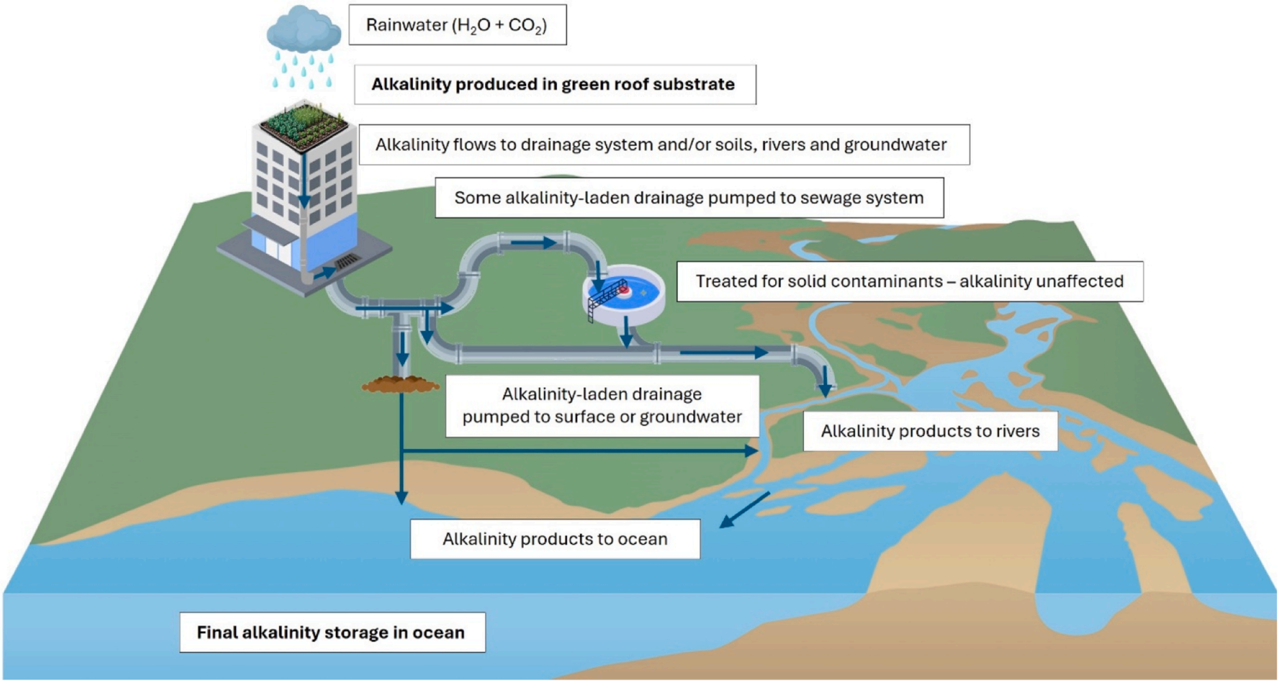

Fig. 2. Fate of alkalinity-laden runoff in urban drainage systems. After alkalinity is generated in the substrate, leached weathering products can follow multiple pathways. Alkalinity-laden solutions will generally enter stormwater drainage or combined sewer systems, ultimately discharged into surface or groundwater, eventually reaching the ocean.

and unnecessary treatment (Monachese et al., 2024; Ossa Ossa et al., 2024; Rodríguez-Rojas et al., 2024).

3. CDR potential for green roofs in Europe

3.1. Theoretical CDR potential

3.1.1. Potential coverage

Urbanisation is one of the defining trends of the 21st century, with more than 50% of the global population now residing in urban areas (Karteris et al., 2016). In developed countries, urbanisation is expected to exceed 80% by 2030, highlighting the need for sustainable municipal planning (Karteris et al., 2016). Roofs represent a significant proportion of urban surfaces, with estimates suggesting they account for ~30% to 32% of the horizontal surface within cities (Frazer, 2005; Monteiro et al., 2017; Oberndorfer et al., 2007). In highly urbanised regions, as much as 50% of impervious surfaces are underutilised roof spaces (Stovin et al., 2012), demonstrating substantial potential for green roof installations. However, precise data on roof areas remain scarce at national levels (Bódis et al., 2019).

Here, we provide preliminary estimates of Europe's CDR potential for green roofs, utilising theoretically available space for green roofs and the idealised (maximum – assuming 100% mobilisation of fluid soluble cations) CDR capacity of a hypothetical feedstock material, with no consideration for real-world conditions, necessitating future empirical case studies and pilot schemes to assess achievable CDR. Assumptions include the amount of feedstock added per 1 × 1 m^2 green roof cassette unit (15 cm substrate thickness, consistent with extensive roof types), along with a generalised feedstock composition. The geochemical properties of a basaltic feedstock are assumed, reflecting its relatively abundant availability in Europe compared with other materials such as dunite and wollastonite. Owing to its global abundance and low concentrations of potentially toxic elements (PTEs), basalt is widely investigated as a rock amendment for ERW (Beerling et al., 2020; Lewis et al., 2021; Renforth et al., 2011; Strefler et al., 2018), making it a highly viable feedstock for ERW green roofs.

Recognising that basaltic rock can vary in composition and mineralogy, a theoretical range of CDR capacity is considered to provide a lower and upper range estimate. This range reflects the wide span of compositions generally exhibited by basalts due to factors relating to various igneous processes (Farmer et al., 2003; Kushiro and Kuno, 1963; Plank and Langmuir, 1988). For this study, a broad selection of basaltic compositions originating from Europe are used to determine a range of theoretical CDR capacities (72 whole rock analyses from basaltic rocks or similar compositions, predominantly from Eifel, Germany, with additional data from Aberdeenshire, Scotland; Gribble, 1965; Haase et al., 2004; Jansen et al., 2024). These compositions were selected because basaltic rocks from these regions have been used in past and ongoing ERW studies and deployments across Europe (e.g., Aberdeenshire Council, 2023; Amann et al., 2022; Rijnders et al., 2024), making them appropriate for theoretical CDR assessment.

Application rates of 5-10 kg feedstock per 1 × 1 m^2 are assumed, with 5 kg representing a conservative estimate and 10 kg reflecting a theoretical maximum applied tonnage. An addition of 5 kg is analogous to an application rate of 50 t/ha, comparable to some standard agricultural ERW studies and deployments (e.g., Beerling et al., 2024; Buckingham and Henderson, 2024; Holden et al., 2024; Ryan et al., 2024). Beyond the notional maximum application rate of 100 t/ha (10 kg per 1 × 1 m^2), adding more feedstock can result in excessive weight for rooftop settings and may have adverse effects on plant health. It can also cause practical issues such as clumping and aggregation of fine particles, which reduce the available reactive surface area and lower dissolution rates (Fan et al., 2022; Hedberg et al., 2019; Isaac, 2024).

The range of theoretical CDR capacities for select basaltic rock compositions is 220-429 kg CO_2/t rock, calculated using the modified Steinour formula (Renforth, 2019; see supplementary material). Under a conservative deployment scenario (5 kg of feedstock per rooftop cassette) and a lower-end CDR capacity (220 kg CO_2/t), the CDR potential of green roofs in Western Europe, covering 4,320 km^2 (2022 value, Table 1; Ürge-Vorsatz et al., 2025), is estimated at 4.75 Mt CO_2 via ERW. In a more optimistic scenario (10 kg of feedstock per cassette and a CDR capacity of 429 kgCO_2/t), the theoretical CDR capacity of roof

Table 1

Global and regional roof areas available for green roofs (Ürge-Vorsatz et al., 2025) and the corresponding theoretical total yield of the geochemical reactions for CDR(i.e., not accounting for weathering rate or other key factors that will affect achievable CDR on relevant timescales) for global and socio-economic regions via ERW.

	Global and regional available roof area for green roofs (billion m^2) (data from Ürge-Vorsatz et al., 2025)			Theoretical CDR capacity as alkalinity production (Mt CO_2)			
	Year 2022	Estimated coverage by 2060	Estimated % increase	2022 conservative scenario	2022 optimistic scenario	2060 conservative scenario	2060 optimistic scenario
Central and Eastern Europe	0.08	0.09	9	0.1	0.3	0.1	0.4
North America	8.5	11.3	33	9.4	36.5	12.4	48.5
Pacific OECD countries	6.4	8.6	34	7.0	27.5	9.4	36.7
Eurasian post-Soviet states	3.6	5.2	45	3.9	15.2	5.7	22.1
East and Central Asia	19.5	31.2	60	21.4	83.6	34.3	133.8
Western Europe	4.3	8.0	85	4.8	18.5	8.8	34.2
South Asia	3.6	6.9	92	3.9	15.4	7.6	29.6
Sub-Saharan Africa	1.9	3.8	103	2.1	8.1	4.2	16.5
Latin America	7.5	17.2	129	8.3	32.3	18.9	73.7
Middle East and North Africa	3.7	9.8	164	4.1	15.9	10.8	42.0
Other Pacific Asia	4.8	13.3	179	5.2	20.5	14.7	57.2
Global coverage	**63.8**	**115.3**	**81**	**70.2**	**273.8**	**126.9**	**494.7**

OECD = Organisation for Economic Co-operation and Development.

coverage in Western Europe is 18.5 Mt CO_2. If European rooftop coverage expands as predicted in the study of Ürge-Vorsatz et al. (2025) to 7980 km^2 by 2060, the theoretical CDR capacity range rises to 9-34 Mt CO_2 (Table 1). Extrapolating assumptions on basalt performance in Europe to other world regions, the current global removal potential for CDR via green roofs is 70 Mt CO_2 (conservative) or 274 Mt CO_2 (optimistic), dominated by contributions from East and Central Asia, North America, Latin America and Pacific regions (Table 1). This range could rise to 127-495 Mt CO_2 by 2060. The estimated CDR reflects only the incremental removal delivered by ERW. Green roofs also sequester carbon biologically through plant growth, which can contribute up to 1.8 kg CO_2 per m^2 (Cai et al., 2019), occurring independently of any ERW contribution.

3.1.2. Caveats and uncertainty

While the theoretical CDR capacity of green roofs in Europe and beyond is promising, realising even a fraction of this potential requires accounting for a range of factors. These estimates represent the theoretical maximum CDR capacity of the selected basalts, based on complete chemical/mineralogical reactivity. However, actual achievable CDR will depend on kinetic factors, local conditions, structural limitations, life-cycle emissions and substrate management. These dynamics must be understood in detail to assess the true viability of green roofs for large-scale CDR, which can only be fully evaluated through real-world implementation and monitoring.

Mineral dissolution kinetics, which govern the timescales over which mineral dissolution occurs, mean that these values can only be achieved over prolonged periods (decades to centuries) due to factors such as surface area, mineralogy, water availability, temperature, pH, biological activity and exposure to acids. Given the higher reactivity of ultramafic and wollastonite-rich rocks, basaltic feedstocks are expected to exhibit slower weathering rates in substrates. The reactivity of basalt itself can vary significantly depending on factors like grain size and mineral composition, with finer-grained basalts generally weathering more quickly (Bullock et al., 2022). Additionally, while basalt is commercially available for large-scale implementation, more reactive feedstocks like wollastonite and olivine may offer greater CDR potential and faster CO_2 uptake (Jariwala et al., 2022; te Pas et al., 2023), though the potentially toxic trace element composition, particularly in the case of olivine and dunite, needs to be considered. Additionally, water availability, microbial presence, plant roots and substrate porosity can all influence weathering rates. As observed in agricultural settings with basalt spreading, initial CDR is typically limited to less than 10% of the theoretical potential over 1-3 years (e.g., Beerling et al., 2024; Dupla et al., 2025; Gaucher et al., 2025; UNDO, 2025). Green roofs, by contrast, may offer more controlled environments with regular irrigation, plant selection and maintenance, which could accelerate weathering rates and enhance CDR potential.

Another key inference is the application rate of feedstock, set at 5-10 kg/m^2 of roof. This estimate is based on general considerations about roof load capacity and substrate configuration, but variations in roof types, load-bearing capacity and substrate material all introduce uncertainty. Lightweight substrates may allow for higher feedstock application, but could affect plant health, nutrient availability and water retention. Further sensitivity analyses are needed to understand how these factors influence both the feasibility and effectiveness of feedstock application. The weight capacity of rooftops must be carefully assessed before deployment, as even conventional green roofs can exceed structural limits on older or lightly engineered buildings (Cascone et al., 2018), while the addition of mineral amendments for ERW will further increase substrate mass. For instance, extensive green roof weight typically ranges from 50 to 150 kg/m^2, and intensive roofs can exceed 350 kg/m^2 (Pérez et al., 2018; Rosasco and Perini, 2019). Many roofs have load capacities of around 300-500 kg/m^2 (Ancion et al., 2021; Gupta, 2024), so integrating green roofs with PV systems, though lighter, still contributes to the overall load. As such, the roof's structural capacity will ultimately determine the feasible substrate depth and feedstock application, ensuring that ERW systems are safe, compliant and viable.

An assumption made here is the available rooftop coverage, based on estimates from Ürge-Vorsatz et al. (2025). While useful, the study highlights that these estimates overlook local variations in rooftop characteristics, human behaviour, zoning laws and climate change impacts, all of which can affect both rooftop space availability and suitability for green roofs or solar panels. Human factors like property owner willingness and urban density introduce considerable uncertainty, and more localised studies are needed to refine these estimates. Addressing these uncertainties through dedicated studies will be critical for refining CDR models and scaling the potential of basalt and other feedstocks on green roofs under diverse conditions. Comprehensive testing of feedstocks, application rates and environmental factors will be necessary to ensure that predicted CDR aligns with real-world performance.

3.2. Legislation and incentives for adoption

While the total theoretical maximum removal potential in urban areas may not match the Gt-scale achievable through conventional rural ERW deployments (Beerling et al., 2020), CDR from green roofs could advance more rapidly. This is due to higher infrastructural readiness, including their modular and engineered design, existing drainage and irrigation systems and easier access for maintenance. Regulatory barriers may also be lower, as green roofs are often already approved within urban planning frameworks and are less affected by land-use or agricultural restrictions. In addition, rooftop installations pose lower perceived risk to landowners compared to agricultural applications, since they do not interfere with primary production systems or income sources and can be piloted without disrupting ongoing operations. These factors may enable a faster transition to kt-scale removal or more. There is currently a bottleneck for achieving significant removal tonnages through ERW in agricultural and industrial settings, in part due to a reluctance to fully commit to ERW as a standalone source of investment (i.e., relying on the nascent carbon market) while significant knowledge gaps still exist (Carbon Gap, 2025; Frontier Climate, 2025). There is also a current preference that ERW serves as a co-benefit (e.g., for the validation of projects to generate carbon credits; Isometric, 2025), where additional sources of income already exist or feedstock additions provide improvements to current production, making adoption lower risk. This is where ERW in green roofs may achieve faster implementation and upscaling, as supportive markets, legislation and incentives for green roof infrastructure either already exist or are being actively developed (Liberalesso et al., 2024). These include established supply chains for green roofing materials, municipal greening policies and financial incentives aimed at promoting nature-based urban solutions.

This is particularly relevant for potential widescale European implementation. For instance, the EU Chapter of the World Green Infrastructure Network has previously published a briefing for policymakers, highlighting key legislative efforts to promote green infrastructure across the EU (Green Roofs for Healthy Cities, 2023). The European Parliament has mandated that all 27 Member States ensure new buildings incorporate climate adaptation measures, including green infrastructure and vegetated surfaces, to enhance climate resilience. Green infrastructure is also included in integrated renovation programmes led by national, regional and local authorities (Table 2). For instance, environmental legislation in France aims to green commercial zones by installing plants and solar panels on roofs (European Commission, 2022). Hamburg offers a green roof subsidy covering up to 60% of installation costs for private and public buildings (Interlace Hub, 2023). Basel, with the highest green roof area per capita, promotes green roofs through incentives and legal mandates (Climate ADAPT, 2020). Madrid's Green Roof Plan encourages rooftop greening by offering urban incentives, such as allowing penthouse construction with simplified licensing (Greenroofs.com, 2025).

These policies, incentives, and legislative frameworks create a favourable environment for the rapid adoption of ERW-based CDR in green roofs. By integrating ERW into existing green infrastructure initiatives, CDR deployment can leverage financial support, regulatory backing and established markets, reducing investment risks and accelerating implementation. The widespread commitment to green infrastructure across Europe, from EU directives to city-level subsidies, provides a strong foundation for scaling CDR in urban settings, bridging the gap between research and large-scale application.

3.3. Co-benefits of MRV and ERW in green roofs

ERW green roof deployments, pilot schemes and feasibility studies, scaled up from relatively simple laboratory settings to highly controlled real-world conditions, may provide a lower-risk and more measurable demonstration of CDR compared to direct incorporation into natural environments such as agricultural fields or forests, where greater complexities may skew or influence evaluations. Controlled drainage channels allow for the direct collection of drainage waters. This is a significant advantage for the MRV process because it can be challenging and costly to extract leachate from agricultural systems. The closed-system nature, controlled drainage and simplified and homogenous substrate structure of green roof systems allow for more direct links between water and soil chemistry, flow and weathering rates. Equipment that may be subject to analytical complexities within a fully open-system natural or agricultural setting, such as fluid or gas flux measurement tools, can potentially operate with greater precision and reliability in controlled environments like in green roofs, where boundary conditions and flow paths are more easily defined and monitored.

Critically, green roofs allow for refined MRV and feasibility studies that can optimise the ERW process. They can benefit from the presence of microbes and other amendments (e.g., biochar) in the substrate alongside the incorporated feedstock, under controlled configurations and with definitive system boundaries. This allows for a more controlled and quantifiable CDR process compared to the complex rural soil systems (Abdalqadir et al., 2024; Clarkson et al., 2024; Santos et al., 2023), and its use may further refine MRV approaches for wider applicability.

While the environmental and urban resilience benefits, such as improved air quality, reduced urban heat, increased biodiversity and better stormwater management, stem primarily from green roofs themselves, the addition of ERW introduces new climate mitigation functions. In particular, green roofs can provide a stable, monitored environment that facilitates MRV of ERW processes, potentially enabling high-certainty carbon crediting. This added functionality could serve as a complementary revenue stream, helping to offset installation and maintenance costs and accelerating green roof adoption in cities. Moreover, synergies with rooftop PV systems can further enhance system performance: green roofs help cool PV panels and improve energy yield (Ajuntament de Barcelona, 2015; Vijayaraghavan, 2016), while PV panels in turn reduce evaporation and enhance water retention by providing shading (Vijayaraghavan, 2016), thus improving weathering rates. Although this work frames ERW as a CDR strategy with green roof benefits as co-benefits, in practice the established environmental and energy functions of green roofs may be the primary drivers of deployment, making additional CDR by ERW itself a potential co-benefit

4. Factors affecting deployment

While green roofs offer a promising avenue for CDR, their widespread adoption is hindered by financial, regulatory and technical barriers. The barriers to the deployment of ERW green roofs largely overlap with those affecting global green roof acceptance and adoption in general. However, some challenges are specific to their use in CDR. The primary barriers include financial costs, regional variability, legislative support and public awareness, infrastructure adequacy and challenges related to MRV.

4.1. Financial costs

The additional costs associated with the installation and maintenance of green roofs have been identified as a major barrier to adoption (Chen et al., 2019; Rahman et al., 2013). These costs include increased expenses for upkeep, design and construction (Shafique et al., 2018). The higher upfront investment required for green roofs can deter building owners, despite potential long-term economic benefits, such as improved energy efficiency and extended roof lifespan (Porsche and Köhler, 2003). In some regions, financial incentives provided by local authorities or governments have been proposed to offset initial expenses and encourage adoption (Doğmuşöz, 2023). However, this is largely limited to more developed countries, such as those in Western Europe (detailed in Section 5 and Table 2).

To address these financial barriers, it has been suggested that green roof implementation should integrate multiple sectors, such as water

Table 2

Assessment of the suitability of countries in the NUTS2 region of Europe for potential ERW green roof deployment, based on available rooftop area (originally designated for solar PV coverage, calculated using population density and total population at a 1 km resolution; Bódis et al., 2019; European Commission, 2019), examples of existing legislation and financial incentives (see supplementary material for detailed examples) and the general climate of each country. A qualitative evaluation of suitability is provided for each country.

	Available roof space (measured for PV, applicable for green roofs) in ha	Examples of existing legislation or incentives	Predominant climate (based on Köppen climate classification)	Possible changes to climate classifcation by 2100	Suitability for rapid ERW green roof deployment
Albania	2409	Preliminary grants, studies, proposals and initiatives in Tirana	Csa, Cfb	Csa hotter	Marginally suitable - Partially appropriate climate
Austria	15,140	Municipal financial grants and subsidies in cities such as Vienna, Linz and Graz	Cfb, Dfb	Cfa/Cfb	Marginally suitable - Governmental incentives
Belgium	18,307	Municipal financial grants and incentives in Flemish Region, Walloon Region and Brussels	Cfb	Cfa	Marginally suitable - Governmental incentives
Bulgaria	14,977	Current laws allow green roofs only to meet minimum green space requirements for certain municipality buildings	Dfa/Dfb, Cfa/Csa	Cfb/Cfa	Marginally suitable - Partially appropriate climate
Croatia	8488	Financial grants for green projects, no specific green roof policies or initiatives	Cfb, Csa/Csb	Csa/Cfa	Marginally suitable - Appropriate climate
Cyprus	3111	Initiatives that indirectly support sustainable building practices, including roof thermal insulation	Csa	More arid	Marginally suitable - Appropriate climate
Czechia	21,604	National subsidies for renovated buildings or low-energy new builds, municipal incentives for Brno	Dfb, Cfb	Cfb	Suitable - Sufficient roof space; Governmental incentives
Denmark	12,062	Copenhagen requires green roofs on all new buildings with roof slopes of less than 30 degrees	Cfb	Cfa	Marginally suitable - Governmental incentives
Estonia	2659	Urban planning for optimal roof usage, including green roofs, no specific policies or incentives	Dfb	Cfb	Currently unsuitable
Finland	10,201	Helsinki-based green roof projects, strategies strategy for increasing and improving the use of green roofs	Dfc/Dfb	Cfb	Currently unsuitable
France	134,651	By law, all new buildings in a commercial zone must partially (at least 30%) cover roofs in either green roofs or solar panels	Cfb, Csa/Csb, Dfb	Cfa	Highly suitable - Abundant roof space; Governmental incentives; Appropriate climate
Germany	152,301	Hamburg strategy to green 70% of new buildings and roofs undergoing renovation, national tax reliefs and municipal funding and incentives	Cfb, Dfb	Cfa	Suitable - Abundant roof space; Governmental incentives
Greece	15,500	National and municipal initiatives, projects and initiatives in Athens and Thessaloniki	Csa	More arid	Suitable - Governmental incentives; Appropriate climate
Hungary	19,060	Mandatory green roofs in Budapest's 12th District, green renovation subsidies including green roofs	Dfa/Dfb	Cfb/Cfa	Marginally suitable -Governmental incentives
Iceland	704	"Turf houses" traditionally used in place of modern green roofs, no dedicated policies for green roofs	ET, Cfc	Cfb	Currently unsuitable
Ireland	5627	Dublin green roof policy guidelines, guidance and supportive frameworks encouraging sustainable practices	Cfb	Cfa	Currently unsuitable
Italy	75,257	Energy-efficiency renovation and green building financial incentives, projects in Milan and Pavia	Csa/Csb, Cfb, Dfb	Csa/Cfa	Marginally suitable -Abundant roof space
Latvia	3011	Policy recommendations and studies, no specific national or municipal incentives for green roofs	Dfb	Cfb	Currently unsuitable
Liechtenstein	53	Encouragement of sustainable roofing systems, no specific national or municipal incentives	Cfb, Dfb	Cfb	Currently unsuitable
Lithuania	5765	Projects in Vilnius and Ignalina region, green roofs encouraged but not incentivised	Dfb	Cfa	Currently unsuitable
Luxembourg	941	Grants for installation of green roofs in Luxembourg City, interactive green roof mapping tool displays usage in city	Cfb	More arid	Marginally suitable -Governmental incentives
Malta	529	Proposals and green paper to introduce mandates for green roofs, Rabat-based project	Csa	Csa/Cfa	Currently unsuitable
Montenegro	967	Encouragement of green roofs as part of building redevelopment, no specific green roof incentives	Csa/Csb, Cfb/Dfb	Cfa	Currently unsuitable
Netherlands	28,214	Rotterdam and Alphen hosting world's first ERW green roof study, national and municipal subsidies, including Rotterdam and Amsterdam	Cfb	Csa/Cfa	Suitable - Sufficient roof space; Governmental incentives
North Macedonia	1804	Studies relating to adoption of regulatory practices, no legislation or incentives for green roofs	Cfa/Csa	Cfb	Currently unsuitable
Norway	5472	Oslo committed to employing 700 ha green roofs by 2030, with standard and guidelines prepared	Dfc/Dfb, Cfb/Cfc	Cfb	Marginally suitable -Governmental incentives
Poland	46,878	National funding programs, municipal support including tax reductions and subsidies	Dfb	Csa	Marginally suitable -Sufficient roof space; Governmental incentives

(*continued on next page*)

Table 2 (*continued*)

	Available roof space (measured for PV, applicable for green roofs) in ha	Examples of existing legislation or incentives	Predominant climate (based on Köppen climate classification)	Possible changes to climate classifcation by 2100	Suitability for rapid ERW green roof deployment
Portugal	17,023	National funding programs, Barreiro municipality investment incentive, project in Porto addressing policies	Csa/Csb, Cfb	Cfb/Cfa	Suitable - Governmental incentives; Appropriate climate
Romania	35,422	Organised efforts to contribute to the development of Romania's green roof market, no specific policies	Dfb/Dfa, Cfb	Cfb/Cfa	Suitable - Sufficient roof space; Partially appropriate climate
Serbia	11,812	Belgrade policy supporting use of green roofs through strategic goals of the Development Strategy of the City	Dfa/Dfb, Cfb/Csa	Cfb	Marginally suitable - Partially appropriate climate
Slovakia	10,822	Financial contribution for the application of a green roof as a water retention measure or as a subsidy from the restoration plan	Dfb, Cfb	Csa/Cfa	Suitable - Governmental incentives; Partially appropriate climate
Slovenia	2869	Ljubljana mandates green roofs for buildings larger than 400 m^2, Kranj setting up strategy for green roofs	Cfb, Csa/Cfb	More arid	Currently unsuitable
Spain	46,169	National product financing programs, Madrid green roof plan to promote green roofs, Barcelona Council offers advice on creating green roofs and obtaining grants and subsidies	Csa/Csb, Cfb, BSk	Cfb	Highly suitable - Sufficient roof space; Governmental incentives; Appropriate climate
Sweden	15,718	Financial incentives, grants and tax breaks for green building projects, Stockholm and Malmö projects	Dfc/Dfb, Cfb	Cfb/Cfa	Marginally suitable - Governmental incentives
Switzerland	11,467	Basel offers subsidies and has mandates that state all new and retrofitted buildings with flat roofs include green spaces, Zürich has similar regulations on flat roofs	Cfb, Dfb/Dfc	Csa/Cfa	Marginally suitable - Governmental incentives
Turkey	36,175	Mandatory green roofs on buildings over 60 thousand m^2 in İzmir, no specific green roof policies	Csa/Csb, Cfa, BSk	Cfa	Suitable - Sufficient roof space; Appropriate climate
United Kingdom	77,117	National financial support for green roofs, green roofs in new London developments and refurbishments, Cornwall programs support installation of green roofs	Cfb	Csa hotter	Suitable - Abundant roof space; Governmental incentives

Köppen climate classification: Af – Tropical rainforest; Am – Tropical monsoon; BSk – Cold semi-arid; Cfa – Humid subtropical; Cfb – Temperate oceanic; Cfc – Subpolar oceanic; Csa – Mediterranean hot-summer; Csb – Mediterranean warm-summer; Dfa – Humid continental hot-summer; Dfb – Humid continental warm-summer; Dfc – Subarctic / boreal; ET – Tundra. Current, historical and predicted future changes in the global distribution of Köppen-Geiger climate zones based on Beck et al. (2023).

management, energy and agriculture (Chen et al., 2019), while any potential financial benefits from CDR may primarily arise through carbon crediting strategies. This would allow for cost-sharing and increase the economic viability of green roofs. Furthermore, raising awareness of life-cycle cost benefits (e.g., long-term energy savings and extended roof life) among stakeholders could facilitate broader acceptance (Bianchini and Hewage, 2012; Hekrle et al., 2023; Teotónio et al., 2018). The use of local materials and vegetation could help reduce transportation and installation costs (Chen et al., 2019).

4.2. *Regional variability and adequacy of infrastructure*

The feasibility of CDR-focused green roofs varies by region due to differences in rooftop availability, climate conditions, technical capabilities, public attitudes and economic circumstances. While research on green roof barriers has been conducted in various locations (e.g., China, Malaysia, Australia, Iran, Cambodia and other areas of Southeast Asia), findings are not universally applicable due to region-specific factors (Chen et al., 2019; Durdyev and Ihtiyar, 2020; Mahdiyar et al., 2020; Sanmargaraja et al., 2019; Zakeri and Mahdiyar, 2020).

Appropriate conditions for an ERW-amended green roof are shaped by rainfall availability, which supplies the water needed for chemical reactions, temperature regimes that influence reaction rates, and anticipated future climate changes that may alter both factors over time. In terms of Köppen climate classification, relatively warm and wet climates, such as tropical rainforest (*Af*), tropical monsoon (*Am*), humid subtropical (*Cfa, Cwa*) and temperate oceanic (*Cfb*), offer the most favourable conditions for ERW due to consistent moisture and moderate to high temperatures. Within Europe, temperate oceanic (*Cfb*) and humid subtropical (*Cfa*) climates provide the closest analogues, with mild to warm temperatures and ample rainfall supporting sustained weathering reactions. Countries with these climates, such as Belgium, Netherlands, Germany, France, Ireland, the UK and Switzerland, currently provide suitable conditions for ERW-amended green roofs. In contrast, southern Mediterranean regions, including Cyprus, Malta, Greece and southern Spain, are less suitable today due to high temperatures and seasonal aridity, which may limit water availability and plant survival. However, some regions within countries that have a different dominant climate may still offer favourable conditions; for example, northwest Spain and Portugal may support ERW in green roof substrates due to a combination of relatively high temperatures (average summer ∼25 °C) and substantial winter rainfall (up to ∼140 mm per month).

With projected climate change (assuming an SSP2-4.5 Shared Socioeconomic Pathway scenario, based on projections of Beck et al., 2023), northern and eastern countries (e.g., Finland, Sweden, Estonia, Poland, Czechia) are projected to become more favourable as warming shifts them toward milder *Cfb* or even *Cfa* climates, enhancing ERW weathering potential. Conversely, some currently suitable southern regions (e.g., Portugal, Spain, Greece, Cyprus, Malta) may become less favourable due to increasing heat and summer drought, highlighting a general northward and inland shift of ERW-optimal conditions across Europe. Warmer regions with high solar potential, such as southern Europe, may still enhance rock weathering rates locally through elevated temperatures and, in some areas, higher precipitation and plant activity. Detailed mapping of rooftop availability and climatic suitability could help identify optimal locations for ERW trials and future deployment.

Infrastructure limitations present another regional barrier to green roof deployment, including a shortage of skilled professionals capable of installing and maintaining green infrastructure (Irga et al., 2017; Rahman et al., 2013). Issues such as poor coordination between disciplines (architectural, civil and environmental engineering), structural weight limitations and roof leakage concerns have been highlighted as significant challenges (Rahman et al., 2013; Shafique et al., 2018; Vijayaraghavan, 2016), and adding CDR-related undertakings (such as feedstock amendments, MRV) to the process may further hamper widescale adoption. Competing demands for rooftop space also pose a challenge in some regions. In addition to private uses such as recreational areas or infrastructure, rooftop CDR strategies must contend with other climate mitigation and adaptation measures, such as the installation of high-albedo (cool) roofs designed to reflect solar radiation and reduce building heat load. While PV systems are widely adopted, green roofs can complement them by improving the efficiency of solar panels through temperature regulation, though more research is needed to assess the impact of solar panels on ERW performance, as well as structural loading requirements (Vijayaraghavan, 2016).

As an added consideration, while suitable silicate and alkaline feedstocks are generally considered widely available, urban-focused ERW for green roofs may face logistical challenges, as these materials need to be transported to decentralised city locations or to facilities where they can be pre-mixed into substrates.

4.3. *Legislative support and public awareness*

Public awareness has been identified as a crucial factor in green roof adoption, often more influential than financial incentives (Durdyev and Ihtiyar, 2020; Pratama et al., 2023; Zakeri and Mahidiyar, 2020), as limited understanding of their benefits and functions can hinder widespread uptake. In some regions, limited expertise, inadequate government policies and weak incentive structures further slow progress (Doğmuşöz, 2023). Moreover, the lack of standardised materials and uncertainty over the long-term environmental impact of components, such as polymer-based drainage and filter layers, require further research (Bianchini and Hewage, 2012; Vijayaraghavan, 2016). Although green roof technology has been implemented in various parts of the world, uptake remains slow in places like Asia and Australia due to a lack of supportive policies and insufficient awareness. Strengthening regulatory frameworks and introducing incentives in larger cities akin to those in some European regions could help overcome these barriers. Furthermore, demonstrating successful case studies whereby additional benefits such as CDR via ERW are achievable could improve confidence among urban designers and developers.

Additionally, the complexity of MRV to ensure the rate of net CDR and lack of existing legislation for carbon removal certification poses a significant challenge to the integration of ERW within green roofs. For example, it remains difficult to distinguish weathering-derived CDR from background soil carbon dynamics or short-term biogenic fluxes. Standardised protocols for sampling, monitoring and verifying mineral dissolution and carbon fate are still under development. Furthermore, most urban planning and building regulations do not yet recognise or account for rooftop CDR, and there is little policy guidance on how to credit such removal within existing carbon markets or certification schemes. Questions also remain regarding the responsibilities of building owners, developers and policymakers in both maintaining green roofs and ensuring accurate MRV. This is due to a combination of fragmented ownership and accountability with privately owned buildings, policy and regulatory haps (CDR via ERW is not yet regulated in such settings) and technical complexity. Clarifying roles and establishing standardised methodologies will be essential for integrating green roofs into broader CDR strategies. The eligibility of green roofs for carbon credits, if pursued, will also require robust verification frameworks and commitments from appropriate personnel. Expanding MRV efforts from individual green roofs to larger urban regions may provide more accurate assessments of green roof environmental performance (Hong et al., 2019), as well as CDR potential.

4.4. *Influence of soil texture*

Soil texture, specifically the proportion of clay, silt and sand, can strongly influence ERW performance through its effects on chemical reactivity, water retention and infiltration-runoff dynamics (Deng et al., 2023; Yang et al., 2021). Fine-textured soils, rich in clay and silt, have high water-holding capacity and large specific surface areas, which enhance chemical interactions between minerals, water and CO_2. In contrast, sandy soils retain less water but have higher saturated hydraulic conductivity (K_s), meaning water moves through them more easily when fully saturated. K_s determines a soil's maximum infiltration rate: when rainfall intensity exceeds this rate, excess water generates runoff; when rainfall is below K_s, infiltration dominates, and surface runoff is minimal (Cheng, 2025).

These hydraulic properties directly influence ERW reactions. In fine soils, CO_2 dissolved in rainwater or diffused from the atmosphere reacts with silicate minerals, forming bicarbonate and releasing calcium and magnesium ions ($CO_2 + H_2O + \text{silicates} \rightarrow HCO_3^- + Ca^{2+}/Mg^{2+}$). High water retention prolongs pore water residence time, sustaining mineral-water-CO_2 interactions and increasing the reaction's overall extent. In sandy soils, rapid drainage may limit water-mineral contact, reducing chemical reactivity; however, high permeability can facilitate CO_2 degassing and promote the precipitation of carbonate minerals ($HCO_3^- + Ca^{2+}/Mg^{2+} \rightarrow \text{carbonate minerals}$) (Li et al., 2025). Soils with intermediate textures, containing balanced proportions of sand, silt and clay, may provide an optimal compromise, combining sufficient infiltration and runoff management with adequate water retention to support ERW reactions.

For green roofs, soil choices usually involve engineered substrates rather than natural topsoil, designed to balance lightweight drainage with water and nutrient retention (Cascone, 2019). These substrates combine inorganic components, such as expanded clay, shale, perlite, pumice or crushed brick, with organic additives like compost or biochar. Sand improves drainage, while additives such as vermiculite or hydrophilic polymers enhance water-holding capacity. Substrate formulations are tailored to roof type (e.g., extensive vs. intensive) and local climate, ensuring adequate water for both plant health and ERW reactions. By selecting substrates with an appropriate balance of particle size, mineral composition and water retention properties, ERW green roofs can maximise chemical weathering while maintaining hydraulic performance, even under variable climatic conditions.

4.5. *Fate of CDR products*

As highlighted in Section 3.1.1, urbanisation has led to significant underutilisation of rooftop surfaces, representing a major opportunity for CDR through green roofs (Monteiro et al., 2017; Stovin et al., 2012). These underused surfaces, which account for around 30–32% of urban horizontal surfaces, have significant potential to support ERW. Once installed, the resultant liquid runoff and outflows from green roofs do not follow the same downstream pathways as conventional ERW products in rural and agricultural areas, such as percolation through soil columns to groundwater or surface waters like streams and rivers, ultimately reaching the ocean. As a result, understanding the fate of runoff containing alkalinity in urban environments is critical for accurate CDR quantification and any possible carbon accounting. The water required for ERW reactions is predominantly derived from rainfall (unless additional watering practices are applied), which percolates through the substrate. The majority of the water exits the green roofs through drainage holes, with some retention within the substrate, uptake by plants and water loss due to evaporation. The runoff pathway, as summarised in Fig. 2, can be summarised as follows:

1. Rainwater enters the green roof substrate and percolates downwards,

2. Water reacts with feedstock, substrate and microbes,
3. Alkalinity is formed (CDR product),
4. Some water may evaporate, be retained in the substrate or be taken up by plants
5. Possible secondary mineral precipitation (e.g., carbonates, clays, oxides) may occur, and
6. The majority of runoff containing the produced alkalinity exits through the drainage holes.

Given that runoff from green roofs is almost entirely rainfall-fed, it is reasonable to assume that the runoff will follow the same pathways as rainwater in urban buildings. However, drainage practices can vary by municipality, and there are several types of sewage systems (Butler et al., 2024; EPA, 2004). In combined sewage systems, wastewater and rainwater flow together to treatment plants, whereas separated systems direct rainwater to surface waters, ditches or the ground, and wastewater to treatment plants. Improved systems handle both rain and wastewater, with some rainwater going to treatment plants while the remainder is discharged into ponds or ditches.

Ultimately, the fate of the alkalinity-laden runoff is to move into surface or groundwaters, either directly or through expulsion from sewerage systems, with or without treatment. Modern urban systems often use improved dual systems to quickly discharge rainwater through storm drains, avoiding unnecessary treatment (Monachese et al., 2024; Poleto and Tassi, 2012). This runoff flows to rivers and groundwater systems, eventually reaching the ocean. In typical ERW deployments, carbon accounting requires reporting for potential leakage from processes such as CO_2 outgassing during carbonate precipitation or secondary mineral formation (e.g., Isometric, 2025).

In green roof ERW deployments, runoff products follow different pathways due to their urban positioning, but some runoff will share similar fates to rural and agricultural-based deployments. For these, downstream losses are considered using MRV protocols, with discount factors for riverine and ocean degassing, or through empirical models (Isometric, 2025). The controlled nature of green rooftops offers the opportunity for more accurate CDR calculations than rural systems, as monitoring is easier due to the limited leakage and defined runoff pathways. However, complications arise once runoff enters drainage systems. If runoff enters segregated stormwater drains, it behaves similarly to typical ERW deployments, where natural processes are accounted for. If runoff enters combined or mixed sewage systems, additional assessments are required to evaluate whether water treatment processes affect alkalinity, potentially leading to CO_2 outgassing.

Most modern systems quickly divert rainwater from treatment processes and discharge it directly to surface or groundwater, so runoff can generally be treated as rainwater under standard MRV approaches. Exceptions should be made only if unusual treatment processes are in place, such as heavy chemical use, which may be restricted to more industrial settings (Kato and Kansha, 2024; Potreck and Tränckner, 2025; Sathya et al., 2022). To ensure accurate carbon credit claims and MRV, it is essential to gather detailed information on the drainage systems of each building.

It is also important to recognise that all ERW deployments, whether urban or rural, encounter inherent system complexities that are not fully understood. Natural soil systems, agricultural practices, river dynamics and oceanic processes are all factors that can complicate carbon accounting in ERW systems. In urban environments, however, the more defined infrastructure of drainage systems means that some of these complexities may be better understood than those associated with natural processes in rural settings. A detailed study on the effects of wastewater treatment on alkalinity would provide valuable insights, though treatment steps would only be applicable to certain urban systems. As a best practice, each rooftop deployment should be assessed on a site-by-site basis, with appropriate discounting decisions based on the specific circumstances. In general, carbon credits and MRV processes should apply standard riverine and oceanic outgassing discounting unless exceptional circumstances arise within the drainage system.

5. Future targets and directions

Europe (particularly Western Europe) likely presents the greatest opportunities for rapid and widescale deployment due to the combination of existing rooftop space (Fig. 3), infrastructure, technical expertise, market presence, legislation and financial incentives (Table 2). For these reasons, European countries, specifically those in the Nomenclature of Territorial Units for Statistics (NUTS) 2 region of the EU, former EU, European Free Trade Association (EFTA) and candidate countries, have been further evaluated for their suitability for future ERW green roof feasibility studies, pilot projects and full-scale deployment, considering both current climatic conditions and projected future climate scenarios that may affect weathering rates and substrate performance. The theoretical global potential for CDR via ERW in green roofs is significant, with promising opportunities in North America and future prospects in parts of Asia and Latin America, where current and projected climatic conditions may be particularly advantageous for ERW. However, it should again be emphasised that these assessments are preliminary, and the feasibility and actual CDR potential will depend on a range of factors, including weathering kinetics, feedstock compatibility and climatic suitability, requiring further investigation through empirical case studies and pilot schemes.

Table 2 summarises the key criteria for ERW green roof implementation, including the distribution of available rooftop space (Fig. 3; based on solar PV-suitable rooftops, estimated from population density and total population at 1 km resolution; Bódis et al., 2019; European Commission, 2019), selected examples of legislation or incentives promoting green roofs in cities, and the general climate of each country. The data for these criteria are used to qualitatively assess the suitability of each country for large-scale ERW green roof deployment. Countries are categorised as currently unsuitable (where available rooftop space, legislation/incentives and climate do not presently support deployment), marginally suitable (at least one of the criteria is deemed positive for deployment), suitable (at least two of the criteria support deployment) or highly suitable (where all three criteria are favourable for deployment). It should be noted that while rooftop slope is generally not a major limitation for solar PV, it can restrict the feasibility of green roof installations. As a result, the area suitable for green roofs may represent only a fraction of the area deemed suitable for PV deployment and requires further substantiation through pilot-scale research.

Germany and France have the largest amounts of available roof space, driven by their extensive urban areas, followed by the United Kingdom and Italy (Fig. 3). Poland and Spain also offer significant roof space availability, while Czechia, the Netherlands, Romania and Turkey have considerable area. These countries also have governmental (national, local or both) and financial incentives to promote the use of green roofs. Though Europe does not generally have the most ideal climatic conditions for ERW (such as the hot, humid conditions typical of more tropical and subtropical regions), coastal Mediterranean climates and areas with high seasonal rainfall can support weathering. Croatia, Cyprus, France, Greece, Portugal, Spain and Turkey experience high seasonal temperatures and mild, wet winters, making them particularly well-suited for ERW under current climate conditions. In certain regions of Albania, Bulgaria, Romania and Slovakia, ERW suitability may be seasonal, depending on local temperature and rainfall patterns.

The qualitative assessment suggests that France is likely the most suitable country for ERW green roof implementation, offering the greatest potential for meaningful removal on relatively short timescales. Spain also demonstrates high suitability, although with less available roof space. Germany and the United Kingdom are strong candidates for rollout, owing to their abundant roof space, existing legislation and incentives. It is also noteworthy that these four countries are well-positioned to secure feedstock supplies of mafic rocks, hosting basalt-producing mines within their borders (Honkisch et al., 2024; Nowell,

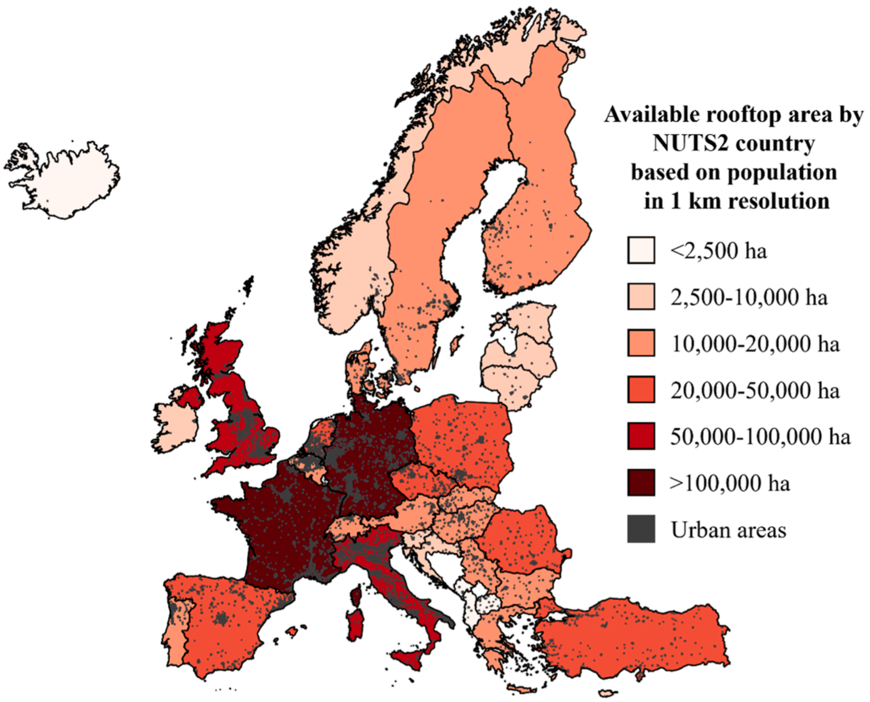

Fig. 3. Distribution of available rooftop area (originally designated to solar PV, aggregated at NUTS2 national level as a function of population density and total population applied in 1 km resolution; Bódis et al., 2019; European Commission, 2019) and densely populated urban areas (Schneider et al., 2003) in select European countries.

2008; Poblete Piedrabuena et al., 2019; Sims, 2017). Czechia, Greece, the Netherlands, Portugal, Romania, Slovakia and Turkey also meet several criteria that could support successful deployment. Countries such as Finland, Greece, Iceland, Italy, Norway, Portugal and Turkey also produce suitable feedstocks, including dunite and wollastonite deposits (Azrague et al., 2016; Gurmendi, 2009; Kremer et al., 2019; Nordkalk, 2022). Having a proximal supplier can reduce both costs and associated transport emissions, leading to a greater net CDR when assessed through life cycle analysis (LCA) and making deployment more economically viable and environmentally effective. However, these theoretical projections should be interpreted with caution. Achievable CDR is likely to be influenced by a range of variables including structural loading, vegetation compatibility, maintenance needs, material sourcing, possible contaminants and LCA emissions. As such, these findings primarily serve as a promising pilot-scale research setting rather than a definitive, large-scale CDR solution at present. Future directions for ERW green roof implementation include the need for more studies exploring a variety of roof types and configurations. This could involve experimenting with different plant species, substrates, feedstocks, biological/microbial additions and the integration of other CDR methods (e.g., biochar), as well as the joint deployment of PV systems. Additionally, studies should consider a range of settings and climates, including projections of future climate suitability, to better understand the broad applicability of green roofs for ERW. Beyond Europe, tropical regions, where ERW rates should be higher and the availability of green roof space is expected to grow, offer significant potential for globally scaling up ERW green roof deployment.

6. Conclusions

Green roofs provide a promising yet preliminary platform for deploying enhanced rock weathering (ERW) as a carbon dioxide removal (CDR) strategy in urban areas. Our initial desktop assessment demonstrates that currently underutilised rooftop spaces could sequester meaningful amounts of CO_2 across Europe and globally, contributing to climate mitigation targets. Several European countries, including France, Germany, Spain, the UK, Italy and the Netherlands, show potential for large-scale deployment, based on rooftop availability, supportive legislation and incentives, and current climate suitability. Globally, ERW green roofs could, under idealised conditions, contribute tens to hundreds of millions of tonnes of CDR per year, with substantial growth potential as rooftop coverage expands over the coming decades. However, these estimates are theoretical and rely on several assumptions that must be tested further in pilot-scale studies. For instance, further empirical research in regions with warmer temperatures and seasonal rainfall, as well as tropical and subtropical areas, may demonstrate favourable conditions for accelerated weathering and long-term carbon sequestration. ERW green roofs also provide multiple co-benefits, including enhanced energy efficiency through improved PV solar panel performance, precise monitoring and optimisation of weathering processes and the potential to accelerate naturally slow weathering reactions to human-relevant timescales of decades rather than millennia.

However, challenges remain. Deployment depends on financial costs, regulatory frameworks, feedstock selection and proximity, substrate texture and composition, plant species and fertilisation strategies, alongside public awareness and understanding of green roof benefits, which can strongly influence adoption. Trace element risks from certain rock amendments must also be managed to ensure environmental safety. Overall, scaling ERW on green roofs bridges the gap between laboratory studies and real-world CDR deployment, serving as promising pilot-scale research avenue for larger rural applications and as standalone urban climate solutions. By integrating ERW into green roofs, cities can support urban decarbonisation while leveraging the established benefits of green roofs, potentially accelerating adoption and helping to de-risk emerging CDR technologies.

CRediT authorship contribution statement

Liam A. Bullock: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rasesh Pokharel:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Amy Lewis:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Peter-Paul Laarhuis:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Robert van der Luyt:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Quirina Rodriguez Mendez:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Sabine Fuss:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Investigation. **David Benavente:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare no competing interests.

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Supplementary materials

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Data availability

Data will be made available on request.

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