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Updated and revised multiannual Roadmaps

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Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy

Research & Innovation Action

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Deliverable 1.22 - Updated and revised Multiannual Roadmaps

Version N°1

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Abbreviations and Acronyms

Acronym	Description
ACES	Africa Centre of Excellence for Sustainable Cooling and Cold Chains
AI	Artificial Intelligence
ARPU	Average Revenue Per User
AU	African Union
BMS	Battery Management System
C&I	Commercial and Industrial
CESP	Comprehensive Energy Solution Planning
CO	Carbon Monoxide
COP	Conference of the Parties
CRM	Customer Relationship Management
DFI	Development Finance Institution
DRC	Democratic Republic of the Congo
DRI	Direct Reduced Iron
DSM	Demand-Side Management
EEE	Electrical and Electronic Equipment
EMS	Energy Management System
EoL	End-of-Life
EoU	End-of-Use

EPC	Engineering, Procurement and Construction (in Section 6.6.9: Electric Pressure Cooker)
EPR	Extended Producer Responsibility
ESCO	Energy Service Company
ESMAP	Energy Sector Management Assistance Program
EU	European Union
EV	Electric Vehicle
FAIR	Findable, Accessible, Interoperable and Reusable
FID	Final Investment Decision
GEM	Global E-waste Monitor
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
ICT	Information and Communication Technology
IEA	International Energy Agency
IGA	Income-Generating Activity
IMG	Interconnected Mini-Grid
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
KPI	Key Performance Indicator

LCA	Life Cycle Assessment
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LEAP-RE	Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy
LFI	Local Financial Institution
LPG	Liquefied Petroleum Gas
MAR	Multi-Annual Roadmap
MEL	Monitoring, Evaluation and Learning
MEPS	Minimum Energy Performance Standards
MoU	Memorandum of Understanding
MRV	Measurement, Reporting and Verification
MSME	Micro, Small and Medium-sized Enterprise
MTTR	Mean Time To Repair
NMF	Non-negative Matrix Factorisation
O&M	Operation and Maintenance
OoS	Out-of-Service
PAR	Peak-to-Average Ratio
PAYGo	Pay-As-You-Go
PCM	Phase-Change Material
PEM	Proton Exchange Membrane

PIC	Prior Informed Consent
PM2.5	Particulate Matter with aerodynamic diameter of 2.5 µm or less
PPE	Personal Protective Equipment
PRO	Producer Responsibility Organisation
PUE	Productive Use of Energy
PV	Photovoltaic
QA	Quality Assurance
R&D	Research and Development
R&I	Research and Innovation
RBF	Results-Based Financing
RE	Renewable Energy
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All
SHS	Solar Home System
SME	Small and Medium-sized Enterprise
SOP	Standard Operating Procedure
SPD / SPP	Small Power Distributor / Small Power Producer

STEEP	Social, Technological, Economic, Environmental and Political
ULAB	Used Lead-Acid Battery
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
WACC	Weighted Average Cost of Capital
WEEE	Waste Electrical and Electronic Equipment
WHO	World Health Organization
WP	Work Package
WRI	World Resources Institute
YAKE	Yet Another Keyword Extractor

Summary

The Multi-Annual Roadmaps (MARs) were originally developed under PRE-LEAP-RE to provide a common framework for structuring joint African–European research and innovation (R&I) cooperation on renewable energy. They organised priority areas around their specific challenges and expected outputs, outcomes and impacts, while already recognising that technological development needed to be accompanied by capacity building, appropriate methodological approaches and attention to the wider policy and socio-economic context. Within LEAP-RE, the MARs have continued to provide a reference framework for connecting research priorities with the long-term objectives of the AU–EU partnership on sustainable energy.

Since the original MARs were formulated, both the energy landscape and the available evidence base have evolved substantially. The 2020–2025 period has seen rapid

development of decentralised renewable-energy systems, digitalisation, productive energy uses, circular-economy approaches and clean-energy services, alongside increasing attention to climate resilience, affordability, inclusion and just-transition considerations. New R&I domains, notably hydrogen, have also gained scientific, policy and project relevance. At the same time, persistent challenges related to energy access, financing, institutional capacity, maintenance, market development and the translation of research results into sustained implementation remain central across the African energy transition.

Against this background, Deliverable 1.22 updates and revises the MARs on the basis of the evidence generated during LEAP-RE and the wider evolution of the sector. The objective is not to replace the original roadmap framework or to define a prescriptive future R&I agenda. Rather, the deliverable identifies **science-based options** for future research, demonstration and learning, while clarifying the scope and interfaces of the MARs and strengthening the evidence needed to connect R&I activities to sustained outcomes and wider development contributions.

The update adopts an explicit **beyond-technology and socio-technical perspective**, operationalised through the Comprehensive Energy Solution Planning (CESP) framework. CESP is used as a planning logic rather than as a rigid project-level procedure. Each MAR is therefore examined from the initial context and needs through the state of the art and emerging technical trajectories, and subsequently through the business, institutional and complementary conditions required for uptake, before considering expected outcomes and impacts. This approach makes explicit a principle already present in the original MARs: technically successful solutions do not automatically produce sustainable energy services or development benefits unless they are appropriate to local needs and supported by viable institutional, financial, social and operational conditions.

The revision is grounded in three complementary evidence streams. First, a **scientometric analysis** examines the evolution of scientific publications and identifies emerging topics and shifts in research attention. Second, a structured review of **grey literature** from international and regional organisations captures deployment trends, policy developments, market signals and implementation bottlenecks that may be under-represented in academic literature. Third, **LEAP-RE project experience and stakeholder insights** connect the roadmap revision to practical evidence generated through AU–EU R&I cooperation. These streams are triangulated through common decision rules: existing scopes are retained where the evidence remains consistent; refined or extended where new dimensions have emerged; interfaces are clarified where substantial overlap exists; and new themes are added only where sufficiently persistent evidence supports their inclusion.

The resulting portfolio comprises seven updated MARs. **MAR1** is clarified as the portfolio-level knowledge and evidence infrastructure supporting the mapping, comparison and periodic updating of AU–EU R&I activities. **MAR2** strengthens the lifecycle perspective on renewable-energy components, moving beyond waste management towards repair, reuse, second-life applications, traceability, reverse logistics and circular value chains. **MAR3 and MAR4** are retained as distinct but contiguous roadmaps within a distributed-energy continuum: MAR3 focuses on stand-alone systems and service-oriented architectures, while MAR4 addresses mini-grids, microgrids, local distribution, smart operation and interconnection. **MAR5** is extended beyond its previous agricultural emphasis to encompass renewable-powered productive uses across value chains, enterprises and essential services. **MAR6** strengthens the combined clean-cooking and domestic and community cold-chain perspective, with greater attention to sustained use, affordability, health, gender and service-delivery models. Finally, **MAR7 – Hydrogen pathways for sustainable energy and industrial systems** is introduced on the basis of converging scientific, policy and LEAP-RE practice evidence. Its scope deliberately avoids assuming hydrogen as a universal solution, instead requiring comparison with alternative pathways and explicit assessment of lifecycle, resource, economic and development conditions.

Across these thematic roadmaps, five **cross-cutting enablers** consistently determine whether validated R&I outputs can progress towards sustained uptake: skills and capacity; standards and interoperability; finance and business models; policy and regulatory pre-conditions; and data governance. These are not proposed as additional MARs, but as enabling conditions whose relevance should be assessed according to the technology, application and context concerned.

The deliverable also establishes a common **Outputs → Outcomes → Impacts** interpretation for monitoring and learning across the MAR portfolio, building directly on the Monitoring, Evaluation and Learning (MEL) framework developed within LEAP-RE. **D5.1 – Monitoring, Evaluation and Learning Plan** established the programme-level logic frame connecting activities and outputs to outcomes and longer-term impacts, while recognising the attribution challenges associated with measuring societal impacts in complex R&I environments and the need for indicators adapted to different interventions, beneficiaries and contexts. **D1.17 – Monitoring and Evaluation System Report of the Pillar 2 projects** subsequently operationalised this logic through cross-project assessment, combining technical achievement with business and economic, social and environmental dimensions, as well as capacity building, stakeholder engagement, sustainability and continuation. Finally, **D1.18 – Report on Monitoring, Evaluation and Learning** strengthened the interpretation of evidence by distinguishing high and medium evidence from illustrative single-project cases and by applying greater caution to claims of replication, continuation, policy influence and wider impact. D1.22 translates these programme-level MEL lessons into a roadmap-level framework: **outputs remain predominantly MAR-specific**, capturing the technologies, methodologies, tools, capacities and evidence directly generated by R&I; **outcomes form a more synergistic layer across MARs**, addressing sustained uptake and performance, operational and financial viability, enabling capacities and institutional arrangements, and replication or continuation beyond individual demonstrations; while **impacts converge around three common development dimensions — human capabilities and essential services; living standards and inclusive economic opportunity; and environmental sustainability and resilience**. These dimensions provide a common portfolio-level lens for assessing the plausible contribution of heterogeneous R&I pathways to development, without implying direct attribution or forcing them into a single composite indicator.

Overall, the revised MARs provide a structured and evidence-informed option space for future AU–EU R&I cooperation. They support funders and programme designers in identifying relevant knowledge and validation gaps, and support researchers and practitioners in designing interventions that generate reusable evidence from technical validation through sustained uptake to development contribution. The proposed options are deliberately not ranked: their relevance depends on local and regional needs, policy objectives, available resources and the maturity and strength of the supporting evidence. In this way, the MARs are positioned as **living, science-based roadmaps**, capable of supporting future strategic reflection and R&I programming while remaining responsive to new evidence and evolving African and European energy-transition priorities.

Keywords

LEAP-RE; Multi-Annual Roadmaps (MARs); AU–EU research and innovation; sustainable energy; renewable energy; Africa; Comprehensive Energy Solution Planning (CESP); socio-technical innovation; Theory of Change; energy transition

1. Background and Scope

The original Multi-Annual Roadmaps (MARs) were developed under PRE-LEAP-RE as a structured basis for joint Africa–Europe research and innovation on renewable energy. They provided a common framework to organise priorities, expected outputs, outcomes and impacts across key areas of cooperation, while recognising that renewable energy innovation in Africa cannot be reduced to technological development alone.

Since then, the context has evolved significantly. LEAP-RE has generated a substantial body of new scientific and practical evidence, while African energy systems have experienced rapid changes in technologies, markets and policy priorities. Between 2019 and 2025, several developments have become particularly relevant for the MARs: the renewed urgency of climate resilience and just transition; the expansion of decentralised renewables and mini-grids; emerging themes such as hydrogen and e-mobility; the growing importance of digitalisation and data governance; and stronger attention to circularity, end-of-life management and socio-economic inclusion. At the same time, many of the structural challenges that motivated the original MARs — limited access, affordability constraints, weak institutional capacity and fragmented R&I efforts — remain.

Against this background, the purpose of the present exercise is not to replace the original MARs with a new strategy, but to update and refine them in light of the evidence gathered during LEAP-RE and the broader evolution of the sector. The updated MARs preserve continuity of scope and logic where appropriate, while clarifying roles, adjusting boundaries between topics and incorporating dimensions such as business models, social inclusion, resilience and responsible innovation.

A central element of this update is the explicit adoption of a **"beyond technologies" perspective**. This does not represent a departure from the PRE-LEAP-RE logic, but makes one of its core assumptions more explicit: technological development needs to be considered together with societal needs, market conditions, business models, deployment pathways, capacity building and long-term impacts. This perspective is consistent with scientific, grey and practice-based literature calling for energy planning approaches that integrate social and institutional considerations alongside techno-economic assessment and evaluate alternative solutions in relation to their social, economic and environmental implications in specific contexts (Liu et al., 2007; Matthey-Junod et al., 2022; Mulugetta et al., 2019).

These dimensions are strongly interconnected across all MAR domains, where long-term success depends on balancing technical feasibility with economic viability, environmental sustainability and social legitimacy.

Recent work on Comprehensive Energy Solution Planning (CESP) (Colombo et al., 2024) provides a useful framework for making this perspective operational. Developed primarily in the context of energy access and off-grid systems, CESP complements engineering planning with a socio-technical perspective that considers local needs, institutional conditions, affordability, implementation capacities and expected development impacts. Its relevance to the MARs lies less in the specific application domain than in the underlying principle: technically sound solutions do not automatically translate into sustainable outcomes.

This becomes particularly clear when moving from **energy technologies to energy services**. The relevant question is not only whether a technology can be designed, tested or deployed, but whether it can provide reliable, affordable and usable services over time and contribute to livelihoods, productive activities, public services, environmental sustainability and just-transition objectives. Although the MARs address diverse domains, their long-term success therefore depends on a recurring set of socio-technical conditions.

The update consequently has two complementary purposes. First, it reviews and, where necessary, revises the thematic focus and expected **Outputs–Outcomes–Impacts** of each MAR on the basis of scientific literature, grey literature and LEAP-RE project experience. Second, it applies a comprehensive planning lens so that each roadmap addresses not only technologies and research topics, but also needs, deployment strategies, business and institutional conditions, and expected development contributions.

The updated MARs therefore remain anchored in the original PRE-LEAP-RE framework while making its comprehensive planning rationale more explicit and operational. They provide an evidence-based update of the roadmap system to support future joint Africa–Europe R&I activities, without turning the deliverable into a prescriptive policy agenda.

2. Methodological Framework

Building on the scope defined above, the MARs update adopts a methodological framework designed to move from evidence collection to roadmap revision through a comprehensive socio-technical lens. The objective is not only to identify new or emerging technologies, but to assess how research and innovation priorities relate to needs, contexts, implementation conditions and expected impacts.

This approach is grounded in the Comprehensive Energy Solution Planning (CESP) framework (Colombo et al., 2024). For the purposes of this deliverable, CESP is not applied as a project-level workflow in a literal sense. Rather, it is used as a planning logic for structuring the MAR update. Its relevance lies in the way it combines engineering-based energy solution planning with social-science perspectives, recognising that energy interventions depend not only on technical feasibility and economic optimisation, but also on local priorities, institutional conditions, affordability, capabilities, business models and long-term sustainability.

As shown in Figure 1, the CESP framework is organised around an iterative sequence of planning phases: context analysis, resource and demand assessment, technical solution design, business model design, complementary activities and impact analysis. The technical phases provide the basis for identifying and sizing energy solutions, while the socio-technical phases ensure that these solutions are interpreted in relation to local needs, implementation capacities, user practices, institutional conditions and long-term development effects.

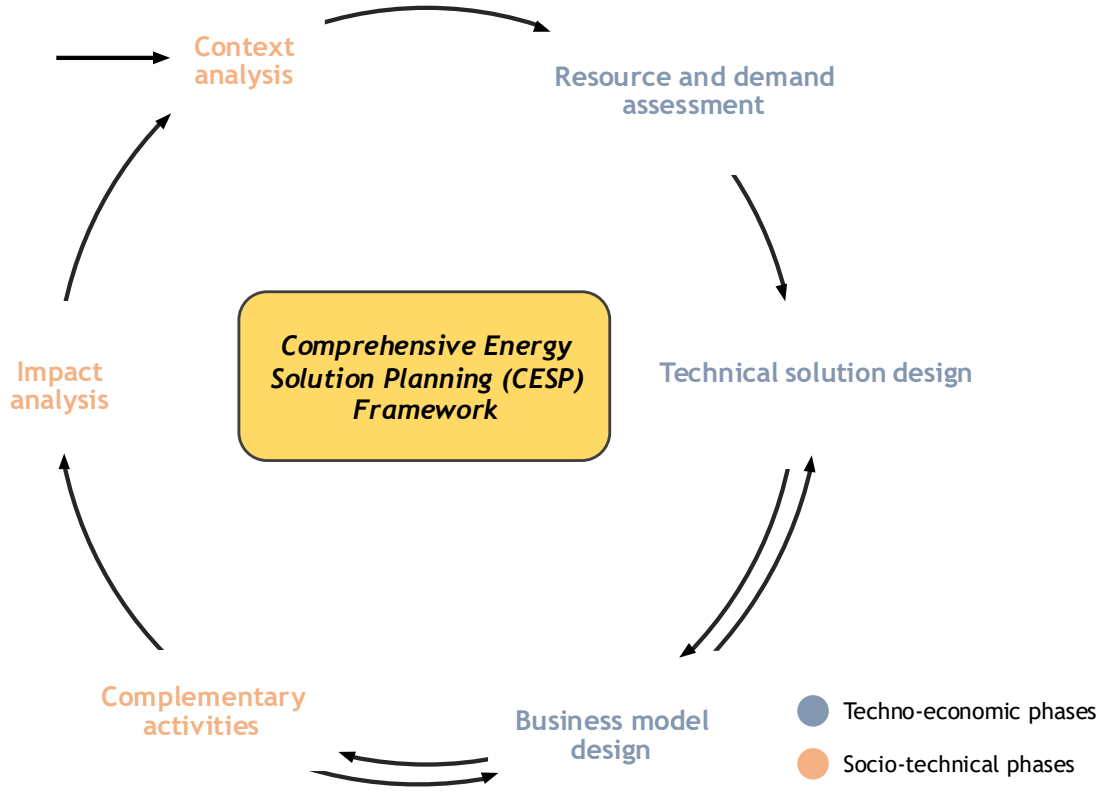


Figure 1 – Comprehensive Energy Solution Planning (CESP) framework: iterative integration of technical and socio-technical planning phases. Source: (Colombo et al., 2024) *licensed under CC-BY 4.0.*

This logic is translated into the MAR update through three complementary evidence streams. First, a scientometric analysis is used to identify how the academic literature related to each MAR has evolved, with particular attention to emerging topics and recent shifts in the 2020–2025 period. Second, grey literature from international and regional organisations is reviewed to capture policy-relevant trends, implementation bottlenecks, market signals and institutional priorities that may not be fully visible in academic publications. Third, LEAP-RE project experience and stakeholder insights are used to connect the update to practical implementation evidence emerging from the programme itself.

Across these evidence streams, the same methodological question is applied: what does the evidence imply for the continued relevance, scope and structure of each MAR? The update therefore proceeds from evidence collection to trend identification, gap analysis and update decisions. Where the evidence confirms the relevance of an original MAR, its scope is retained. Where new dimensions have become more prominent, the MAR is refined or extended. Where boundaries between roadmaps appear blurred, synergies or possible restructuring are highlighted. Where emerging themes appear relevant but not yet sufficiently consolidated, they are treated as cross-cutting or conditional areas rather than automatically becoming new standalone MARs.

This methodological choice is reflected in the structure of the updated MAR sheets. The CESP phases are not applied mechanically as a project workflow, but are translated into a roadmap structure that allows each MAR to be read through context, diagnosis, technical trajectories, implementation conditions and expected impacts.

Table 1 – Correspondence between CESP phases and the updated MAR sheet structure

CESP phase	Updated MAR sheet section	Function in the MAR update
CESP 1 – Context analysis	Why now	Identifies the key shifts in the topic since 2020 and clarifies why the roadmap requires revision.
CESP 2 – Diagnosis	State of the art in a nutshell	Summarises the scientific and grey literature within the common evidence window, providing the diagnostic basis for the update.
CESP 3 – Technical solution design	Signals from literature	Captures emerging trends, weak signals and gaps from recent studies, including comparison between pre-2020 and 2020–2025 evidence.
	Insights from LEAP-RE projects	Integrates lessons, evidence and needs emerging from the LEAP-RE project portfolio and stakeholder interviews.
	Suggested R&I options	Identifies possible research and innovation directions emerging from the evidence base, without turning them into a prescriptive agenda.
CESP 4 – Business model design	Beyond-technology framing	Examines social, market, policy and institutional dimensions shaping uptake and feasibility.
CESP 5 – Complementary activities		Captures enabling actions such as capacity building, standards, data, finance, stakeholder engagement and safeguards.
CESP 6 – Impact analysis	Theory of Change	Clarifies how R&I actions are expected to lead from outputs to outcomes and impacts.
	Indicator framework and verification methods	Defines what should be measured, monitored and documented.
	Interoperability and synergies with other MARs	Identifies interfaces with other roadmap areas and cross-cutting implications for the overall MAR system.

Cross-cutting dimensions such as digitalisation, standards, finance, inclusion, climate resilience and capacity building are therefore treated as enabling conditions throughout the analysis rather than as secondary considerations. In this way, the updated MARs

remain continuous with the original PRE-LEAP-RE roadmap logic, while adopting a more explicit and evidence-based socio-technical framing.

The following section revisits the original MARs as the point of departure for the update.

3. Original MARs

Under PRE-LEAP-RE, six MARs were defined to structure joint Africa–Europe R&I priorities on renewable energy. In their original form, they covered the following areas:

- **MAR1 – Mapping joint research and innovation actions for next-step development of Renewable Energy Systems specific challenges**
  A cross-cutting roadmap aimed at identifying, classifying and prioritising joint R&I needs across technologies, applications and regions, and at supporting a more coherent programming of AU–EU collaborative activities.

- **MAR2 – End of life of renewable energy components**
  Focused on the environmental, technical and socio-economic aspects of end-of-life management for renewable energy components, including recycling, reuse, safe disposal, and the development of circular economy approaches.

- **MAR3 – Smart stand-alone systems**
  Addressed design, integration and optimisation of stand-alone renewable energy systems and mini-grids, with attention to reliability, affordability, smart control and integration of different energy uses. Under the present update, the multi-user, local-network coordination functions originally grouped here are allocated to MAR4, while MAR3 is retained for stand-alone configurations; see the MAR3–MAR4 scope note in Section 6.3.

- **MAR4 – Smart grids for off-grid applications**
  Concentrated on grid-connected and local distribution applications relevant for off-grid or weak-grid contexts, including smart operation, integration of distributed generation and enhanced quality of service.

- **MAR5 – Processes and appliances for productive uses**
  Covered renewable-energy-based processes and appliances to support productive activities, with an emphasis on agriculture and agro-processing, rural industrial processes and energy services that generate income.

- **MAR6 – Innovative solutions for priority domestic uses (clean cooking and cold chain)**
  Focused on household-level energy services, in particular clean cooking, domestic heating and cooling, and cold chain solutions for food and health, with a view to improving well-being and basic service provision.

The present document treats these six MARs as the starting point. The update process refines their boundaries (for example, expanding MAR5 beyond agriculture-only productive uses, and considering closer integration of MAR3 and MAR4) and clarifies their respective roles, while maintaining the original intention: to provide an evidence-based, medium- to long-term orientation for AU–EU joint R&I activities on renewable energy.

4. Methodology for Updating the MARs

The update of the MARs is based on a **triangulation of three main evidence streams**—scientometric analysis, LEAP-RE practice insights and a structured grey literature scan—combined with a set of cross-cutting design lenses (beyond-technology framing,

responsible research and innovation, gender and inclusion, climate resilience). The objective is to ensure that any modification or confirmation of a MAR is clearly traceable back to explicit evidence.

4.1 Scientometric analysis

The scientometric component developed a dedicated pipeline to analyse the evolution of research associated with the thematic MARs. The original analysis covered **MAR2–MAR6**. **MAR1 was excluded from the scientometric pipeline by design**, because its function is to map, connect and anticipate R&I developments across the portfolio rather than to represent a bounded thematic research field for which a single publication corpus can be meaningfully constructed. **MAR7 was added at a later stage of the update process**, after convergence across the other evidence streams indicated that hydrogen had developed into a sufficiently distinct R&I domain; it was therefore subjected to a later scientometric analysis compared with MAR2–MAR6.

For each MAR:

- A **Scopus query** was constructed using keywords derived from the original MAR texts and related policy documents. Keyword extraction was supported by the YAKE algorithm and refined through expert judgement to ensure coverage of relevant concepts and African contexts.

- The resulting corpus of publications (titles and abstracts) was processed using a **bag-of-words representation** and subjected to **topic modelling** based on Non-negative Matrix Factorisation (NMF). The number of topics was selected using the silhouette index, balancing interpretability and granularity.

- The temporal evolution of topics was examined by splitting the corpus into two periods: a **pre-2020 baseline** and a **2020–2025 window**, in order to detect "recent turns" in the literature. This allowed identification of topics whose prominence increased or decreased in the more recent period.

- A set of **"hot papers"** was then identified for each MAR by combining citation counts with a **time-decay factor**, so that recent but influential articles were not overshadowed by older classics. These papers were manually screened to extract key recommendations, emerging themes and research gaps.

The scientometric analysis provided, for each MAR, a structured view of how the academic discourse has shifted over time, which topics have gained or lost relevance, and where new research fronts with African relevance are emerging. These signals are used in the MAR sheets to inform the "Signals from literature" sections and to support decisions on narrowing, broadening or re-framing MAR scopes.

Evidence window and update rule. For MAR2–MAR6, the comparative scientometric analysis retains the common **pre-2020 versus 2020–2025** temporal structure established in the original analytical pipeline. The evidence base for this version of the deliverable was finalised in **August 2026**. Evidence becoming available in 2026 was incorporated selectively where it constituted either final LEAP-RE programme evidence or an authoritative update that materially affected the interpretation of a roadmap; such evidence supplements the common 2020–2025 analytical window rather than retrospectively reopening the full evidence search for all MARs. **MAR7 is the explicit scientometric exception:** because the roadmap was introduced after the original analysis and its dedicated scientometric assessment was carried out later, its recent-literature corpus extends through **2026**. The same analytical logic was retained, including construction of an Africa-relevant corpus, topic modelling and comparison between the historical baseline and the recent research landscape.

4.2 LEAP-RE practice and stakeholder insights

The second evidence stream comes from **LEAP-RE implementation itself**, in particular from semi-structured interviews with leaders of the joint-call work packages (WP9–WP16) and from a mapping of LEAP-RE projects against the original MARs.

- **Semi-structured interviews** were conducted with WP leaders using a common guide. The questions covered, inter alia: perceived relevance and usefulness of the MARs; overlaps and gaps between MARs; emerging topics not adequately captured in the original set (e.g. hydrogen, digitalisation); and suggestions for improving the MAR structure, including social and economic dimensions.

- Interview transcripts and notes were analysed using a **thematic coding frame** that captured recurring concerns (e.g. the role of MAR1, the relationship between MAR3 and MAR4, the need to broaden MAR5 beyond agriculture), as well as cross-cutting issues such as equity, capacity building, and collaboration between projects.

- In parallel, the LEAP-RE **project portfolio** was mapped onto the MARs to understand which themes attracted actual project activity, which MARs were under- or over-represented, and where projects naturally spanned multiple MARs.

MAR7 is a partial exception to this practice-evidence stream: because hydrogen was not treated as a dedicated MAR during the original WP9–WP16 interview round, no hydrogen-specific interview evidence was collected through that exercise. Its practice evidence instead derives from D1.18 – Report on Monitoring, Evaluation and Learning, whose later Pillar 1 assessment interviews (extending into 2025–2026) captured the hydrogen-relevant LEAP-RE projects (HyAfrica, D3T4H2S). This evidence is appraised on the same basis as the interview and project-mapping evidence described above, and is treated as practice evidence rather than as an independent fourth evidence stream. D5.1, D1.17 and D1.18 also jointly inform the common Outputs–Outcomes–Impacts logic applied across all seven MARs, as set out in the Summary.

Attribution policy for interview evidence. Insights from the WP-leader interviews are reported generically as "WP leaders" or "interviewees"; no finding or position is attributed to a specific, identifiable work package, consistent with the basis on which the interviews were conducted. Direct quotations are used sparingly, to illustrate a specific, clearly delimited observation, rather than as extended verbatim material. Named project results are cited only where they derive from material already in the public domain (e.g., published deliverables, technical reports). Throughout the MAR sections, interview-based statements should be read as a record of practitioner perception unless the surrounding text explicitly cites project documentation or independently verified evidence; the three evidence types are not interchangeable and should not be treated as carrying equal evidentiary weight.

This practice lens ensures that the MAR update does not rely solely on publications and global reports, but also reflects the experience of researchers and practitioners engaged in concrete Africa–Europe collaboration under LEAP-RE.

4.3 Grey literature

The third evidence stream is a **targeted scan of grey literature** from major international and regional organisations working on energy and development in Africa, including (among others) the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the World Bank and ESMAP, UN agencies (UNDP, UNIDO, UNECA, UNDESA) and selected initiatives such as SEforALL.

Rather than a narrative review, the scan followed a **structured reading grid**:

- Documents were selected where they had a clear focus on **Africa** and contained analytical or prospective content relevant to one or more MARs (e.g. sectoral outlooks, technology roadmaps, programme evaluations).

- For each MAR, key documents were reviewed to extract **headline signals** for the 2020–2025 period: changes in deployment trends, emerging policy priorities, technology cost and performance developments, implementation bottlenecks, and social or environmental concerns.

- These signals were then used to complement and challenge the scientometric findings, especially for aspects that tend to be under-represented in academic literature, such as policy instruments, finance, institutional capacity, and on-the-ground programme performance.

Grey literature thus provides a practice-oriented and policy-relevant counterpoint to the more academic scientometric stream, helping to ground the MAR update in real-world trends and implementation experience.

4.4 Decision rules for MAR updates

For each MAR, the three evidence streams were synthesised through a common logic:

1. **Evidence collection**: scientometric topics and recent and high-impact publication signals; interview themes and LEAP-RE project mapping; and grey-literature evidence.

2. **Trend identification**: areas of convergence and divergence across the evidence streams, including topics gaining prominence after 2020, recurring implementation issues identified by stakeholders, and priorities or constraints highlighted in recent reports.

3. **Gap and boundary analysis**: themes, enabling conditions or interfaces that appear relevant to future R&I but are weakly represented, unevenly covered across the evidence streams, or insufficiently captured by the original MAR boundaries. This includes, for example, social inclusion, business models, data governance and interfaces between emerging applications and existing MARs.

4. **Update decision**: on this basis, the original MAR architecture was assessed according to five possible responses:

    - **Retain** where the original scope remains supported by the evidence;

    - **Refine or reposition** where the underlying scope remains relevant but its function, boundaries or emphasis require clarification;

    - **Extend** where adjacent domains are sufficiently evidenced to warrant inclusion within an existing MAR;

    - **Restructure or consider merging** where substantial overlap exists and the evidence indicates that separate treatment may no longer add analytical value;

    - **Add** where a new theme shows sustained convergence across scientific literature, grey literature and AU–EU R&I practice, and is sufficiently distinct from the existing MARs to justify a dedicated roadmap.

These rules were applied as an evidence-guided framework rather than as an automatic scoring system. The three evidence streams were triangulated rather than assumed to

carry equal weight, and differences in evidence strength, maturity and stakeholder interpretation were retained where relevant. Consequently, evidence of overlap does not automatically imply merger, and an emerging signal does not automatically justify the creation of a new MAR.

Suggested R&I options across MAR1–MAR7 are also labelled by track — Validation, Demonstration, or Scale-up — set in italics immediately after each option, indicating the primary stage of R&I maturity it targets: Validation covers proof-of-concept and controlled testing under real operating conditions; Demonstration covers field-level piloting and replication under realistic institutional and market conditions; and Scale-up covers portfolio- or continental-level replication once an option has already been validated and demonstrated. An option may carry two adjacent tracks (e.g. Validation and Demonstration, or Demonstration and Scale-up) where the evidence supports work spanning both stages; no option spans non-adjacent tracks or all three at once.

For ease of reference, the update decision reached for each MAR is summarised below; the underlying evidence and full reasoning are set out in the discussion above and in the individual MAR sheets in Chapter 6.

MAR1 — Mapping joint R&I actions.

Decision: refine or reposition.

Evidence basis: stakeholders found the original wording hard to interpret, because "joint research and innovation" spans the whole programme rather than one specific theme. In addition, the original PRE-LEAP-RE version of MAR1 already described it as a shared mapping and evidence database, so this change brings MAR1 back to that original idea rather than introducing a new one.

Key boundary change: repositioned as the portfolio's knowledge-infrastructure layer rather than a technology-specific roadmap; excluded from the scientometric pipeline by design.

Remaining uncertainty: governance, resourcing and update responsibility for a sustained evidence service are not yet assigned.

MAR2 — End-of-life, second-life and environmental impacts.

Decision: retain.

Evidence basis: continued scientometric, grey-literature and practice signal for lifecycle and circularity issues across the portfolio.

Key boundary change: none material; role clarified as the portfolio's lifecycle and circularity layer.

Remaining uncertainty: the practical allocation of lifecycle responsibilities (EPR and PRO financing, enforcement and the integration of informal actors) differs across national contexts and has yet to be tested at scale.

MAR3 — Smart stand-alone systems and MAR4 — Smart grids for off-grid applications.

Decision: retain both, with a clarified functional boundary between them.

Evidence basis: divided stakeholder views on whether to merge MAR3 and MAR4; scientometric and practice evidence confirming substantial continuity but also distinct system-architecture and coordination questions.

Key boundary change: a mirrored, functional (not capacity-based) boundary statement added to both chapters, distinguishing stand-alone configurations (MAR3) from networked, multi-user distribution systems (MAR4).

Remaining uncertainty: a future consolidation into a single decentralised-energy roadmap remains a credible option for later roadmap cycles, should they be organised around system function rather than inherited categories.

MAR5 — Processes and appliances for productive uses (beyond agriculture).

Decision: extend. Evidence basis: stakeholder and grey-literature evidence that an agriculture-only framing excluded relevant productive-use R&I; the PRE-LEAP-RE formulation already referenced non-agricultural productive uses.

Key boundary change: scope broadened beyond agriculture to productive uses generally, with a mirrored cold-chain boundary statement added versus MAR6.

Remaining uncertainty: none flagged beyond the general evidence-strength caveats in Section 6.5.8.

MAR6 — Innovative solutions for priority domestic uses (clean cooking and cold chain).

Decision: extend. Evidence basis: 2020–2025 evidence treating clean cooking and household and community cooling as jointly essential SDG infrastructure.

Key boundary change: scope broadened from a cooking-focused roadmap to a combined cooking-and-cooling roadmap, with a mirrored cold-chain boundary statement added versus MAR5.

Remaining uncertainty: none flagged beyond the general evidence-strength caveats in Section 6.6.8.

MAR7 — Hydrogen pathways for sustainable energy and industrial systems.

Decision: add. Evidence basis: a later, dedicated scientometric analysis (corpus extending through 2026) together with grey-literature and MEL and project evidence converging on hydrogen as a sufficiently distinct R&I domain.

Key boundary change: new roadmap; interfaces with MAR2–MAR6 defined explicitly in each chapter's interoperability section.

Remaining uncertainty: deployment maturity is explicitly uneven across pathways; the roadmap is framed as a conditional pathway roadmap rather than a deployment commitment.

5. Portfolio-level Findings and Implications

The portfolio-level reading of the updated MARs confirms the continued relevance of the thematic architecture established under PRE-LEAP-RE, while also showing that the boundaries between some roadmaps have become less clear as technologies, applications and enabling conditions have evolved. The strongest common finding is that the MARs can no longer be interpreted primarily as technology categories. Across the portfolio, the evidence increasingly links technological innovation with affordability, business models, regulation, institutional capacity, skills, user needs, environmental sustainability, data and long-term operation. This supports the beyond-technology perspective adopted in this update and the treatment of the MARs as **socio-technical R&I pathways**, rather than as

independent lists of technologies. This direction is consistent both with stakeholder feedback collected during LEAP-RE and with the Comprehensive Energy Solution Planning approach used as the methodological lens for the revision.

At the same time, the roadmaps retain different functions within the portfolio. **MAR1** operates at the level of knowledge, coordination and anticipation of R&I needs; **MAR2** addresses lifecycle and circularity issues that cut across renewable-energy technologies; **MAR3 and MAR4** address decentralised energy supply at different system configurations and scales; and **MAR5 and MAR6** move progressively towards the energy services and end uses enabled by those systems. MAR7 addresses hydrogen as a distinct emerging energy and industrial pathway that interacts with several of these domains. These distinctions remain useful, but the updated portfolio should be understood as an interconnected architecture rather than as seven isolated thematic compartments. In particular, lifecycle management, productive uses, digitalisation, storage, financing, capacity building and policy conditions frequently span more than one MAR.

MAR1 requires the clearest conceptual repositioning. Stakeholder interviews had already identified its original formulation as comparatively difficult to interpret because "joint research and innovation" is, by definition, transversal to the entire programme. We consequently propose returning MAR1 towards its earlier function of monitoring emerging technologies and contexts, including research that does not yet fit established application-oriented roadmaps. This interpretation is also consistent with the PRE-LEAP-RE formulation, in which MAR1 was conceived as a continuously updated mapping of scientific and grey literature, R&I initiatives, actors, technologies, applications and readiness levels supporting future EU–AU research cooperation. The implication of the present update is therefore to clarify MAR1 as the portfolio's **knowledge infrastructure for R&I**: a capability for detecting emerging themes, structuring evidence, identifying gaps and connecting research communities, rather than a competing technology-specific research domain.

The strongest scope overlap remains between **MAR3 and MAR4**. Scientometric analysis and stakeholder interviews confirm substantial continuity between smart stand-alone systems and smart mini-grids and microgrids, particularly around decentralised renewable generation, hybridisation, storage, monitoring, load management and community-oriented deployment. Stakeholder consultation nevertheless produced a divided view on whether the two MARs should be merged: some project leaders favoured a single distributed-energy roadmap spanning different degrees of centralisation, while others considered differences in application context, system architecture and user interaction sufficiently important to retain separate roadmaps. The present update therefore does not force a merger, but positions MAR3 and MAR4 as **distinct but contiguous**. MAR3 remains centred on stand-alone and highly decentralised systems serving individual households, institutions or dispersed loads, whereas MAR4 addresses multi-user local distribution systems in which network coordination, protection, power quality, metering and control, system expansion and possible grid interconnection become defining R&I questions. The boundary is therefore **functional rather than capacity-based**: shared technologies are differentiated according to the system role they perform rather than by an arbitrary size threshold. At the same time, a future consolidation into a broader roadmap on decentralised energy systems remains a credible option should future roadmap cycles be organised around system functions and levels of centralisation rather than inherited thematic categories; in such a structure, stand-alone systems, community systems, mini-grids and microgrids could become differentiated pathways within a common decentralised-energy roadmap.

For **MAR5**, the evidence supports broadening the interpretation of productive use beyond an essentially agricultural framing. Stakeholder analysis explicitly identified the agricultural restriction as potentially excluding useful R&I activities that generate income or productive value through energy but fall outside agri-food systems. Recent grey literature reinforces the diversification of productive-use applications towards cooling, processing, services,

health-related applications and emerging mobility-related loads, while continuing to identify finance, affordability, quality assurance and market development as major constraints. Importantly, this represents less a departure from the original MAR architecture than a rebalancing of it: the PRE-LEAP-RE formulation already referred to productive appliances supporting **other income-generating activities, rural industrial processes and healthcare delivery** alongside agriculture. MAR5 should consequently be interpreted around the broader question of how reliable and sustainable energy can enable **productive activities, enterprise development and local value creation**, with agriculture remaining a major application domain rather than the boundary of the roadmap.

A further portfolio-level issue concerns **hydrogen**. Earlier analyses already detected hydrogen within the scientific literature on hybrid and microgrid systems, particularly as a possible storage and flexibility option. On that evidence alone, hydrogen could reasonably have remained a cross-cutting technology addressed where relevant within MAR3, MAR4 or MAR5. The evidence base available for the present update is, however, substantially stronger. Hydrogen has developed into a distinct African and AU–EU R&I domain encompassing production pathways, industrial uses, derivatives, storage, infrastructure, modelling, sustainability, water requirements, regulation and emerging natural-hydrogen research. The dedicated hydrogen review therefore concludes that the signal is sufficiently persistent and distinct to justify an additional MAR, while stressing that deployment maturity remains uneven and that hydrogen should not be presumed preferable to direct electrification or alternative storage technologies.

Accordingly, **hydrogen is best represented as a dedicated roadmap while remaining interoperable with the rest of the portfolio**. Dedicated MAR status provides space to address research questions that cannot be adequately captured as a subsidiary storage technology—notably industrial feedstocks and derivatives, fertilizer and iron and steel applications, hydrogen-specific infrastructure, certification, water and electricity additionality, safety and system-level sustainability. At the same time, hydrogen should continue to appear within MAR3–MAR5 where it performs a material system function, for example as long-duration storage, within hybrid systems, or as an input to productive and industrial processes. This avoids both extremes: fragmenting every cross-cutting technology into a new roadmap, or hiding a strategically significant R&I field inside roadmaps designed for other purposes.

Overall, the portfolio review suggests that the principal need is **not a complete replacement of the MAR architecture, but clearer functional boundaries combined with stronger interfaces between roadmaps**. MAR1 provides the evidence and knowledge layer; MAR2 introduces lifecycle responsibility across technologies; MAR3 and MAR4 cover complementary configurations of decentralised energy supply; MAR5 and MAR6 connect energy systems to productive and priority household and community services; and hydrogen adds a distinct emerging energy and industrial pathway while interacting with several of these domains. Cross-cutting enablers—including skills and capacity, finance and business models, policy and regulation, standards, interoperability and data governance—should therefore be treated as common conditions for the success of the portfolio rather than assigned exclusively to any individual MAR.

This interpretation also reinforces a point emerging from the original stakeholder consultation: the MARs should function not only as thematic classifications but also as **connectors between related R&I activities**. Project leaders perceived insufficient interaction between initiatives working on related themes and explicitly identified the MARs as a potential mechanism for improving such collaboration. The interoperability sections introduced in the updated MAR sheets respond directly to this finding, making overlaps visible and encouraging knowledge transfer without requiring all related research questions to be collapsed into a single roadmap.

6. Updated MAR Sheets

6.1 MAR1 – Mapping joint R&I actions

MAR1 differs from the other roadmaps in nature and function. Whereas MAR2–MAR7 each address a thematic field of research and innovation, MAR1 is a transversal roadmap whose purpose is to organise and structure the shared evidence base needed to orient joint Africa–Europe research and innovation actions on sustainable energy, while defining the requirements for its periodic review and updating. In this sense, MAR1 is not a technology roadmap in the narrow sense, but the portfolio's knowledge infrastructure: it maps who is working on what, under which conditions, with which methods, results, gaps, stakeholders and implementation logics.

In the original PRE-LEAP-RE formulation, MAR1 already contained this intuition through the idea of a common mapping exercise and shared database of initiatives, literature and actors. The present update clarifies and strengthens that role. MAR1 is reframed as the portfolio-level evidence and knowledge layer that enables the other MARs to be compared, traced and periodically reassessed. It provides an evidence-informed basis for subsequent strategic reflection, stakeholder deliberation and joint R&I priority-setting, without itself prescribing a future R&I agenda. Its function is therefore to support prioritisation, reduce fragmentation, improve visibility of ongoing and completed actions, and connect scientific signals with implementation experience, policy developments and stakeholder needs.

6.1.1 Why now

- **Policy and deployment shift (since 2020)**: The number of active roadmaps, global and regional outlooks, implementation reports and policy tools relevant to the LEAP-RE portfolio has expanded quickly, alongside a growing body of project-based knowledge generated by the partnership itself; the challenge is no longer a lack of information but the difficulty of structuring it for coherent decision-making and joint R&I programming.

- **Research and technology shift**: The thematic landscape has become more complex, with circularity, digitalisation, climate resilience, productive uses, energy data governance, clean cooking transitions, hydrogen and innovation finance increasingly cutting across multiple MARs, making a simple "one project, one roadmap" logic less realistic.

- **LEAP-RE and practice signal**: Portfolio-wide implementation experience shows that joint R&I initiatives cannot be assessed through technical outputs alone: business models, institutional conditions, stakeholder configurations, social inclusion, gender, financing structures and local capacity increasingly determine whether an innovation pathway is relevant, scalable and just.

- **Implication**: This evidence supports **refining and repositioning** MAR1 as the portfolio's knowledge-infrastructure layer — a structured evidence and mapping function rather than a technology-specific roadmap — while retaining the common nine-section sheet for comparability with MAR2–MAR7.

6.1.2 State of the art in a nutshell

The state of the art for MAR1 is not a matter of technological maturity, but of how mature the knowledge, mapping and coordination system is.

At its most basic level, mapping consists in compiling projects, actors and publications. However, the state of the art has moved beyond simple inventories. Today, an effective mapping function requires at least five capabilities:

i. a shared taxonomy of themes, technologies, applications and stakeholders;

ii. traceable links between evidence sources and update decisions;

iii. a minimum common set of indicators and metadata to compare initiatives;

iv. the ability to capture cross-cutting dimensions such as gender, resilience, business models and policy relevance; and

v. a process for periodic updating rather than one-off reporting.

In this perspective, the most advanced form of MAR1 is a dynamic evidence function that combines scientific literature, project portfolio information, stakeholder insights and grey literature into a structured, searchable and updateable knowledge base. Such a system should not only answer descriptive questions ("what exists?"), but also strategic ones ("where are the gaps?", "which approaches are emerging?", "which actors are missing?", "which themes overlap?", "what is ready for validation, demonstration or scale-up?").

At the same time, several weaknesses remain common in roadmap and portfolio mapping exercises. Data are often fragmented across projects and institutions; metadata are inconsistent; projects are tagged too broadly or too narrowly; outcomes are poorly documented beyond immediate deliverables; and social or institutional dimensions are under-specified compared to technical ones. In many cases, roadmap exercises also struggle to remain active after the initial publication phase. The updated MAR1 should therefore be explicit that its ambition is not only to map knowledge, but to make that knowledge comparable, updateable and decision-relevant.

6.1.3 Signals from literature and portfolio evidence

MAR1 is treated differently from the thematic MARs in the scientometric component of this update. Because its subject is the **mapping, anticipation and connection of R&I activity across domains**, rather than a discrete technology or application field, it was not assigned a standalone publication corpus or topic model. Its evidence base instead draws on the cross-MAR scientometric results, portfolio mapping, stakeholder evidence and the evolution of the wider R&I landscape. This methodological exception is defined in Section 4.1 and is consistent with the original scientometric design.

The strongest signal emerging from the overall review is that MAR1 was perceived as important but insufficiently defined. In practice, "joint research and innovation" is a transversal concern that permeates the entire programme, which made MAR1 appear nebulous when treated as if it were simply another thematic field. Stakeholder feedback suggests that MAR1 should instead be clarified as the roadmap that monitors contexts, tracks emerging needs and hosts research and innovation topics that cut across or fall between the other MARs.

A second signal is that thematic boundaries are increasingly porous. Several initiatives naturally span multiple MARs, for example where off-grid systems intersect with productive use, cold chains, circularity, digital monitoring, or inclusion questions. This makes the mapping function more—not less—important. MAR1 should therefore be able to record not only primary thematic allocation, but also cross-MAR interfaces, enabling factors and use-case archetypes.

A third signal concerns the need to move beyond a purely engineering framing. Across the portfolio, interviews and project experience indicate that technical descriptions alone are no longer sufficient to orient future collaboration. A useful mapping system must also document business models, implementation conditions, user groups, institutional bottlenecks, governance arrangements and social implications.

A fourth signal is the growing need for collaboration and clustering among projects. Several stakeholders highlighted that the MARs should act not only as a classification scheme, but as a catalyst for exchange between initiatives working on related questions. This implies that MAR1 should not be limited to passive mapping; it should be written as an active tool for testing portfolio-analysis and gap-detection methods for identifying potential thematic complementarities, reusable approaches, shared evidence needs and opportunities for cross-project collaboration.

6.1.4 Insights from LEAP-RE projects

The practice lens suggests four main update directions for MAR1.

First, MAR1 should be explicitly redefined as a shared monitoring and intelligence function for the whole roadmap system. Its task is to track the evolution of technologies, use contexts, actors, evidence, and gaps that matter across the portfolio, including those not yet mature enough to fit neatly inside one thematic roadmap.

Second, MAR1 should provide a common structuring language across the MARs. Several interviewees argued for more homogeneous framing between thematic priorities and for a broader technical–economic–social perspective. MAR1 can respond to this by defining shared categories and descriptors across all roadmaps, making projects and evidence easier to compare.

Third, MAR1 should strengthen the link between thematic priorities and target stakeholders. The updated mapping should not only identify technologies or research domains, but also show which actor groups are concerned in each area: researchers, firms, operators, public authorities, communities, financiers, civil society organisations, and users. This makes the roadmap system more actionable for future calls, clustering and policy dialogue.

Fourth, MAR1 should support collaboration between projects. Instead of functioning only as a repository, it should help identify thematic complementarities, missing links, reusable methodologies, shared metrics, and opportunities for coordination among initiatives that would otherwise remain isolated.

6.1.5 Suggested R&I options

The evidence reviewed for MAR1 points towards a progression from **common classification methods**, through **validated portfolio-learning and update procedures**, towards a **living roadmap function** capable of supporting cumulative Africa–Europe R&I programming. Because MAR1 is transversal, the proposed R&I options concern the methods and knowledge infrastructure through which emerging and cross-cutting R&I priorities can be identified, compared and periodically reassessed.

- **Develop and validate a shared taxonomy and multi-tagging approach for joint R&I actions**, covering thematic domains, technologies, applications, use cases, stakeholder groups, geographical contexts, maturity stages and relevant cross-cutting dimensions. The approach should allow initiatives to be associated with multiple MARs where appropriate rather than forcing mutually exclusive classification. *(Track: Validation)*

- **Develop and validate a minimum evidence and metadata architecture for portfolio-level comparison**, including common descriptors for R&I outputs, intended and observed outcomes, implementation context, stakeholder involvement, business and delivery logic, inclusion, resilience, lifecycle considerations and policy relevance. The objective is not to impose identical project indicators, but to establish sufficient commonality for evidence to be aggregated and compared across heterogeneous initiatives. *(Track: Validation)*

- **Demonstrate a transparent evidence-synthesis and roadmap-review protocol** combining scientific literature, grey literature and project and stakeholder evidence, with explicit rules for identifying convergence, emerging signals, gaps and potential changes to MAR scope. The protocol should maintain traceability between evidence and proposed roadmap revisions while remaining compatible with subsequent stakeholder deliberation, foresight and strategic priority-setting. *(Track: Demonstration)*

- **Test portfolio-analysis, clustering and gap-detection methods that use roadmap evidence to support collaboration and cumulative learning.** These methods should assess whether structured mapping can reveal complementary projects, reusable methods and indicators, under-represented actors or geographies, cross-MAR interfaces and areas of unnecessary duplication, and whether such evidence results in meaningful collaboration or follow-up activity. *(Track: Demonstration)*

- **Develop and validate governance, interoperability, validation and update approaches for sustained roadmap evidence services**, assessing the institutional responsibilities, data-governance arrangements, resourcing requirements and stakeholder-engagement mechanisms needed to maintain portfolio evidence beyond individual project cycles and support future Africa–Europe R&I processes. *(Track: Demonstration and Scale-up)*

6.1.6 Beyond-technology framing: needs, strategies, business models, risks

The R&I options identified above can improve portfolio learning and future programming only if the resulting mapping methods and evidence infrastructures are **used, maintained and trusted by the actors for whom they are intended**. In line with the CESP4–5 perspective, this section therefore does not introduce additional mapping or analytical tools. Instead, it focuses on the institutional, organisational, financial and participatory conditions required for the R&I solutions proposed above to become a sustained common service for the Africa–Europe R&I partnership.

Needs and uptake conditions

The central need addressed by MAR1 is for a shared evidence infrastructure that allows heterogeneous R&I activities to be interpreted in a coherent, transparent and cumulative way without erasing the diversity of African contexts, research questions and implementation pathways.

Priority users include:

- **programme designers and funding organisations**, which require evidence on gaps, overlaps, maturity and emerging directions to inform future programming;

- **researchers and research institutions**, which need visibility on existing work, complementary capabilities, methods, infrastructures, datasets and open research questions;
- **policymakers and public authorities**, which require accessible synthesis connecting scientific evidence with implementation experience and societal needs;
- **project coordinators, practitioners and innovation actors**, which benefit from identifying related initiatives, reusable approaches and possible collaboration pathways;
- **civil society organisations, communities and other local stakeholders**, whose priorities and experience need to be visible if roadmap evidence is to remain context-sensitive and legitimate.

The principal uptake barriers are therefore not technological. They include fragmented reporting, inconsistent terminology, limited incentives to contribute or update information, uneven documentation of outcomes, inaccessible or non-interoperable data, and uncertainty about how mapped evidence will actually be used.

Governance and stewardship

A living evidence system requires clear institutional responsibility. Relevant governance arrangements should specify:

- who is responsible for maintaining the taxonomy and minimum evidence requirements;
- who validates submitted information and resolves ambiguous or multiple classifications;
- how update decisions are documented and reviewed;
- how African and European institutions share responsibility for stewardship and agenda-setting;
- how scientific independence is protected while maintaining relevance to funders and policy processes;
- how disagreements, missing evidence and uncertainty are represented rather than concealed.

Governance should avoid a centralised model in which one institution becomes the sole gatekeeper of what counts as relevant R&I. Shared stewardship, transparent classification rules and periodic stakeholder review can reduce this risk while preserving methodological consistency.

Sustainability and resourcing model

For MAR1, the equivalent of a business-model question concerns the **long-term resourcing of the common knowledge service**. A mapping system has little value if it is intensively populated during one project and then becomes obsolete.

Sustainable implementation therefore requires:

- clearly assigned institutional responsibility beyond individual deliverables;

- proportionate resources for curation, validation, maintenance and periodic synthesis;
- integration with existing project reporting wherever possible, rather than creating parallel reporting burdens;
- simple contribution procedures and incentives for projects and institutions to keep information current;
- appropriate open-access arrangements, while recognising legitimate restrictions related to confidential, commercially sensitive or personal information;
- interoperability with future programme-level knowledge repositories, monitoring systems and roadmap processes.

The objective should be a **minimum viable evidence infrastructure that can be sustained**, rather than an excessively complex database that is comprehensive at launch but difficult to maintain.

Complementary activities and capacities

The usefulness of MAR1 also depends on capacities and activities surrounding the information system itself. Relevant complementary actions include:

- training project teams and programme actors in common reporting and evidence-classification approaches;
- supporting data management, FAIR and open-science practices and documentation standards where appropriate;
- creating regular portfolio-learning and clustering opportunities in which mapped evidence is actively interpreted;
- involving African research institutions, policymakers, civil-society organisations and other relevant stakeholders in periodic validation of gaps and emerging priorities;
- strengthening science-policy and science-innovation interfaces so that roadmap evidence can move beyond documentation into programming, collaboration and learning.

These activities are complementary to the R&I methods proposed in Section 6.1.5. They determine whether validated mapping tools become part of routine institutional practice rather than remaining stand-alone research outputs.

Risks and safeguards

The beyond-technology perspective highlights several risks specific to a portfolio-level knowledge infrastructure.

- **Vagueness and scope inflation.** If MAR1 attempts to encompass every possible R&I topic without clear classification rules, it risks becoming a repository without analytical value. A defined taxonomy, minimum evidence requirements and transparent update criteria are required to maintain focus.
- **Duplication and reporting burden.** A new mapping system can reproduce information already collected by projects, funders or repositories while increasing

administrative workload. Interoperability, reuse of existing reporting and a minimum-data principle should therefore guide implementation.

- **Reductionism and false comparability.** Common indicators and categories can create the impression that heterogeneous projects are directly comparable when their contexts, maturity and objectives differ substantially. Common descriptors should support structured comparison without eliminating contextual interpretation.

- **Representation and visibility bias.** Better-resourced institutions, English-language publications, formally documented projects or highly networked actors may become disproportionately visible, while local research organisations, community knowledge and less formal innovation ecosystems remain under-represented. Geographic, institutional and stakeholder representation should therefore be monitored explicitly.

- **Agenda-setting bias.** Mapping is not neutral if the evidence included determines which topics appear important. Transparent inclusion criteria, plural evidence sources and balanced Africa–Europe stewardship are necessary to prevent the evidence infrastructure from reproducing existing inequalities in research visibility or priority setting.

- **Obsolescence.** A technically successful mapping exercise can rapidly lose strategic value if it is not updated. Update frequency, institutional responsibility and evidence freshness should therefore be treated as core performance dimensions.

- **Overclaiming of influence.** Identification of a gap, citation of a roadmap or discussion of a recommendation does not demonstrate that MAR1 influenced a funding decision, policy process or subsequent R&I action. Claims of use and influence should be supported by documentary evidence and interpreted according to their strength.

By embedding governance, sustainable stewardship, institutional capacities, participation and explicit safeguards around the R&I methods developed under Section 6.1.5, MAR1 becomes a roadmap for **sustained evidence-informed portfolio learning**, rather than simply a database of projects and publications.

6.1.7 Theory of Change

The Theory of Change for MAR1 differs from those of the thematic MARs in the object of intervention, but follows the same causal discipline. The core pathway is that **validated mapping, classification and evidence-synthesis methods, together with comparable portfolio evidence, can support more informed and transparent R&I prioritisation when they are taken up through functioning governance arrangements, sustained stewardship and regular use by research, funding and policy actors**. These outcomes can improve the coherence, inclusiveness and adaptability of the wider Africa–Europe R&I portfolio and, through the thematic R&I actions that are subsequently selected and implemented, contribute indirectly to wider development objectives.

The causal distance between MAR1 and development impacts is therefore greater than for MAR2–MAR7. A functioning database, roadmap observatory or evidence synthesis does not itself improve energy access, livelihoods, health or environmental performance. Its contribution occurs through better-informed programming, stronger coordination and greater visibility of needs, actors and evidence that subsequently shape thematic R&I decisions.

Outputs — validated R&I mapping methods and evidence

- **Validated portfolio-classification and mapping approaches** are developed and tested, including shared taxonomies, multi-MAR tagging, stakeholder and geographical descriptors, maturity categories and cross-cutting dimensions that allow heterogeneous R&I initiatives to be represented consistently without erasing contextual differences.

- **Replicable evidence-integration and roadmap-update methods** are developed and validated, combining scientific literature, grey literature and project and stakeholder evidence through transparent synthesis, evidence-strength and decision-traceability procedures.

- **Comparable portfolio-level evidence and synthesis products** are generated, identifying thematic concentrations, cross-MAR interfaces, under-represented actors and contexts, emerging research directions, evidence gaps and opportunities for clustering or complementary R&I.

Outcomes — uptake, viability and enabling capacity

- **Roadmap evidence is routinely used by relevant research, funding and policy actors** to inform programme design, thematic review, clustering, consultation and other strategic R&I processes.

- **Capacity and enabling conditions for sustained stewardship and periodic updating are strengthened**, including clearer responsibilities, workable data-governance arrangements, update procedures and continuity requirements.

- **Cross-project and cross-MAR learning improves**, with mapped evidence supporting identification of complementary initiatives, exchange of methods and data, joint activities and more explicit management of overlaps and gaps.

- **Representation and visibility of diverse Africa–Europe R&I actors improve**, including stronger visibility of African research institutions, locally relevant implementation evidence and stakeholder groups that may be poorly represented in conventional publication- or project-centred mapping.

- **Validated mapping and update approaches are reused or institutionalised beyond the initial setting**, including incorporation into subsequent programme monitoring, roadmap revisions, funding or consultation processes.

Impacts — development contributions

At impact level, MAR1 contributes indirectly through the quality of the R&I portfolio that its evidence helps to shape. Its contribution pathways are organised according to the common impact dimensions adopted across the updated MARs.

- **Human capabilities and essential services.** More systematic identification of unmet needs, evidence gaps and underserved contexts can contribute to future R&I portfolios that are better targeted towards reliable and affordable energy services supporting health, education, water, food, communication and other essential services. These effects arise through the thematic R&I actions informed by MAR1 rather than through the mapping system itself.

- **Living standards and inclusive economic opportunity.** More inclusive and transparent R&I mapping can contribute to stronger participation of African institutions and other under-represented actors in collaborative research, improved identification of locally relevant innovation opportunities, and better targeting of R&I towards productive activities, employment, skills and livelihood priorities.

- **Environmental sustainability and resilience.** Systematic integration of climate, lifecycle, resource, resilience and environmental evidence into portfolio mapping can contribute to future R&I choices that better anticipate environmental trade-offs, climate risks and system resilience, while allowing lessons generated in one MAR to inform decisions across the wider portfolio.

Impact interpretation. These statements describe indirect contribution pathways rather than direct attribution. Evidence that MAR1 identifies a priority, maps an actor or produces a synthesis should not be interpreted as evidence that subsequent development effects were caused by MAR1. Stronger claims require evidence that MAR1 outputs were actually used in a subsequent R&I, funding or policy decision and that the downstream intervention itself generated the reported effects.

6.1.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR1 should generate to support monitoring, evaluation and learning at portfolio level. Project- or programme-specific targets should be defined by the relevant funding or coordination instrument, taking account of the scale of the evidence base, institutional responsibilities, available resources and intended users.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators assess whether the mapping, classification and evidence-synthesis approaches proposed under MAR1 have been developed and validated. Outcome indicators assess whether these approaches are maintained, used and translated into portfolio learning, collaboration and programming. Impact-contribution indicators use the common trans-MAR development dimensions while recognising that MAR1 contributes to them only indirectly through the quality and orientation of subsequent R&I decisions.

Output indicators – R&I outputs and technical validation

Table 2 – MAR1 Output Indicators

Indicator	Definition and Evidence Expected	Verification method
Validated taxonomy and classification framework	Evidence that a documented taxonomy covering themes, technologies, applications, stakeholders, geographies, maturity stages and cross-cutting dimensions has been tested on a heterogeneous R&I portfolio; ability to support multiple MAR associations where relevant; documented classification ambiguities and revisions.	Taxonomy documentation; coding manuals; pilot datasets; inter-coder or expert-validation exercises; version history; stakeholder review records.
Validated minimum metadata and evidence architecture	Degree to which common project descriptors, output and outcome fields, implementation-context variables and relevant socio-technical dimensions can be applied consistently across initiatives without disproportionate reporting burden.	Metadata schema; completed pilot records; completeness and missing-data analysis; contributor feedback; data-quality checks; schema and version documentation.
Validated evidence-	Evidence that scientific, grey-literature and project and stakeholder inputs can be combined through a documented and	Update protocol; evidence registers; synthesis reports; audit trail linking

integration and update protocol	repeatable update process with explicit evidence-strength and decision rules.	evidence to roadmap decisions; expert or stakeholder validation.
Portfolio coverage and evidence completeness	Share and diversity of relevant initiatives represented using the common framework, together with completeness of required fields and identification of systematic evidence gaps. Coverage should be interpreted by geography, institution type and thematic domain rather than only as an aggregate percentage.	Portfolio database; coverage analysis; metadata-completeness reports; comparison with source project and funding lists; gap assessments.
Cross-MAR and stakeholder visibility	Extent to which the mapping identifies multiple-MAR relevance, cross-cutting themes, stakeholder groups, geographical contexts and other interfaces needed for portfolio-level analysis.	Multi-tagging records; stakeholder and geographic maps; cross-MAR matrices; portfolio-analysis outputs; validation workshops.

Outcome indicators – uptake, viability and enabling conditions

Table 3 – MAR1 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Use in R&I programming and strategic decision-making	Documented cases in which MAR1 evidence, methods or synthesis products are used to inform roadmap revision, call scoping, portfolio review, stakeholder consultation, research-priority discussion or other R&I programming processes. Mere dissemination or citation should not be treated as demonstrated influence.	Call or programme documents; meeting records; roadmap revisions; decision notes; citations linked to documented decisions; interviews with responsible programme actors.
Stewardship and update continuity	Evidence that responsibility, resources and procedures for maintaining the mapping system exist or are progressively established	Governance documents; assigned roles; budget and resource records; update logs; version histories; maintenance and data-quality reports.
Cross-project collaboration and cumulative learning	Evidence that MAR1 evidence, tools, taxonomies or convening activities generate collaboration and cumulative learning across projects, institutions or research communities, such as joint analytical work, shared use of MAR1 evidence products, cross-project working groups or documented learning exchanges on related research and innovation themes.	Joint outputs or publications; records of cross-project working groups or consultations; documented use of MAR1 evidence products by other project teams; participant feedback; meeting or workshop records evidencing collaboration.
Reuse and replication of MAR1 methods	Adoption or adaptation of validated taxonomy, metadata, evidence-synthesis or update methods by other programmes, institutions, funding processes or future roadmap exercises.	Programme and institutional documentation; repository records; methodological citations; adoption records; subsequent roadmap or monitoring frameworks.
Inclusive representation in the evidence base	Degree to which African institutions, local research organisations, civil-society actors and other relevant stakeholder categories are represented in mapping, consultation	Disaggregated portfolio and stakeholder data; participation records; institutional and geographic coverage

	and validation processes, including identification of systematic visibility gaps.	analysis; qualitative assessment of missing or under-represented groups.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR1 contributes to them through the specific pathway of improved evidence, coordination, research programming and learning that inform and strengthen the thematic R&I decisions subsequently taken across the portfolio.

Table 4 – MAR1 Impact Indicators

Common Impact Dimension	MAR1 contribution	Verification method
Human capabilities and essential services	MAR1 can contribute by improving the evidence available to prioritise R&I addressing unmet energy-service needs in health, education, water, food, communication and other essential services, particularly in underserved contexts. The relevant evidence is therefore whether portfolio decisions informed by MAR1 increase attention to identified needs, rather than direct service improvements attributable to the mapping system.	Traceable links between identified gaps and subsequent calls and projects; portfolio composition over time; programming documents; documented prioritisation of underserved contexts or essential-service needs; downstream evidence generated by the relevant thematic MARs.
Living standards and inclusive economic opportunity	MAR1 can contribute by increasing visibility and participation of African institutions and under-represented actors and by improving identification of R&I opportunities connected to productive activity, employment, skills and locally relevant innovation.	Portfolio and partnership composition; participation and leadership data; institutional and geographic disaggregation; documented changes in programming; downstream economic and inclusion evidence reported under thematic MARs.
Environmental sustainability and resilience	MAR1 can contribute by ensuring that climate, circularity, resource, lifecycle and resilience considerations are systematically visible in portfolio analysis and influence subsequent R&I prioritisation.	Cross-cutting tagging and gap analyses; roadmap and call documents; evidence of identified environmental and resilience gaps informing subsequent R&I actions; downstream environmental evidence generated under thematic MARs.

These common dimensions allow MAR1 to remain comparable with the thematic MARs while recognising its different position in the causal chain. Development performance should therefore normally be assessed through the thematic interventions that MAR1 helps to orient, rather than attributed directly to MAR1 itself.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR1 should be interpreted according to its **strength, maturity and position in the decision chain**. Where possible, quantitative portfolio indicators should be triangulated with documentary and stakeholder evidence.

A populated database or completed mapping exercise demonstrates an **output**, not uptake. A recommendation discussed in a workshop demonstrates relevance, not demonstrated influence on programming or policy. Identification of a complementary project or potential partner should not be reported as collaboration unless subsequent joint activity is documented. Similarly, an emerging theme identified by MAR1 should be distinguished from its inclusion in a future roadmap or call, its inclusion in a funded project, and its subsequent implementation.

Single cases in which MAR1 evidence appears to have informed a decision should normally be reported as illustrative unless supported by documentary evidence or repeated use across several processes. Stronger claims of institutionalisation require evidence that governance, resourcing and updating continue beyond the initial activity.

Policy relevance should be distinguished from demonstrated policy influence, and proposed follow-up activity from funded or implemented continuation. This evidence discipline allows MAR1 to capture emerging strategic value without overstating its influence on subsequent R&I decisions or downstream development outcomes.

6.1.9 Interoperability and synergies with other MARs

MAR1 is the enabling layer that allows all other MARs to function as parts of a coherent portfolio rather than as isolated thematic texts.

- **With MAR2**, MAR1 helps track where lifecycle, circularity and environmental-risk issues arise across the portfolio, while MAR2 provides categories, indicators and material-flow logic that enrich the overall mapping system.
- **With MAR3 and MAR4**, MAR1 supports comparison between stand-alone systems, mini-grids and other distributed architectures by capturing application contexts, deployment models, reliability concerns and user segments in a common language.
- **With MAR5**, MAR1 helps make visible the diversity of productive-use applications, business models and beneficiary groups, allowing productive-use evidence to inform future joint programming beyond narrow sectoral silos.
- **With MAR6**, MAR1 helps connect household-level and community-level priorities—such as clean cooking, cooling, health and inclusion—to the broader evidence base and to infrastructure-oriented themes.
- **With MAR7**, MAR1 helps position hydrogen within the wider R&I portfolio, identifying intersections with storage, productive uses, infrastructure and lifecycle issues while distinguishing hydrogen-specific research needs from topics already covered by other MARs.

Overall, MAR1 functions as the shared evidence and coordination infrastructure of the MAR portfolio. It does not compete with the thematic roadmaps; it makes them usable, comparable and updateable over time.

6.2 MAR2 – End-of-life, second-life and environmental impacts

6.2.1 Why now

- **Policy and deployment shift (since 2020)**: Transboundary control over used equipment and e-waste tightened materially in 2025: the Basel Convention COP-15

E-waste Amendments now require prior informed consent for e-waste shipments, reinforced by the regional Bamako Convention, while EU instruments (WEEE, the Batteries Regulation) and World Bank and ESMAP guidance increasingly treat credible reverse logistics and end-of-life management as a bankability requirement rather than an optional safeguard. Sources: (Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa, 1991; Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal - E-Waste Amendments, 2022; Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE), as Amended by Directive (EU) 2024/884, 2012; Regulation (EU) 2023/1542 Concerning Batteries and Waste Batteries (Batteries Regulation), 2023; United States Environmental Protection Agency, n.d.; World Bank & Energy Sector Management Assistance Program, 2024d)

- **Research and technology shift**: MAR2 research spiked around 2020, and the post-2020 centre of gravity has shifted toward "deployable circularity": informal-sector and urban-mining livelihoods, EV and battery storage, lithium-ion recovery and metals, repair ecosystems, and circular manufacturing and business models, alongside persistent environmental and health-risk threads.

- **LEAP-RE and practice signal**: Interviewees confirm MAR2 was not directly covered by Pillar 2 LEAP-RE projects, but stress that the missing piece is building "the entire process chain around waste" rather than more awareness of the problem — a business-model shift that only pays off if coupled with policy coordination (EPR and PRO financing, standards, enforcement, routing decisions).

- **Implication**: This evidence supports **retaining** MAR2 as the portfolio's lifecycle-and-circularity layer: no material boundary change is needed, though its role is clarified relative to MAR3–MAR6 as the layer through which circularity issues that cut across renewable-energy technologies are addressed.

6.2.2 State of the art in a nutshell

- **Technology maturity** — MAR2 spans three waste streams with different hazards and economics: **used lead-acid batteries (ULAB)**, a legacy stream where recycling exists at scale but poses severe public-health hazards under weak controls; **lithium-ion batteries**, a fast-rising stream where safe handling, testing, repurposing and compliant recycling are still evolving; and **PV modules**, a slower but already-tracked e-waste category projected to rise sharply toward 2030, making now the window to put systems in place before volumes hit. Sources: (International Renewable Energy Agency & IEA Photovoltaic Power Systems Programme, 2016; United Nations Institute for Training and Research & International Telecommunication Union, 2024; World Health Organization, n.d.)

- **Design standards and quality assurance** — the frontier is traceability and controlled flows, not general awareness. The Basel Convention's E-waste Amendments now subject e-waste broadly to Prior Informed Consent, and from 1 January 2025 cross-border shipments for recovery or disposal require prior written consent from importing and transit countries. In parallel, EU product-chain rules (WEEE scope for PV since 2012; the EU Batteries Regulation) are hardening lifecycle expectations that reach beyond Europe via supply chains and procurement norms. Sources: (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal - E-Waste Amendments, 2022; Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE), as Amended by Directive (EU) 2024/884, 2012; Regulation (EU) 2023/1542 Concerning Batteries and Waste Batteries (Batteries Regulation), 2023)

- **Operational practice** — in off-grid solar and decentralised systems, "deal with waste later" is no longer the state of the art. Implementation guidance now pushes interventions across the full product lifecycle via the 5Rs (reduce, reuse, repair, refurbish, recycle): design and service models should slow the waste stream before scaling recycling. Sources: (World Bank, 2024; World Bank & Energy Sector Management Assistance Program, 2024d)

- **End-of-use vs end-of-life** — this distinction is now a practical governance tool, not just terminology. Treating end-of-use (EoU) as the point where value can still be retained (reuse, repair, refurbish or repurpose), versus end-of-life (EoL) where only recycling or disposal remain, matters because premature "waste" designation destroys value and can push usable components into unsafe channels. UNEP notes that in EPR contexts the "producer" often includes importers and distributors — important for Africa, where market entry is frequently importer-led. Sources: (United Nations Environment Programme, 2021)

- **Business models that scale** — the bottleneck is reverse-logistics finance, not chemistry. Practice is converging on embedding take-back into existing channels (PAYGo and service networks, operator O&M logistics, retailer and agent collection points) plus aggregation hubs that make treatment viable, with EPR- and PRO-type funding as the most robust system-level path since end-of-life costs require ongoing finance. Sources: (United Nations Industrial Development Organization & Global Alliance on Circular Economy and Resource Efficiency, 2023; World Bank & Energy Sector Management Assistance Program, 2024d)

- **Component-specific handling** — safety requirements differ sharply by component. PV modules are mostly non-hazardous by mass but contain chemistry-dependent hazardous materials subject to jurisdiction-specific classification (e.g. leaching tests); uncontrolled lead-acid recycling causes major contamination and exposure; and damaged or poorly handled lithium-ion batteries carry fire, explosion and thermal-runaway risk requiring dedicated storage, transport and triage. Sources: (International Renewable Energy Agency & IEA Photovoltaic Power Systems Programme, 2016; Occupational Safety and Health Administration, n.d.; World Health Organization, n.d.)

- **Binding constraints** — Africa's collection baseline and enforcement realities are the hard edge MAR2 must design for. GEM 2024 puts Africa's documented formal collection and recycling rate at about 0.7% regionally, with several subregions near 0%, and identifies major ports as entry points for used EEE that circumvent the Basel and Bamako Conventions. MAR2 cannot assume neat borders or fully formal supply chains; enforcement and informality are design constraints, not exceptions. Sources: (Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa, 1991; Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal - E-Waste Amendments, 2022; United Nations Institute for Training and Research & International Telecommunication Union, 2024)

6.2.3 Signals from literature

Top emerging topics (2020–2025 lens)

MAR2's post-2020 literature does not just grow — it *re-centres*. The scientometric analysis shows **a spike in MAR2-related publications in 2020**, with several topic trends evolving after that (including a decline in "blood" as a dominant label, and sporadic "dumpsites" signals).

Looking specifically at the **topics extracted from 2020 onwards**, the strongest "recent turns" cluster into a few clear families:

- **Informal sector, livelihoods, and worker risk move to the centre** — post-2020 topics explicitly foreground *informal sector*, *livelihoods and urban mining*, and *worker health risks*, signalling that MAR2 research is increasingly treating circularity as a socio-economic system with real distributional consequences (not just a technical waste stream).

- **EV-linked storage and the Li-ion wave become a first-class theme** — the emergence of "vehicles–cell–storage–battery" and "lithium-ion recovery" topics shows the literature pivoting from general e-waste toward *energy-transition-specific* stocks and flows, where safety, routing decisions, and recovery economics become unavoidable.

- **Repair ecosystems appear as their own "circularity pathway," not a footnote** — the dedicated "repair–Kenya–solar–companies–economy" topic is a strong signal that value retention through service networks (repair and refurbishment) is being studied as a real economic sector — exactly the kind of "EoU gate" logic MAR2 needs.

- **Circular manufacturing and business models enter explicitly** — "manufacturing–sustainable–circular–model–business" shows up as a standalone post-2020 topic, reflecting a shift toward governance and market design: who pays, who captures value, and what makes circularity investable.

- **Contamination and lead exposure remain "load-bearing," but are less alone** — soil and metal contamination, lead recovery and treatment, and children and exposure signals remain prominent, but they now sit alongside EV and Li-ion and business model topics rather than dominating the landscape.

- **Governance shows up as management + surveys and awareness + international context** — multiple post-2020 topics combine "management–countries–african–international" and "respondents–survey–awareness," suggesting that the field is actively probing what institutions and behavioural conditions make EoL systems function (or fail).

- **A cross-signal links waste with climate and water framing** — the appearance of "water–change–climate–region–index" does not mean MAR2 becomes a climate MAR, but it *does* suggest growing work that ties e-waste burdens to broader environmental stressors and regional risk framing.

What changed compared to the "all-years" baseline

The all-years topic set still contains strong **general e-waste signatures** (WEEE and EEE flows, ICT and electronics, phones, classic contamination case-study markers). Post-2020, the centre of gravity shifts: **vehicles, batteries and Li-ion recovery**, **repair economies**, and **circular business models** become much more explicit — i.e., MAR2 starts looking like an *energy-transition circularity* problem, not only an "electronics pollution" problem.

"Hot papers": what they suggest for next R&I moves

The scientometric analysis identifies "hot papers" as influential, topic-representative works adjusted to avoid older papers winning by sheer time-in-circulation (via citation decay logic). Read together with the post-2020 topic structure, these papers indicate where the influential conversation is heading:

- **Treat the EoU gate as the highest-leverage intervention point** — the rise of repair and circular business model topics implies that much of the value (and harm prevention) happens *before* waste designation. This supports R&I on triage and testing protocols, warranty and accountability models, and routing rules that keep reusable components in safe channels.

- **Make Li-ion routing and safety "system engineering," not lab work alone** — vehicles, storage and Li-ion recovery topics reinforce that the next wave of work is about safe handling, provenance and data access, standardised testing, and end-of-second-life obligations — the factors that determine whether second-life is beneficial or becomes delayed dumping.

- **Design circularity around informality, not against it** — the prominence of informal sector + worker risk topics is a warning: ignoring informal actors does not remove them; it just removes safeguards. The research frontier here is: incentive design, safer process upgrades, licensing pathways, and fair value sharing.

- **Keep legacy hazards (lead, exposure) non-negotiable** — contamination and exposure topics remain prominent, so MAR2 should treat lead-acid and toxic exposure control as "must-haves," while building newer Li-ion and PV systems.

- **Hot Papers**: (Asante, 2012; Fayiga et al., 2018; Gollakota et al., 2020; Leusch, 2018; Manickum & John, 2014)

Meta-signal: the MAR2 literature is increasingly *interdisciplinary by necessity* — it is sliding from "what is the pollution" into "what are the institutions, markets, and service networks that prevent pollution while keeping value."

6.2.4 Insights from LEAP-RE projects

Practice insights for MAR2 draw on the **semi-structured interviews with WP leaders (WP9–WP16)**. A key practical caveat is that **MAR2 was not directly covered by any of the interviewed projects**, so the practice lens is necessarily *cross-cutting*: it captures how implementers perceive the MAR2 gap, where it shows up indirectly through other MARs, and what they think is missing for this topic to become actionable.

- **Beyond engineering: partners want MARs to force a broader framing (technical–economic–social).**
  A majority of interviewees felt the MARs remain too tightly framed around technical aspects and argued for a broader perspective. WP leaders explicitly proposed standardising each MAR into **technical, economic, and social** sub-categories to keep the framing open-minded and comparable across themes. This is especially relevant for MAR2 because "end-of-life" is not primarily a lab problem in Africa — it is a systems problem shaped by incentives, enforcement, service networks, and livelihoods.

- **MAR2 is "missing in practice," but not "low priority": WP leaders flag urgency and the need for an end-to-end process chain.**
  The interview analysis records a very clear signal: **"MAR2 is not covered in any project subject to the interviews,"** yet its importance was underlined by WP leaders, together with the practical requirement to **"create the entire process chain around waste."** In other words, practitioners are not asking for more problem statements; they are asking for the operational chain (collection → triage → routing → safe treatment) that makes circularity real.

- **MAR2 is a hidden dependency for other MARs: e-waste is produced "elsewhere," even if MAR2 is not funded explicitly.**

A useful nuance from the interview synthesis is that MAR2 is impactful beyond "its own" thematic space, because initiatives under other roadmaps can still contribute substantially to e-waste streams (batteries, electronics, appliances). This argues for positioning MAR2 not as an isolated environmental topic, but as a portfolio safeguard that must interface tightly with MAR3–MAR6.

- **Practitioners notice an imbalance between "access technologies" MARs and "end-use" MARs — and they want clearer stakeholder anchoring.** WP leaders highlighted that several MARs are dedicated to technologies granting access (explicitly naming **MAR2, MAR3, MAR4**), while others are more end-use focused. In addition, WP leaders' interviews highlighted the need to correlate each thematic priority with its **target stakeholders**. For MAR2, this reinforces that the roadmap should explicitly name and organise around actors who can actually carry the process chain: importers and distributors, PAYGo and mini-grid operators, repair networks, waste handlers and recyclers, customs and standards bodies, and local authorities.

- **Use MARs as collaboration catalysts — partners want them to convene learning across projects, not just label topics.** A "majority of leaders" suggested that MARs should be used as a **catalyst to promote collaboration between projects working on similar themes**, which they felt was lacking. For MAR2, this is particularly actionable: circularity only works when energy-access actors (operators, service agents, procurement) are connected to waste and circular-economy actors (collection, refurbishment, compliance, treatment). MAR2 can provide the shared language and minimum protocols that let these groups actually coordinate.

Implication for the MAR2 update: treat MAR2 as an **end-to-end operating system** (stakeholders + process chain + incentives), framed explicitly in **technical–economic–social** terms, and written to be usable by the organisations that already have field logistics (PAYGo, mini-grid and O&M networks) as well as by the institutions that govern flows (environment agencies, standards and customs, EPR and PRO structures).

6.2.5 Suggested R&I options

Based on the convergence of recent scientific literature, grey-literature evidence and LEAP-RE stakeholder insights, the following R&I options are proposed as areas for further research, validation, demonstration and replication. They are intended as research directions rather than prescriptive deployment pathways and should be adapted to the material streams, regulatory frameworks, market conditions and existing service infrastructures of the application context.

- **Develop and validate EoU triage, testing and refurbishment pathways** embedded in existing energy-service networks, including PAYGo agents, mini-grid O&M teams, distributors and EPC contractors. Research should establish practical decision protocols for distinguishing components suitable for reuse, repair, refurbishment, repurposing or final treatment, and assess their effects on asset-life extension, collection and routing rates, safety, costs and local value creation. *(Track: Validation)*

- **Compare and demonstrate collection and return-incentive mechanisms** for batteries, PV modules and power electronics, including deposit-return, buy-back, PAYGo-linked take-back clauses, warranty or upgrade trade-ins and community collection points. Research should identify which combinations increase the share of out-of-service components entering managed channels, while controlling transaction costs, preventing leakage to unsafe routes and remaining accessible to

different user groups and market actors. *(Track: Demonstration)*

- **Develop and validate traceability and routing toolchains for renewable-energy components**, combining component identification and chain-of-custody records with standardised testing and routing protocols. Particular attention should be given to battery chemistry and state-of-health, provenance and asset history, and documentation required for EPR and PRO systems and compliant transboundary movements, so that lifecycle responsibility can be verified from collection to final destination.
  (Track: Validation)

- **Test safety-gated second-life pathways for lithium-ion batteries in stationary applications**, including mini-grids, C&I systems and productive-use facilities. Research should develop and validate qualification criteria based on provenance, state-of-health, performance and safety testing, and compare second-life and new batteries in terms of degradation, reliability, lifecycle cost and safety under real operating conditions. Demonstrations should also define end-of-second-life responsibilities and verified downstream recycling routes. *(Track: Demonstration)*

- **Demonstrate end-to-end management models for priority EoL streams**, with particular attention to used lead-acid batteries and other component classes requiring controlled handling, dismantling, pre-processing or treatment. Research should combine collection and aggregation, safe handling protocols, qualified treatment routes, worker and environmental safeguards, and appropriate formal–informal interfaces, and assess which configurations can deliver verified safe management under realistic institutional and market conditions. *(Track: Demonstration)*

- **Scale up replicable circularity-compliance models across renewable-energy portfolios and geographical contexts**, combining modular SOPs, training and certification, traceability systems, qualified collection and treatment networks, procurement and take-back requirements, and finance-linked eligibility or performance criteria. Multi-site implementation should assess whether these packages can be transferred across operators and countries while maintaining verified routing, safety and environmental performance and manageable lifecycle costs
  .*(Track: Scale-up)*

6.2.6 Beyond-technology framing: needs, strategies, business models, risks

The R&I options identified above can contribute to safer and more circular management of renewable-energy components only if they are embedded in viable economic arrangements, functioning institutions and appropriate local capacities. For MAR2, the challenge is therefore not only to develop better technical solutions for repair, refurbishment, second-life use and recycling, but to establish the conditions under which components are actually collected, correctly classified, safely routed and retained within controlled value chains. In line with the CESP4–5 perspective, this section focuses on the business models, institutional arrangements, complementary activities and safeguards required for uptake, replication and long-term sustainability.

Needs and uptake conditions

End-of-use (EoU), out-of-service (OoS) and end-of-life (EoL) management is particularly important where renewable-energy hardware is scaling rapidly while reverse-logistics and waste-management infrastructure remain limited, including off-grid solar systems, mini-grids, C&I PV and storage, and emerging battery-intensive applications. The key challenge is to create a functioning lifecycle system in which components reaching the end of their first use are captured and assessed before being routed towards reuse, repair, refurbishment, repurposing, recycling or final disposal. This distinction between EoU and genuine EoL is important because premature waste designation can destroy residual value, while inappropriate reuse can merely postpone environmental and safety risks. The MAR2 grey-literature analysis makes this distinction central to the circular value-chain logic. Sources: (United Nations Environment Programme, 2021; United Nations Institute for Training and Research & International Telecommunication Union, 2024; World Bank & Energy Sector Management Assistance Program, 2024d)

Priority actors include:

- **Manufacturers, importers, distributors and renewable-energy developers**, whose product choices, procurement requirements, warranties and producer-responsibility obligations influence lifecycle performance from market entry onwards.

- **Energy-service and field-logistics actors**, including PAYGo companies, mini-grid operators, EPC and O&M contractors, retailers and technicians, which already maintain customer relationships and physical service networks and can therefore act as collection, take-back and first-stage triage points.

- **Repairers, refurbishers, aggregators and recyclers**, including SMEs and informal-sector actors already participating in component recovery and material flows.

- **Public authorities and regulatory actors**, including environmental and energy authorities, standards bodies, customs and ports, local governments, and Basel and Bamako focal points, whose decisions determine component classification, licensing, transport and treatment requirements.

- **Workers, users and communities exposed to lifecycle risks**, particularly workers and communities associated with informal dismantling or hazardous battery processing.

Across these actors, recurrent barriers include dispersed and uncertain waste volumes, high reverse-logistics costs, limited qualified treatment capacity, weak or fragmented enforcement, unclear allocation of lifecycle responsibilities, incomplete information on component provenance and condition, and the persistence of informal collection and processing networks. The stakeholder evidence similarly indicates that the practical gap is the absence of the **whole process chain** connecting collection, triage, routing and safe treatment, rather than simply a lack of awareness of e-waste.

Business models, financing and lifecycle responsibility

Circular management creates costs before it creates recoverable value. Collection, transport, diagnostic testing, safe storage, refurbishment, treatment and compliant disposal therefore require business and financing models that allocate costs and responsibilities across the component lifecycle rather than leaving them to the final user or waste holder.

Relevant arrangements include:

- **Extended Producer Responsibility (EPR) and Producer Responsibility Organisation (PRO) models**, capable of providing dedicated and continuing financing for collection and treatment and assigning responsibility to producers, importers or distributors according to the applicable regulatory framework.

- **Service-based models with embedded take-back**, including PAYGo, leasing, energy-as-a-service and O&M contracts in which replacement, retrieval and downstream routing form part of the service relationship rather than being separated from it.

- **Deposit-return, buy-back and trade-in mechanisms**, particularly for batteries and other components with sufficient residual value, provided that testing, fraud prevention and safe routing are built into the model.

- **Aggregator and refurbishment models**, where local or regional SMEs consolidate volumes, undertake diagnostics, repair and refurbishment, and create sufficient scale for compliant downstream recycling.

- **Procurement- and finance-linked circularity requirements**, including take-back clauses, repairability and spare-parts requirements, traceability obligations, eligibility criteria and results-based mechanisms linked to verified lifecycle performance.

The grey-literature evidence particularly supports the need for dedicated financing of collection and treatment through EPR- and PRO-type arrangements, while also identifying service networks and refurbishment hubs as potential mechanisms for integrating reverse logistics and local value creation.

No single model will be appropriate across all component classes and national contexts. MAR2 should therefore treat **who owns the component, who finances its return, who is responsible for its condition and who remains accountable for its final destination** as explicit design questions. Circularity costs should also not be transferred in ways that undermine affordability of renewable-energy services or create incentives for users to bypass formal collection channels.

Institutional conditions and complementary activities

The long-term viability of the R&I options also depends on an enabling environment extending beyond the individual technical intervention. Relevant complementary activities include:

- **Clear classification and routing rules** distinguishing equipment suitable for continued use, repair or refurbishment from genuine waste, together with compliant procedures for transboundary movements where national treatment capacity is insufficient.

- **Licensing, standards and quality-assurance systems** for collectors, repairers, refurbishers, second-life applications, transporters and treatment facilities, including appropriate safety and performance requirements for components returned to service.

- **Capacity building for technicians, waste operators and public institutions**, including diagnostic skills, safe handling and storage, battery and PV-specific procedures, inspection, emergency response, customs controls and lifecycle reporting.

- **Structured integration of informal actors**, where feasible, through training, safer working practices, registration or licensing pathways, access to protective equipment and formal collection arrangements rather than assuming that informality can simply be eliminated through regulation.

- **Traceability and information systems** capable of documenting component identity, provenance, condition, ownership changes and downstream routing, while remaining proportionate to local institutional and operational capacity.

- **Regional coordination and treatment pathways**, particularly where national waste volumes do not justify specialised recycling infrastructure and aggregation or compliant cross-border treatment offers a more realistic solution.

- **Coordination between energy and environmental institutions**, so that renewable-energy deployment programmes, procurement frameworks and financing mechanisms incorporate lifecycle requirements rather than treating EoL management as a separate waste-sector responsibility.

These activities are not optional additions to a technically successful circularity pilot. They constitute the enabling environment through which validated triage systems, take-back mechanisms, traceability tools and second-life pathways can become operationally sustainable and replicable. This is consistent with the CESP5 logic that complementary activities are necessary where the intervention alone cannot generate the conditions required for sustained outcomes.

Risks and safeguards

The beyond-technology perspective is particularly important for MAR2 because apparently positive outcomes such as "more recycling", "more second-life use" or "more jobs" can produce adverse effects if safety, quality and distributional consequences are ignored.

- **Worker and community health risks.** Informal or poorly controlled lead-acid battery processing can generate severe occupational and environmental exposure. Collection and recycling pathways should therefore include controlled handling and treatment, worker protection, emissions and effluent controls, and appropriate monitoring.

- **Battery safety risks.** Damaged or poorly characterised lithium-ion batteries may create thermal-runaway, fire and chemical hazards. Second-life and recycling pathways require identification, isolation, safe storage and transport, qualified testing and emergency-response procedures.

- **Delayed disposal through inappropriate second life.** Repurposing should not become a mechanism for transferring degraded or unsafe components to users or countries with weaker controls. Second-life applications should therefore require verified provenance and condition, defined performance and safety criteria, and a credible end-of-second-life route.

- **Leakage and illicit transboundary flows.** Misclassification of waste as used equipment and diversion from documented routes can undermine both environmental protection and legitimate circular businesses. Chain-of-custody documentation, appropriate inspection and verified downstream treatment are therefore essential.

- **Livelihood and inclusion risks.** Formalisation strategies can unintentionally exclude informal collectors and dismantlers who currently depend on material recovery for income. Where feasible, transition pathways should combine safety

improvement and formal integration with attention to livelihoods, fair remuneration and access to new repair, collection and refurbishment opportunities.

- **False circularity and weak accountability.** Collection or take-back should not itself be interpreted as successful lifecycle management if the final destination is unknown. Claims of recycling, refurbishment or compliant disposal should be supported by documented routing and, where appropriate, independent verification.

By embedding these business-model, institutional and safeguarding conditions, MAR2 becomes a roadmap for **safe and value-retaining lifecycle management**, rather than a catalogue of recycling technologies. The R&I solutions developed and validated under the preceding technical layer are thereby connected to the financing mechanisms, responsibilities, local capacities and complementary activities required for uptake and sustained operation under CESP4–5.

6.2.7 Theory of Change

The Theory of Change for MAR2 follows the original Outputs–Outcomes–Impacts logic of the MARs while updating it through the comprehensive planning perspective adopted in this deliverable. For end-of-use and end-of-life management of renewable-energy components, the core causal pathway is that validated lifecycle-management solutions, operational protocols and evidence can enable safer capture, value retention and verified routing of renewable-energy components when they are taken up through viable business and financing arrangements, supported by functioning institutions, local service capacities and clear lifecycle responsibilities, and replicated beyond isolated demonstrators.

These outcomes are expected to contribute to safer and more inclusive renewable-energy transitions, local economic opportunity, and environmental sustainability and resilience. The relationship is contributory rather than deterministic: wider societal impacts depend on regulation, enforcement, market conditions, infrastructure, user behaviour and other factors beyond an individual R&I intervention. This distinction is consistent with the LEAP-RE MEL framework, which links immediate outputs to outcomes and intermediate impacts and ultimately to wider societal impacts while recognising attribution challenges in complex R&I environments.

Outputs — validated R&I solutions and evidence

- **Validated EoU assessment and value-retention methods are developed and tested** for relevant renewable-energy components, including practical protocols for identification, diagnostic testing, grading, repair, refurbishment, repurposing and safety-gated second-life use, with component-specific criteria for batteries, PV modules and power electronics.

- **Collection, traceability and end-to-end routing models are developed and demonstrated**, including return-incentive mechanisms, chain-of-custody systems, classification and routing rules, and controlled management pathways for priority EoL streams from collection and aggregation through qualified treatment or compliant disposal.

- **Replicable operational and compliance toolchains are produced and validated**, including SOPs for safe handling, storage and transport; traceability and reporting templates; second-life qualification procedures; training and certification packages; and specifications relevant to EPR and PRO, procurement, take-back and transboundary movement requirements.

- **Comparable lifecycle evidence is generated across pilots and implementation contexts**, covering component condition and lifetime extension,

capture and routing, safety, treatment performance, reverse-logistics and lifecycle costs, environmental performance and distributional effects, enabling comparison between alternative circularity approaches and informing subsequent R&I and deployment decisions.

Outcomes — uptake, viability and enabling capacity

- **Out-of-service and end-of-life components are increasingly captured and routed through safer, documented lifecycle pathways**, with reduced leakage into uncontrolled dumping, hazardous processing or unknown downstream destinations and with routing decisions based on component condition and verified treatment options.

- **Viable EoU value-retention and lifecycle-financing models become operational**, enabling repair, refurbishment and safe second-life use where appropriate, while supporting the recurrent costs of collection, aggregation, traceability and treatment through context-appropriate take-back, service, EPR and PRO, procurement or other financing arrangements.

- **Institutional responsibilities and local circular-service capacities become functional in practice**, including clearer roles for producers and importers, operators and public authorities; qualified collection, repair, refurbishment and treatment actors; trained technicians and handlers; workable standards and licensing procedures; and safer integration of informal actors where relevant.

- **Validated lifecycle-management solutions and models are taken up or replicated beyond the initial R&I setting**, through adoption by operators, programmes, public authorities or producer-responsibility systems, adaptation to additional component streams or locations, incorporation into procurement and service contracts, or progression towards multi-site and regional circular value chains.

Impacts — development contributions

At impact level, MAR2 is expected to **contribute to, rather than independently determine**, wider development effects. The contribution pathways are organised according to the common impact dimensions adopted across the MARs.

- **Human capabilities and essential services contribution:** safer collection, handling, refurbishment and treatment of renewable-energy components can contribute to reduced occupational and community exposure to lead, hazardous substances, fires and other lifecycle risks. By supporting safe asset-life extension, reliable replacement and responsible component management, MAR2 can also contribute to the continuity and affordability of energy systems underpinning health, education, water, communication and other essential services.

- **Living standards and inclusive economic opportunity contribution:** functioning circular value chains can contribute to skilled employment, safer livelihoods and SME development in collection, logistics, repair, refurbishment and compliant treatment, while value retention and longer component lifetimes can reduce replacement costs and support affordability of renewable-energy services. Distribution of these benefits should be assessed across gender, age, income and relevant vulnerable or informal-worker groups rather than inferred from aggregate employment or collection figures.

- **Environmental sustainability and resilience contribution:** improved value retention, verified recycling and safer final treatment can contribute to reduced

hazardous leakage, uncontrolled burning and contamination, lower premature disposal of renewable-energy components, and reduced demand for virgin materials and associated lifecycle impacts where supported by evidence. More robust local and regional repair, refurbishment, collection and treatment systems can also improve resilience to equipment, supply-chain and cross-border disruptions.

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of collection, treatment, replication or institutional uptake does not by itself demonstrate that MAR2 interventions caused changes in health, livelihoods or environmental outcomes. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.2.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR2 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of component type and maturity, intervention scale, geographical and institutional context, existing waste-management infrastructure and available resources.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators capture the R&I products and their technical and operational validation. Outcome indicators assess whether validated approaches translate into safer managed flows, viable lifecycle arrangements, functioning institutional and service capacities, and uptake beyond the original demonstrator. Impact-contribution indicators use the common trans-MAR human-development dimensions and assess the wider changes to which MAR2 interventions may plausibly contribute. This follows the LEAP-RE MEL logic, in which indicators should correspond to the appropriate stage of the performance chain rather than combine technical outputs, behavioural changes and long-term impacts in one undifferentiated KPI set.

Output indicators – R&I outputs and technical validation

Table 5 – MAR2 Output Indicators

Indicator	Definition and Evidence Expected	Verification method
Validated lifecycle-management solutions and protocols	Evidence that EoU and EoL solutions have been developed and tested for relevant component streams. This may include diagnostic and triage procedures; repair and refurbishment pathways; safety-gated second-life qualification; safe handling, storage and transport procedures; and end-to-end management models for priority EoL streams. Validation should specify component class, operating context, decision criteria and applicable safety and performance thresholds.	Test and validation protocols; diagnostic and performance records; pilot and demonstrator reports; safety assessments; SOP validation; comparison with predefined technical and safety criteria; expert or third-party review where appropriate.
Validated collection, traceability and	Evidence that mechanisms for bringing OoS and EoL components into managed channels and documenting their subsequent route have been tested under real or representative conditions. Relevant measures may include return participation,	Collection logs; asset and component registers; chain-of-custody records; routing records; digital or paper traceability systems; refurbishment records; treatment certificates; PIC and

routing toolchains	traceability completeness, component identification, chain-of-custody continuity, routing towards reuse, repair, refurbishment, second-life use, recycling or disposal, and verified downstream destination.	transboundary documentation where applicable; pilot audits.
Comparable technical, safety and lifecycle evidence generated	Evidence generated using clearly defined and reproducible metrics that allows comparison between alternative lifecycle-management approaches and contexts. Depending on the intervention, this may include capture and routing performance, component condition and lifetime extension, safety performance, treatment outcomes, reverse-logistics and lifecycle costs, and relevant environmental or distributional effects.	Baseline and monitoring datasets; defined calculation methods and units; component histories; incident records; cost accounts; material-flow records; environmental measurements or lifecycle assessment where relevant; documented data-quality checks.

Outcome indicators – uptake, viability and enabling conditions

Table 6 – MAR2 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Managed capture and verified routing performance	Evidence that OoS and EoL components are routinely entering documented managed channels and reaching an appropriate and verified destination. Relevant measures may include capture rate by component class; routing shares across reuse, repair, refurbishment, repurposing for second-life use, recycling and disposal; traceability completeness; and share reaching verified treatment or redeployment destinations. The denominator and definitions used for "OoS", "captured", "reused" and "treated" should be explicit.	Asset and deployment registries and retirement estimates; collection logs; diagnostic and routing records; chain-of-custody documentation; refurbishment and redeployment records; treatment certificates; periodic material-flow reconciliation and downstream audits.
Viability and value retention of circular lifecycle models	Evidence that collection, reverse logistics, testing, refurbishment, second-life and treatment can operate through financially and operationally viable arrangements. Relevant measures may include reverse-logistics cost per unit/kg, share of lifecycle-management costs covered by stable financing, component lifetime extension, value retained through repair and refurbishment, lifecycle-cost effects and affordability implications for operators or users.	Cost and revenue accounts; EPR and PRO financial records where applicable; service and procurement contracts; unit-cost and lifecycle-cost analysis; component lifetime and performance records; warranty and return data; operator and user expenditure data where relevant.
Safe and inclusive operational and service capacity	Evidence that local actors have the skills, equipment, working arrangements and organisational capacity required to undertake lifecycle-management functions safely and consistently. Relevant measures may include SOP compliance, incident frequency and severity, competency and training, PPE and safety practices, qualified collection, refurbishment and treatment actors, and participation of informal actors,	Repeat operational and facility audits; incident and corrective-action registers; competency assessments; training and PPE records; licences and qualifications; workforce and role records; worker surveys and interviews; grievance mechanisms; remuneration or livelihood evidence where appropriate.

	women, youth or other relevant groups in safer and economically meaningful roles.	
Functional lifecycle-responsibility and institutional mechanisms	Evidence that lifecycle responsibilities and enabling mechanisms are **actually applied in practice**, rather than merely existing in policy documents. This may include functioning EPR and PRO arrangements, take-back obligations, procurement clauses, recycler qualification, licensing and standards, customs and PIC procedures, institutional coordination and clearly assigned responsibilities among producers and importers, operators and public authorities.	EPR and PRO operational and financial records; implemented procurement and service contracts; licences and permits; inspection and enforcement records; customs and PIC documentation; institutional procedures; meeting and coordination records; corroborated interviews with responsible actors.
Replication and uptake beyond the initial R&I setting	Evidence that validated MAR2 solutions are being adopted, adapted or institutionalised beyond the original pilot or demonstrator. Uptake may include use of validated SOPs, traceability systems, take-back models, refurbishment and second-life protocols, procurement requirements or lifecycle-management models by additional operators, sites, programmes or public institutions. A replication plan or expression of interest alone does not constitute uptake.	Operational records from additional sites; signed adoption or implementation agreements; procurement and contracts incorporating the approach; programme documentation; independently confirmed use by adopting organisations; funded follow-up activities; multi-site monitoring data.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR2 contributes to them through the specific pathway of safe, circular and value-retaining lifecycle management of renewable-energy components.

Table 7 – MAR2 Impact Indicators

Common Impact Dimension	MAR2 contribution	Verification method
Human capabilities and essential services	Safer lifecycle management of renewable-energy components contributes to reducing occupational and community exposure to hazardous substances, unsafe processing, battery fires and other EoL-related risks. Repair, refurbishment and responsible replacement can also support continuity and affordability of energy systems serving households and essential services.	Baseline and follow-up occupational and community safety data; incident and exposure records; environmental monitoring where relevant; worker and community surveys; service-continuity and maintenance records where applicable.
Living standards and inclusive economic opportunity	Circular value chains can contribute to safer livelihoods, skilled employment, SME development and local value creation in collection, logistics, repair, refurbishment and compliant treatment. Extending component lifetimes and retaining value can also reduce replacement costs for operators and users.	Employment and enterprise records; job-quality and remuneration evidence; workforce data disaggregated by relevant groups; SME and service-provider records; component lifetime and replacement-cost data; operator and user cost evidence.

Environmental sustainability and resilience	Value retention, verified recycling and safe treatment can contribute to reduced hazardous leakage, uncontrolled disposal and premature component retirement, while potentially reducing demand for virgin materials and associated lifecycle impacts. Stronger local and regional repair, collection and treatment systems can also improve resilience to supply-chain and equipment disruptions.	Material-flow and verified treatment records; environmental monitoring; component lifetime data; lifecycle or material-footprint assessment where justified; records of uncontrolled losses and disposal; longitudinal evidence on continuity of lifecycle-management services during disruptions.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR2 should be interpreted according to its strength, maturity and position in the causal chain. Where possible, quantitative monitoring data should be triangulated with documentary and stakeholder evidence. For MAR2, evidence from a single lifecycle-management pilot, collection scheme, refurbishment pathway or second-life demonstrator should be treated as illustrative rather than generalised to the wider portfolio. Stronger claims concerning safe routing, financial viability, institutional uptake, replication or wider development impacts should require evidence from multiple sites, actors or independent sources. Policy relevance should be distinguished from demonstrated policy influence, while proposed replication or follow-up activities should be distinguished from funded continuation and from actual implementation or sustained uptake. At impact level, evidence should normally support a plausible contribution pathway rather than direct attribution to the R&I intervention.

6.2.9 Interoperability and synergies with other MARs

MAR2 provides the portfolio's lifecycle and circularity layer: it aims to ensure that scale-up under MAR3–MAR7 does not generate unmanaged hazardous-waste streams, and that value retention through repair, refurbishment and second-life use becomes part of the energy-access economy. It is therefore most effective when treated as a set of operating rules, incentives and service networks on which the other MARs can build, rather than as a standalone environmental appendix.

- **MAR1 – Mapping joint R&I actions**
  MAR1 provides the portfolio-level "knowledge infrastructure" to prioritize where lifecycle interventions matter most (which technologies, which geographies, which delivery models). MAR2, in return, supplies **component taxonomies, material-flow logic, and a minimum KPI set** (collection and capture, routing shares across the 5Rs, verified treatment) that MAR1 can use to map risks and opportunities consistently across the programme.

- **MAR3 – Smart stand-alone systems**
  MAR3 is one of the biggest upstream generators of MAR2-relevant flows: **batteries, controllers, inverters, appliances**. The strongest synergy is operational: MAR3 service channels (PAYGo agents, installers, O&M teams) are the natural anchors for **collection, triage at end-of-use, take-back clauses, and refurbishment loops**. Conversely, MAR2 strengthens MAR3 bankability by enabling **design-for-repair**, component traceability, and credible end-of-life routing—so "smart stand-alone" is lifecycle-smart, not just digitally smart.

- **MAR4 – Smart grids for off-grid applications**
  Mini-grids concentrate electronics and storage at a higher scale (meters, switchgear, inverters, batteries, comms gear), which makes MAR2 both more feasible (aggregation is easier) and higher-stakes (failures create bigger material hotspots). MAR4's push for interoperability and data systems should explicitly include **circularity interoperability**: IDs, logs, asset registers, and routing documentation that allow components to be tracked through replacement cycles and managed under EPR and PRO or equivalent schemes. MAR2 also reduces the "stranded asset" risk when assets are upgraded or grid-interconnected—because upgrades often mean early retirement of components unless the EoU gate is designed well.

- **MAR5 – Processes and appliances for productive uses**
  MAR5 expands the portfolio's component universe beyond the energy core into **motors, pumps, refrigeration units, power electronics, and productive appliances**—often the most repairable and job-intensive part of the chain. MAR2 provides the logic to avoid "dumping by modernization": specifying repair and refurbishment pathways, QA for refurbished appliances, and safe handling for hazardous fractions (batteries, e-waste, refrigerants where relevant). MAR5, in return, creates demand and business cases for **refurb hubs and technician ecosystems**, which are exactly the kinds of local value-retention layers MAR2 needs.

- **MAR6 – Priority domestic uses (clean cooking and cold chain)**
  MAR6 intersects with MAR2 in two main ways: (i) **appliance churn** (cookstoves, e-cooking devices, small refrigeration, electronics), and (ii) **cold-chain components** that raise end-of-life issues beyond "electronics" (especially refrigerants and insulation materials, depending on technology). MAR2 ensures that domestic-scale transitions do not create a new wave of unmanaged waste, by aligning procurement and service models with take-back, repairability, and verified downstream treatment. MAR6, in return, provides the user-side lens (sustained use, affordability, inclusion) that MAR2 needs so circular systems do not become exclusionary or impose hidden costs on households.

- **MAR7 – Hydrogen pathways for sustainable energy and industrial systems**
  The interface between MAR2 and MAR7 would concern primarily the **lifecycle implications of emerging hydrogen technology chains**. Electrolysers, fuel cells, power electronics, storage vessels and associated balance-of-system components introduce material, durability, safety and end-of-life considerations that should be addressed before deployment reaches significant scale. MAR2 can therefore provide a **cross-cutting lifecycle and circularity framework**, including design for durability and repair, traceability, take-back arrangements, reuse or refurbishment pathways, and appropriate treatment and recycling routes. This does not make hydrogen a core MAR2 domain; rather, MAR2 should engage where hydrogen technologies generate **distinct material flows or lifecycle risks** that are not adequately covered by existing renewable-energy component value chains.

Overall, MAR2 functions as the portfolio's **safeguard and value-retention layer: it protects health and the environment while supporting local employment and affordability through repair, refurbishment and, where safe, second-life use, so that the other MARs can scale without creating unmanaged environmental liabilities**.

6.3 MAR3 – Smart stand-alone systems

Scope and relationship with MAR4

MAR3 and MAR4 are retained as distinct but contiguous roadmaps, applying the same functional rule stated in the MAR4 scope note. MAR3 covers autonomous, stand-alone supply packages that do not require a shared local distribution or coordination layer, serving individual households, institutions or dispersed loads. MAR4 covers shared local networks that require multi-node distribution, coordinated dispatch, protection, power quality management or interconnection. Household or user counts and system capacity are typical, contextual features of each configuration; on their own, they are not decisive for classification.

6.3.1 Why now

- **Policy and deployment shift (since 2020)**: Major access outlooks continue to converge on stand-alone systems as the least-cost backbone for dispersed rural access, but increasingly treat affordability, consumer finance and cost-of-capital as design constraints to be built into the architecture rather than programme side-notes — a shift amplified in remote and fragile contexts where delivery costs are higher. Sources: (International Energy Agency, 2022, 2025; World Bank et al., 2024)

- **Research and technology shift**: Grey literature and the scientometric signal point to the same shift: stand-alone solutions are moving toward modular, digital, monitorable architectures with embedded telemetry and standardised components, while post-2020 research clusters show a parallel move from basic-access narratives toward service delivery, user behaviour and viability conditions — stand-alone is "no longer lighting-only". Sources: (Sustainable Energy for All & Mini-Grids Partnership, 2024; World Bank et al., 2024)

- **LEAP-RE and practice signal**: LEAP-RE interviewees repeatedly stressed the need to move beyond a purely engineering framing and structure MAR3 through technical, economic and social dimensions.

- **Implication**: This evidence supports **retaining** MAR3 as a distinct roadmap from MAR4, with a mirrored, functional (not capacity-based) boundary added between the two: MAR3 covers stand-alone configurations, MAR4 covers networked, multi-user distribution systems.

6.3.2 State of the art in a nutshell

- **Technology maturity** — the state of the art is dominated by PV + battery stand-alone solutions and nanogrid and small stand-alone cluster architectures, increasingly paired with remote monitoring and modular expansion paths; hybridisation (diesel, storage or biomass) appears in the literature as the reliability "safety net" in certain contexts. Sources: (International Energy Agency, 2025; Sustainable Energy for All & Mini-Grids Partnership, 2024; World Bank et al., 2024)

- **Design standards and quality assurance** — the "bankable" stand-alone system now depends on quality components, protection and safe wiring, and stronger attention to lifecycle and end-of-life workflows (batteries, electronics), which is increasingly treated as an implementation requirement. Sources: (United Nations Industrial Development Organization, 2021; United States Agency for International Development & Power Africa, 2021; World Bank & Energy Sector Management Assistance Program, 2024d)

- **Business models that actually scale** — the leading patterns remain PAYGo and consumer finance for household systems, blended and RBF structures for harder-to-serve segments, and structured toolchains that connect geospatial planning → demand estimation → sizing → finance models. Sources: (United Nations Development Programme, 2022; World Bank et al., 2024; World Bank & Energy Sector Management Assistance Program, 2024b)

- **Binding constraints** — affordability ceilings, dispersed last-mile servicing, O&M capacity, and "sustainability" beyond hardware (governance, spares logistics, customer support) are consistently treated as the adoption gatekeepers. Sources: (International Energy Agency, 2025; RMI et al., 2025; World Bank et al., 2024)

6.3.3 Signals from literature

Top emerging topics (2020–2025 lens):

Post-2020 MAR3 publications show a clear shift from "access as an outcome" to "access as a system," where viability, policy, and user-side evidence become explicit:

Business viability becomes first-class — post-2020 topics include "business–planning–framework" and LCOE and load cost threads, signalling the pivot toward deployability and scalability logic rather than one-off optimal designs.

Policy and constraints become explicit — the inclusion of "challenges–lack–evidence–policy" in post-2020 topics indicates a stronger research focus on barriers and enabling conditions, not only on technical configurations.

User evidence and demand realism rises — "customers–survey–data" appears as a distinct post-2020 topic, consistent with a shift toward data-driven, community-centric and adoption-aware design.

Reliability through hybridisation and storage is reinforced — "diesel–storage–isolated–hybrid–battery" forms a dedicated post-2020 topic, reflecting the continued need for reliability strategies under real-world constraints.

"Hot papers": what they suggest for next R&I moves

The weighted-citation "hot papers" selected for MAR3 cluster around **deployable hybrid architectures**, **storage for reliability**, and the **gap between modelling and field reality**. They also align with post-2020 topic signals (e.g., *biomass–simulation–microgrid–HOMER–viability*, *diesel–storage–isolated–hybrid–battery*, and the emergence of *policy–challenges* as coupled concerns).

- **From "PV+battery only" to context-fit hybrid portfolios** — Recent high-impact studies emphasise **biomass, biogas** and **hydrokinetic + pumped hydro** as credible options where local resources, logistics, and maintenance skills support them. The implication is to fund R&I that expands the *menu of viable architectures* (not just component efficiency), with explicit "where does this make sense?" rules and resource-screening methods.

- **Make modelling tools reflect what developers actually need** — The literature highlights a practical risk: when widely used design tools cannot represent key technologies or degradation dynamics adequately, projects tend to converge on what is easiest to model rather than what is most deployable. A concrete R&I direction is **toolchain work** (validated component models, open datasets, reproducible workflows) that reduces friction from feasibility study → bankable design.

- **Storage becomes a first-class design axis (not an afterthought)** — Across studies on **hydrogen-based storage for critical loads**, **battery degradation and lifecycle costing**, and **pumped hydro storage**, a consistent message emerges: reliability is achieved through storage + control and must be costed honestly over time. This pushes MAR3 R&I toward lifecycle performance (degradation, maintenance, replacements) and resilience-aware sizing rather than static LCOE snapshots.

- **Design for critical services, not average households** — High-impact work increasingly treats stand-alone systems as enabling infrastructure for **service-delivery nodes** (health, education, water), where failure has outsized consequences. R&I should therefore test architectures against critical-load metrics (uptime, power quality, autonomy during outages, repair time) and encode "minimum reliability specs" into demonstrators.

- **Close the business-model ↔ on-site reality gap** — The literature repeatedly signals that technical performance alone does not translate into durable deployment. The next wave of R&I is about aligning tariffs, O&M capacity, payment behaviour, and demand growth with the technical design so systems do not look strong in spreadsheets while underperforming in villages.

- **Hot Papers:** (Ayodele et al., 2021; Kusakana, 2015; Lai, 2017; Moner-Girona et al., 2018; Ribo-Perez et al., 2021)

Meta-signal: across the hot-paper set, scaling is framed as requiring **higher-level support**—from policy design to stakeholder involvement—rather than better optimisation alone, matching the post-2020 coupling between technical choices and policy–challenges.

6.3.4 Insights from LEAP-RE projects

Practice insights for this MAR are grounded in semi-structured interviews with leaders of LEAP-RE joint call projects (WPs 9–16). A recurring message is the need to **depart from a purely engineering perspective** across thematic priorities, and treat context, users, and enabling conditions as first-class elements of the roadmap.

Interview evidence also confirmed a **porous interface with MAR4**; the portfolio-level rationale for retaining the two roadmaps is discussed in Chapter 5 and operationalised through the MAR4 scope definition.

Storage should be made explicit (not treated as a component footnote). Interview feedback flags that, in an updated version, the importance of **storage solutions** should be highlighted more clearly. For MAR3 specifically, this reinforces that "smart stand-alone" is not just PV sizing, but reliability engineering, lifecycle performance, and practical O&M under constrained contexts.

Use MARs as collaboration catalysts, not only classifications. A final point raised by a majority of interviewed leaders is that MARs should be used to catalyse collaboration between projects working on similar themes—an aspect they perceived as underdeveloped. For MAR3, this implies positioning the roadmap as a shared umbrella for stand-alone architectures, storage and reliability, monitoring and maintenance approaches, and user-centred deployment models that can be reused across countries and project settings.

6.3.5 Suggested R&I options

Based on the convergence of recent scientific literature, grey-literature evidence and LEAP-RE practice insights, the following R&I options are proposed as areas for further research, validation, demonstration and replication. They are intended as research directions rather than prescriptive deployment pathways and should be adapted to the service criticality, remoteness, financing model and technical and O&M capacity of the stand-alone deployment context.

- **Investigate "service-ready" stand-alone packages for critical nodes** (health posts, vaccine refrigeration, water points, schools) under diverse climate and remoteness conditions, to quantify reliability (uptime, autonomy hours), lifecycle cost, and service outcomes (e.g., cold-chain compliance, water availability). *(Track: Validation)*

- **Compare storage and hybridisation strategies for reliability** (PV+battery only vs PV+battery+limited diesel vs PV+battery+biomass, biogas or hydrokinetic where feasible), to identify context-fit architectures that minimise lifecycle cost and emissions while meeting defined reliability targets. *(Track: Demonstration)*

- **Develop and validate lifecycle-aware sizing and finance toolchains** (demand estimation including appliance uptake, battery degradation and replacement pathways, cost-of-capital sensitivity), to reduce the feasibility-study → bankable-design gap for stand-alone deployments. *(Track: Validation)*

- **Test digital O&M and predictive maintenance approaches** (remote diagnostics, anomaly detection, spare-part logistics optimisation) in dispersed rural portfolios, to measure effects on downtime, mean time to repair, operating costs, and customer retention. *(Track: Demonstration)*

- **Investigate affordability and sustained-use mechanisms in PAYGo and service-based models** (tenor alignment with seasonal incomes, flexible repayment, targeted subsidies or vouchers, consumer protection), to determine which designs maximise sustained use and minimise debt stress and disconnections among vulnerable households. *(Track: Validation)*

- **Scale up standardized "portfolio deployment" models** (repeatable reference architectures + QA + technician certification + take-back and EoL workflows) across multiple regions and countries, to evaluate replication speed, service quality, and environmental performance (battery and e-waste take-back rates) at scale. *(Track: Scale-up)*

6.3.6 Beyond-technology framing: needs, strategies, business models, risks

The technical options identified above will translate into sustained energy services only if they are matched by viable delivery arrangements and by the institutional, financial and local capacities required for operation over time. In line with the CESP4–5 perspective, this section therefore focuses not on additional technology priorities, but on the conditions shaping uptake, affordability, sustained use and lifecycle sustainability of smart stand-alone systems. This distinction is particularly important for MAR3, where technical feasibility is often already established but long-term performance depends strongly on user fit, servicing capacity, financing and local enabling conditions.

Needs and uptake conditions

Smart stand-alone systems are particularly relevant in **remote, low-density and underserved contexts** where grid extension is slow or uneconomic and where individual or small-cluster solutions may provide the most appropriate pathway to electricity services. Their value should be assessed not only through connection or installed capacity, but through the extent to which they provide **reliable, affordable and usable energy services over time**. The existing MAR3 evidence already identifies affordability, dispersed servicing, weak repair capacity, exposure to shocks and limited operational data as recurring constraints.

Priority users and stakeholders include:

- **Off-grid households**, requiring safe and affordable electricity for lighting, communications and domestic appliances, often under highly constrained and seasonal cash flows.
- **Critical service institutions**, including health posts, schools, water-supply points and refrigeration facilities, where interruptions in electricity supply can directly affect essential services.
- **Small productive and informal users**, whose electricity demand may initially be limited but can expand through access to productive appliances and services, creating important interfaces with MAR5 and MAR6.
- **Service and maintenance actors**, including technicians, last-mile agents, SMEs and cooperatives, whose availability and competence strongly influence system uptime, repair times and user trust.
- **Public agencies, financiers and development actors**, including rural electrification agencies, local authorities, financial institutions, donors and DFIs, whose decisions influence affordability, quality assurance, financing conditions and the geographical reach of stand-alone solutions.

Across these groups, the central challenge is to align the **energy service offered with actual needs, purchasing capacity, appliance use, local capabilities and expected demand evolution**. Stand-alone systems should therefore be understood as **service-oriented systems rather than isolated devices**: hardware and controls remain necessary, but sustained access depends equally on user fit, maintenance, finance, after-sales support and lifecycle responsibilities.

Business models, affordability and ownership

The viability of MAR3 solutions depends on the distribution of ownership, payment, maintenance and replacement responsibilities across the system lifecycle. No single delivery model is appropriate across the diversity of stand-alone applications.

Relevant arrangements include **PAYGo and lease-to-own models**, **energy-as-a-service models**, **community-managed or shared systems**, and **public-institution anchored models** for critical services. Each creates different incentives and risks concerning maintenance, asset ownership, customer protection and long-term replacement.

Particular attention should be given to:

- **Payment structures compatible with irregular and seasonal incomes,** including flexible repayment schedules and mobile-money-based micro-payments where appropriate.

- **Service-based arrangements** in which providers retain responsibility for system performance, maintenance or component replacement rather than transferring all lifecycle risk to the user at purchase.

- **Targeted subsidies or support mechanisms** for vulnerable households and high-social-value services where market-based payment alone cannot provide meaningful access.

- **Blended and results-based financing mechanisms** that support affordability while rewarding verified service delivery, reliability and maintenance performance rather than hardware deployment alone.

- **Clear lifecycle responsibilities,** particularly for batteries and other components requiring periodic replacement, so that initial affordability does not conceal future costs that users or institutions cannot sustain.

Affordability should therefore be evaluated beyond the initial purchase price or nominal monthly payment. It includes **total cost of service, repayment burden, appliance costs, maintenance and replacement costs, income variability, and the consequences of missed payments or disconnection**. This is particularly important for PAYGo systems, where nominal access can coexist with intermittent or discontinued use if payment obligations are not sustainable.

Institutional conditions and complementary activities

Long-term sustainability also depends on an enabling environment extending beyond the energy system itself. In remote settings, these complementary activities are particularly important because weak logistics, limited institutional capacity and long travel distances can turn relatively minor technical failures into prolonged loss of service.

Relevant complementary activities include:

- **Local maintenance and repair ecosystems,** including technician training and certification, last-mile service networks, access to diagnostic tools and reliable spare-parts supply chains.

- **After-sales and consumer-support arrangements,** with clear responsibilities for warranties, faults, payment disputes and system replacement or upgrading.

- **Quality assurance and consumer protection,** including appropriate technical standards, procurement requirements, certification and mechanisms to reduce the diffusion of low-quality or counterfeit components.

- **Demand-enabling activities,** including access to efficient domestic and productive appliances, user training and appropriate financing, so that energy services can evolve beyond basic lighting where demand and system capacity permit.

- **Capacity building for public institutions and local organisations,** especially where schools, health facilities or water services depend on stand-alone systems and require explicit O&M budgets, asset-management responsibilities and continuity planning.

- **User and community engagement,** including identification of priorities, understanding of payment capacity and energy-use practices, feedback mechanisms and attention to intra-household or community differences in access and control.

- **Data and digital capacity,** including appropriate use of remote monitoring and PAYGo data, clear data-governance arrangements, cybersecurity awareness and the operational capacity to translate monitoring data into maintenance decisions.

- **Lifecycle and circularity arrangements,** including repairability, component tracking, take-back mechanisms and safe end-of-life pathways for batteries, panels, controllers and electronics, in coordination with MAR2.

- **Planning for evolution and transition,** so that modular systems can be expanded, upgraded or—where settlement density and demand subsequently justify it—linked to the networked configurations addressed under MAR4.

Within the CESP logic, these activities are not secondary additions to a technically completed project. They constitute the **local enabling environment through which a technically functional stand-alone system can become a sustained energy service**.

Risks and safeguards

The beyond-technology perspective also requires MAR3 interventions to identify who may be excluded or harmed and how risks can be mitigated throughout deployment and operation.

- **Affordability and financial exclusion.** PAYGo terms, deposits, appliance costs or repayment schedules may exclude poorer users, generate debt stress or lead to repeated disconnections. Safeguards include transparent pricing, flexible repayment arrangements, appropriate consumer protection, targeted support where justified, and monitoring of default and disconnection patterns.

- **Gender and social exclusion.** Energy access benefits may be distributed unevenly within households or communities, while ownership or payment arrangements may reproduce existing inequalities in control over assets and income. Safeguards include disaggregated needs assessment, gender-responsive engagement and monitoring of who uses, controls and benefits from the energy service.

- **Technical safety and service quality.** Unsafe installations, battery hazards, poor-quality components or inadequate maintenance can create physical risks and rapidly undermine user confidence. Relevant safeguards include minimum standards, certification, quality assurance, training, maintenance protocols and transparent service-performance requirements.

- **Data and digital risks.** PAYGo platforms, remote monitoring and digital payment systems create risks related to privacy, digital exclusion, cybersecurity and dependency on proprietary systems. Appropriate data-governance principles, user protection, inclusive payment options and proportionate interoperability requirements should accompany digitalisation.

- **Environmental and end-of-life risks.** Stand-alone deployment creates growing flows of batteries, electronics, panels and controllers, with risks of unsafe disposal or informal treatment if reverse-logistics systems are absent. Safeguards include lifecycle planning, repairability, take-back and recycling pathways, component traceability and explicit coordination with MAR2.

- **Institutional fragility and continuity.** Systems may become stranded when local governance is weak, public institutions lack O&M budgets, service companies leave the market, or conflict and climate events interrupt supply chains. Clear allocation of maintenance responsibilities, local capacity building, contingency arrangements and monitoring capable of triggering timely intervention are therefore necessary.

By embedding these conditions, MAR3 is framed as a roadmap for **reliable, affordable and sustainable stand-alone energy services**, rather than as a catalogue of stand-alone technologies. The technical R&I directions identified under CESP3 are thereby connected to the business models, local capacities, complementary activities and safeguards required for uptake and sustained operation under CESP4–5.

6.3.7 Theory of Change

The Theory of Change for MAR3 follows the original Outputs–Outcomes–Impacts logic of the MARs while updating it through the comprehensive planning perspective adopted in this deliverable. For smart stand-alone systems, the core causal pathway is that better designed, context-appropriate and service-oriented technical packages, combined with viable delivery models and local operation capacities, can improve the sustained use of reliable decentralised electricity services in remote and underserved areas. These outcomes are expected to contribute to human development, inclusive socio-economic value creation, and sustainability and resilience.

Outputs — validated R&I solutions and evidence

- **Context-appropriate smart stand-alone system solutions are developed and technically validated,** combining renewable generation, storage, controls, monitoring and efficient end-use appliances where relevant, including configurations for households, productive users and critical service nodes.

- **Replicable design and decision-support methods are produced and validated,** including demand estimation, resource assessment, sizing, control, quality-assurance and lifecycle-performance approaches suitable for different African contexts.

- **Comparable technical evidence is generated** on reliability, service availability, energy delivered, renewable fraction, storage degradation, safety and component performance, enabling comparison between configurations and informing future R&I and deployment decisions.

Outcomes — uptake, viability and enabling capacity

- **Stand-alone electricity services are adopted and sustained** by households, productive users and institutions, with appropriate service quality, appliance compatibility and user retention.

- **Viable delivery and financing arrangements improve affordability and service continuity**, including context-appropriate PAYGo, energy-as-a-service, subsidy or public-service models where relevant.

- **Local service ecosystems and institutional capacities are strengthened**, including trained technicians, O&M responsibilities, spare-parts and logistics arrangements, maintenance escalation procedures and relevant governance mechanisms.

- **Validated solutions, methods and tools are replicated or taken up beyond the original R&I setting**, including adaptation to new sites, use by operators or public agencies, and incorporation into subsequent R&I or deployment activities.

Impacts — development contributions

At impact level, MAR3 is expected to contribute to, rather than independently determine, wider development effects. The contribution pathways are organised according to the common impact dimensions adopted across the MARs.

- **Human capabilities and essential services contribution: i**mproved ability of households and communities to access and use reliable energy-enabled health, education, water, communication and other essential services.

- **Living standards and inclusive economic opportunity contribution:** improved opportunities for productive activities, enterprise development, income generation, employment and skills, with attention to women, vulnerable groups and remote communities.

- **Environmental sustainability and resilience contribution:** reduced dependence on polluting or unsafe energy alternatives, increased use of renewable energy, improved continuity of essential services during shocks, and stronger capacity to maintain and restore decentralised energy systems.

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of system deployment, service continuity or replication does not by itself demonstrate that an R&I intervention caused changes in access, livelihoods or resilience. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.3.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR3 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of technology maturity, intervention type and implementation context.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators refer to the technical and service performance of smart stand-alone systems. Outcome indicators capture the extent to which these systems enable reliable, affordable and useful energy services. Impact indicators are treated as common trans-MAR dimensions, so that MAR3 can be assessed consistently with the rest of the roadmap portfolio.

Output indicators – R&I outputs and technical validation

Table 8 – MAR3 Output Indicators

Indicator	Definition and Evidence Expected	Verification method

Validated stand-alone system solutions	Number and type of context-appropriate system configurations developed and tested under relevant operating conditions; degree to which predefined technical, safety and service requirements are met.	Design documentation; commissioning reports; test protocols; field-validation reports; relevant standards and certification evidence.
Validated design and decision-support tools	Methods or tools for demand estimation, sizing, control, lifecycle analysis or quality assurance that are documented, reproducible and tested against field or benchmark evidence.	Tool documentation; open repositories where applicable; benchmark tests; validation datasets; expert and user testing.
Technical performance evidence	Availability, outage frequency and duration, MTTR, energy delivered, renewable fraction, storage state-of-health, component degradation and other technology-specific performance measures.	System telemetry; meters; inverter, controller and BMS logs; maintenance and replacement records; technical inspection.

Outcome indicators – uptake, viability and enabling conditions

Table 9 – MAR3 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Sustained service uptake and retention	Continued use of the energy service after initial connection or adoption; retention, disconnection and reconnection and dropout patterns.	Operator and CRM data; follow-up surveys; user records.
Affordability and financial viability	Energy expenditure relative to household or enterprise resources; payment performance; evidence that the delivery model can sustain service provision.	Baseline and follow-up surveys; billing and PAYGo data; operator financial records.
Use and continuity of energy-enabled services	Sustained use for household, productive or public-service applications and continuity of services such as health, water, education, refrigeration or digital services.	Appliance and load data; facility records; service logs; surveys and field observation.
Local O&M and institutional capacity	Ability of local actors to perform routine maintenance, respond to faults, access spare parts and manage escalation without disproportionate external support.	Maintenance records; competency assessments; response-time records; spare-part inventories; interviews.
Replication and knowledge uptake	Evidence that validated solutions, methods or tools are used by other projects, operators, agencies or locations, or form the basis for funded follow-up activities.	Adoption records; new deployments; contracts; citations in technical and procurement documents; funded follow-up agreements.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR3 contributes to them through the specific pathway of reliable decentralised electricity services.

Table 10 – MAR3 Impact Indicators

Common Impact Dimension	MAR3 contribution	Verification method
Human capabilities and essential services	Reliable energy enables improved access to and functioning of health, education, water, communication and other essential services.	Health, education and water facility service indicators; hours of service; service interruptions; time-use or user-welfare proxies; baseline and follow-up evidence.
Living standards and inclusive economic opportunity	Energy services support productive use, enterprise activity, income opportunities, employment and skills while remaining affordable to target users.	Enterprise activity; productive-use uptake; employment and training records; income and revenue proxies where credible; affordability measures; gender and vulnerability disaggregation.
Environmental sustainability and resilience	Renewable stand-alone systems reduce reliance on polluting alternatives and maintain or restore essential services under shocks.	Fuel displacement; renewable share; relevant emissions and lifecycle indicators; downtime under shocks; restoration time; resilience case evidence.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR3 should be interpreted according to its strength, maturity and position in the causal chain. Where possible, quantitative monitoring data should be triangulated with documentary and stakeholder evidence. Single demonstrators or case studies should be reported as illustrative rather than generalised to the MAR portfolio, while stronger claims of uptake, replication or impact should require evidence from multiple sources or cases. Policy relevance should be distinguished from demonstrated policy influence, and proposed follow-up activities from funded or implemented continuation.

6.3.9 Interoperability and synergies with other MARs

MAR3 focuses on smart stand-alone systems (SHS, nanogrids and small stand-alone packages) for remote and underserved contexts. Its role is strongly interlinked with other MARs because stand-alone architectures define what end-uses are feasible, how systems are sized, and how sustainability (including end-of-life) is ensured.

- **MAR1 – Mapping joint R&I actions**

MAR1 provides the overarching evidence base to prioritise where stand-alone solutions deliver the highest marginal value (remote settlements, fragile contexts, critical service nodes). MAR3 contributes "deployment archetypes" (household SHS, institution-focused stand-alone systems, clustered nanogrids) and evidence on what makes them scalable (affordability, O&M, reliability), which should feed back into joint programming priorities.

- **MAR2 – End-of-life, second-life and environmental impacts**

MAR3 is a major source of lifecycle material flows (batteries, electronics, panels, controllers). Effective take-back, repair, refurbishment and recycling pathways are prerequisites for sustainable scale-up. MAR2 provides the circularity logic and safeguards (collection incentives, safe handling, second-life options) that MAR3 should anticipate through design-for-repair, component traceability and procurement requirements.

- **MAR4 – Smart grids for off-grid applications**

MAR4 provides the networked evolution pathway for MAR3 systems where demand growth, settlement density or grid development justify local distribution. Shared technologies such as storage, monitoring and load management should therefore be designed with interoperability in mind, while MAR4 addresses the additional coordination, protection and interconnection requirements of multi-user networks.

- **MAR5 – Processes and appliances for productive uses**

Stand-alone systems often remain "lighting-only" unless coupled with productive appliances and demand stimulation. MAR5 provides the productive-use load profiles and appliance and service models that can upgrade MAR3 deployments into income- and service-enabling systems (e.g., pumps, milling, cold appliances). Conversely, MAR3 constrains what productive uses are feasible off-grid (power quality, peak loads, storage sizing), and therefore must align with MAR5 on appliance efficiency and compatibility.

- **MAR6 – Priority domestic uses (clean cooking and cold chain)**

Domestic loads (especially refrigeration and electric cooking where feasible) are key drivers of system sizing and financial viability for stand-alone deployments. MAR6 provides appliance-side requirements (duty cycles, peaks, temperature compliance, safety) and user behaviour patterns (fuel stacking, cooking routines) that MAR3 must incorporate into design and monitoring. MAR3 provides the infrastructure layer (reliability, affordability, O&M) that determines whether domestic services can be sustained.

- **MAR7 – Hydrogen pathways for sustainable energy and industrial systems**

The interface between MAR3 and MAR7 is expected to remain limited and application-specific. Hydrogen may be considered within stand-alone systems where it offers a credible role for long-duration or seasonal storage, resilience, or operation in highly constrained remote contexts. However, it should not be treated as a default storage pathway for MAR3. In most stand-alone applications, reliability and flexibility are more directly addressed through battery storage, hybrid generation architectures, demand-side management, and appropriate system sizing. Hydrogen-related R&I should therefore enter MAR3 only where comparative evidence demonstrates a clear system-level advantage over more mature alternatives.

6.4 MAR4 – Smart grids for off-grid applications

Scope and relationship with MAR3

MAR3 and MAR4 are retained as **distinct but contiguous roadmaps**. Their boundary is defined primarily by system architecture and function rather than by a fixed capacity threshold. User counts and system capacity are typical, contextual features of a deployment; on their own, they are not decisive for classification, which instead follows whether a shared local distribution and coordination layer is required. **MAR3 focuses on stand-alone renewable energy systems serving individual households, institutions and small clusters of users**, where the main R&I questions concern appropriate generation and storage architectures, demand and service requirements,

sizing, affordability, operation and lifecycle sustainability. **MAR4 focuses on mini-grids, microgrids and local distribution systems serving multiple users and loads**, where network-level functions—including coordinated operation, protection, power quality, smart metering and control, demand management and interaction among distributed assets—become central.

The boundary is therefore intentionally **porous rather than absolute**. Storage, monitoring, control, demand estimation and productive-use integration are relevant to both MARs. However, MAR4 encompasses the additional challenges associated with **community-scale distribution and system coordination**, including weak-grid and undergrid applications, grid-interactive operation, and mini-grid–mini-grid or mini-grid–main-grid interconnection. As demand, settlement density and service requirements increase, systems initially falling within MAR3 may therefore evolve towards the architectures addressed under MAR4.

6.4.1 Why now

- **Policy and deployment shift (since 2020)**: Mini-grids have moved from a "nice option" to a core electrification pathway, with scale-up narratives now targeting hundreds of millions of people through portfolio approaches; anchor and commercial loads and bundled appliance financing are treated as core to system design rather than a side-benefit, and regulation increasingly "engineers out" grid-arrival risk through predictable options when the main grid arrives (SPD or SPP, asset buyout, coexistence). Sources: (CLASP, 2025; International Energy Agency, 2022, 2025; Sustainable Energy for All & Mini-Grids Partnership, 2024; World Bank & Energy Sector Management Assistance Program, 2022)

- **Research and technology shift**: The "off-grid vs on-grid" line is blurring, with undergrid and grid-interactive mini-grids and mini-grid clusters increasingly positioned as a reliability solution in weak-grid areas rather than only remote villages; the scientometric signal confirms "smart" becoming increasingly literal, with strong post-2020 clustering around fault detection and restoration, forecasting, big data and learning, and optimal hybrid sizing and control. Sources: (RMI, 2025; World Bank & Energy Sector Management Assistance Program, 2024c)

- **LEAP-RE and practice signal**: LEAP-RE project leaders call for storage to be treated as a first-class design element rather than a component footnote, and for MAR4 to act as a collaboration catalyst across mini-grid and microgrid projects facing shared interconnection, coordination and governance questions.

- **Implication**: This evidence supports **retaining** MAR4 as a distinct roadmap from MAR3, with a mirrored, functional boundary clarifying MAR4 as covering networked, multi-user distribution systems.

6.4.2 State of the art in a nutshell

- **Cost and performance is no longer the bottleneck it was in 2018** — "best-in-class" solar-hybrid mini-grid LCOE fell from **~$0.55/kWh (2018)** to **~$0.38/kWh (2021)** (approximately -31%), driven by cheaper PV modules, batteries and inverters, and scale efficiencies. Sources: (World Bank & Energy Sector Management Assistance Program, 2022)

- **Digitalisation is now "standard kit"** — smart meters + mobile payments enable prepaid or credit schemes, remote connection and disconnection, real-time tracking and basic load limiting; operators also use electrification-as-a-service add-ons

(financing equipment to grow demand). Sources: (World Bank & Energy Sector Management Assistance Program, 2022)

- **Demand stimulation is built into mini-grid design and financing** — the state of the art explicitly treats productive and anchor loads and appliance financing as core to viability (not "nice impacts"), including "productive use overlays" to raise utilisation and customers' ability to pay. Sources: (CLASP, 2025; RMI et al., 2025; World Bank & Energy Sector Management Assistance Program, 2022)

- **Regulation is shifting from bespoke approvals to replicable pipelines** — the toolkit now includes competitive and "multi-attribute" tenders, tariff-setting options (incl. cost-reflective logics and subsidy regimes), and "portfolio" thinking to reduce per-site transaction costs. Sources: (World Bank & Energy Sector Management Assistance Program, 2022)

- **Grid-interactive mini-grids are becoming the reference architecture** — mini-grids are increasingly designed to connect, island, and reconnect to improve reliability and unlock revenue opportunities; "undergrid" arrangements rely on contractual instruments (e.g., Nigeria tripartite templates) to manage roles and risk. Sources: (World Bank & Energy Sector Management Assistance Program, 2022, 2024c)

- **Mini-grid ↔ mini-grid interconnection is emerging as a serious reliability lever** — IMGs are framed as able to stabilize systems and reduce losses; one documented interconnection case in the DRC shows large diesel displacement (-77% then -96% as availability improved). This is illustrative of the potential reliability benefit of interconnection rather than a general result confirmed across contexts. Sources: (RMI, 2025; RMI et al., 2025)

6.4.3 Signals from literature

Top emerging topics (2020–2025 lens):

Post-2020 MAR4 publications show a clear broadening from "hybrid sizing–optimisation" into *operational intelligence + reliability + decision support*:

From optimisation to operations — classic sizing and algorithm threads persist (e.g., "algorithm–sizing"), but "optimal" disappears as an explicit topic label post-2020, suggesting optimisation is becoming *embedded and implicit* in broader design toolchains rather than a standalone research goal.

Reliability becomes first-class — "fault detection–restoration" and "voltage–loss–reliability" topics become prominent, signalling a shift toward grid-quality and service continuity in distribution networks for mini-grids and microgrids.

Forecasting + data + learning move centre-stage — a dedicated "forecasting–data–prediction–learning" topic appears, highlighting predictive analytics as a key lever for planning and operation (dispatch, storage use, uncertainty management).

Decision-support and siting strengthen — the emergence of "multi-criteria–decision-making" indicates growing emphasis on structured decision processes (site selection, design trade-offs, stakeholder constraints).

Hydrogen storage shows up inside "smart grids for off-grid" — a specific hydrogen and fuel-cell topic appears among post-2020 clusters, signalling an R&I vector focused on flexibility and reliability rather than "hydrogen for its own sake".

Scope widens toward institutions and services — a "future challenges–healthcare–university" topic suggests MAR4 research increasingly connects grid architectures to broader service-delivery and institutional contexts (beyond household electrification).

"Hot papers": what they suggest for next R&I moves

The weighted-citation "hot papers" selected for MAR4 cluster around **advanced optimisation**, **AI forecasting**, **hybrid control**, **hydrogen storage**, and **socio-technical adoption constraints**:

- **Next-gen optimisation for hybrid architectures** — improved meta-heuristics for configuring PV, wind and fuel-cell hybrids point to continuing gains from better solvers, but in service of deployable design pipelines.
- **AI forecasting as an operational core** — deep-learning approaches for short-term PV forecasting show up as "hot", consistent with the post-2020 forecasting topic and the need to manage uncertainty in dispatch and storage.
- **Hydrogen as reliability and flexibility storage** — hot-paper emphasis on PV and fuel-cell systems including hydrogen storage supports the framing of hydrogen in MAR4 as an enabling flexibility option for off-grid and weak-grid reliability.
- **Control strategies for hybrid assets** — controller-focused work (e.g., wind generator control via hybrid AI schemes) highlights the R&I push from "design once" to "operate well" under variability.
- **Socio-technical constraints are explicit** — a STEEP-model paper on remote-community microgrids appears among hot papers, reinforcing that technology performance must be co-designed with policy, economics, and local stakeholder realities.
- **Hot Papers:** (Akinyele et al., 2018; Dairi et al., 2020; Okundamiya, 2021; Soliman et al., 2018; Sultan et al., 2021)

Synthesised implication for the MAR4 update: prioritize R&I that couples **forecasting + control + reliability engineering**, treats **maintenance as a performance lever and local job channel**, and keeps **hydrogen storage** in-scope as a flexibility tool for resilient mini-grids and microgrids.

6.4.4 Insights from LEAP-RE projects

Practice insights for this MAR are grounded in semi-structured interviews with leaders of LEAP-RE joint call projects.

Beyond engineering: force a broader framing.

Across interviews, leaders felt the current MARs lean too hard on technical descriptions, and argued for a wider framing that explicitly includes **economic and social** dimensions. One proposal was to standardise each MAR definition into **technical–economic–social** sub-categories to keep the roadmap "open-minded" and comparable across themes.

Interview evidence also confirmed the porous interface with MAR3; the scope distinction is defined above, while the remainder of this section focuses on implications specific to networked mini-grid and microgrid systems.

Storage must be upgraded from "nice add-on" to a first-class element.

Interview feedback flags that an updated framing should explicitly highlight **storage solutions** as a core design axis (not a component footnote), consistent with the way reliability, flexibility, and grid-interaction constraints show up in real deployments.

Use MAR4 as a collaboration catalyst (projects want a shared umbrella).

A recurring message (from a majority of leaders) was that MARs should do more than classify topics—they should actively **catalyse collaboration** among projects working on adjacent themes. For MAR4, that means using the roadmap to convene joint learning across mini-grids and microgrids, interconnection and coordination questions, and stakeholder and governance issues that cut across countries and regulatory regimes.

6.4.5 Suggested R&I options

Based on the convergence of recent scientific literature, grey-literature evidence and LEAP-RE practice insights, the following R&I options are proposed as evidence-supported directions for further research, validation and demonstration. They are intended as **research directions rather than prescriptive deployment pathways**, and should be adapted to the technical, socio-economic and institutional conditions of the application context.

- **Develop and test grid-interactive mini-grid architectures** combining islanding and reconnection capabilities, protection and control strategies, storage integration, and appropriate utility–developer interfaces in weak-grid and undergrid African contexts. Research should quantify impacts on reliability, power quality, system costs and tariffs, while assessing feasible arrangements for value sharing and system operation under real conditions. *(Track: Demonstration)*

- **Test interconnected mini-grid configurations and clustered systems** where multiple geographically proximate mini-grids could exchange power and share flexibility resources. Demonstrations should assess impacts on uptime, renewable utilisation, diesel displacement, reserve requirements and service quality, together with the technical and organisational arrangements required for dispatch, settlements, asset ownership and maintenance accountability. *(Track: Demonstration)*

- **Develop and validate data-driven approaches for mini-grid operation and maintenance**, including renewable-generation and load forecasting, anomaly and fault detection, predictive maintenance, storage management and automated or assisted dispatch. Research should assess whether these approaches can reduce downtime and O&M costs, improve asset lifetime and power quality, and remain applicable under the data, connectivity and skills constraints characteristic of dispersed systems. *(Track: Validation)*

- **Compare and validate demand-development and demand-flexibility strategies as part of mini-grid design,** including anchor-load integration, productive-use development, appliance financing and controllable loads such as electric cooking, cooling and water pumping. Research should identify which combinations improve system utilisation, revenue stability and affordability while maintaining acceptable reliability and power-quality levels. *(Track: Validation)*

- **Develop and assess interoperability-by-design approaches for mini-grid technologies and digital systems**, including open or standardised data models, meter and payment interfaces, modular hardware and control architectures, and

appropriate cybersecurity and data-governance provisions. Research should evaluate their potential to reduce vendor lock-in, facilitate component replacement and upgrading, and lower technical and transaction barriers to replication across operators and countries. *(Track: Validation)*

- **Evaluate and validate multi-site and portfolio delivery models for mini-grid deployment and replication**, including standardised technical specifications, streamlined development processes, contractual approaches for grid arrival and interconnection, results-based financing mechanisms and alternative risk-allocation arrangements. Comparative research should assess their effects on project-development time and costs, investment mobilisation, service quality and replicability across different regulatory and market contexts. *(Track: Scale-up)*

6.4.6 Beyond-technology framing: needs, strategies, business models, risks

The technical options identified above will translate into sustained electricity services only if they are matched by viable delivery arrangements and by the institutional, financial and local capacities required for operation over time. In line with the CESP4–5 perspective, this section therefore focuses not on additional technology priorities, but on the **conditions shaping uptake, viability, replication and long-term sustainability** of smart mini-grid and microgrid solutions.

Needs and uptake conditions (who, where and in what context)

Smart grids for off-grid and weak-grid applications are particularly relevant in rural and peri-urban contexts where electricity access is constrained not only by physical connection, but also by **reliability, affordability, service quality and the capacity to sustain operation over time**. Priority actors and users include:

- **Households and underserved communities**, for whom tariffs, connection costs, payment flexibility and service reliability determine whether electricity can be used beyond basic consumption.

- **Productive and anchor users,** including agro-processing, cold storage, telecom, water services, health facilities and schools, whose demand can increase system utilisation while requiring higher levels of service quality and continuity.

- **Mini-grid developers and operators,** who face uncertain demand, high financing and transaction costs, dispersed O&M requirements and risks associated with future grid arrival.

- **Utilities and public authorities,** whose roles become increasingly important as systems move from isolated operation towards weak-grid, undergrid and interconnected configurations.

- **Local institutions, technicians and service providers,** whose capabilities influence maintenance response, spare-parts availability, customer relations and long-term system performance.

Across these actors, recurrent constraints include low and uncertain demand, limited ability to pay, high cost of capital, weak local O&M ecosystems, fragmented regulatory procedures and uncertainty over the evolution of the main grid. MAR4 therefore treats smart mini-grids and microgrids as **service-delivery systems whose sustainability depends on**

the alignment of technical performance with financial, institutional and social conditions.

Business models, affordability and ownership

No single ownership or revenue model is appropriate across the diversity of MAR4 contexts. Relevant arrangements include **private developer-owned, utility-led or utility-partnered, community or cooperative, and public- or municipal-anchored models**, with different allocations of investment, operational and demand risk.

Their viability depends particularly on:

- **Tariff and payment structures** that balance cost recovery with affordability and transparency, including differentiated service levels or targeted support where appropriate.
- **Anchor-load and productive-use arrangements** capable of stabilising revenues while avoiding excessive dependence on a single customer or activity.
- **Portfolio approaches** that aggregate multiple sites to diversify risk and reduce project-development, procurement, monitoring and financing costs.
- **Performance-based service arrangements** in which reliability, power quality and maintenance response are treated as part of the service proposition rather than merely technical characteristics.
- **Appropriate financing structures,** including grants, concessional or blended finance, results-based financing, guarantees and local-currency instruments according to project maturity and market conditions.

Affordability should be assessed beyond the nominal tariff alone. Connection fees, appliance costs, payment schedules, income seasonality and the risk of disconnection all affect whether users can make sustained and productive use of the service. Financial viability and affordability should therefore be considered jointly rather than treated as competing objectives.

Institutional conditions and complementary activities

The long-term sustainability of MAR4 solutions also depends on an enabling environment extending beyond the electricity infrastructure itself. Relevant complementary activities include:

- **Clear and predictable regulatory arrangements** for licensing, tariff approval, service-quality requirements and consumer protection.
- **Defined grid-arrival and interconnection procedures**, including technical requirements, ownership implications, compensation arrangements and responsibilities among developers, utilities and public authorities.
- **Local O&M ecosystems**, including technician training and certification, spare-parts availability, maintenance contracts and escalation pathways for faults that cannot be resolved locally.
- **Capacity building for regulators, utilities and local authorities**, particularly for emerging grid-interactive and interconnected configurations requiring new technical and organisational competences.

- **Community and user engagement** throughout design and operation, including mechanisms for communication, grievance handling and participation in decisions affecting tariffs, service levels and local infrastructure.

- **Demand-enabling activities**, such as appliance access, productive-use development, business support and links to local markets, where these are necessary for electricity access to translate into sustained use and improved system economics.

- **Data and digital capacity**, including appropriate governance of metering and customer data, cybersecurity awareness, interoperable information systems and the skills required to use operational data in planning and maintenance.

- **Lifecycle and environmental arrangements**, including maintenance, repairability, asset tracking and end-of-life pathways for batteries, meters, power electronics and other components, in coordination with MAR2.

These activities should not be treated as optional additions to a technically completed project. Within the CESP logic, they constitute part of the enabling environment through which technically viable systems can become operationally sustainable and capable of delivering durable services. CESP explicitly identifies complementary activities as a means of supporting long-term sustainability beyond energy provision alone.

Risks and safeguards

The beyond-technology perspective also requires explicit consideration of potential exclusion, unintended effects and implementation failures.

- **Affordability and exclusion.** Cost-reflective tariffs, connection charges or rigid payment arrangements may exclude low-income users or result in nominal connection without meaningful electricity use. Relevant safeguards include transparent pricing, appropriate payment flexibility, targeted support where justified, and monitoring of disconnection and consumption patterns.

- **Institutional and governance risks.** Unclear responsibilities, unstable regulation or disputes associated with grid arrival and interconnection can undermine investment and system continuity. Responsibilities, contractual arrangements, oversight and dispute-resolution mechanisms should therefore be clearly defined.

- **Technical safety and service-quality risks.** Poor installation, protection or maintenance may expose users to safety hazards, damage appliances and erode trust. Appropriate standards, quality assurance, training, inspection and maintenance systems are consequently part of the enabling environment rather than purely technical considerations.

- **Data and digital risks.** Smart metering, automated control and digital payment systems create risks related to privacy, cybersecurity, digital exclusion and dependency on proprietary platforms. Data governance, user protection and interoperability should therefore accompany digitalisation.

- **Environmental and lifecycle risks.** Batteries, power electronics and other components generate lifecycle impacts and end-of-life liabilities, while poorly operated hybrid systems may continue to rely substantially on diesel generation. Lifecycle planning, repair and replacement arrangements, safe take-back or disposal pathways and monitoring of fuel displacement should therefore be incorporated from the outset.

6.4.7 Theory of Change

The Theory of Change for MAR4 follows the original Outputs–Outcomes–Impacts logic of the MARs while updating it through the comprehensive planning perspective adopted in this deliverable. For smart grids in off-grid and weak-grid applications, the core causal pathway is that **better designed and validated network architectures, operational and decision-support methods, and interoperability solutions can improve the sustained provision of reliable, affordable and renewable electricity services at community scale when they are taken up through viable operational and financing models, supported by functioning institutional arrangements and local service capacities, and replicated beyond isolated demonstrators.** These outcomes are expected to contribute to human development and essential services, inclusive socio-economic value creation, and environmental sustainability and resilience.

Outputs — validated R&I solutions and evidence

- **Context-appropriate smart mini-grid and microgrid architectures and demonstrators are developed and technically validated,** integrating renewable generation, storage, protection, metering, monitoring and control according to local demand and service requirements, including grid-interactive and mini-grid–mini-grid configurations where relevant.

- **Replicable planning, operation and decision-support methods are produced and validated,** including demand and anchor-load assessment, system sizing, forecasting, dispatch and storage management, fault detection and restoration, power-quality management, and approaches for grid interaction and interconnection.

- **Interoperability and integration specifications, protocols and tools are developed and tested,** including modular technical interfaces, meter and payment interoperability, data models, communication protocols and standardisation-relevant technical specifications, with appropriate consideration of cybersecurity and data-governance requirements.

- **Comparable datasets and technical-operational evidence are generated,** covering reliability, power quality, energy delivered, system losses, renewable fraction, storage performance, diesel displacement, O&M requirements and, where applicable, islanding, synchronisation and power exchange, enabling comparison between configurations and informing subsequent R&I, standardisation and deployment decisions.

Outcomes — uptake, viability and enabling capacity

- **Reliable and affordable electricity services are sustained and effectively used in off-grid and weak-grid communities,** with improved service continuity, power quality and fault response, and with service levels capable of supporting households, productive users and critical facilities. The relevant outcome is therefore not simply connection or installed capacity, but continued use of electricity services of adequate quality over time.

- **Operational and financial viability of mini-grid and microgrid services improves,** supported by appropriate demand development, productive and anchor loads, tariff and payment arrangements, financing mechanisms and effective O&M. Viability should be reflected in the ability of operators to maintain service quality, cover recurrent operational requirements and respond to evolving demand without undermining affordability.

- **Institutional arrangements and local service capacities become functional in practice,** including workable licensing, grid-arrival, interconnection and compensation procedures where relevant; clearly allocated operational and governance responsibilities; trained technicians and operators; functioning maintenance and spare-parts arrangements; and sufficient capacity among utilities, regulators, local authorities and community organisations to manage the systems over time.

- **Validated solutions, methods and delivery models are taken up or replicated beyond the initial R&I setting,** through adoption by operators, utilities or public authorities, adaptation to additional sites, incorporation into multi-site portfolios, or progression towards grid-interactive and interconnected configurations where technically, economically and institutionally appropriate.

Impacts — development contributions

At impact level, MAR4 is expected to **contribute to**, rather than independently determine, wider development effects. The contribution pathways are organised according to the common impact dimensions adopted across the MARs.

- **Human capabilities and essential services:** sustained access to reliable community-scale electricity can contribute to improved availability and functioning of health, education, water, communication and other essential services, particularly in rural and underserved areas.

- **Living standards and inclusive economic opportunity:** reliable and affordable electricity services can contribute to productive-use uptake, enterprise activity, income-generating opportunities, employment and skills development, with attention to whether benefits reach women, vulnerable groups and underserved communities.

- **Environmental sustainability and resilience:** higher renewable-energy shares, reduced diesel use and improved system operation can contribute to lower reliance on polluting energy alternatives and associated environmental impacts, while resilient mini-grid and microgrid architectures can support continuity and recovery of essential electricity services during grid outages, fuel-supply disruptions, extreme events and other shocks.

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of technical performance, service uptake or replication does not by itself demonstrate that an R&I intervention caused changes in livelihoods, health, economic activity or resilience. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.4.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR4 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of **technology maturity, intervention scale and type, geographical and institutional context, and available resources**.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators capture R&I products and the technical validation of smart mini-grid and microgrid solutions. Outcome indicators assess whether

those solutions translate into sustained service, operational and financial viability, functioning enabling conditions and uptake beyond the original demonstrator. Impact indicators use the common trans-MAR human-development dimensions, allowing MAR4 to be assessed consistently with the rest of the roadmap portfolio.

Output indicators – R&I outputs and technical validation

Table 11 – MAR4 Output Indicators

Indicator	Definition and Evidence Expected	Verification method
Validated smart mini-grid and microgrid architectures and demonstrators	Number and type of context-appropriate architectures developed and tested under relevant operating conditions, including generation, storage, protection, metering, monitoring and control; grid-interactive or interconnected configurations where relevant; degree to which predefined technical, safety and service requirements are met.	Design documentation; commissioning reports; test protocols; field-validation reports; electrical safety and protection tests; relevant standards and certification evidence.
Validated planning, control and decision-support methods	Methods or tools for demand and anchor-load assessment, sizing, forecasting, dispatch, storage management, fault detection and restoration, power-quality management or interconnection that are documented, reproducible and tested against field or benchmark evidence.	Tool and methodology documentation; repositories where applicable; benchmark tests; validation datasets; simulation-to-field comparison; expert and operator testing.
Validated interoperability and integration approaches	Technical specifications, interfaces, protocols or tools enabling component, meter, payment, data and control-system interoperability; evidence of compatibility, modularity and appropriate cybersecurity and data-governance provisions.	Interface and integration tests; protocol documentation; compatibility and conformance testing; cybersecurity assessment; data-governance documentation; multi-vendor testing where feasible.
Technical and operational performance evidence	Comparable evidence on **reliability** (SAIDI, SAIFI or appropriate mini-grid equivalents, outage frequency and duration, MTTR), **power quality** (voltage and frequency compliance), technical and non-technical losses, energy delivered, renewable fraction, storage performance, diesel runtime and fuel consumption and, where relevant, islanding, synchronisation and power exchange between mini-grids or with the main grid.	Smart-meter and feeder data; SCADA, EMS, inverter, controller and BMS telemetry; outage and maintenance logs; fuel records; power-quality measurements; interconnection and event registers; technical inspections.

Outcome indicators – uptake, viability and enabling conditions

Table 12 – MAR4 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Sustained service uptake and quality	Continued use of electricity services after initial connection or intervention; customer retention and disconnection and reconnection patterns; service availability	Smart-meter and CRM records; billing data; outage records; follow-up surveys; service-level records; Multi-

	and evolution towards higher service levels; demand evolution over time.	Tier Framework or equivalent service-quality measures where applicable.
Affordability and operational and financial viability	Evidence that electricity remains affordable to intended users while the service model can sustain recurrent operation. Relevant evidence may include energy expenditure relative to income or resources, collection rate, arrears, ARPU, cost-recovery gap, load factor, peak-to-average ratio and O&M expenditure.	Baseline and follow-up household and enterprise surveys; tariff and billing records; operator financial accounts; smart-meter data; subsidy and RBF records; audited or documented O&M costs.
Use and continuity of energy-enabled services	Extent to which reliable electricity supports productive and anchor loads and essential public services. Evidence may include share of consumption from productive and anchor users, number and retention of productive customers and continuity of electricity-dependent health, water, education, cooling or other critical services.	Metered load data by customer category; anchor-load contracts; facility and service logs; productive-user records; surveys; field observation.
Functional regulatory and institutional arrangements	Evidence that relevant licensing, permitting, tariff, grid-arrival, interconnection and compensation arrangements are not only defined but applied in practice. Relevant process evidence includes time-to-license, time-to-commission, approval costs, application of contractual arrangements and resolution of interconnection or governance issues.	Licensing and permitting records; project-development timelines; regulatory decisions; utility and developer agreements; interconnection contracts; compensation records; dispute-resolution documentation.
Local O&M and institutional capacity	Ability of technicians, operators, utilities, regulators, local authorities and other relevant actors to undertake their assigned functions, respond to faults, access spare parts, operate monitoring and control systems and manage escalation without disproportionate external support.	Maintenance records; MTTR and response-time records; competency assessments; training and certification records; spare-parts inventories; operator and institutional interviews.
Replication and uptake beyond the demonstrator	Evidence that validated architectures, methods, tools or delivery models are adopted by other sites, operators, utilities or public authorities, incorporated into multi-site portfolios, procurement or planning processes, or form the basis for funded follow-up and interconnected or grid-interactive deployments.	New deployment records; contracts and procurement documents; operator and utility adoption records; portfolio expansion; citations in technical or regulatory documents; funded follow-up agreements.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR4 contributes to them through the specific pathway of **reliable, affordable and increasingly networked community-scale electricity services**.

Table 13 – MAR4 Impact Indicators

Common Impact Dimension	MAR4 contribution	Verification method

Human capabilities and essential services	Reliable community-scale electricity can contribute to improved access to and functioning of health, education, water, communication and other essential services, particularly in rural and underserved areas.	Health, education and water facility service indicators; service hours and interruptions; electricity-dependent service availability; user-welfare or time-use proxies; baseline and follow-up evidence.
Living standards and inclusive economic opportunity	Reliable and affordable electricity can contribute to productive-use uptake, enterprise activity, income-generating opportunities, employment and skills development. Distribution of benefits should be assessed across gender, income, age and other relevant vulnerability dimensions rather than inferred from aggregate connection numbers.	Enterprise and productive-use records; employment and training data; income or revenue proxies where credible; affordability evidence; household and enterprise surveys; gender and vulnerability disaggregation; qualitative evidence on access and control over benefits.
Environmental sustainability and resilience	Higher renewable shares and reduced diesel use can contribute to lower reliance on polluting energy alternatives, while smart, grid-interactive or interconnected systems can contribute to continuity and recovery of essential services during outages, fuel disruptions, extreme events and other shocks.	Renewable fraction and fuel displacement; diesel runtime and fuel records; relevant GHG and lifecycle indicators; service downtime during shocks; restoration time; islanding and backup performance; resilience case evidence.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR4 should be interpreted according to its **strength, maturity and position in the causal chain**. Quantitative performance data should, where feasible, be triangulated with independent operational records, documentary evidence or stakeholder evidence rather than relying on a single source. Results from a **single demonstrator, site or project should normally be treated as illustrative rather than generalisable**; stronger claims concerning replication, scalability or wider impact require evidence across multiple sites, cases or independent sources.

Evidence of **policy or regulatory relevance should not be interpreted as demonstrated policy influence** unless a traceable link between the R&I result and the subsequent policy or regulatory decision can be established. Likewise, an identified follow-up opportunity, proposal or replication plan should be distinguished from a **funded continuation**, and funded continuation from actual implementation or sustained uptake. At impact level, evidence should continue to be interpreted primarily as evidence of **plausible contribution rather than direct attribution**, unless the evaluation design is capable of addressing counterfactual influences.

6.4.9 Interoperability and synergies with other MARs

MAR4 focuses on **smart grids for off-grid and weak-grid applications** (mini-grids, microgrids, grid-interactive and interconnected configurations). Its role is inherently systemic: it links generation and storage (MAR3), demand creation (MAR5–6), lifecycle sustainability (MAR2) and portfolio planning (MAR1).

- **MAR1 – Mapping joint R&I actions**
  MAR1 provides the portfolio-level evidence base to prioritise where mini-grids deliver the highest marginal value (rural clusters, peri-urban undergrid zones,

critical service corridors). MAR4 feeds back "grid-intelligence use cases" (interconnection rules, reliability engineering, tariff and toolkit needs, demand stimulation models) that can be translated into joint programming priorities and call topics.

- **MAR2 – End-of-life, second-life and environmental impacts** Mini-grids concentrate material flows (batteries, inverters, meters, control electronics, sometimes diesel gensets). MAR2 provides circularity logic and safeguards (repairability, take-back, recycling pathways, second-life options) that MAR4 should anticipate through procurement requirements, asset tracking, and RBF conditions tied to lifecycle compliance.

- **MAR3 – Smart stand-alone systems** MAR3 provides the stand-alone demand, service and component-level requirements that can feed into later mini-grid and microgrid development. MAR4 addresses the additional coordination, protection, power-quality management and interconnection requirements that arise once multiple users and distributed assets operate through a local network.

- **MAR5 – Processes and appliances for productive uses** Productive and anchor loads (agro-processing, cold storage, telecom, water pumping, workshops) are central to mini-grid viability and drive demand growth. MAR5 supplies the productive-use appliance and service logic and load profiles; MAR4 supplies the grid-side intelligence (tariff design, demand-side management, protection, reliability engineering) needed to integrate those loads without degrading service. Jointly, they should align on appliance efficiency, power quality requirements, and business models that stimulate demand while maintaining affordability.

- **MAR6 – Priority domestic uses (clean cooking and cold chain)** Domestic loads increasingly shape peak demand and system economics (especially refrigeration and e-cooking where feasible). MAR6 contributes appliance-side requirements (duty cycles, peak profiles, safety) and user behaviour realities (fuel stacking, payment patterns). MAR4 provides the operational tools (DSM, smart metering, tariff structures) to integrate these loads and raise service tiers without destabilising systems—making "domestic services" a planned part of grid design, not an afterthought.

- **MAR7 – Hydrogen pathways for sustainable energy and industrial systems** The main interface with MAR4 concerns **flexibility and long-duration storage in specific microgrid contexts**, particularly where high reliability or seasonal balancing is required. Hydrogen should nevertheless remain a niche option within MAR4 and be considered only where comparative evidence shows advantages over batteries and other hybridisation strategies.

6.5 MAR5 – Processes and appliances for productive uses (beyond agriculture)

This MAR now covers renewable-powered processes and appliances for productive uses in rural and peri-urban Africa, across agriculture, agro-processing, rural MSMEs and essential services (e.g. cold chains, workshops, service hubs). Compared to 2019, the scope explicitly goes beyond agriculture-only PUE, strengthening attention to business models, social inclusion and local institutions, while sharing cold-chain and appliance interfaces with MAR6 on priority domestic uses. Cold-chain applications are understood here as commercial, value-chain and enterprise-linked cooling (for example, agri-food cold storage

and trade logistics); household- and community-level cold chain, including health-related refrigeration, is addressed under MAR6.

6.5.1 Why now

- **Policy and deployment shift (since 2020)**: Cold chains have moved from a peripheral concern to core SDG infrastructure, with sustainable-cooling initiatives (ACES and allied programmes) now quantifying losses and codifying efficiency and natural-refrigerant standards, while blended finance, results-based financing, PAYGo and lease-to-own and appliance-financing facilities have scaled to address the sector's persistent affordability and capex and credit bottlenecks. Sources: (International Finance Corporation & United Nations Environment Programme, 2024; Sustainable Energy for All, 2022; Sustainable Energy for All & CLASP, 2023; United Nations Environment Programme & United for Efficiency, n.d.; World Resources Institute, 2024a)

- **Research and technology shift**: Post-2020 MAR5 literature shows a reinforcing pivot from pure engineering toward households, women's empowerment, governance and yield themes, consistent with documented willingness to adopt and measurable country-level markets for solar pumps, refrigeration and milling. Sources: (International Renewable Energy Agency, 2025a; International Renewable Energy Agency & Food and Agriculture Organization of the United Nations, 2021)

- **LEAP-RE and practice signal**: WP leaders flag the need to broaden MAR5 beyond an agriculture-only framing to capture other productive end-uses emerging across LEAP-RE projects.

- **Implication**: This evidence supports **extending** MAR5 beyond agriculture to productive uses generally, with a mirrored cold-chain boundary statement added versus MAR6, consistent with the original PRE-LEAP-RE formulation, which already referenced non-agricultural productive uses.

6.5.2 State of the art in a nutshell

- **Technology maturity** — *Most mature*: **solar water pumps**; *advancing*: **solar refrigeration and cold rooms** and **agro-processing technologies (e.g., milling)** integrated with stand-alone systems or mini-grids. Sources: (Nefco & Beyond the Grid Fund for Africa, 2023; World Bank et al., 2019)

- **Design and performance standards** — an efficiency-first approach is increasingly combined with appropriate insulation, operation and maintenance (O&M), and the use of **low-global-warming-potential refrigerants**, including natural refrigerants such as **R290 (propane)**. Appliance and cooling-system specifications are increasingly aligned with the objectives of the **Kigali Amendment to the Montreal Protocol**, particularly the phase-down of hydrofluorocarbons (HFCs). Sources: (International Finance Corporation & United Nations Environment Programme, 2024; United Nations Industrial Development Organization, n.d.)

- **Business models that support uptake** — **results-based financing (RBF) facilities**, credit lines and guarantees channelled through **local financial institutions (LFIs)**, **pay-as-you-go (PAYGo) and lease-to-own models**, and **cooling-as-a-service** can reduce upfront affordability barriers and link payments more closely to service provision and performance. Sources: (Nefco & Beyond the Grid Fund for Africa, 2023; Sustainable Energy for All & CLASP, 2023; World Bank et al., 2019; World Resources Institute, 2024a, 2024b)

- **Measured outcomes** — productive-use-of-energy (**PUE**) interventions can improve agricultural productivity and incomes; for example, evidence reviewed by WRI reports an approximately **185% increase in mango yield per tree following a solar-irrigation retrofit in Tanzania** (a single documented case, not a confirmed general effect). Cold-storage programmes likewise report income gains and employment creation. Sources: (United Nations Development Programme, UN Capital Development Fund, et al., 2025; World Resources Institute, 2024a)

- **Binding constraints** — affordability for smallholders and **micro, small and medium-sized enterprises (MSMEs)**, last-mile **service and maintenance capacity**, and compliance with **quality assurance (QA)** requirements and **minimum energy performance standards (MEPS)** remain important adoption gatekeepers. Sources: (Sustainable Energy for All & CLASP, 2023; World Bank et al., 2019)

6.5.3 Signals from literature

- Top emerging topics (2020–2025 lens):

Post-2020 MAR5-related publications show a clear shift from generic "energy for agriculture" towards a more socio-economic and governance-oriented framing of productive uses:

Poverty and livelihoods at the core – The stronger presence of "poverty" in recent topics reflects how farming is treated explicitly as an income-generating activity, with PUE positioned as a lever for rural livelihoods rather than just a technical efficiency fix.

Yield and "trends" as quantified outcomes – New topics built around "trends" and "yield" point to more rigorous, data-driven analysis of productivity gains and performance over time, including crop yield responses to water and energy interventions.

From "biofuel" to "waste" and circularity – The disappearance of "biofuel" and the emergence of "waste" indicate a pivot towards waste management, agricultural residues and alternative bioenergy sources, linking PUE with circular bio-economy logics along the value chain.

Governance and policy frameworks – A new governance-centred topic signals growing attention to how institutions, policies and rules shape agricultural development and the diffusion of PUE solutions, not just the technologies themselves.

Overall, the scientometric comparison suggests **a narrowing of perspective around community empowerment and resilience-building strategies**, with productive uses in agriculture increasingly framed as instruments for social and economic resilience in vulnerable rural areas.

- "Hot papers": what they suggest for next R&I moves

The weighted-citation "hot papers" associated with MAR5 cluster around four interconnected themes: smallholder decision-making, climate adaptation, land-use dynamics and water policy. Together, they point to a more integrated, resource-aware research agenda for productive uses:

- **Smallholder adoption of technologies and adaptation strategies (Ethiopia)** – Recent econometric studies on agricultural technology adoption and climate adaptation strategies in Ethiopian regions (e.g. North Shoa, Eastern Tigray) highlight how income, education, risk perception, extension services and access to credit drive farmers' decisions. They argue for **PUE interventions that are co-**

designed with extension, finance and advisory services, rather than "equipment-only" projects.

- **Land-use and land-cover dynamics in intensifying catchments (Finchaa, Ethiopia)** – Work on land-use change in the Finchaa catchment shows how agricultural intensification, water use and ecosystem pressures interact over time. For MAR5 this supports **PUE research that is explicitly coupled with landscape and watershed planning**, to avoid locking in unsustainable patterns.

- **Water footprint and climate vulnerability in North Africa (Morocco)** – Studies on national water-footprint assessment and climate vulnerability in Morocco argue for integrated water–land–energy planning at policy level. For productive uses this translates into **resource mapping of water and energy availability, coupled with tools to make trade-offs visible to farmers and planners**, especially under climate stress.

- **Hot Papers**: (Dibaba et al., 2020; Gebru et al., 2020; Massresha et al., 2021; Schilling et al., 2012; Schyns & Hoekstra, 2014)

Across these "hot papers", a common recommendation emerges: **combine resource mapping with community sensitization on water–land–energy trade-offs, strengthen awareness of climate risks, and design financial mechanisms that make resilient PUE options investable for farmers and local institutions**.

6.5.4 Insights from LEAP-RE projects

Scope beyond agriculture-only productive uses.

WP leaders explicitly noted that restricting MAR5 to agricultural productive uses risks leaving relevant initiatives "orphan" of a roadmap. They proposed loosening the agricultural constraint so that MAR5 can host a broader set of productive end-uses that are clearly useful but not strictly agri-focused. This supports reframing MAR5 around "processes and appliances for productive uses" across rural value chains, not only farming.

Tri-dimensional framing: technical–economic–social.

Interviewees felt that existing MARs, including MAR5, are too close to purely technical descriptions. WP leaders proposed standardising each MAR around three sub-dimensions—technical, economic and social—to force a more open, cross-disciplinary approach. For MAR5 this translates into: (i) appliance and system performance, (ii) viable business and financing models, and (iii) social and institutional conditions for uptake and sustained productive use. Stakeholders also called for MAR5 to act as a catalyst for collaboration between projects addressing related productive-use themes.

Clear linkage between themes and target stakeholders.

WP leaders' interviews stressed the need to correlate each MAR with clearly identified stakeholder groups. For MAR5, this implies making explicit which productive users are in focus (e.g. smallholder farmers, agro-processors, rural MSMEs, cooperatives, women's groups), so that R&I on appliances and processes is grounded in concrete user segments rather than generic "productive uses".

Beyond engineering: embedding socio-economic determinants.

Both the scientometric and interview results converge on the need to move beyond a strictly engineering perspective across all thematic priorities. In MAR5, practice experience reinforces that technical solutions for productive uses only deliver impact when coupled

with attention to livelihoods, poverty dynamics, skills, and local institutions—elements that should be explicitly reflected in the updated roadmap text.

Financing timing should track harvest cycles.

Interviews highlight seasonal cash-flow constraints for productive-use financing and the need to align repayment tenors with harvest cycles, alongside calls for operator-led demand stimulation alongside appliance roll-out.

6.5.5 Suggested R&I options

Based on the convergence of recent scientific literature, grey-literature evidence and LEAP-RE practice insights, the following R&I options are proposed as areas for further research, validation, demonstration and replication. They are intended as research directions rather than prescriptive deployment pathways and should be adapted to the productive activity, energy-service requirements, resource conditions and socio-economic context of application.

- **Develop and validate integrated productive-use packages combining energy supply, efficient appliances and process design across different productive sectors**, including agriculture and agro-processing, cooling and cold chains, rural manufacturing and workshops, water-related activities and other locally relevant MSME applications. Research should compare configurations in terms of energy performance, reliability, utilisation, lifecycle cost, productivity and value addition under real operating conditions. *(Track: Validation)*

- **Develop and demonstrate energy-efficient and renewable-powered processing and cooling solutions adapted to variable and decentralised electricity supply**, including efficient motors and drives, thermal and mechanical processes, refrigeration and cold-storage systems, and load-flexible productive equipment. Research should assess performance under heat, dust, voltage variability, intermittent supply and other operating conditions relevant to African rural and peri-urban contexts, while addressing efficiency, refrigerant choice and maintainability.
  (Track: Demonstration)

- **Develop and validate productive-load integration and flexibility approaches for stand-alone systems, mini-grids and weak grids**, considering appliance duty cycles, starting and peak loads, controllability, storage interaction and seasonal demand. Research should determine how productive loads can improve system utilisation and renewable-energy use without compromising reliability, power quality or service to other users. *(Track: Validation)*

- **Develop and test digital tools for productive-use system design, operation and performance monitoring**, including demand and load-profile estimation, smart metering, remote diagnostics, appliance-level monitoring, predictive maintenance and data-supported optimisation of productive processes. Research should assess whether these tools can increase utilisation, reduce downtime and operating costs, and generate sufficiently robust evidence on productive and energy-service performance under limited-connectivity and capacity conditions. *(Track: Demonstration)*

- **Develop and validate resource-aware planning and design methods for productive-use applications**, integrating energy requirements with relevant water, land, biomass and climate constraints. Particular attention should be given

to irrigation, cooling, processing and bio-based productive activities where increased energy availability may generate resource trade-offs. Research should identify context-appropriate configurations that improve productive performance while avoiding unsustainable resource use and environmental burden shifting. *(Track: Validation)*

- **Demonstrate replicable and modular productive-use configurations across multiple productive sectors and application contexts**, using standardised or adaptable appliance specifications, interfaces, monitoring protocols and quality-assurance procedures. Multi-site demonstrations should evaluate whether successful configurations can be transferred across communities, enterprises and countries while maintaining technical performance, service quality, repairability and compatibility with local energy systems. *(Track: Scale-up)*

6.5.6 Beyond-technology framing: needs, strategies, business models, risks

The R&I options identified above can translate into sustained productive-use services and broader livelihood benefits only if they are matched by viable delivery and ownership arrangements, affordable financing, access to markets, and the local institutional and service capacities required to operate and maintain productive assets over time. In line with the CESP4–5 perspective, this section therefore does not introduce additional technology priorities, but focuses on the enabling conditions that shape uptake, affordability, sustained utilisation, operational and financial viability, replication and long-term sustainability of productive-use solutions.

This distinction is particularly important for MAR5. Technically effective appliances and productive processes do not automatically generate economic or development benefits. Their contribution depends on whether users can afford and use them consistently, whether adequate maintenance and service ecosystems are available, whether financing mechanisms are compatible with productive cash flows, and whether enterprises and producers can access markets and capture sufficient value from the activities enabled by energy. Productive-use interventions should therefore be considered as part of broader socio-technical systems in which technology, business models, institutional conditions, user capabilities and market linkages jointly determine whether energy access can support lasting productive and livelihood outcomes. This framing is consistent with the comprehensive planning logic adopted across the updated MARs.

Needs and uptake conditions

Productive-use solutions are particularly relevant in rural and peri-urban contexts where limited access to reliable and affordable energy constrains income-generating activities, local value addition and the provision of productive services. Following the broadened scope of MAR5, these applications should not be restricted to agriculture, but considered across productive activities where improved energy services can support enterprise development, productivity and local economic opportunity.

Priority users and stakeholders include:

- **Smallholder farmers and producer organisations**, whose productive activities depend on access to energy for irrigation, processing, preservation and other stages of agri-food value chains.

- **Rural and peri-urban MSMEs and cooperatives**, including enterprises involved in processing, manufacturing, workshops, retail and other energy-dependent activities.

- **Productive-service providers**, including operators of shared processing, cooling, water, logistics and other service infrastructures that can serve multiple producers or enterprises.

- **Women- and youth-led enterprises and income-generating activities**, for which access to productive assets, finance, skills and markets may be constrained by existing economic and social inequalities.

- **Energy-service providers, cooperatives and local intermediaries**, which may connect productive users with equipment, maintenance, finance, market information and other services required for sustained operation.

Across these groups, the central challenge is not simply whether an appliance or productive process can be technically operated, but whether there is sufficient and sustained productive demand and a viable route through which the resulting goods or services can generate value. Productive-use equipment may remain underutilised where demand is highly seasonal, working capital is insufficient, markets are fragmented or inaccessible, or maintenance and input supply are unreliable. Technology choice and system sizing should therefore be informed by the wider productive activity, including demand patterns, value-chain position, market access, resource availability and expected evolution of the enterprise.

MAR5 consequently treats productive use not as the provision of isolated appliances, but as an **energy-service and productive-activity system** in which energy availability, equipment utilisation, enterprise capabilities and market conditions interact. Sustained uptake requires alignment between what the energy service enables and the ability of users to convert that service into productive and economic value.

Business models, affordability and ownership

For MAR5, business-model design determines not only whether productive-use assets can be financed, but also who owns them, who bears operating and maintenance responsibilities, how revenues are generated and how the economic value created is distributed. No single model is appropriate across the diversity of productive activities, asset sizes, user groups and market conditions covered by the roadmap.

Relevant **ownership arrangements** include:

- individual ownership by farmers, entrepreneurs or MSMEs where asset utilisation and revenues are sufficient to justify dedicated equipment;

- collective or cooperative ownership of shared productive assets, particularly where individual demand or purchasing capacity is insufficient;

- developer-, utility-, ESCO- or social-enterprise ownership, where the productive asset is operated as part of a broader energy or productive-service offer.

These ownership structures can be combined with different **service and revenue models**. Pay-per-use, pay-per-hour or pay-per-unit-of-service arrangements can allow users to access milling, cooling, pumping or other productive services without purchasing the underlying asset. PAYGo and lease-to-own arrangements may be appropriate for smaller individual appliances, particularly where repayment schedules can be aligned with productive revenues. Service-based approaches can also bundle equipment with

maintenance, technical assistance or other support, shifting part of the performance and lifecycle responsibility from the individual user to the service provider.

A separate issue is the **capital and risk-sharing architecture** required to make these models affordable and investable. Productive-use assets often face high upfront costs while revenues may be seasonal, uncertain or delayed. Relevant mechanisms therefore include micro- and meso-finance adapted to productive cash flows, results-based financing, blended and concessional finance, credit guarantees and other risk-sharing instruments. Targeted subsidies may also be justified where productive-use investments generate wider development or public benefits but remain unaffordable under purely commercial financing conditions.

Affordability should consequently be assessed over the productive cycle rather than through upfront equipment cost alone. Financing arrangements need to consider repayment capacity, seasonality, asset utilisation, operating expenditures and working-capital requirements, while avoiding situations in which increased access to equipment results in unsustainable debt. Business models should ultimately be evaluated according to whether they support sustained utilisation, adequate maintenance, financial viability and an equitable distribution of productive benefits.

Institutional conditions and complementary activities

The long-term viability of productive-use solutions also depends on an enabling environment extending beyond both the energy system and the productive appliance itself. In line with the CESP5 perspective, complementary activities should be considered part of the intervention logic rather than optional additions introduced after technical deployment.

Relevant enabling conditions include:

- **Technical and business capabilities**, including training for operators and technicians, locally accessible maintenance and repair services, spare-parts availability, and managerial and entrepreneurial skills required to operate productive activities sustainably.

- **Market linkages and demand-enabling activities**, including aggregation of producers or users, access to buyers and off-takers, logistics, market information and business-development support. Where markets are weak or fragmented, increasing productive capacity alone may not translate into higher revenues or sustained equipment utilisation.

- **Standards and quality assurance**, covering appliance performance and efficiency, electrical and occupational safety, installation practices and, where relevant, food quality and cold-chain requirements. Appropriate testing, certification and monitoring can reduce equipment failure, safety risks and market fragmentation.

- **Financial-sector capacity and access to working capital**, including the ability of local financial institutions to assess productive-use investments, understand seasonal and sector-specific risk profiles and provide finance not only for the asset itself but also for inputs and working capital required to use it productively.

- **Resource and sectoral governance**, particularly where productive activities depend on water, land, biomass or other constrained resources. Irrigation and other energy-enabled productive activities should be considered together with resource availability, competing uses and climate risks so that higher energy access does not enable unsustainable extraction or environmental pressure.

- **Local institutional arrangements**, including clear responsibilities for shared assets, transparent rules for access and revenue distribution, and appropriate roles for cooperatives, producer organisations, SMEs, municipalities and other local intermediaries. Such arrangements are particularly important where productive infrastructure is collectively owned or serves several user groups.

Complementary activities should therefore connect energy innovation with the wider ecosystem in which productive value is created. Capacity building, finance, market access, standards and institutional support are not substitutes for technically sound solutions, but they influence whether those solutions remain operational, affordable and productive after the initial demonstration period.

Risks and safeguards

The beyond-technology perspective also requires productive-use interventions to be assessed for potential exclusion, unintended effects and environmental or socio-economic trade-offs.

- **Inclusion and distributional risks.** Productive assets, access to finance and the revenues generated may be captured disproportionately by better-resourced enterprises, larger producers or established local actors, potentially reinforcing existing inequalities. Safeguards include transparent access and governance arrangements, attention to women- and youth-led enterprises and other underserved groups, and monitoring not only participation but also ownership, decision-making and distribution of economic benefits.

- **Affordability and indebtedness risks.** Credit and PAYGo arrangements can expand access to productive assets but may also expose users to unsustainable repayment obligations where revenues are uncertain or seasonal. Financing should therefore be aligned with realistic cash flows and productive performance, with transparent terms, appropriate risk-sharing and monitoring of repayment stress and asset repossession or discontinuation.

- **Occupational, product and food-safety risks.** Productive equipment can introduce electrical, mechanical and workplace hazards, while failure of refrigeration or processing systems may affect food quality and other temperature-sensitive products. Standards, certification, operator training, maintenance protocols and appropriate performance monitoring should therefore accompany deployment.

- **Resource and rebound risks.** Improved access to energy can lower the cost of pumping, processing or other productive activities and thereby increase demand for water, land, biomass or energy itself. Productivity gains should therefore not automatically be interpreted as sustainability gains. Resource use and relevant rebound effects should be monitored, particularly for irrigation and other activities exposed to water–land–energy–climate trade-offs.

- **Environmental and lifecycle risks.** Productive-use systems can generate additional material and waste streams through motors, pumps, batteries, power electronics, refrigeration equipment and other appliances. Refrigerant leakage and inappropriate disposal may create additional climate and environmental impacts. Efficient equipment, repairability, appropriate refrigerants, maintenance and end-of-life arrangements should consequently be considered from the outset, with lifecycle management coordinated with **MAR2** where relevant.

By embedding needs and uptake conditions, business-model and financing considerations, complementary activities and explicit safeguards, MAR5 becomes a roadmap for the **sustained productive use of energy rather than simply the deployment of**

productive appliances. This framing retains the technological and process innovation identified in the R&I options while making explicit the market, financial, institutional and social conditions through which those innovations can contribute to productive value creation and longer-term development outcomes.

6.5.7 Theory of Change

For productive uses of energy, the core causal pathway is that **context-appropriate productive-use processes and appliances, supported by validated design methods, service and delivery approaches, and evidence on their performance, can enable sustained productive use when accompanied by viable financing, market linkages and local operational capacities**. These outcomes can in turn contribute to improved human capabilities, inclusive economic opportunity, and environmental sustainability and resilience.

The pathway is not automatic. The availability of productive-use equipment does not by itself imply increased productivity, income, employment or resilience. These effects depend on utilisation, access to inputs and markets, enterprise capabilities, financing conditions, resource availability and the wider economic and institutional context. At impact level, MAR5 should therefore be interpreted primarily in terms of **plausible contribution pathways rather than direct attribution**, unless an evaluation design is capable of isolating the effects of the R&I intervention.

Outputs — validated R&I solutions and evidence

- ***Context-appropriate productive-use solutions and processes are developed and validated*** *for relevant productive sectors and user groups, including agriculture and agro-processing, cooling and cold chains, rural manufacturing and workshops, water-related activities and other locally relevant MSME applications.*

- ***Replicable design, integration and decision-support methods are developed and validated****, including productive-demand and load assessment, resource assessment, appliance and process sizing, integration with stand-alone systems, mini-grids, microgrids or weak grids, energy-efficiency assessment, monitoring and quality-assurance protocols and, where relevant, methods for considering water, land, climate and lifecycle constraints.*

- ***Comparable technical, operational and socio-economic evidence is generated*** *across demonstrators and implementation contexts, covering utilisation, reliability, energy performance, operating costs, productive performance and value addition where measurable, resource use, affordability and the distribution of access and benefits across relevant user groups.*

Outcomes — uptake, viability and enabling capacity

- ***Sustained uptake and utilisation of productive-use energy services*** *by farmers, enterprises, cooperatives and other productive actors, with productive assets remaining operational and used beyond initial installation or demonstration periods.*

- ***Improved productive performance and value addition****, where sustained productive use results in measurable changes such as increased processing capacity or productivity, improved product quality, reduced operating time or reduced process and post-harvest losses.*

- ***More viable and affordable productive-service arrangements**, supported by ownership, payment and financing models appropriate to productive cash flows and capable of covering recurrent operation, maintenance and replacement requirements without undermining user affordability.*

- ***Strengthened local service, enterprise and institutional capacity**, including operation and maintenance, repair and spare-parts provision, access to finance and working capital, business-development support, market and off-taker linkages, quality assurance and workable arrangements for shared or service-based productive assets.*

- ***Replication and uptake beyond the initial R&I setting**, through adoption or adaptation of validated productive-use solutions, methods or service approaches by additional enterprises, communities, operators, programmes or financing channels.*

Impacts — development contributions

At impact level, MAR5 is expected to contribute to, rather than independently determine, wider development effects. The contribution pathways are organised according to the common impact dimensions adopted across the MARs.

- ***Human capabilities and essential services:** sustained access to productive energy services can contribute to improved food availability and nutrition, reduced drudgery and time burdens, safer and more effective working conditions, improved access to water-related services and, where relevant, stronger cold chains supporting food and other essential services.*

- ***Living standards and inclusive economic opportunity:** productive-use solutions can contribute to increased local value creation, enterprise development, income-generating opportunities, employment and skills development. These effects should be assessed with attention to their distribution across gender, age, income, enterprise size and other relevant dimensions of vulnerability and exclusion.*

- ***Environmental sustainability and resilience:** renewable-powered and energy-efficient productive processes can contribute to reduced fossil-fuel dependence, lower energy intensity and process losses, and more resilient livelihoods and value chains. These benefits should be assessed alongside potential trade-offs associated with increased water, land or biomass use, rebound effects, refrigerants, equipment lifecycles and end-of-life management.*

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of enterprise uptake, service continuity or replication does not by itself demonstrate that an R&I intervention caused changes in income, employment or resilience. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.5.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR5 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of the productive activity, technology maturity, intervention scale and type, geographical and institutional context, and available resources.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators assess whether productive-use solutions, methods and validation evidence have been generated under relevant operating conditions. Outcome indicators assess whether these outputs translate into sustained productive use, productive performance, viable and affordable service arrangements, functioning enabling capacities and uptake beyond the original demonstrator. Impact-contribution indicators use the common trans-MAR human-development dimensions and assess the wider development changes to which sustained productive use of energy may contribute.

Output indicators – R&I outputs and technical validation

Table 14 – MAR5 Output Indicators

Indicator	Definition and Evidence Expected	Verification method
Validated productive-use solutions and processes	Number and type of context-appropriate productive-use appliances, processes or integrated packages developed and tested under relevant operating conditions; degree to which predefined technical, energy-efficiency, safety, reliability and productive-service requirements are met. Applications may include agriculture and agro-processing, cooling and cold chains, rural manufacturing and workshops, water-related activities and other locally relevant MSME uses.	Design and technical documentation; commissioning reports; test protocols; field-validation reports; equipment and process measurements; relevant standards or certification evidence.
Validated design, integration and decision-support methods	Methods or tools for productive-demand and load assessment, resource assessment, appliance and process sizing, integration with stand-alone systems, mini-grids, microgrids or weak grids, energy-efficiency assessment, monitoring and quality assurance that are documented, reproducible and tested against field or benchmark evidence. Where relevant, methods should also address water, land, climate and lifecycle constraints.	Methodology and tool documentation; repositories where applicable; benchmark tests; validation datasets; simulation-to-field comparison; field testing; expert or practitioner assessment.
Technical, operational and socio-economic evidence generated	Comparable evidence generated across demonstrators and implementation contexts on utilisation, reliability, energy performance, operating costs, productive performance and value addition where measurable, process or post-harvest losses where relevant, resource use, affordability and distribution of access and benefits across relevant user groups.	Equipment meters and telemetry; operating and maintenance logs; production and enterprise records; cost records; baseline and follow-up surveys; field observation; gender-, age-, income- or vulnerability-disaggregated evidence where relevant.

Outcome indicators – uptake, viability and enabling conditions

Table 15 – MAR5 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Sustained productive-use	Continued use of the productive appliance, process or service beyond initial installation	Equipment runtime and load data; service-provider or operator records;

uptake and utilisation	or demonstration; utilisation relative to expected productive capacity; evidence of retention, discontinuation, seasonality and reasons for under-utilisation. Uptake should be assessed across relevant user groups rather than through aggregate installation numbers alone.	PAYGo and transaction records where applicable; production logs; follow-up surveys; field observation; user records disaggregated by relevant characteristics.
Productive performance and value addition	Measurable changes in the productive activity associated with sustained use, such as increased processing capacity or productivity, improved product quality, reduced operating or processing time, reduced process or post-harvest losses, or increased value added. Indicators should be selected according to the productive activity rather than applying a single portfolio-wide productivity metric.	Baseline and follow-up production and enterprise records; process measurements; cooperative records; crop or production data; cold-chain temperature and spoilage records where relevant; product-quality measurements; user surveys and field observation.
Affordability and operational and financial viability	Evidence that users can afford to access and continue using the productive service and that the applicable ownership, payment or financing arrangement can support recurrent operation, maintenance and replacement requirements. Assessment should account for seasonal revenues, working-capital requirements, repayment performance and risks of financial stress.	Asset and service costs; tariffs and service fees; billing, PAYGo or loan-repayment records; operator and enterprise financial records; cash-flow evidence; affordability surveys; records of default, repossession or discontinuation where applicable.
Local service, enterprise and institutional capacity	Ability of local actors to operate, maintain and repair productive assets; access spare parts and technical support; manage shared or service-based assets; access relevant business and financial services; and maintain functioning market or off-taker linkages without disproportionate dependence on external project support.	Maintenance and repair records; technician and operator competency assessments; spare-parts and service-response records; training records; cooperative and service-provider documentation; working-capital or finance records; market and off-taker agreements; stakeholder interviews.
Replication and uptake beyond the initial R&I setting	Evidence that validated productive-use solutions, methods or service approaches are adopted or adapted beyond the original demonstrator, including use by additional enterprises or communities, transfer to other sectors or locations, adoption by operators or financial institutions, or incorporation into subsequent programmes and funded activities.	Additional installations or users; adoption records; service contracts; procurement records; third-party use of methods and specifications; programme documentation; funded follow-up agreements; evidence of implementation at additional sites.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR5 contributes to them through the specific pathway of **sustained productive energy services and the productive activities they enable**.

Table 16 – MAR5 Impact Indicators

Common Impact Dimension	MAR5 contribution	Verification method

Human capabilities and essential services	Sustained productive-use services can contribute to improved food availability and nutrition through reduced losses and improved processing or preservation; reduced drudgery and time burdens; safer and more effective working conditions; improved water-related services; and, where relevant, cold chains supporting food and other essential services.	Food-loss, food-availability or service indicators where relevant; time-use surveys; occupational-safety records; water-service indicators; cold-chain and service records; baseline and follow-up household or user evidence; qualitative evidence on changes in capabilities and well-being.
Living standards and inclusive economic opportunity	Productive-use services can contribute to increased local value creation, enterprise development, income-generating opportunities, employment and skills development. Distribution of these benefits should be assessed across gender, age, income, enterprise size and other relevant vulnerability dimensions rather than inferred from aggregate numbers of appliances, users or jobs.	Enterprise activity and survival records; revenue or income proxies where credible; employment and training records; household and enterprise surveys; livelihood evidence; gender and vulnerability disaggregation; qualitative evidence on ownership, decision-making and control over economic benefits.
Environmental sustainability and resilience	Renewable-powered and energy-efficient productive processes can contribute to reduced fossil-fuel dependence, lower energy intensity and process losses, and more resilient livelihoods and value chains. These contributions should be assessed together with potential trade-offs associated with water, land and biomass use, rebound effects, refrigerants, equipment lifecycles and end-of-life management.	Renewable-energy share and fuel-displacement data; energy-intensity indicators; relevant GHG and lifecycle indicators; water and other resource-use data; waste and product-loss records; refrigerant records where relevant; repair and EoL records; evidence of service continuity or recovery during climatic, market or supply-chain shocks.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR5 should be interpreted according to its strength, maturity and position in the causal chain. Where possible, quantitative performance and enterprise data should be triangulated with documentary and stakeholder evidence. Results from a single productive-use pilot, enterprise or demonstrator should be treated as illustrative rather than generalised to the wider portfolio; stronger claims concerning viability, replication, income effects or wider development impacts should require evidence from multiple sites, enterprises or independent sources. Policy relevance should be distinguished from demonstrated policy influence, and a proposed follow-up or replication plan should be distinguished from funded continuation and from actual implementation or sustained uptake.

6.5.9 Interoperability and synergies with other MARs

MAR5 is structurally interlinked with several other MARs and should be read as the "productive use" backbone of the portfolio:

- **MAR1 – Mapping joint R&I actions -** MAR1 provides the overarching evidence base, foresight and prioritisation that identify where productive uses of energy can most effectively unlock development gains (e.g. specific value chains, regions, or user groups). Insights from MAR5 pilots and studies should in turn feed back into MAR1 as concrete "use cases" for future joint programming.

- **MAR2 – End-of-life, second-life and environmental impacts -** Many PUE appliances (motors, pumps, cold rooms, batteries, electronics, refrigerants) raise end-of-life and circularity challenges. MAR5 therefore depends on MAR2 for sustainable materials choices, EoL strategies, repair and remanufacturing approaches, and safe refrigerant and battery management in rural contexts.

- **MAR3 – Smart stand-alone systems -** A large share of PUE in rural Africa will be powered by stand-alone systems and, where local distribution is available, by mini-grids and microgrids. MAR3 addresses the stand-alone configurations, while MAR4 addresses mini-grid, microgrid and local-network supply (see the MAR3–MAR4 scope note); MAR5 focuses on the productive loads they enable in either case. Design choices in MAR3 and MAR4 (sizing, storage, control strategies) must therefore take into account MAR5's load profiles, appliance characteristics and business models.

- **MAR4 – Smart grids for off-grid applications -** Where mini-grids and local distribution systems are used, productive uses are often the anchor loads that determine financial viability. MAR5 and MAR4 are mutually reinforcing: MAR4 provides the grid-side intelligence, protection and planning tools, while MAR5 specifies the nature, timing and flexibility of productive loads and the service models built around them.

- **MAR6 – Priority domestic uses (clean cooking and cold chain) -** There is a strong overlap between productive and domestic uses for certain appliances and services, particularly **cold chains, e-cooking and multi-functional devices**. MAR5 concentrates on commercial, value-chain and enterprise-linked cold chains and other IGA-linked appliances; MAR6 on household- and community-level cold chain, cooking and basic services. Together they should ensure consistent approaches to appliance efficiency, affordability, quality assurance and gender-responsive design.

- **MAR7 – Hydrogen pathways for sustainable energy and industrial systems -** The main interface with MAR5 concerns **industrial and transport-related productive uses**, including fertiliser production, process heat and logistics. MAR5 contributes the perspective on **local value creation, enterprise participation and livelihood effects** associated with hydrogen-enabled productive activities.

6.6 MAR6 – Innovative solutions for priority domestic uses (clean cooking and cold chain)

This MAR now covers innovative, scalable solutions for priority domestic energy uses in rural and peri-urban Africa—specifically clean cooking and household and community cold chain services (food safety and essential health-related refrigeration). Compared to 2019, the scope is broadened from cooking-focused interventions to a combined cooking + cooling perspective, reflecting 2020–2025 evidence that both are increasingly treated as essential SDG infrastructure. The updated MAR strengthens attention to sustained use, affordability and service and finance models, while keeping clear interfaces with MAR5 on productive cold chains and with MAR3–MAR4 on delivery infrastructures. Cold-chain applications here cover household- and community-level cooling, including health-related refrigeration in settings such as vaccine stores and health facilities; commercial, value-chain and enterprise-linked cold chains are addressed under MAR5. The "domestic uses" label is retained from the original PRE-LEAP-RE title for continuity; its scope, as used throughout this chapter, extends beyond the household to community and essential public-service settings.

6.6.1 Why now

- **Policy and deployment shift (since 2020)**: Clean cooking and cold chains have both been redefined as core SDG infrastructure rather than peripheral welfare issues: major reports now frame them as central to health, equity and infrastructure strategy, with electricity-based cooking gaining ground in peri-urban areas while LPG and improved biomass dominate rural contexts, and cold storage recognised as essential for safe food, vaccines and medicines alongside its productive role in MAR5. Sources: (International Energy Agency, n.d., 2022; International Renewable Energy Agency, 2023; Sustainable Energy for All, 2022; United Nations Environment Programme & United for Efficiency, n.d.; United Nations Industrial Development Organization, n.d.; World Bank & Energy Sector Management Assistance Program, n.d.)

- **Research and technology shift**: Post-2020 academic literature shows a pivot away from combustion-efficiency and hardware framing toward outcomes and use — household air pollution and respiratory health, poverty and access, and cookstove adoption and fuel stacking.

- **LEAP-RE and practice signal**: WP leaders note that clean cooking and cold-chain needs are foundational to well-being but fall between existing MARs, calling for MAR6 to claim a clearer coordination role across appliance standards, performance metrics and household-level outcome tracking, with attention to distinct user types and hidden vulnerabilities (e.g. women-headed households, informal renters).

- **Implication**: This evidence supports **extending** MAR6 from a cooking-focused roadmap to a combined cooking-and-cooling roadmap, with a mirrored cold-chain boundary statement added versus MAR5.

6.6.2 State of the art in a nutshell

- **Technology maturity** — Most mature: LPG and improved biomass stoves in rural contexts, solar home systems with basic cooling. Advancing: electric cooking appliances (induction, resistive) in mini-grid and peri-urban settings; solar direct-drive fridges and freezers for household and community use. Sources: (International Energy Agency, n.d.; United Nations Development Programme, Food and Agriculture Organization of the United Nations, et al., 2025; World Bank et al., 2019).

- **Design standards** — Clean cooking now integrates emissions thresholds (e.g., WHO PM2.5), efficiency, and safety (ISO tier frameworks); cold appliances increasingly Kigali-aligned, with donor specs converging on natural refrigerants (e.g., R600a, R290), insulation, and durability. Sources: (International Finance Corporation & United Nations Environment Programme, 2024; United Nations Environment Programme & United for Efficiency, n.d.; World Bank & Energy Sector Management Assistance Program, n.d.)

- **Business models that actually reach households** — Uptake is driven by affordability and ease of use: PAYGo, lease-to-own, appliance-as-a-service models are gaining traction, especially where bundled with maintenance, behavioural nudges, and community engagement. Sources: (Sustainable Energy for All, 2022; United Nations Development Programme, Food and Agriculture Organization of the United Nations, et al., 2025; World Resources Institute, 2024a)

- **Measured outcomes** — Electric cooking pilots show reduced cooking time, lower exposure to indoor air pollution, and meaningful time savings for women and girls. Cold-chain pilots for households (e.g., fish and meat storage) improve dietary diversity and food safety. Vaccine cold-chain upgrades reduce spoilage and increase immunisation reliability. Sources: (Sustainable Energy for All, 2022; United Nations

Development Programme, Food and Agriculture Organization of the United Nations, et al., 2025)

- **Binding constraints** — Clean cooking progress is slowed by fuel stacking, lack of last-mile servicing, and affordability for lowest-income groups. Cold appliance deployment is limited by upfront costs, uncertainty about user payments, and fragmented ownership models. Sources: (United Nations Environment Programme & United for Efficiency, n.d.; World Bank et al., 2019)

6.6.3 Signals from literature

- Top emerging topics (2020–2025 lens):

Post-2020 publications related to MAR6 reveal a transition from generic energy access narratives to more user-centred, health-conscious and infrastructure-focused framings of domestic energy services:

Clean cooking reframed as a health and development issue – The prominence of indoor air pollution, exposure and child respiratory infection in recent clusters, alongside a growing poverty and access topic, suggests that clean cooking is increasingly analysed not just as a fuel switch but as a public health and poverty-related intervention. This aligns with a reframing of cooking energy as a cross-sectoral enabler for SDGs.

Adoption, choice and fuel stacking – A post-2020 topic combining "adoption," "cookstoves," "choice" and "stacking" points to a more grounded understanding of what drives or inhibits technology uptake. This supports a shift from technical potential to real-world usage and decision-making.

Overall, the scientometric signal suggests that domestic uses of energy are increasingly positioned within a broader socio-technical framework that centres health, poverty and user behaviour—pushing clean cooking toward closer integration with energy planning and public-health delivery. Because the MAR6 corpus was built around the original, cooking-focused scope, the cooling and cold-chain dimension of the updated MAR6 is evidenced by the grey-literature and practice streams (Sections 6.6.1, 6.6.2 and 6.6.4) rather than by this topic model.

- "Hot papers": what they suggest for next R&I moves

The most cited recent papers within the MAR6 cluster gravitate around two cross-cutting themes: household air pollution and health, and the behavioural and economic drivers of cooking-energy choice and sustained use.

- **Air quality and household health in rural Africa** – Papers examining PM2.5 and black carbon exposure from biomass cooking highlight strong associations with respiratory illness, particularly for women and children. These findings reinforce the argument for electrification of cooking as a health intervention and justify tighter emissions thresholds in appliance selection.

- **Behavioural drivers of fuel choice and sustained use** – Studies exploring cooking transitions in East and West Africa show that affordability, taste, speed, and gendered time burdens all weigh heavily in household decisions. R&I should therefore focus on human-centred design and service models that reflect real constraints, not just emissions and efficiency.

- **Hot Papers**: (Beltramo et al., 2015; Jurisoo et al., 2018; Ochieng et al., 2020; Twumasi et al., 2021; Van Vliet, 2013)

Together, these "hot papers" argue for a multi-impact research agenda for MAR6, grounded in co-design with users, coupling of energy and service delivery sectors, and measurement of outcomes in terms of health, sustained use and inclusion—not just technical performance.

6.6.4 Insights from LEAP-RE projects

Practice insights for this MAR are grounded in semi-structured interviews with leaders of LEAP-RE joint call projects (WPs 9–16).

From hardware to health, care and resilience.

Interviewees emphasised that energy access strategies often overlook the daily realities of household needs—especially for cooking, food storage, and basic care. WP leaders argued that domestic energy use is central to well-being and resilience, not secondary to economic or productive applications. MAR6 should therefore elevate cooking and cold chain solutions as key levers for health, time use and gender equity.

Tri-dimensional framing: technical, behavioural, financial.

WP leaders advocated for structuring MAR6 around three intersecting dimensions: (i) technical performance and reliability of domestic appliances; (ii) behavioural alignment with cultural and household practices (e.g. cooking methods, food preferences, care routines); and (iii) financial realism, including fuel stacking, recurrent costs and affordability thresholds. This framing would support a more grounded and context-sensitive R&I pipeline.

User segmentation and hidden vulnerabilities.

Interviews stressed that "households" are not homogeneous. WP leaders highlighted that interventions should distinguish between different user types—e.g. women-headed households, informal renters, households with health-related cold storage needs—each with distinct constraints and risks. MAR6 should promote disaggregated targeting and inclusive appliance and service design.

Cross-cutting relevance, underdeveloped roadmap role.

Despite their foundational role in quality of life, domestic energy uses often remain "everyone's responsibility but no one's lead." WP leaders noted that clean cooking and cold chains tend to fall between MARs, despite strong overlap with MAR5 (cold chain, appliance design) and MAR3 and MAR4 (delivery infrastructure). MAR6 should claim a clearer coordination role to ensure coherence in standards, performance metrics and household-level outcome tracking.

MARs as shared learning platforms.

As in other themes, WP leaders called for MARs to be more than inventories of R&I needs—they should function as shared reference points across projects. For MAR6, this means curating insights on appliance deployment models, usage monitoring, behaviour change strategies and impact evidence from clean cooking and cold chain pilots across the portfolio.

Acceptance depends on fit with daily routines, not just economics.

WP leaders report that cooking-device acceptance depends on taste, speed and compatibility with social routines, not just economics or emissions, and flag demand volatility for shared cold rooms when ownership and accountability are unclear.

Reporting rarely captures end-use and health outcomes.

Interviews stress the need for more consistent KPI frameworks and data collection on end-use behaviour, health impacts and user satisfaction — domains often missing from RE project reporting.

6.6.5 Suggested R&I options

Based on the convergence of recent scientific literature, grey-literature evidence and LEAP-RE practice insights, the following R&I options are proposed as areas for further research, validation, demonstration and replication. They are intended as research directions rather than prescriptive deployment pathways and should be adapted to local cooking practices, energy infrastructures, climatic conditions and service requirements.

- **Develop and validate context-appropriate clean cooking packages** across urban, peri-urban and rural settings, comparing appliance and fuel and energy configurations under real cooking practices and fuel-stacking behaviours. Research should quantify cooking performance, energy use and efficiency, PM2.5/CO exposure, safety and total cost of cooking, while documenting sustained-use patterns across different household contexts. *(Track: Validation)*

- **Compare tiered clean cooking transition pathways**—including improved biomass solutions, LPG or ethanol, and electric cooking, as well as direct-to-e-cooking where feasible—under different infrastructure and fuel-supply conditions. Research should identify which pathways best combine sustained use, affordability, emissions reduction, safety and compatibility with local cooking practices, rather than assuming a single transition route across contexts. *(Track: Demonstration)*

- **Develop and test e-cooking integration with stand-alone systems, mini-grids and weak grids**, using appropriate appliance selection, load management, storage coordination and demand-side management strategies. Research should assess impacts on peak demand, renewable-energy utilisation, storage operation, reliability and power quality while maintaining acceptable cooking speed, convenience and service quality for users. *(Track: Demonstration)*

- **Develop and validate last-mile domestic and community cooling packages** for household food preservation and essential health-related refrigeration, combining efficient appliances with appropriate thermal buffering or storage where relevant. Research should assess energy performance, thermal autonomy, temperature compliance, reliability and maintainability under high ambient temperatures, outages, weak-grid conditions and constrained servicing environments, while prioritising efficient and low-GWP cooling solutions. *(Track: Validation)*

- **Develop and validate monitoring, diagnostics and maintenance approaches for distributed cooking and cooling appliances**, including appliance-level monitoring, temperature logging, remote fault detection and preventive-maintenance tools where appropriate. Research should determine whether these approaches reduce downtime and temperature excursions, improve maintenance responsiveness and asset lifetime, and remain usable under limited connectivity and local technical-capacity conditions. *(Track: Validation)*

- **Scale up standardised and lifecycle-aware cooking and cooling configurations across multiple contexts**, combining minimum performance and safety requirements, quality-assurance protocols, compatibility with different energy-supply systems, repairability and environmentally sound refrigerant and end-of-life choices. Multi-site demonstrations should assess whether validated

configurations can be replicated while maintaining service quality, technical performance, safety and environmental sustainability. *(Track: Scale-up)*

6.6.6 Beyond-technology framing: needs, strategies, business models, risks

The R&I options identified above can translate into sustained clean cooking and cooling services only if they are matched by viable delivery and ownership arrangements, affordable and predictable energy or fuel costs, behaviourally appropriate service models, and the institutional and local capacities required for operation and maintenance over time. In line with the CESP4–5 perspective, this section therefore does not introduce additional technology priorities, but focuses on the conditions shaping uptake, affordability, sustained use, service reliability, replication and long-term sustainability.

This distinction is particularly important for MAR6. Technically effective cooking or cooling appliances do not automatically deliver health, nutrition, gender or resilience benefits. Clean cooking transitions may be undermined by fuel stacking, recurrent energy costs, cultural preferences or unreliable supply, while refrigeration assets may remain unused or fail to protect food and medicines if maintenance, temperature monitoring or institutional accountability are weak. Priority domestic energy uses should therefore be understood as socio-technical services in which appliance performance, user practices, affordability, supply chains, service provision and institutional arrangements jointly determine whether benefits are sustained.

Needs and uptake conditions

Clean cooking and domestic and community cooling services are essential to health, nutrition, time use and household resilience, particularly in settings where modern energy services remain unaffordable, unreliable or inaccessible. Needs vary substantially across households and service settings and should therefore be assessed through disaggregated user and service profiles rather than assuming a homogeneous category of "household demand".

Priority users and stakeholders include:

- **Low-income households relying on traditional biomass, charcoal, kerosene or multiple cooking fuels**, for which recurrent energy expenditure, fuel availability, cooking practices and appliance costs strongly influence whether cleaner solutions are adopted and sustained.
- **Women and girls**, who frequently bear disproportionate burdens associated with fuel collection, cooking, household air pollution and unpaid care work, while not necessarily controlling decisions over appliance purchase, fuel expenditure or household assets.
- **Households requiring reliable food preservation**, particularly in hot climates or unreliable-electricity contexts where lack of cooling can increase food spoilage, constrain dietary diversity and reduce household resilience to shocks.
- **Health facilities and community service points requiring temperature-controlled storage**, where refrigeration reliability, maintenance response and clear responsibility for equipment operation directly affect the continuity and quality of essential services.
- **Vulnerable or underserved households**, including renters, displaced populations, elderly-led households and users with irregular or very low incomes,

who may be systematically excluded by infrastructure requirements, upfront costs or conventional credit and ownership arrangements.

Across these groups, the central challenge is not merely access to an appliance, but whether the service fits everyday practices and can be used consistently over time. For cooking, this requires attention to meal types, taste, cooking speed, household size, fuel availability and stacking practices as well as price. For cooling, it requires sufficient and reliable energy supply, appropriate appliance capacity, temperature performance, maintenance and clear responsibility for use. Uptake should therefore be understood as **sustained service use**, not simply appliance acquisition or initial adoption.

Business models, affordability and ownership

For MAR6, business-model design determines who acquires or controls the appliance, how recurring energy, fuel and maintenance costs are paid, who is responsible for service continuity, and how financial risk is distributed between households, service providers and public institutions. No single model is appropriate across the diversity of cooking and cooling applications covered by the roadmap.

Relevant **ownership arrangements** include direct household ownership for lower-cost appliances; lease-to-own or provider-retained ownership for more capital-intensive equipment; community or cooperative ownership of shared cooling assets; and public, facility or service-company ownership for refrigeration supporting health and other community services. In public and semi-public settings, ownership should be accompanied by explicit responsibility for operation, maintenance, temperature monitoring, replacement and budgeting, since nominal asset ownership does not necessarily ensure accountability for service continuity.

These arrangements can be combined with different **payment and service models**. PAYGo, pay-as-you-cook and lease-to-own approaches can reduce upfront barriers by distributing costs over time. Appliance-as-a-service or cooling-as-a-service models can shift ownership and maintenance responsibility towards specialised providers, while shared community services can reduce the cost of access where individual ownership is not viable. For cooking, service models also need to account for the continued cost and availability of fuels or electricity, since affordable appliance acquisition alone does not guarantee sustained transition away from traditional fuels.

A separate issue concerns the **capital and risk-sharing mechanisms** required to reach lower-income and vulnerable users. Relevant approaches include targeted subsidies or vouchers, results-based financing, concessional or blended finance, carbon and climate-finance mechanisms where appropriate, and links with social-protection or health programmes. Their performance should be assessed not only in terms of numbers of appliances distributed, but also sustained use, service affordability, quality compliance and the distribution of benefits across different household groups.

Affordability should therefore be considered through **total service cost**, including appliance acquisition or repayment, fuel or electricity expenditure, maintenance and replacement costs. Financing arrangements should be compatible with irregular household incomes and should avoid creating debt burdens that lead to discontinuation, repossession or a return to polluting fuels.

Institutional conditions and complementary activities

The long-term performance of clean cooking and cooling services depends on an enabling environment extending beyond both the appliance and its financing arrangement. In line with the CESP5 perspective, complementary activities should be considered part of the intervention logic where they are necessary for sustained use and service continuity.

Relevant enabling conditions include:

- **User engagement and behaviour support**, including co-design, awareness activities, practical demonstrations and user education that account for cooking practices, food preferences, perceived safety, convenience and fuel-stacking behaviour. Behavioural support should inform rather than prescribe household choices and should be sensitive to intra-household decision-making.

- **Local technical capacity and after-sales services**, including trained stove technicians, electricians, refrigeration technicians and local service agents; access to spare parts and consumables; maintenance protocols; and viable arrangements for fault reporting and repair. Distributed appliances require service ecosystems capable of responding after the initial project or warranty period.

- **Fuel and energy supply-chain reliability**, including adequate availability and quality of LPG, ethanol, biomass-derived fuels or electricity where these are part of the cooking pathway, and reliable electricity supply for cooling. Transitions should not depend on fuels or services whose local supply cannot reasonably be sustained.

- **Standards, quality assurance and service monitoring**, covering appliance efficiency, emissions and safety for cooking; energy performance, refrigerant choice and temperature compliance for cooling; and appropriate testing, certification and monitoring procedures. Quality assurance is particularly important where low-quality appliances can undermine health benefits, user trust or cold-chain integrity.

- **Institutional accountability for shared and public-service assets**, particularly refrigeration in health posts, schools and community facilities. Responsibilities for operation, maintenance budgets, temperature monitoring, replacement and escalation of failures should be clearly assigned rather than assumed to follow automatically from asset ownership.

- **Cross-sector coordination**, reflecting that clean cooking and cooling sit at the intersection of energy, health, nutrition, agriculture, gender, environment and social protection. Coordination between relevant ministries, local authorities, health systems, energy providers and development actors can help integrate cooking and cooling into wider service-delivery and planning frameworks rather than treating them as isolated appliance programmes.

- **Knowledge and data systems**, including comparable evidence on sustained use, fuel stacking, affordability, appliance failures, temperature compliance, household satisfaction and differentiated outcomes across user groups. Shared monitoring approaches can support learning across projects and improve the evidence base for future R&I and deployment decisions.

Complementary activities should therefore connect appliance innovation with the wider service ecosystem required for sustained use. Behavioural engagement, maintenance capacity, supply chains, standards, institutional accountability and cross-sector coordination are not substitutes for technically sound appliances, but they determine whether those appliances continue to deliver useful and safe energy services after initial deployment.

Risks and safeguards

The beyond-technology perspective also requires MAR6 interventions to identify potential exclusion, unintended effects and service failures and to embed appropriate safeguards from the outset.

- **Social exclusion and unequal control over benefits.** Appliance access, ownership and household spending decisions may reproduce existing gender and socio-economic inequalities, while credit-based models may systematically exclude poorer households, renters or users without formal financial histories. Safeguards include disaggregated needs assessment, inclusive eligibility and payment arrangements, participatory engagement, and monitoring of who uses, controls and benefits from the service rather than participation alone.

- **Affordability, indebtedness and transition-reversal risks.** High appliance payments, volatile fuel or electricity prices, or poorly aligned repayment structures may generate debt stress or lead households to discontinue use and return to traditional fuels. Safeguards include transparent total-cost information, flexible payment arrangements, targeted support where justified, consumer protection and monitoring of fuel stacking, default, repossession and discontinuation.

- **Health, safety and service-integrity risks.** Poor combustion, unsafe fuels, electrical faults, burns or fires can undermine the health rationale for clean cooking, while unreliable refrigeration or inadequate temperature control can lead to food or medicine spoilage. Safeguards include appropriate performance and safety standards, installation and O&M protocols, user training, temperature monitoring and clear procedures for responding to service failures.

- **Environmental and lifecycle risks.** Cooking transitions may create environmental burdens through unsustainable biomass sourcing or poorly managed fuel supply chains, while cooling systems may generate climate impacts through inefficient energy use, refrigerant leakage and unmanaged appliance, battery and electronic waste. Safeguards include efficient appliances, sustainable fuel sourcing, low-GWP refrigerants, repairability, appropriate refrigerant recovery and lifecycle and end-of-life arrangements coordinated with MAR2.

- **Institutional fragility and service discontinuity.** Appliances and shared infrastructure may become stranded when maintenance responsibilities are unclear, public facilities lack recurrent O&M budgets, service providers withdraw, or fuel and spare-parts supply chains fail. Safeguards include explicit allocation of responsibilities, locally accessible servicing capacity, recurrent-cost planning, contingency arrangements and monitoring systems able to identify and respond to deterioration in service quality.

By embedding needs and sustained-use conditions, viable business and ownership arrangements, complementary activities and explicit safeguards, MAR6 is framed as a roadmap for **reliable, affordable and sustained priority domestic energy services.** The technical R&I directions identified under CESP3 are thereby connected to the behavioural, financial, institutional and service conditions required for uptake and long-term viability under CESP4–5.

6.6.7 Theory of Change

The Theory of Change for MAR6 follows the original Outputs–Outcomes–Impacts logic of the MARs while updating it through the comprehensive planning perspective adopted in this deliverable. For priority domestic energy uses, the core causal pathway is that **context-appropriate clean cooking and cooling solutions, supported by validated design and monitoring approaches and robust evidence on their real-world performance, can enable sustained and safe energy services when they are taken up through affordable service arrangements, reliable energy or fuel supply, appropriate user practices, and functioning local maintenance and institutional capacities**. These outcomes can in turn contribute to improved human capabilities and

essential services, more inclusive living standards and economic opportunity, and environmental sustainability and resilience.

The pathway is contributory rather than automatic. The distribution or successful technical operation of a stove, cooker or refrigerator does not by itself demonstrate improvements in health, nutrition, gender equity or resilience. Such effects depend on sustained use, fuel stacking, household practices and decision-making, affordability, service reliability, maintenance and wider socio-economic and institutional conditions. Directly measurable changes such as reduced pollutant exposure, cooking time, temperature excursions or food spoilage may be treated as outcomes where supported by appropriate evidence; broader health, welfare and resilience effects should be interpreted primarily as **development contributions rather than directly attributable impacts**, unless the evaluation design supports stronger causal claims.

Outputs — validated R&I solutions and evidence

- ***Context-appropriate clean cooking and cooling solutions are developed and validated*** *under relevant rural, peri-urban and underserved conditions. These may include different cooking fuels and appliances, electric cooking configurations, efficient domestic and community refrigeration, thermal-storage or buffering options, and their integration with stand-alone systems, mini-grids or weak grids where relevant.*

- ***Replicable design, integration and monitoring approaches are developed and validated****, including methods for appliance selection and sizing, cooking- and cooling-load assessment, integration with energy supply and storage, emissions and safety testing, temperature monitoring, remote diagnostics, maintenance planning and quality assurance.*

- ***Comparable technical, operational and socio-economic evidence is generated*** *across demonstrators and user contexts, covering sustained use and fuel stacking, appliance and energy performance, emissions or exposure where measurable, cooling reliability and temperature compliance, total service cost, maintenance and downtime, user satisfaction, time use and distribution of access and benefits across relevant user groups.*

Outcomes — uptake, viability and enabling capacity

- ***Sustained uptake and use of clean cooking and cooling services****, with appliances remaining operational and routinely used beyond initial adoption or demonstration periods. For cooking, this includes evidence on the share of cooking needs met by cleaner solutions and the persistence or reduction of fuel stacking; for cooling, it includes continued use and availability of adequate refrigeration services.*

- ***Improved quality and performance of priority domestic energy services****, including reduced pollutant exposure and unsafe cooking practices, shorter or less burdensome cooking and fuel-collection activities, improved temperature compliance and refrigeration reliability, and reduced food, medicine or vaccine spoilage where directly measurable.*

- ***More viable and affordable cooking and cooling service arrangements****, supported by ownership, payment, financing and service models that reflect household purchasing capacity and recurrent fuel or electricity costs while providing for maintenance and replacement without creating unsustainable financial stress.*

- ***Strengthened local service and institutional capacity*** *to sustain domestic energy services, including functioning after-sales and repair networks, trained cooking and refrigeration technicians, reliable fuel and spare-parts supply chains, quality assurance, and clear operational and maintenance responsibilities for shared or public-service cooling assets.*

- ***Replication and uptake beyond the initial R&I setting****, through adoption or adaptation of validated cooking and cooling solutions, methods or service approaches by additional households, communities, service providers, public programmes or institutions, while maintaining appropriate performance, affordability, safety and service quality.*

Impacts — development contributions

At impact level, MAR6 is expected to contribute to, rather than independently determine, wider development effects, through sustained access to safe, affordable and reliable priority domestic energy services. These contribution pathways are organised according to the common impact dimensions adopted across the updated MARs.

- **Human capabilities and essential services.** Sustained clean cooking and cooling services can contribute to improved health through reduced exposure to household air pollution and safer cooking conditions; improved food availability, nutrition and food safety through reliable refrigeration; greater continuity of temperature-sensitive health services; and reduced time and physical burdens associated with fuel collection, cooking and household care.

- **Living standards and inclusive economic opportunity.** Affordable and reliable domestic energy services can contribute to reduced household energy and time burdens, improved quality of life and greater resilience of household consumption and care activities. Time savings and safer domestic energy services may expand opportunities for education, rest and income-generating activities, particularly for women and girls. Local distribution, maintenance and service provision can also support employment and enterprise opportunities. These benefits should be assessed with attention to their distribution across gender, age, income, tenure status and other relevant dimensions of vulnerability and exclusion.

- **Environmental sustainability and resilience.** Cleaner and more efficient cooking can contribute to reduced pressure on unsustainably harvested biomass, lower emissions of greenhouse gases and short-lived climate pollutants, and reduced local environmental degradation. Efficient cooling, low-GWP refrigerants and reduced food losses can lower the environmental burden associated with refrigeration and spoilage. These benefits should be assessed alongside lifecycle impacts from appliances, batteries, refrigerants and other components, while considering the ability of cooking and cooling services to remain functional during outages, fuel-price shocks, extreme heat and other disruptions.

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of sustained use, service uptake or replication does not by itself demonstrate that an R&I intervention caused changes in health, time burdens or household resilience. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.6.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under

MAR6 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of technology and service maturity, intervention scale and type, geographical and institutional context, user characteristics and available resources.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators capture validated cooking and cooling solutions, methods and the evidence generated through R&I. Outcome indicators assess whether these outputs translate into sustained use, improved service performance, affordable and viable delivery arrangements, functioning enabling capacities and uptake beyond the original demonstrator. Impact-contribution indicators use the common trans-MAR human-development dimensions and assess the wider development changes to which sustained clean cooking and cooling services may plausibly contribute.

Output indicators – R&I outputs and technical validation

Table 17 – MAR6 Output Indicators

Indicator	Definition and Evidence Expected	Verification method
Validated clean cooking and cooling solutions	Number and type of context-appropriate cooking and cooling solutions developed and tested under relevant operating and user conditions; degree to which predefined performance, efficiency, emissions, safety, temperature-control, reliability and service requirements are met. Validation should reflect real cooking practices, climatic conditions and electricity or fuel-supply constraints where relevant.	Design and technical documentation; commissioning reports; laboratory and field-test protocols; emissions and safety tests; energy-use measurements; temperature and thermal-performance records; field-validation reports; relevant standards or certification evidence.
Validated design, integration and monitoring approaches	Methods, tools or protocols for appliance selection and sizing, cooking- and cooling-load assessment, integration with stand-alone systems, mini-grids or weak grids, demand-side management, emissions or exposure monitoring, temperature monitoring, diagnostics, maintenance planning and quality assurance that are documented, reproducible and tested against field or benchmark evidence.	Methodology and tool documentation; repositories where applicable; benchmark testing; validation datasets; simulation-to-field comparisons; monitoring-system records; expert, technician or user testing.
Technical, operational and socio-economic evidence generated	Comparable evidence across demonstrators and user contexts on sustained appliance use and fuel stacking, energy and fuel consumption, appliance efficiency and reliability, emissions or exposure where measurable, cooling uptime and temperature compliance, maintenance and downtime, total service cost, user satisfaction, time use and distribution of access and benefits across relevant user groups.	Smart-meter or appliance-monitoring data; fuel-use records; stove-use monitors where appropriate; PM2.5/CO measurements; temperature loggers; maintenance and fault records; cost and payment records; baseline and follow-up surveys; time-use data; qualitative interviews; gender-, income- and vulnerability-disaggregated evidence where relevant.

Outcome indicators – uptake, viability and enabling conditions

Table 18 – MAR6 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Sustained uptake and use of clean cooking and cooling services	Continued and routine use beyond initial acquisition, installation or demonstration. For cooking, evidence should capture the proportion of cooking needs met by cleaner solutions and the persistence or reduction of fuel stacking. For cooling, evidence should capture continued availability and use of the refrigeration service rather than appliance ownership alone.	Stove-use monitoring where feasible; fuel or electricity consumption records; PAYGo and service-provider data; appliance runtime data; follow-up household surveys; user diaries; field observation; retention and discontinuation records.
Quality and performance of priority domestic energy services	Measurable improvement in the service delivered, including reduced pollutant exposure or unsafe cooking practices, reduced cooking or fuel-collection burdens, adequate cooking-service performance, improved cooling uptime and temperature compliance, and reduced food, medicine or vaccine spoilage where relevant. Measures should be selected according to the service rather than treated as universal indicators for all interventions.	Baseline and follow-up PM2.5 or CO measurements where feasible; cooking-time and time-use surveys; safety records; temperature logger data; cold-chain compliance records; food or medicine spoilage records; service-outage and maintenance logs; user satisfaction surveys.
Affordability and operational and financial viability	Evidence that households or service users can access and continue using cooking or cooling services under the applicable ownership, payment or financing arrangement, while recurrent electricity, fuel, maintenance and replacement costs remain manageable. Service-provider viability should also be assessed where relevant, together with payment stress, discontinuation or reversion to polluting alternatives.	Total-cost-of-cooking or cooling calculations; appliance and fuel and electricity expenditure; tariffs and service fees; PAYGo or loan-repayment data; operator and provider financial records; affordability surveys; records of default, repossession, discontinuation or fuel switching.
Local service and institutional capacity	Ability of local actors and institutions to sustain the service through functioning after-sales support, maintenance and repair, trained technicians, spare-parts and fuel supply, quality assurance and clear responsibility for shared or public-service cooling assets. Capacity should be demonstrated through functioning arrangements rather than training numbers alone.	Technician competency assessments; repair and maintenance records; service-response times; spare-parts and supply-chain records; training records combined with evidence of subsequent practice; service contracts; O&M budgets; institutional responsibility matrices; stakeholder interviews.
Replication and uptake beyond the initial R&I setting	Evidence that validated cooking or cooling solutions, methods or service approaches are adopted or adapted beyond the original demonstrator by additional households, communities, service providers, health facilities, public programmes or other institutions while maintaining appropriate service quality, affordability and safety.	Additional installations or active service users; procurement and service contracts; third-party adoption records; institutional or programme documentation; funded follow-up activities; evidence of implementation at additional sites; use of validated methods or specifications by other actors.

In MAR6, **appliance acquisition should not be treated as equivalent to sustained service uptake**. This distinction is particularly important for clean cooking, where stacking of multiple fuels and technologies may persist after adoption, and for refrigeration, where

ownership does not demonstrate adequate uptime or temperature compliance. Where possible, self-reported use should therefore be triangulated with operational, energy-use or service-performance evidence.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR6 contributes to them through the specific pathway of sustained access to safe, affordable and reliable clean cooking and cooling services.

Table 19 – MAR6 Impact Indicators

Common Impact Dimension	MAR6 contribution	Verification method
Human capabilities and essential services	Sustained clean cooking and cooling services can contribute to reduced exposure to household air pollution and unsafe cooking conditions; improved food availability, nutrition and food safety; continuity of temperature-sensitive health services; and reduced time and physical burdens associated with fuel collection, cooking and household care.	Household health and exposure indicators where appropriate; PM2.5/CO evidence; time-use surveys; food-availability, nutrition or food-safety indicators; cold-chain and health-service continuity records; baseline and follow-up household evidence; qualitative evidence on changes in capabilities and wellbeing.
Living standards and inclusive economic opportunity	Affordable and reliable cooking and cooling services can contribute to reduced household energy and time burdens, improved quality of life and greater resilience of household consumption and care activities. Time savings may expand opportunities for education, rest or income-generating activities, while appliance distribution, maintenance and service provision may support local employment and enterprise activity. Distribution of benefits should be assessed across gender, age, income, tenure status and other relevant vulnerability dimensions.	Household expenditure and time-use surveys; education or livelihood indicators where relevant; employment, enterprise and training records; household and user surveys; gender and vulnerability disaggregation; qualitative evidence on appliance ownership, household decision-making and control over economic or time-use benefits.
Environmental sustainability and resilience	Cleaner and more efficient cooking can contribute to lower consumption of unsustainably harvested biomass, reduced greenhouse-gas and short-lived climate-pollutant emissions and reduced local environmental pressure. Efficient cooling, appropriate refrigerants and reduced food losses can lower environmental burdens, while robust service arrangements can improve continuity during outages, fuel-price shocks, extreme heat and other disruptions. These contributions should be assessed alongside appliance, battery, refrigerant and end-of-life impacts.	Fuel displacement and consumption data; renewable-energy share where relevant; emissions or lifecycle estimates; biomass-sourcing evidence; refrigerant type and leakage and service records; food-loss data; repair and EoL records; shock and service-continuity records; evidence of fallback practices and recovery after disruptions.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR6 should be interpreted according to its strength, maturity and position in the causal chain. Where feasible, quantitative monitoring should be triangulated with documentary, operational and stakeholder evidence. Self-reported adoption or satisfaction alone should not be treated as sufficient evidence of sustained clean cooking or cooling performance where direct-use or service-performance data can reasonably be collected.

Single households, facilities, communities or demonstrators should normally be reported as **illustrative cases rather than generalised to the MAR portfolio**. Stronger claims concerning sustained adoption, health improvement, gender effects, replication or wider resilience require evidence from multiple cases, sites or independent sources. In particular, reductions in measured pollutant exposure, cooking time or food spoilage in a specific demonstrator should not automatically be extrapolated into population-level health, livelihood or nutrition impacts.

Evidence of policy relevance should be distinguished from demonstrated policy influence. Similarly, an identified scale-up opportunity or replication plan should be distinguished from a **funded continuation**, and funded continuation from **implemented and sustained replication**. This distinction allows promising pathways to be recognised without overstating the maturity or reach of the available evidence.

6.6.9 Interoperability and synergies with other MARs

MAR6 focuses on **priority domestic uses** (clean cooking and household and community cold chain). It is therefore cross-cutting by nature, because domestic demand shapes system sizing, finance and social impacts across the portfolio. Key interfaces are:

- **MAR1 – Mapping joint R&I actions -** MAR1 provides the overarching evidence base to prioritise where clean cooking and domestic cooling deliver the highest development returns (health, gender, nutrition, resilience). In return, MAR6 contributes "use-case archetypes" (e.g., peri-urban e-cooking, rural clean fuels, household cooling poverty, vaccine cold-chain nodes) that inform joint programming priorities and investment focus.

- **MAR2 – End-of-life, second-life and environmental impacts -** MAR6 is a major generator of end-of-life streams: cookstoves, cylinders and regulators, batteries, power electronics, and especially **refrigeration components and refrigerants**. MAR2 provides the circularity, take-back, safe handling and recycling logic needed to prevent e-waste growth and refrigerant leakage (Kigali alignment). MAR6 should specify domestic appliance requirements that anticipate MAR2 solutions (repairability, modularity, collection incentives).

- **MAR3 – Smart stand-alone systems -** Domestic appliances are core loads for stand-alone systems (SHS, nanogrids), and cooking and cooling often determine whether systems remain low-power "lighting-only" or become transformational. MAR3 provides the design and control strategies (sizing, storage, load management, monitoring) that make e-cooking and efficient refrigeration technically feasible off-grid. MAR6 specifies the appliance-side requirements (duty cycles, peak loads, safety) and user behaviour patterns needed to design systems correctly.

- **MAR4 – Smart grids for off-grid applications -** Where mini-grids and weak grids are present, domestic cooking and cooling loads strongly affect **peak demand**, tariff design, and reliability. MAR4's grid-side intelligence (DSM, protection, planning tools) is needed to integrate e-cooking and community cooling without destabilising systems. MAR6 contributes demand profiles and flexibility

opportunities (e.g., EPC scheduling, thermal storage and PCM buffering) to improve grid economics and service quality.

- **MAR5 – Processes and appliances for productive uses -** MAR5 and MAR6 have a deliberate "interface" around **cold chains and appliance markets**. MAR5 treats cold chains and refrigeration as productive and income-related infrastructure (value chains, enterprises); MAR6 treats them as domestic and essential service infrastructure (nutrition, health, household resilience). The two MARs should align on: appliance efficiency and quality assurance, refrigerant choices, service and financing models, and metrics—while clearly distinguishing commercial cold storage from household, community and health cold-chain needs.

- **MAR7 – Hydrogen pathways for sustainable energy and industrial systems -** The interface with MAR6 is **limited and primarily indirect**, mainly through upstream energy-system and affordability implications. Hydrogen is not a priority pathway for household cooking or cooling; it should therefore be considered within MAR6 only where it materially affects **energy-service costs, infrastructure choices or system planning**.

Overall, MAR6 functions as the portfolio's **human-development anchor**: it ensures that technology and system innovations (MAR3–4) and productive-use scaling (MAR5) remain connected to health, gender equity, nutrition and resilience outcomes—while MAR2 ensures the domestic appliance transition is environmentally sustainable.

6.7 MAR7 – Hydrogen pathways for sustainable energy and industrial systems

This MAR covers hydrogen-specific research and innovation pathways that may contribute to sustainable energy and industrial systems in African contexts. It includes renewable-hydrogen production and enabling technologies; productive and industrial uses; hydrogen derivatives, storage, carriers and infrastructure; system integration where hydrogen has a demonstrated comparative function; and natural or geological hydrogen as a distinct exploratory research pathway. The scope is deliberately broader than a narrow "green hydrogen" label, because sustainability is treated as an outcome to be demonstrated through lifecycle, resource, development and justice evidence rather than as an intrinsic property of the molecule.

The MAR does not assume that hydrogen should be used across all sectors. It prioritises applications in which direct electrification or other lower-loss alternatives are difficult, and requires comparative assessment before hydrogen is proposed for electricity storage, mobility or remote-energy systems. Other low-carbon hydrogen routes may be examined as transition or reference pathways where relevant to existing African industrial systems, but they should be distinguished from renewable hydrogen and assessed through transparent lifecycle greenhouse-gas, methane, capture-rate and lock-in criteria.

The addition of MAR7 is supported by three-way concurrence: a persistent policy and grey-literature signal; a dedicated Africa-hydrogen scientometric analysis; and concrete LEAP-RE practice through relevant Pillar 1 projects. Unlike MAR2–MAR6, MAR7 was **not part of the original scientometric pipeline** and was analysed only after the preceding evidence streams indicated that hydrogen warranted consideration as a distinct roadmap. Its dedicated scientometric analysis therefore applies the same general analytical logic but extends the recent-literature window through 2026. The associated grey-literature and programme evidence was likewise updated to the August 2026 evidence freeze, including authoritative 2026 material where it materially affected the assessment of maturity or scope.

6.7.1 Why now

- **Policy and deployment shift (since 2020)**: Hydrogen has become a structural African and AU–EU R&I priority rather than a short announcement cycle: South Africa and Namibia adopted formal strategies in 2021–2022, Kenya followed in 2023, Egypt, Morocco and Mauritania strengthened frameworks in 2024, and the AU Summit adopted the African Green Hydrogen Strategy and Action Plan in February 2025 — against an existing industrial base of roughly 3.1 Mt of hydrogen used in 2024, mostly for ammonia production, concentrated in Egypt, Algeria, Nigeria and South Africa. Sources: (African Union Commission, 2025; Arab Republic of Egypt, 2024; Department of Science and Innovation, 2021; International Energy Agency, 2026; International Renewable Energy Agency, 2025b; Ministere de l'Industrie et du Commerce / MICEPP, 2024; Ministry of Energy and Petroleum, 2022; Republic of Kenya et al., 2023; Republic of Namibia, 2022; United Nations Economic Commission for Africa, 2026)

- **Research and technology shift**: The scientific field has differentiated rapidly since 2020: the dedicated scientometric analysis found a large post-2021 publication increase and a shift from five broad historical themes to eight specialised topics, with renewable production splitting into solar-electrolysis and wind pathways, trade splitting into geopolitics and export, and ammonia and logistics, natural hydrogen emerging as an independent research family, and fuel-cell mobility newly differentiated.

- **LEAP-RE and practice signal**: LEAP-RE Pillar 1 projects already generate hydrogen-specific evidence — natural-hydrogen prospectivity and field exploration, roadmap development, capacity building, advanced storage systems, digital twins, and permeability and cryogenic storage-vessel research — showing that MAR7 builds on an existing base of AU–EU research practice rather than starting from zero.

- **Implication**: This evidence supports **adding** hydrogen as a new, distinct MAR, but with two caveats the roadmap must carry explicitly: low-emissions deployment remains far below policy ambition (around 6 kt of low-emissions production and only one project at final investment decision, against a 31-project, 1.2 Mt pipeline), and the roadmap must be framed around sustainable pathways broader than "green hydrogen" — compared explicitly against direct electrification — rather than as a deployment commitment.

6.7.2 State of the art in a nutshell

- **Demand hierarchy and industrial pathways** - Current African hydrogen use is dominated by incumbent industrial demand, especially ammonia, fertiliser, refining and chemicals; African fertiliser-use goals and an unusually high share of DRI-based ironmaking make this the clearest and strongest near- to medium-term R&I case, ahead of evidence-supported new uses in iron and steel, methanol and selected shipping or heavy-transport applications. R&I questions include process flexibility and retrofits, product quality, variable-renewable integration, sustainable carbon sourcing, industrial symbiosis and local beneficiation. Generic hydrogen use in buildings, household energy or all transport modes is not supported by the reviewed evidence. Sources: (European Commission & Namibia Green Hydrogen Programme, 2025; International Energy Agency, 2026; International Renewable Energy Agency et al., 2024; United Nations Economic Commission for Africa, 2026)

- **Renewable production and enabling technologies** - Water electrolysis is technologically established, but project performance and cost are strongly

conditioned by renewable-electricity cost and profile, electrolyser utilisation, balance-of-plant design, water quality, heat and dust exposure, degradation, maintenance, financing and grid connection. African R&I priorities therefore extend beyond electrolyser efficiency to dynamic operation, durability, water-treatment integration, locally maintainable balance-of-plant systems, materials, testing and potential local manufacture. Biological and other renewable routes remain relevant where feedstock, lifecycle and scale conditions are credible. Sources: (European Commission Joint Research Centre, 2023; International Renewable Energy Agency, 2020, 2025b; United Nations Industrial Development Organization et al., 2025; World Bank & Energy Sector Management Assistance Program, 2024a)

- **Storage, carriers and infrastructure** - Hydrogen may have value for long-duration or seasonal storage, resilient remote systems and specialised mobility, but conversion losses and low utilisation can make it less competitive than batteries, transmission, grid reinforcement, pumped storage or direct electrification -- a conditional R&I niche requiring system-boundary comparisons, storage-material and vessel testing, and validated control strategies. Carriers such as ammonia, methanol and liquid hydrogen extend reach but add conversion losses and infrastructure dependencies; the state of the art is moving from generic export potential toward location-specific supply-chain optimisation, port and pipeline planning, lifecycle accounting and shared-infrastructure models, with Europe an important but uncertain future market. Sources: (European Commission & European Hydrogen Backbone initiative, 2020; Hydrogen Europe, 2024; International Energy Agency, 2026; International Renewable Energy Agency & Ammonia Energy Association, 2022; International Renewable Energy Agency & World Trade Organization, 2024; LEAP-RE D3T4H2S project consortium, 2023)

- **Natural or geological hydrogen** - Natural hydrogen has emerged as a legitimate research field, supported by African field evidence and LEAP-RE Pillar 1. Its maturity is nevertheless low. Surface or soil-gas anomalies and seeps are not reserves: the chain from source, migration, reservoir and seal to recoverable accumulation, sustainable flow rate and commercial energy service remains unresolved. The pathway therefore belongs in MAR7 as exploratory resource science, with clear maturity gates before demonstration or production claims. Sources: (International Energy Agency, 2026; LEAP-RE HyAfrica project consortium, 2022)

- P**olicy, standards, certification and market architecture** - Project eligibility and revenues increasingly depend on operational definitions, including renewable-electricity additionality and temporal and geographical matching, lifecycle greenhouse-gas thresholds, guarantees of origin, safety codes, permitting and derivative accounting. These rules interact with power-purchase agreements, dispatch, infrastructure location and bankability. R&I is needed where measurement, interoperability, African application, lifecycle accounting or system design remain unresolved; routine compliance should not be relabelled as research. Sources: (Commission Delegated Regulation (EU) 2023/1184 Establishing a Methodology for Renewable Fuels of Non-Biological Origin, 2023; Commission Delegated Regulation (EU) 2023/1185 Establishing a Minimum Threshold for Greenhouse Gas Emissions Savings of Recycled Carbon Fuels, 2023; Commission Delegated Regulation (EU) 2025/2359 on the Methodology for Low-Carbon Fuels, 2025; International Organization for Standardization, 2020, 2025; International Renewable Energy Agency & World Trade Organization, 2024; United Nations Industrial Development Organization et al., 2025)

- **Geographical differentiation** - North Africa has the most mature hydrogen-industrial cluster, with existing demand, ports and proximity to European markets. Southern Africa combines an established hydrogen R&D ecosystem, DRI, mining and chemical capabilities and emerging demonstrations. West Africa spans

incumbent Nigerian demand, Mauritanian infrastructure and regulatory development, and exploratory natural-hydrogen work in Togo. Kenya provides the clearest East African strategy linking dedicated renewables to fertiliser and methanol import substitution. These are different R&I archetypes and should not be collapsed into one continental project pipeline. Sources: (African Union Commission, 2025; Arab Republic of Egypt, 2024; Department of Science and Innovation, 2021; European Commission & Namibia Green Hydrogen Programme, 2025; International Energy Agency, 2026; International Renewable Energy Agency, 2025b; LEAP-RE HyAfrica project consortium, 2022; Ministere de l'Industrie et du Commerce / MICEPP, 2024; Ministry of Energy and Petroleum, 2022; Republic of Kenya et al., 2023; Republic of Namibia, 2022; United Nations Industrial Development Organization & Global Environment Facility, 2024; World Bank, 2025)

6.7.3 Signals from literature

Top emerging topics (2020–2026 lens)

Post-2020 hydrogen-related publications show a clear differentiation of the research landscape, with conventional feedstock-based routes (coal gasification, syngas) receding as a standalone topic and the centre of gravity shifting toward renewable, resource-specific pathways. Rather than treating hydrogen as a single production technology, recent research increasingly distinguishes between production pathways, system functions, industrial uses, infrastructure, policy and resource exploration.

- **Renewable hydrogen production becomes technology- and resource-specific** — solar PV-powered electrolysis, PEM systems, water requirements and conversion efficiency form a major recent research stream alongside a smaller but still visible biohydrogen component, while onshore and offshore wind-to-hydrogen emerges as its own resource-assessment, site-selection and techno-economic literature. The signal is increasingly about how hydrogen is produced under specific resource and operating conditions rather than generic production potential.

- **Trade, carriers and value chains become distinct research fields** — one stream addresses Africa–Europe export strategy, country risk, import economics and the political economy of hydrogen trade, while a parallel stream separates ammonia and hydrogen-carrier selection, pipelines, shipping, supply chains and comparative transport costs from production itself. Together they reflect growing attention to who produces hydrogen, where value is captured, how it moves, and how credible future demand actually is.

- **Natural and geological hydrogen emerges as an independent, early-stage research front** — geological systems, rocks, seeps, prospectivity, exploration methods and resource characterisation form a distinct post-2020 topic. Its emergence indicates growing scientific interest, but not equivalent evidence of recoverable reserves or commercial maturity.

- **Policy research moves from ambition toward implementation readiness** — national strategies, legal frameworks, institutional capacity, public acceptance and implementation conditions become increasingly prominent, suggesting hydrogen policy is being studied less as target-setting and more as whether projects can actually move toward implementation.

- **Downstream applications diversify beyond production** — fuel-cell vehicles, refuelling behaviour and infrastructure form a recognisable application stream, alongside continued research on hybrid renewable systems, storage configurations, grid interaction and dispatch where hydrogen is assessed as one flexibility option

among several. Their growing prominence in the literature should not be read as evidence that either pathway is already preferred in African contexts.

"Hot papers": what they suggest for next R&I moves

The weighted-citation hot papers reinforce the recent topic signals while pointing toward a more conditional and evidence-based hydrogen R&I agenda.

- **Move natural hydrogen from geological indication to resource appraisal** — evidence from Bourakebougou in Mali shows the scientific relevance of dynamic natural-hydrogen systems, but also highlights unresolved questions around reservoir connectivity, recharge, residence time, in-situ generation and sustainable production rates. Future R&I should therefore prioritise exploration methods, resource classification, monitoring and production evidence before wider deployment claims are made.

- **Validate renewable hydrogen production and storage against real African operating conditions and competing alternatives** — experimental PV-powered PEM electrolysis work in the Algerian Sahara demonstrates technical feasibility under high solar-resource conditions but points to the need for longer-duration, larger-scale validation covering heat, dust, water sourcing and quality, degradation, control and maintenance; parallel optimisation studies of PV, wind and fuel-cell systems in Egypt illustrate potential storage roles but expose a gap between modelled optimal configurations and operational evidence. R&I should compare hydrogen explicitly with batteries, grid reinforcement, demand flexibility and other storage options under lifecycle and reliability criteria.

- **Assess trade pathways through finance, infrastructure and local development rather than LCOH alone** — comparative research involving Egypt and Morocco shows that carrier and export choices depend on cost of capital, infrastructure, reliability, domestic demand and end-use configuration. Future work should also examine local value chains, employment and the opportunity cost of export-oriented versus domestic productive-use pathways.

- **Treat policy and institutional capacity as part of the innovation pathway** — Southern African research highlights the importance of hydrogen-specific strategies, regulation, standards, R&D capacity, market creation and institutional coordination. This suggests that technical demonstrations should be accompanied by research on the enabling conditions required for uptake, while recognising that policy frameworks evolve and evidence must be periodically updated.

- **Hot Papers**: (Hampp et al., 2023; Imasiku et al., 2021; Khelfaoui et al., 2021; Maiga et al., 2023; Sultan et al., 2021)

Overall, the scientometric evidence points away from a generic "hydrogen economy" framing and toward multiple context-dependent hydrogen pathways. The strongest recent research signals concern renewable production under specific resource conditions, industrial derivatives and carriers, system integration, policy and market readiness, and an exploratory natural-hydrogen branch. These signals support further R&I, but also reinforce the need to compare hydrogen with alternative technical pathways and to distinguish scientific emergence from deployment maturity.

6.7.4 Insights from LEAP-RE projects

The original interview exercise did not generate a hydrogen-specific recommendation, because hydrogen was not a dedicated MAR in that analysis. The practice evidence used

here therefore comes from later LEAP-RE project documentation and the 2025-2026 Monitoring, Evaluation and Learning interviews. This section relies on the D1.18 evidence.

- **HyAfrica - natural-hydrogen resource assessment and roadmaps** - HyAfrica links Portugal, Germany, Morocco, Mozambique, South Africa and Togo. The project generated significant geological datasets, field evidence, exploration workflows, roadmaps and capacity-development activities, and its networks are continuing into Horizon Europe and bilateral instruments. Its importance is methodological: it demonstrates how natural-hydrogen R&I can combine geoscience, socioeconomic assessment, business-model thinking and local capacity. Its evidence does not establish recoverable reserves, commercial flow rates or deployment readiness.

- **HyAfrica - implementation lessons** - Access to government geological data was described as "really, really tough", requiring repeated in-person engagement and costs above the initial budget. Remote sites, field logistics, national data standards and short project timelines constrained the work. Future projects should secure data-sharing agreements, permissions and field-access arrangements before technical work begins; budget local students and institutions for sustained field activity; and define evidence gates from occurrence to prospect, tested accumulation, resource and reserve.

- **D3T4H2S - digital twins and advanced liquid-hydrogen storage** - D3T4H2S combined finite-element analysis, AI modelling and permeability quantification across linked work packages, with attention to materials and cryogenic storage-vessel behaviour. Four Q1 papers were produced; four LEAP-SE applications and a Horizon Europe Twinning proposal were prepared. This establishes a credible AU–EU R&I trajectory in storage materials, sensing, modelling and predictive maintenance, but the evidence should not be interpreted as industrial deployment readiness without verified prototype performance and scale-up data.

- **D3T4H2S - funding architecture affected the technical sequence** - The cascade structure meant that delays to an early work package stalled subsequent tasks. European partners received funding on time while African partners did not, creating a structural imbalance that compounded across the project. The coordinator concluded that the administrative delays could not be absorbed in a two-year research cycle. Hydrogen projects with coupled laboratory, field and prototype work therefore require funding-readiness checks, realistic duration, budget equity and protected African-led research tasks.

- **Cross-portfolio lessons are directly relevant to MAR7** - The MEL evidence recommends a needs-assessment phase before technical work; early MOUs for critical external data; explicit allowance for customs and equipment delays; open-source architecture and data documentation where possible; sustainability and exploitation planning from Year 1; and follow-up preparation 12-18 months before project close. Policy relevance should be separated from demonstrated policy influence, and a proposal or follow-up plan from a funded and implemented continuation.

- **Practice evidence remains concentrated** - HyAfrica and D3T4H2S provide valuable but complementary cases. They do not yet constitute a balanced demonstration portfolio across renewable production, ammonia and fertiliser, steel, trade infrastructure, power-system integration and community impacts. Future calls should therefore fill evidence gaps rather than infer continent-wide readiness from two projects.

6.7.5 Suggested R&I options

The following options identify research directions emerging from convergence across the scientific literature, grey literature and LEAP-RE practice. They are not a prescriptive deployment agenda. Each option should be selected only where a defined African need, credible demand, comparative advantage over alternatives and sufficient enabling conditions are demonstrated.

- **Develop integrated hydrogen-pathway assessment tools** that combine demand, renewable-resource profiles, grid conditions, water and land availability, infrastructure, cost of capital, lifecycle emissions and social and environmental impacts in spatially explicit decision models, built on harmonised African data and scenario baselines. Research should require counterfactual comparison against direct electrification, batteries, thermal or pumped storage and other alternatives under common service boundaries, and develop lifecycle and sustainability methods that quantify performance directly rather than relying on colour labels as a proxy. *(Track: Validation)*

- **Validate electrolysis and balance-of-plant performance under African climatic and power-system conditions**, including heat, dust, salinity, variable renewables, weak grids and curtailment, together with water sourcing, treatment and circular-use pathways and options for reducing critical-material and supply-chain vulnerabilities. Research should report efficiency, degradation, availability and maintenance over meaningful durations, and test modular, phased production architectures that follow firm demand rather than pre-committing to export-scale infrastructure. *(Track: Validation)*

- **Test hydrogen integration in existing African industrial demand**, particularly ammonia and fertiliser production, DRI and green-iron pathways, and selected methanol and chemicals applications with credible feedstock and offtake, prioritising domestic use and food-security or industrial objectives before assuming export markets. Research should evaluate retrofit strategies, plant dynamics, product cost and reliability, and identify which equipment, engineering and downstream activities can be competitively localised, including their effects on jobs and distribution of benefits. *(Track: Demonstration)*

- **Advance hydrogen storage materials, vessels and digital monitoring** (permeability, embrittlement, cryogenic behaviour, leakage detection, predictive maintenance), and compare ammonia, methanol, liquid hydrogen and other carriers on full conversion-chain efficiency, cost, safety and lifecycle emissions. Research should demonstrate long-duration storage and mobility applications only where system modelling shows a service need not better met by direct electricity, batteries or grid reinforcement, using heavy-duty, long-range, mining, port or shipping niches as the explicit test cases. *(Track: Demonstration)*

- **Develop and validate prospectivity, exploration and resource- and maturity-classification workflows for natural hydrogen** across African geological settings, integrating geological, geophysical, geochemical and soil-gas evidence with standardised flow-testing and uncertainty reporting. Research should assess environmental, safety, regulatory and economic conditions before any deployment step, and build African geoscience and regulatory capacity, while explicitly not attaching production or cost targets to this earliest-stage exploratory domain. *(Track: Validation)*

- **Develop the measurement, safety and evidence-discipline conditions that all hydrogen pathways depend on**, including interoperable certification and verification methods (guarantees of origin, temporal and spatial electricity matching, lifecycle carbon and leakage accounting), safety codes and emergency-response capability adapted to local conditions, and the skills, curricula and shared

research infrastructure needed to sustain this work. Research should apply fixed maturity categories and stage gates throughout, so that concepts, feasibility studies, FID projects and operating demonstrations are never aggregated into a single readiness claim. *(Track: Validation and Demonstration)*

6.7.6 Beyond-technology framing: needs, strategies, business models, risks

Hydrogen projects combine resource conversion, infrastructure, industrial demand, finance and geopolitical choices. Their feasibility and development contribution cannot be inferred from resource potential or component efficiency alone. In line with the CESP framing used across the updated MARs, MAR7 therefore treats technical design, business models, enabling activities, social and environmental safeguards and impact evidence as an integrated and iterative process.

Needs and uptake conditions

- **Start with the problem and end-use, not with the molecule** - Define the industrial, system, transport or resource problem hydrogen is intended to solve; identify current and future demand, quality and reliability requirements; and test whether hydrogen is preferred to direct electrification or other options.

- **Differentiate incumbent demand, new domestic demand and exports** - Existing ammonia, chemicals, refining and DRI facilities provide different transition pathways from greenfield export projects. Domestic fertiliser, materials and industrial uses should be evaluated alongside exports, with transparent trade-offs and opportunity costs.

- **Use phased decisions and real maturity evidence** - Resource potential, investor interest and land reservation are early signals, not proof of bankability or operation. Development decisions should be tied to demand, permits, financing, offtake, infrastructure and validated performance gates.

Resource and system conditions

- **Renewable-electricity additionality and grid interaction** - Electrolysers can support renewable integration and flexible demand, but can also compete with electricity access, raise network costs or rely on carbon-intensive marginal generation. Projects should quantify dedicated or new renewable supply, grid exchanges, curtailment, electricity-price effects and alternative uses of power.

- **Water, land and biodiversity** - Water use is often manageable at project level but can become material in water-stressed basins or when upstream power and derivative production are included. Water source, quality, competing demand, brine and wastewater, land footprint, biodiversity and cumulative infrastructure effects require site-specific assessment and participation by affected users.

- **Infrastructure and spatial sequencing** - Production, industrial demand, ports, pipelines, storage and electricity networks must be co-optimised. Hydrogen valleys or hubs may share infrastructure and lower risk, but they require credible anchor demand, governance and sequencing rather than assumed network effects.

Business models and finance

- **Bankability depends on power, cost of capital and utilisation** - Electricity cost and profile, electrolyser capex, WACC, capacity factor, infrastructure and water

treatment strongly shape cost. Generic USD/kg targets without financing and boundary assumptions should not be treated as evidence.

- **Firm offtake is a primary design condition** - Long-term contracts, creditworthy counterparties, price-indexation, product certification and infrastructure access influence FID. Export demand should be scenario-tested, including lower European demand, delayed infrastructure and alternative carrier prices.

- **Public support should be transparent and development-linked** - Grants, concessional finance, guarantees, contracts for difference, auctions and shared infrastructure can de-risk early projects, but public risk exposure and opportunity costs should be disclosed. Support should be linked to learning, emissions performance, domestic value, skills, and measurable public benefits rather than capacity announcements alone.

- **Phased and modular models can reduce stranded-asset risk** - Anchor-demand, cluster, valley, tolling, shared-infrastructure and modular expansion models should be tested against large integrated mega-projects, with clear allocation of demand, construction, currency, technology and policy risk.

Complementary activities and enabling environment

- **Regulation, permitting and institutional coordination** - Clarify responsibilities across energy, industry, water, environment, mining, land, safety, ports and trade authorities. One-stop processes can reduce delay, but should not weaken safeguards or participation.

- **Standards, certification and market interoperability** - Develop African capability to measure, verify and certify renewable and low-carbon hydrogen and derivatives; align with relevant international markets without making external rules the sole determinant of domestic pathway design.

- **Skills, laboratories and research infrastructure** - Hydrogen requires capabilities across electrochemistry, power systems, process engineering, materials, cryogenics, geoscience, safety, lifecycle assessment, finance and social science. Shared testing facilities, metrology and certification laboratories, field schools and maintenance networks are needed for durable local capability.

- **Data governance and open science** - Geological, industrial, grid, water and commercial data may be sensitive or fragmented. Projects should identify critical external data at proposal stage, secure agreements, define access and sovereignty rules, and publish reusable methods and non-sensitive datasets where possible.

- **Participation, local ownership and benefit-sharing** - Municipalities, communities, workers, local firms, water users and affected landholders should participate early enough to shape location, design, safeguards and benefit arrangements. Consultation after core decisions are fixed is not sufficient evidence of procedural justice.

Risks and safeguards

- **Hydrogen exceptionalism and technology lock-in** - A hydrogen label can attract support even where direct electrification is cheaper and more efficient. Safeguard: require counterfactual comparison and stage-gated decisions, and reassess pathways as prices, grids and demand evolve.

- **Electricity-access and price trade-offs** - Large electrolysers may compete for scarce renewable investment or network capacity. Safeguard: quantify additional supply, grid impacts, tariffs and domestic service opportunity costs; avoid treating export electricity embodied in hydrogen as development-neutral.

- **Water, land, biodiversity and cumulative impacts** - Individual projects may report small direct water use while ignoring upstream generation, desalination, derivatives and multiple projects in one basin. Safeguard: basin- and landscape-level assessment, transparent water balances, cumulative analysis, monitoring and enforceable mitigation.

- **Export dependence, weak offtake and stranded infrastructure** - Announced European or global demand may not materialise at expected prices. Safeguard: use multiple demand scenarios, modular sequencing, domestic-use options, contract-quality tests and independent maturity tracking.

- **Limited local value capture and unequal distribution** - Foreign-owned mega-projects may create few durable local benefits while using land, water and public finance. Safeguard: capability-based localisation, transparent fiscal and ownership arrangements, job-quality and supplier metrics, and monitoring of who receives benefits and bears costs.

- **Safety, leakage and lifecycle uncertainty** - Hydrogen can leak, embrittle materials and create fire and explosion hazards; indirect climate effects remain uncertain. Safeguard: conservative design, sensing, training, inspection, emergency planning, lifecycle MRV and explicit uncertainty reporting.

- **Greenwashing and carbon lock-in** - Colour terminology can hide fossil inputs, methane emissions, capture underperformance or carbon-intensive electricity. Safeguard: pathway-specific lifecycle thresholds, actual operating data and transparent treatment of transitional assets and lock-in risk.

- **Natural-hydrogen speculation** - Occurrences can be converted prematurely into reserve, cost or economic-development claims. Safeguard: geological and resource-classification standards, independent review, flow and recharge evidence, environmental baseline and separation of exploration from production targets.

- **Programme and partnership inequity** - Funding and administrative delays can transfer technical risk to African partners and shorten field validation. Safeguard: funding-readiness checks, adequate African budgets and leadership, realistic durations, local procurement plans, early data agreements and flexible but traceable work-plan adjustment.

By embedding these conditions around the technical options in Section 6.7.5, MAR7 becomes a roadmap for testing sustainable hydrogen pathways rather than a catalogue of hydrogen technologies or announced projects.

6.7.7 Theory of Change

The Theory of Change for MAR7 follows the same Outputs–Outcomes–Impacts logic used across the updated MARs. The core causal pathway is that **context-appropriate hydrogen technologies, pathway-assessment methods and comparable evidence** can support credible hydrogen choices when they are taken up through viable demand and business arrangements, functioning regulatory and safety frameworks, adequate skills and infrastructure, and explicit environmental and social safeguards. These outcomes can contribute to industrial decarbonisation, inclusive economic opportunity and environmental

sustainability and resilience where hydrogen is demonstrably appropriate relative to available alternatives.

The pathway is contributory rather than automatic. A resource map, low modelled production cost, successful component test or announced offtake does not by itself demonstrate a viable hydrogen pathway or development impact. Results depend on demand, electricity and water availability, financing, infrastructure, regulation, safety, local capabilities and the distribution of benefits. Natural-hydrogen occurrences are further upstream and require progressive evidence from prospectivity and appraisal before any production or development claim is justified.

Outputs — validated R&I solutions and evidence

- **Context-appropriate hydrogen technologies and integrated pathways** are developed and validated under relevant African operating conditions, covering renewable production and water integration, industrial uses and derivatives, storage and carriers, and selected system applications where hydrogen demonstrates comparative value.

- **Replicable pathway-assessment, design and decision-support methods** are developed and validated to compare hydrogen pathways with relevant alternatives under demand, resource, infrastructure, economic, lifecycle and development constraints.

- **Natural-hydrogen exploration and appraisal approaches** are developed and validated with explicit evidence gates from occurrence and prospectivity to tested accumulation and resource characterisation, without assuming production readiness.

- **Comparable technical, economic, lifecycle and socio-economic evidence** is generated across pathways and contexts, including performance, safety, cost and finance, demand, resource use, emissions, local capabilities and distributional effects.

Outcomes — uptake, viability and enabling capacity

- **Hydrogen pathways are selected, refined, progressed or rejected on the basis of evidence**, comparison with alternatives and transparent maturity criteria rather than resource potential, colour labels or announced projects alone.

- **Validated pathways demonstrate sustained performance and credible demand**, with technical reliability, safety, resource requirements, lifecycle performance and business or industrial viability established beyond initial modelling or commissioning.

- **Enabling capacities and institutional arrangements become functional**, including appropriate regulation, standards and certification, safety systems, research and testing capability, technical skills and coordination across relevant energy, industry, water and environmental actors.

- **Validated approaches progress beyond isolated R&I settings where maturity gates are met**, through uptake by industrial operators, planners, regulators, research infrastructures or follow-on demonstrations; for natural hydrogen, progression primarily means stronger prospectivity and appraisal evidence rather than premature deployment.

Impacts — development contributions

- **Human capabilities and essential services contribution** - Hydrogen pathways can contribute indirectly to food security and essential services through lower-emissions fertiliser, resilient industrial inputs and, in justified cases, reliable energy for critical or remote applications. These contributions depend on affordability, availability and whether the pathway serves domestic needs rather than displacing electricity, water or public investment priorities.

- **Living standards and inclusive economic opportunity contribution** - Sustainable hydrogen pathways can contribute to industrial upgrading, local beneficiation, enterprise and supplier development, skilled employment and research capability. Benefits should be assessed across ownership, geography, gender, age, income, enterprise size and worker category rather than inferred from aggregate investment or job announcements.

- **Environmental sustainability and resilience contribution** - Renewable and genuinely low-emissions hydrogen can contribute to decarbonising incumbent industrial hydrogen and selected hard-to-electrify activities, increasing renewable integration and diversifying industrial systems. These benefits must be assessed together with electricity additionality, water and land use, biodiversity, materials, leakage, infrastructure, derivative losses, decommissioning and resilience to market, climate and supply-chain shocks.

Impact interpretation. These impact statements describe plausible contribution pathways rather than direct attribution claims. Evidence of technical validation, industrial uptake or replication does not by itself demonstrate that a hydrogen R&I intervention caused changes in industrial development, energy access or resilience. Stronger impact claims require appropriate baseline and follow-up evidence and, where causal attribution is intended, an evaluation design capable of addressing counterfactual influences.

6.7.8 Indicator framework and verification methods

The indicators below are intended as a **roadmap-level evidence framework rather than as fixed project targets**. They identify the evidence that future R&I actions under MAR7 should generate to support monitoring, evaluation and learning at portfolio level. Project- or call-specific targets should be defined by the relevant funding instrument, taking account of pathway and technology maturity, intervention scale and type, industrial and geographic context, data availability and the position of the activity in the research-to-deployment chain.

The monitoring framework distinguishes between **output, outcome and impact-contribution indicators**. Output indicators capture validated hydrogen solutions, methods and comparable evidence. Outcome indicators assess whether those outputs translate into evidence-based pathway choices, sustained performance, credible demand and finance, functioning enabling capacities and maturity progression beyond the original R&I setting. Impact-contribution indicators use the common trans-MAR human-development dimensions and assess the wider changes to which appropriate hydrogen pathways may plausibly contribute.

Output indicators – R&I outputs and technical validation

Table 20 – MAR7 Output Indicators

Indicator	Definition and Evidence Expected	Verification method

Validated hydrogen technologies and integrated pathways	Context-appropriate hydrogen solutions are developed and tested under relevant operating conditions. Depending on the pathway, this may include renewable production and water integration, industrial conversion and derivatives, storage and carriers, infrastructure or selected system applications. Validation should address performance, reliability, safety, degradation, resource use and comparison with relevant alternatives where appropriate.	Design and commissioning documentation; laboratory and field-test protocols; operational telemetry; energy, water and material balances; degradation and maintenance records; safety and product-quality tests; pilot or demonstrator reports; relevant certification or independent technical review.
Validated pathway-assessment and decision-support methods	Methods or tools for assessing demand, resources, infrastructure, system integration, cost and finance, lifecycle performance and development implications are documented, reproducible and tested against cases or benchmark evidence. Hydrogen pathways should be compared with relevant non-hydrogen alternatives using transparent boundaries and uncertainty assumptions.	Methodology and model documentation; repositories where applicable; assumptions and boundary registers; validation datasets; benchmark and sensitivity tests; case-study comparison; stakeholder or practitioner review.
Validated natural-hydrogen exploration and appraisal methods	Prospectivity, geological, geophysical and geochemical assessment, sampling, flow testing and resource-appraisal approaches are developed and validated with explicit uncertainty and maturity gates. Occurrences or anomalies are distinguished from tested resources and reserves.	Field survey and QA/QC records; geological and geophysical datasets; sampling and well and flow-test data; time-series gas measurements; resource-classification reports; uncertainty registers; independent geological review.
Comparable technical, economic, lifecycle and socio-economic evidence generated	Evidence is generated using defined units, baselines and system boundaries to allow comparison across hydrogen pathways and contexts. Relevant dimensions include performance, cost and financing, water, land and material use, lifecycle emissions and leakage, demand and offtake, safety, local capabilities and distribution of benefits.	Baseline and monitoring datasets; cost and financing records; LCA and MRV documentation; resource-use data; surveys and interviews; supplier, employment and skills data; gender, ownership and vulnerability disaggregation; independent review where appropriate.

Outcome indicators – uptake, viability and enabling conditions

Table 21 – MAR7 Outcome Indicators

Indicator	Definition and Evidence Expected	Verification method
Evidence-based pathway selection and maturity progression	Evidence that projects or institutions use comparative assessment and defined maturity gates to select, redesign, pause or reject pathways. Progress is reported from concept and feasibility through FID, construction, operation or resource classification without aggregating unlike stages.	Decision records; stage-gate reviews; feasibility and FID documentation; independent technical reviews; portfolio maturity registers; documented comparison with alternatives; reasons for redesign, pause or rejection.
Sustained performance,	Validated pathways demonstrate reliable and safe operation together with credible demand or offtake and operational and financial conditions capable of supporting	Operational and maintenance records; performance telemetry; safety and reliability data; offtake agreements or demand evidence; utilisation records;

demand and viability	continued use. Evidence should go beyond initial modelling, commissioning or announced demand.	operating-cost and revenue data; financing or business-model documentation; independent technical or commercial review where appropriate.
Functional enabling arrangements and local capacity	Regulation, certification, safety systems, institutional coordination, research and testing capability, technical skills and O&M and service capacity are established and function in practice to support pathway implementation and continued operation.	Regulatory and certification records; institutional agreements; safety procedures and audits; training and competency records; laboratory and testing accreditation where applicable; staffing and service records; stakeholder interviews; evidence of functioning coordination mechanisms.
Replication, uptake and continuation beyond the demonstrator	Validated technologies, methods or approaches are taken up by additional operators, sites, institutions, planners or follow-on R&I activities. Evidence should distinguish proposed continuation from funded, implemented or operational replication and uptake.	Replication agreements; procurement or adoption records; additional sites or users; funded follow-on projects; documented integration into planning or regulatory processes; investment decisions; implementation records; evidence of continued operation beyond the original demonstration period.

In MAR7, an announcement, strategy target or resource potential should not be treated as an outcome. Similarly, a laboratory efficiency, modelled USD/kg value or detected natural-H2 anomaly does not demonstrate a viable project or resource. The relevant outcome is progression through transparent technical, demand, finance, regulatory, environmental and social evidence gates.

Impact-contribution indicators – common human-development dimensions

The following impact dimensions should be used consistently across all MARs. MAR7 contributes to them through the specific pathways of lower-emissions industrial production, context-appropriate energy-system functions, local industrial and research capability, and exploratory resource knowledge.

Table 22 – MAR7 Impact Indicators

Common Impact Dimension	MAR7 contribution	Verification method
Human capabilities and essential services	Appropriate hydrogen pathways may contribute to food security and essential services through lower-emissions and reliable fertiliser supply, resilient industrial inputs, and selected critical or remote energy applications. The contribution should be assessed against affordability and availability and against possible diversion of electricity, water or public finance from more direct services.	Fertiliser availability and cost and domestic-use evidence where relevant; continuity of justified critical-energy applications; electricity and water opportunity-cost analysis; service and affordability indicators; baseline and follow-up data; food-system or essential-service evidence; documented alternative comparison.
Living standards and inclusive economic opportunity	Hydrogen R&I may contribute to industrial upgrading, beneficiation, supplier and enterprise development, skilled jobs, research capability and new services. Distribution of benefits should be assessed across ownership, location, gender, age, income, enterprise size and worker	Employment, wage and job-quality records; supplier and enterprise records; local procurement, manufacturing and service evidence; training-to-employment and skill-retention data; ownership and fiscal evidence; household, community and

	category rather than inferred from total investment or announced employment.	worker surveys; gender and vulnerability disaggregation; qualitative benefit-distribution evidence.
Environmental sustainability and resilience	Hydrogen can contribute to lower lifecycle emissions from existing industrial H2 and selected hard-to-electrify activities, renewable integration and diversified industrial systems. Contributions must be assessed together with electricity additionality, water and land use, biodiversity, materials, leakage, infrastructure, derivative losses, decommissioning and resilience to market, climate and supply-chain shocks.	Lifecycle GHG and MRV data; renewable-electricity and grid-interaction records; water and land balances; biodiversity and environmental monitoring; hydrogen leakage and safety records; material and EoL evidence; fuel and feedstock displacement; shock, price and supply-chain stress tests; restoration or continuity evidence.

The three dimensions are defined at portfolio level in Chapter 8.3, which also explains why they are not intended to reproduce the Human Development Index or to generate a composite MAR impact index.

Evidence interpretation

Evidence generated under MAR7 should be interpreted according to its strength, maturity, geography and position in the causal chain. Where feasible, quantitative data should be triangulated with technical records, documentary evidence, independent review and stakeholder evidence. Promotional targets, proprietary project pipelines and advocacy sources should be checked against official or reproducible data and clearly labelled where methods are unavailable.

A single laboratory test, pilot, industrial site, geological field or comparative model should normally be reported as illustrative rather than generalised to the African hydrogen portfolio. Stronger claims of technical readiness, bankability, replication, industrial impact or sustainable resource require evidence across multiple operating periods, sites, independent sources or maturity stages. In particular, a soil-gas anomaly or seep does not establish a recoverable natural-H2 resource; a low modelled LCOH does not establish FID; and an MoU or investor request does not establish firm offtake or an operating market.

Evidence of policy relevance should be distinguished from demonstrated policy influence. Likewise, an identified continuation pathway or submitted proposal should be distinguished from funded continuation, and funded continuation from implemented and sustained uptake. At impact level, employment, food-security, industrialisation and environmental claims should normally be interpreted as plausible contributions unless the evaluation design can address counterfactual influences and distributional effects.

6.7.9 Interoperability and synergies with other MARs

MAR7 owns the hydrogen-specific resource, conversion, storage, derivative, safety, certification and lifecycle chain. It does not absorb the broader planning, circularity, electricity-system, productive-use or domestic-service functions of the other MARs. Clear interfaces prevent hydrogen from becoming a catch-all theme and make comparative research possible.

- **MAR1 – Mapping joint R&I actions** - MAR1 provides the portfolio evidence architecture for tracking hydrogen projects, actors, geographies, maturity, infrastructure, demand, policy and cross-cutting gaps. MAR7 feeds back hydrogen-specific pathway taxonomies, stage-gate categories, data requirements and evidence gaps for the living roadmap observatory. Announced, FID, construction, operating and demonstrated-market stages should be mapped separately.

- **MAR2 – End-of-life, second-life and environmental impacts** - Electrolysers, fuel cells, power electronics, catalysts, membranes, tanks, composite vessels, sensors and associated renewable and storage assets create material and end-of-life obligations. MAR2 provides circularity, repairability, traceability, critical-material and safe-treatment logic; MAR7 provides hydrogen-specific degradation, contamination, pressure and cryogenic safety and decommissioning requirements.

- **MAR3 - Smart stand-alone systems** - Hydrogen may provide storage, backup or fuel-cell services in specialised remote or critical stand-alone systems. MAR3 owns service-oriented system design and operation; MAR7 owns hydrogen production, storage and safety. Joint R&I should include explicit comparison with batteries, direct renewables and other alternatives and should avoid inserting hydrogen into stand-alone systems without a demonstrated long-duration or resilience need.

- **MAR4 – Smart grids for off-grid applications** - Flexible electrolysers, sector coupling, hydrogen storage and fuel cells may interact with mini-grids, microgrids and weak grids. MAR4 provides grid planning, control, protection, interconnection and demand-management logic; MAR7 provides hydrogen conversion, storage, industrial demand and safety models. Joint work should quantify grid reinforcement, electricity additionality, power quality, dispatch and tariff effects.

- **MAR5 – Processes and appliances for productive uses** - MAR5 is the main interface for ammonia and fertiliser, DRI and steel, chemicals, methanol, industrial heat, mining, logistics and selected mobility. MAR7 addresses the hydrogen-specific conversion and supply chain; MAR5 assesses productive performance, value chains, enterprise participation, local value and livelihood or industrial-development effects. Jointly they should ensure that export pathways are compared with domestic industrial and productive uses.

- **MAR6 – Priority domestic uses (clean cooking and cold chain)** - The reviewed evidence does not support a direct household hydrogen agenda. Interactions are indirect, for example through fertiliser and food security, electricity-system implications or justified resilient power for health and cold-chain nodes. MAR6 retains ownership of household cooking, cooling, affordability and user outcomes; any MAR7 link should be evidence-triggered rather than imposed for symmetry.

- **Cross-MAR enabling conditions** - Skills, research infrastructure, standards, data governance, finance, local ownership, gender and justice should use shared concepts and evidence rules across the portfolio. Hydrogen projects should contribute reusable datasets and pathway evidence to MAR1, lifecycle evidence to MAR2, system-performance evidence to MAR3-MAR4, productive and industrial outcomes to MAR5, and only relevant indirect service evidence to MAR6.

Overall, MAR7 functions as a conditional pathway roadmap. It enables AU–EU R&I to determine where hydrogen and its derivatives are technically credible, economically and institutionally viable, environmentally sustainable and developmentally preferable - and equally, where they are not.

7. Cross-cutting Enablers

The updated MARs address distinct technological and application domains, but the evidence reviewed across the portfolio shows that their ability to generate sustained outcomes depends on a recurrent set of enabling conditions. These conditions are not additional thematic priorities and should not be interpreted as separate MARs. Rather, they are **cross-cutting dimensions that influence whether R&I outputs can move from**

technical validation towards uptake, replication and longer-term development contribution.

This framing is consistent with the comprehensive planning perspective adopted in this deliverable. Technical performance remains necessary, but it is rarely sufficient to explain whether a solution can operate reliably, be maintained locally, remain affordable, comply with applicable rules, interact with other systems, or generate evidence that can be reused beyond an individual demonstrator. The same enabling conditions therefore recur across the different MARs, although their relative importance and specific form vary by technology, scale, geography and application.

Five enabling areas emerge particularly consistently across the updated roadmap portfolio: **skills and capacity; standards and interoperability; finance and business models; policy and regulatory pre-conditions; and data governance**.

7.1 Skills and capacity

Human and institutional capacity remains a fundamental condition for converting R&I results into sustained capabilities. The original PRE-LEAP-RE framework already recognised capacity building as a transversal component of the MARs, distinguishing between **individual, institutional and system-level capacity**. The updated MARs reinforce this approach while making clearer that the relevant skills extend beyond purely technical competences.

At the **individual level**, future R&I actions may require specialised competences for system design, installation, operation, maintenance, repair, diagnostics and safe end-of-life handling, depending on the MAR concerned. At the same time, technical competences increasingly need to be complemented by capabilities in energy planning, digital systems, business-model development, stakeholder engagement, environmental and social assessment, entrepreneurship and communication with policymakers and end users.

At the **institutional level**, the challenge concerns the ability of universities, research centres, utilities, firms, public agencies and other organisations to retain and apply these competences over time. Relevant capacities include laboratory and testing infrastructure, operation and maintenance systems, research and data management, technology transfer, quality assurance, knowledge retention, and the ability to establish lasting interfaces with industry, communities and public authorities.

At the **system level**, capacity concerns the wider innovation environment within which individual projects operate. Regulators, standards bodies, financing institutions, vocational-training systems, local authorities, civil society organisations and other actors may all affect whether an innovation can move beyond demonstration. Strengthening these interfaces is particularly important where solutions require coordination across sectors, institutions or jurisdictions.

Capacity building should therefore not be reduced to the number of training activities or participants reached. From a roadmap perspective, the more relevant question is whether R&I activities leave behind **usable and sustained capabilities**: people able to operate and adapt solutions, organisations able to support them, and local or national ecosystems able to reproduce and further develop the knowledge generated.

7.2 Standards and interoperability

As renewable-energy solutions become more modular, digitalised and interconnected, standards and interoperability become increasingly important for quality, safety,

replicability and long-term system evolution. Their relevance extends across the MAR portfolio, although the specific requirements differ considerably between applications.

For stand-alone systems, mini-grids and microgrids, interoperability may concern modular components, meters, control architectures, communication protocols, payment interfaces and future interconnection with other systems or the main grid. For productive-use and domestic appliances, standards can support minimum performance, energy efficiency, safety and product quality. For circularity and end-of-life management, they may concern component identification, testing, repair and refurbishment criteria, traceability, transport, treatment and safe return to service.

A stronger standards perspective can also reduce dependence on proprietary systems and facilitate maintenance, replacement, upgrading and replication. This is particularly relevant where equipment must remain operational for periods longer than the duration of the R&I project itself, or where local operators need to integrate components obtained from different suppliers.

At the same time, **harmonisation should not be treated as an objective in itself**. Standards need to be appropriate to the technological maturity, local market conditions, institutional capabilities and regulatory context in which solutions are expected to operate. Excessive or poorly adapted requirements can create additional cost and barriers to entry, while insufficient quality assurance can result in unsafe equipment, poor performance and loss of user confidence.

Future R&I should therefore help identify where common specifications, testing procedures and interoperable architectures can support scale and knowledge transfer, while documenting where contextual adaptation remains necessary. The objective is not uniformity across the MARs, but sufficient compatibility and transparency to allow solutions, components and knowledge to interact effectively.

7.3 Finance and business models

Across the MARs, financing and business-model conditions repeatedly emerge as determinants of whether technically validated innovations can be deployed and sustained. High upfront costs, limited access to capital, affordability constraints, uncertain demand, currency and market risks, and the absence of long-term revenue mechanisms can prevent otherwise promising technologies from progressing beyond pilot scale.

The relevant question for R&I is therefore not simply how to reduce technology costs, but **how costs, risks, revenues and responsibilities are distributed across the actors involved**. Appropriate models vary substantially by application. They may include direct sales, PAYGo and lease-to-own approaches, energy- or appliance-as-a-service models, public or community ownership, performance-based contracts, producer-responsibility arrangements, or combinations of these approaches.

Similarly, financing instruments may include grants, concessional finance, guarantees, results-based finance, blended structures, local lending and climate-finance mechanisms where appropriate. These instruments address different barriers and stages of maturity and should not be considered interchangeable. Their effectiveness depends on local capital markets, customer profiles, regulatory conditions, technology maturity and the distribution of risks between public and private actors.

An important distinction must also be retained between **financial viability and affordability**. A model capable of recovering its costs is not necessarily affordable to underserved households or small enterprises, while a highly subsidised model may increase access without establishing a credible pathway for continued service provision. Research is therefore needed on the conditions under which different combinations of tariffs,

subsidies, appliance finance, productive demand, risk-sharing instruments and ownership arrangements can reconcile these objectives.

Business-model research should also consider responsibilities across the full lifecycle. Maintenance, replacement, reverse logistics, repair and end-of-life management generate costs that are often omitted from pilot-stage assessments. Incorporating them from the outset can provide a more realistic assessment of scalability and long-term sustainability.

The MARs should consequently treat finance and business models as **co-designed elements of the innovation pathway**, rather than as mechanisms to be identified only after technical development has been completed.

7.4 Policy and regulatory pre-conditions

R&I solutions operate within regulatory and institutional systems that determine what can be deployed, by whom, under which conditions and with what responsibilities. Understanding these conditions early is therefore essential for identifying realistic research and demonstration pathways.

The relevant regulatory questions differ across the MARs. They may include licensing and permitting; tariff and subsidy rules; grid connection and interconnection requirements; service-quality and consumer-protection provisions; equipment safety and efficiency standards; waste classification and extended producer responsibility; import and customs procedures; environmental and social safeguards; or rules governing emerging technologies and markets.

These conditions should not be treated solely as external barriers to innovation. Regulatory arrangements can themselves become subjects of R&I, particularly where new technologies or business models expose gaps in existing frameworks. Demonstrators can generate evidence on alternative regulatory approaches, implementation procedures and risk-allocation mechanisms, provided that such findings are interpreted according to their context and evidence strength.

The diversity of African energy systems also argues against assuming a single enabling policy package. Different countries and regions have distinct market structures, institutional capacities, energy-access conditions and development priorities. Future R&I should therefore make regulatory assumptions explicit, test the transferability of approaches across contexts and distinguish between **policy relevance and demonstrated policy influence**.

A cross-cutting objective of the MAR portfolio is thus to strengthen the connection between scientific evidence and the institutions responsible for planning and regulation, without positioning the MARs themselves as a prescriptive policy agenda.

7.5 Data governance

Digitalisation and increasing use of data create opportunities across the entire MAR portfolio. Resource and demand data support planning; operational data enable system optimisation and preventive maintenance; customer and payment information underpin new service models; asset and component data can support traceability and circularity; and monitoring data are necessary for evaluating R&I outcomes and comparing evidence across projects.

However, greater availability of data does not automatically generate better decisions. Data may be fragmented, inconsistent, inaccessible, proprietary or collected using incompatible definitions and formats. Conversely, some datasets contain personal,

commercially sensitive, security-related or strategically important information and cannot simply be made openly available.

Data governance should therefore address the complete chain from **data generation and ownership to quality, access, interoperability, protection, reuse and long-term stewardship**. Future R&I actions should define who generates and controls relevant data, how quality and metadata are ensured, what information can be shared, and under what conditions it may be reused by researchers, public institutions, operators and communities.

FAIR and open-science principles can support transparency, reproducibility and knowledge transfer where appropriate, particularly for research methods, non-sensitive datasets, models and tools. They should nevertheless be combined with proportionate provisions for privacy, informed consent, cybersecurity, commercial confidentiality and legitimate concerns over data ownership and sovereignty.

Interoperable data structures are particularly valuable at portfolio level. Common definitions and minimum metadata can facilitate comparison between demonstrators and allow evidence generated under one MAR to inform another without requiring identical monitoring systems across all projects. At the same time, data requirements should remain proportionate: excessive reporting can divert resources from implementation without necessarily improving learning.

Data governance should therefore be understood as both a **technical and institutional enabler**. Its purpose is not to maximise data collection, but to ensure that relevant information remains trustworthy, usable, appropriately protected and capable of supporting learning beyond individual project cycles.

Taken together, these five areas define a common enabling layer for the updated MAR portfolio. **Not every R&I action is expected to address every enabler to the same extent.** Rather, projects should identify which enabling conditions are material to their proposed innovation pathway and generate evidence on how they affect technical validation, uptake and replication.

This distinction is important for interpreting R&I maturity. A successful technical demonstration does not by itself demonstrate scalability where essential skills are unavailable, components cannot interact with local systems, users cannot afford the service, regulation prevents deployment, or the evidence required for operation and learning cannot be accessed. Conversely, enabling conditions cannot substitute for technical performance. The updated MARs therefore treat technological development and its enabling environment as interdependent elements of the same socio-technical innovation process.

The following chapter translates this cross-cutting perspective into a common set of output, outcome and impact-contribution indicators that can support comparison and learning across the MAR portfolio without imposing uniform project-level targets.

8. Cross-cutting Indicator Framework

The indicator frameworks developed for the individual MARs follow a common Outputs–Outcomes–Impacts logic, but the degree of harmonisation that is meaningful differs along the causal chain. A single uniform indicator set would not adequately represent the diversity of R&I activities covered by the MAR portfolio. Conversely, completely separate indicator systems would make it difficult to identify synergies and assess the wider contribution of the portfolio.

The interpretation of the three levels has been **informed by the comprehensive planning perspective adopted throughout the MAR update**. Rather than applying the CESP phases as a rigid classification, this perspective helps distinguish between three progressively broader questions. At **output level**, the focus is on the solutions, methods and evidence that R&I can directly develop and validate. At **outcome level**, the focus shifts to whether these outputs become usable and sustained under real-world technical, financial, institutional, regulatory and capacity conditions. At **impact level**, the focus moves further downstream to the wider human-development, socio-economic and environmental changes to which successful R&I pathways may contribute. In this sense, the Theory of Change provides the causal structure, while the comprehensive-planning perspective helps ensure that the transition from technical results to development contribution explicitly accounts for the conditions required for uptake and long-term sustainability.

This distinction also explains why harmonisation increases progressively along the causal chain. **Outputs remain predominantly MAR-specific**, because the R&I artefacts and validation requirements differ substantially between thematic domains. **Outcomes are synergistic across MARs**, because different technologies repeatedly depend on similar conditions for sustained uptake, viability, enabling capacity and replication. **Impacts converge on a common portfolio-level development lens**, because ultimately the different R&I pathways are expected to contribute to a shared set of human-development, socio-economic, environmental and resilience objectives.

The updated MARs therefore adopt a **layered indicator architecture**: diversity is preserved where technological and research specificity matters, while comparability is progressively introduced where common enabling conditions and development objectives emerge.

Table 23 – Indicator categories adopted within the MARs

Indicator level	Degree of harmonisation across MARs	Main monitoring question	Portfolio Function
Outputs — validated R&I solutions and evidence	Mainly MAR-specific	What solutions, methods, tools and evidence have been developed and validated?	Assess R&I progress and technical or methodological maturity within each MAR.
Outcomes — uptake, viability and enabling capacity	Synergistic across MARs, with pathway-specific indicators	Are validated outputs being sustained, used, supported by viable arrangements and taken up beyond the original R&I setting?	Identify common enabling conditions, interfaces and complementarities between MARs.
Impacts — development contributions	Common across the MAR portfolio	To which wider human-development, economic, environmental and resilience changes may the R&I pathways plausibly contribute?	Provide a common portfolio-level framework for interpreting longer-term development contribution.

8.1 Outputs: MAR-specific evidence of R&I progress

Outputs lie closest to the research and innovation intervention and can therefore be defined and verified with the greatest specificity. They concern the artefacts and evidence directly generated by R&I: validated technologies, demonstrators, methodologies, planning and decision-support tools, technical protocols, datasets, standards-related approaches and comparable performance evidence.

Their content necessarily differs across the MARs. Validation of a stand-alone energy system cannot be assessed through the same indicators as end-of-life management, productive-use appliances, clean cooking, hydrogen pathways or an R&I mapping system. Each MAR therefore retains its own output indicators and verification methods, reflecting its technical scope, maturity and expected R&I products.

Cross-MAR comparison at this level should consequently not seek to aggregate unlike technical indicators. Instead, the common portfolio-level question is whether R&I actions generate **documented, reproducible and contextually validated solutions and evidence** that can support progression towards subsequent outcomes.

8.2 Outcomes: a synergistic layer across the MARs

Greater convergence becomes visible at outcome level. Although the specific form of an outcome depends on the MAR, similar questions recur once an R&I output moves from validation towards sustained application.

Across the thematic MARs, four broad outcome functions repeatedly emerge:

- **Sustained uptake, use or performance.** A validated solution must continue to operate, be used or inform decisions beyond initial testing or installation. Depending on the MAR, this may concern continued electricity service, productive utilisation, clean cooking adoption, functioning circular-material flows, hydrogen pathway progression or routine use of roadmap evidence.

- **Operational and financial viability.** Technical performance must be accompanied by delivery, ownership, financing or service arrangements capable of sustaining operation. Affordability is particularly important where end users bear costs, while other MARs require evidence of viable lifecycle financing, credible demand or off-take, or sustained institutional resourcing.

- **Functional enabling capacity and institutional arrangements.** Skills, maintenance and service ecosystems, standards, regulatory procedures, institutional responsibilities, data systems and other enabling mechanisms need to function in practice rather than exist only as project recommendations.

- **Replication, uptake and continuation beyond the initial R&I setting.** Evidence that validated solutions, methods or approaches are adopted by additional actors, locations, programmes or institutions represents a stronger outcome than successful completion of a single demonstrator.

These outcome families should be understood as **synergistic rather than identical indicators**. Their precise definitions and verification methods remain MAR-specific. MAR2, for example, needs evidence of verified collection and routing of end-of-life components, whereas MAR3 and MAR4 focus on sustained energy-service provision, MAR5 on productive

utilisation and value addition, MAR6 on sustained cooking and cooling practices, and MAR7 on evidence-based pathway progression and credible demand. MAR1 occupies a different position in the causal chain: its outcomes concern use of roadmap evidence, sustained stewardship, cross-project learning and institutionalisation rather than operation of an energy technology.

This intermediate level is also where many of the strongest **interactions between MARs** become visible. Reliable stand-alone, mini-grid or microgrid services developed under MAR3 and MAR4 can enable the productive and domestic services addressed by MAR5 and MAR6; lifecycle arrangements under MAR2 affect the sustainability of assets deployed across those MARs; MAR1 can make evidence and lessons transferable across the portfolio; and emerging pathways such as hydrogen interact with electricity systems, productive uses and lifecycle management. Outcome monitoring can therefore identify not only whether individual MARs progress, but whether complementarities across the roadmap portfolio are functioning.

8.3 Impacts: a common portfolio-level development lens

At impact level, further harmonisation is both possible and desirable. Technologies and R&I pathways differ, but their ultimate relevance to the AU–EU sustainable-energy partnership lies in whether they contribute to wider development objectives.

The updated MARs therefore use three common impact dimensions:

Human capabilities and essential services

This dimension concerns the extent to which R&I pathways can contribute to people's ability to access and benefit from essential services and opportunities. Depending on the pathway, relevant contributions may include improved health and safety, food and nutrition, education, water services, communication, reduced drudgery and time burdens, or continuity of essential services.

The causal pathway varies substantially between MARs. Clean cooking may contribute through reduced exposure to household air pollution; reliable electricity through better functioning of health or education facilities; productive energy through food preservation or water services; circularity through reduced exposure to hazardous materials and improved continuity of renewable-energy assets. These effects should therefore be assessed through pathway-appropriate evidence rather than through a single universal metric.

Living standards and inclusive economic opportunity

This dimension captures contributions to livelihoods, productive activity, affordability, enterprise development, employment, skills and local value creation.

The emphasis is not only on the aggregate quantity of economic activity generated, but also on **who participates and who benefits**. Where relevant, evidence should therefore be disaggregated across gender, age, income, geography, enterprise size, ownership and other dimensions of vulnerability or exclusion. Numbers of jobs, enterprises, connections or technologies deployed should not by themselves be interpreted as evidence of inclusive economic impact.

Environmental sustainability and resilience

This dimension captures both the environmental performance of R&I pathways and their capacity to remain functional under changing or adverse conditions. Relevant contributions may include reduced fossil-fuel use and emissions, improved resource efficiency, reduced hazardous waste or pollution, lower lifecycle impacts and stronger capacity of energy services, livelihoods and value chains to withstand and recover from climatic, economic, supply-chain or infrastructure shocks.

Assessment should also capture potential trade-offs. Renewable-energy innovation is not environmentally beneficial by definition: material requirements, water and land use, refrigerants, rebound effects, component lifecycles, waste streams and infrastructure requirements can shift environmental burdens between sectors or locations. Environmental and resilience claims should therefore be supported by appropriate system boundaries and lifecycle evidence.

These three dimensions are inspired by human-development approaches that consider health, education and living standards, while adding environmental sustainability and resilience as an explicit dimension required by the energy-transition context. They are **not intended to reproduce the Human Development Index or to create a new composite MAR impact index**.

More fundamentally, what is common across the MARs is the **impact dimension and assessment question, not necessarily the individual numerical indicator**. A PM2.5 exposure measure relevant to MAR6, a food-loss indicator under MAR5, service downtime under MAR3 or MAR4, hazardous-exposure evidence under MAR2, or lifecycle-emission data under MAR7 may all inform the common impact architecture without being directly aggregable. Portfolio assessment should preserve these causal differences rather than forcing them into an artificial common metric.

8.4 Portfolio-level interpretation and aggregation

The resulting architecture allows evidence to be progressively synthesised as it moves along the causal chain.

Output evidence should primarily be aggregated within individual MARs or across technically comparable activities. **Outcome evidence** can additionally be synthesised across MARs according to shared functions such as sustained uptake, viability, enabling capacity and replication, allowing recurrent barriers and synergies to be identified. **Impact evidence** should be synthesised across the entire portfolio through the three common development dimensions.

Quantitative aggregation should only be undertaken where definitions, denominators, system boundaries and data-collection methods are sufficiently comparable. Where this is not possible, structured qualitative and quantitative synthesis is preferable to summing heterogeneous indicators.

This principle extends to the level of individual indicators. Several indicator rows in Sections 6.1.8–6.7.8 identify more than one candidate quantitative measure within the same entry (for example, related but distinct ratios, shares or rates). This reflects the deliberate roadmap-level, non-prescriptive character of the indicator framework: it identifies the relevant evidence base and family of metrics rather than pre-selecting a single project target. Where a project, call or reporting exercise nonetheless reports one of these measures as a quantitative indicator, the specific metric used, together with its numerator, denominator, unit of measurement and observation period, should be stated explicitly, so that the resulting value is unambiguous and can be compared consistently across reporting cycles.

Impact assessment must also reflect the increasing distance between the R&I intervention and the observed development effect. Outputs can often be directly attributed to a project; outcomes generally require evidence that those outputs are actually used and sustained; wider development impacts are influenced by multiple external factors. The MAR framework therefore treats impacts primarily as **contribution pathways rather than automatic attribution claims**, unless an evaluation design is capable of addressing counterfactual influences.

Accordingly, evidence should be interpreted according to its strength and maturity. Quantitative monitoring should, where feasible, be triangulated with operational, documentary and stakeholder evidence. A single demonstrator or case should normally be treated as illustrative rather than generalised to the portfolio. Claims of replication, scale or wider impact require evidence across multiple cases or independent sources. Policy relevance should be distinguished from demonstrated policy influence, and proposed continuation from funded continuation, implementation and sustained uptake.

This layered approach preserves the diversity of the individual MARs while creating progressively stronger comparability towards the impact level. It therefore allows the roadmap portfolio to answer three complementary questions: **what has R&I produced; whether those results have become viable and usable; and to what wider development objectives the resulting pathways can plausibly contribute.**

8.5 Reference definitions for commonly cited technical and financial indicators

A small number of indicators in Chapter 6 refer to technical or financial ratios that are widely used in the energy-access and power-systems literature but are not spelled out in full within the indicator tables. For reference, and without altering the roadmap-level character of the indicator framework, these are commonly defined as follows:

- **SAIDI (System Average Interruption Duration Index) –** total customer-minutes of sustained supply interruption in a period, divided by the total number of customers served in that period.
- **SAIFI (System Average Interruption Frequency Index) –** total number of sustained customer interruptions in a period, divided by the total number of customers served in that period.
- **ARPU (Average Revenue Per User) –** total recurring service revenue collected in a period, divided by the average number of active customers or users over that period.
- **Collection rate –** revenue collected in a period, divided by revenue billed over the same period, expressed as a percentage.
- **Cost-recovery gap –** operating and maintenance costs incurred in a period, minus revenue collected in the same period, expressed as an absolute value or as a share of costs.
- **Load factor –** average load served over a period, divided by the peak load recorded in the same period.
- **Peak-to-average ratio (PAR) –** peak load recorded in a period, divided by the average load over the same period.

- **Capture rate (MAR2) –** number or mass of out-of-service or end-of-life units entering a documented managed channel in a period, divided by the estimated number or mass of units reaching end-of-service in the same period, for a specified component class.

Where an indicator table cites one of these measures without further specification, the definitions above should be assumed unless a MAR-specific definition is given in the relevant section.

9. Recommendations

The updated MARs provide a set of **science-based options for future research and innovation**, derived from the triangulation of scientific literature, grey literature and LEAP-RE project and stakeholder evidence. They are intended to inform funders, programme designers, researchers and practitioners about credible areas for further investigation, demonstration and learning. They should not be interpreted as a ranked research agenda or as a prescriptive allocation of future funding.

This distinction is important. The evidence reviewed in this deliverable varies considerably in maturity and strength across technologies, applications and geographical contexts. Some pathways are supported by multiple mature demonstrators and implementation experience; others remain emerging research questions or context-specific opportunities. The MARs therefore identify **where further R&I is justified and what evidence it should generate**, while decisions on relative priority, timing and resource allocation remain the responsibility of the relevant AU–EU, national and regional programming and funding processes.

The recommendations can be interpreted along the common **Outputs** → **Outcomes** → **Impacts** structure used throughout the updated MARs.

9.1 From R&I options to validated outputs

At **output level**, future R&I should concentrate on generating robust and reusable evidence on the technical and methodological questions identified within each MAR.

For **funders and programme designers**, this implies supporting R&I actions that:

- address clearly identified knowledge or validation gaps rather than reproducing existing demonstrations;
- define the context, baseline, system boundaries and maturity of the proposed intervention;
- generate comparable evidence on performance, reliability, safety, costs, resource requirements and other MAR-specific criteria;
- test relevant alternatives where the research question concerns technology or pathway choice;
- provide sufficient documentation for methods, tools and results to be assessed and, where appropriate, reproduced or reused;
- incorporate lifecycle, interoperability and data requirements early enough for them to inform design rather than being treated only after deployment.

For **researchers and practitioners**, demonstrators should consequently be treated not only as installations or technological proofs of concept but as **evidence-generating R&I environments**. Successful performance, operational difficulties, failed assumptions and contextual constraints are all relevant results when documented systematically. This is particularly important for avoiding repeated pilot activity that produces limited cumulative learning.

The appropriate output therefore differs by MAR, but the underlying recommendation is common: future R&I should leave behind **validated solutions and evidence that can inform subsequent decisions**, rather than isolated technical results.

9.2 From validated outputs to sustained outcomes

The strongest cross-MAR message of the update is that technical validation alone is insufficient to demonstrate a credible pathway towards uptake. Future R&I should therefore give greater attention to the conditions through which outputs become operationally, institutionally and economically usable.

For **funders and programme designers**, this means that demonstration and scale-oriented activities should, where relevant:

- integrate skills, maintenance and institutional capacity into the intervention;
- investigate viable financing, ownership and business-model arrangements;
- address affordability and accessibility where end users bear the cost of the service;
- identify regulatory, permitting, standards and interoperability conditions that may enable or constrain implementation;
- provide for appropriate data governance, monitoring and knowledge retention;
- examine lifecycle responsibilities, including maintenance, replacement and end-of-life management;
- generate evidence of sustained use, replication or institutional uptake rather than treating deployment itself as evidence of an outcome.

For **practitioners**, these considerations imply engaging the actors who will ultimately operate, finance, regulate, maintain or use the innovation early enough to influence its design. The appropriate configuration will remain context-specific: the MARs do not support a universal business model, regulatory package or ownership structure across African energy systems.

Outcome-oriented R&I should therefore ask a different question from technical validation: not only **"does the solution work?"**, but **"under what conditions does it continue to work, for whom, and with what capacity to be sustained or reproduced?"**

This is also the level at which synergies between MARs should be deliberately exploited. Lifecycle and circularity considerations from MAR2 can inform the assets investigated under MAR3–MAR7; infrastructure and service models under MAR3 and MAR4 interact with the productive and domestic uses addressed by MAR5 and MAR6; and MAR1 can provide the common evidence infrastructure through which these experiences become visible and reusable across the portfolio. Cross-MAR collaboration should therefore be encouraged

where it resolves a real interface or evidence gap, rather than imposed solely for thematic completeness.

9.3 From outcomes to development contribution

At **impact level**, funders and practitioners should adopt greater caution rather than greater numerical ambition. Wider changes in human capabilities, living standards, economic opportunity, environmental sustainability and resilience result from multiple interacting factors and generally extend beyond the direct control and duration of individual R&I projects.

Future programmes should therefore use the common impact dimensions defined in this deliverable to establish **contribution pathways**, while avoiding the assumption that every project should demonstrate attributable societal impact within its implementation period.

For **funders**, this implies matching expectations to the maturity and scale of the intervention. Early-stage R&I can reasonably be expected to articulate and test the assumptions connecting its outputs to future outcomes, whereas mature demonstrations may be able to generate direct evidence of sustained service, livelihood, environmental or institutional effects. Requiring distant development impacts from immature research can encourage weak attribution claims rather than better evidence.

For **practitioners**, development effects should be measured through indicators appropriate to the pathway concerned and, where relevant, disaggregated to identify who benefits and who may bear costs or risks. Quantitative evidence should be combined with operational, documentary and stakeholder evidence where this improves interpretation.

Across the portfolio, impact should consequently be assessed as the **plausible and evidenced contribution of R&I pathways to wider development objectives**, rather than as an automatic consequence of technological deployment.

9.4 Use evidence strength to guide future decisions

Finally, the MAR update recommends that future programming retain the evidence discipline used in this deliverable. Emerging topics should remain visible without being promoted prematurely, while mature areas should not automatically receive higher priority simply because more evidence already exists.

In particular:

- individual demonstrators and case studies should normally be treated as **illustrative evidence** rather than evidence of general applicability;
- stronger claims of replication, scalability or wider impact should require evidence from multiple cases, contexts or independent sources;
- policy relevance should be distinguished from **demonstrated policy influence**;
- intentions, proposals and announced projects should be distinguished from **funded, implemented and operational activities**;
- technological maturity should be distinguished from market, institutional and implementation maturity;

- absence of evidence for a pathway should not automatically be interpreted as evidence against it, but should determine the degree of confidence with which recommendations are expressed.

These principles are consistent with the monitoring and evaluation logic developed within LEAP-RE, in which indicators and evidence requirements need to reflect the intervention, beneficiaries and context rather than assuming a single linear route from research activity to societal impact.

The resulting recommendation is therefore deliberately not a ranked list of technologies or research themes. **The updated MARs define an evidence-informed option space for future AU–EU R&I cooperation.** Within that space, funders can select and combine research priorities according to policy objectives, national and regional needs, available resources and evidence maturity; researchers and practitioners can use the MARs to design interventions that generate stronger and more reusable evidence from technical validation through sustained uptake to development contribution.

In this way, the MARs remain what they are intended to be: **living, science-based roadmaps that inform future research and innovation decisions without predetermining them.**

10. Conclusions

The update and revision of the seven Multiannual Roadmaps (MARs) represent an important achievement of the LEAP-RE programme and a valuable contribution to the consolidation of the AU–EU partnership on Climate Change and Sustainable Energy (CCSE). Building on scientific evidence, emerging technological developments, project experience and stakeholder contributions, the updated roadmaps provide a structured and forward-looking knowledge base to foster future research and innovation cooperation between the two continents.

The seven MARs presented in this deliverable highlight the diversity and complementarity of sustainable energy challenges and opportunities across both continents. They also demonstrate that the success of sustainable energy innovation depends not only on scientific and technological performance, but equally on appropriate governance, infrastructure, regulatory frameworks, stakeholder engagement, financing mechanisms and skills development.

In this perspective, institutional cooperation and capacity building remain essential. Long-term partnerships, including institutional twinning, shared research infrastructures, coordinated funding mechanisms and sustained knowledge exchange, can help transform project-based collaboration into durable AU–EU research and innovation networks. Such mechanisms are particularly important for ensuring that the benefits of cooperation continue beyond individual project funding cycles.

Looking ahead, the updated MARs offer a useful foundation for supporting the continuity and evolution of the AU–EU CCSE partnership, including future joint programming initiatives. Their implementation will require coordinated institutional engagement, appropriate resource mobilisation, periodic reassessment of emerging priorities and mechanisms to monitor progress towards measurable outcomes.

The success of the updated Multiannual Roadmaps should be measured not only by the quality of the research priorities, but also by their capacity to stimulate sustained cooperation and to contribute to an inclusive, resilient and sustainable energy transition.

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