ENANDES Project: Enhancing Adaptive Capacity of Andean Communities through Climate Services (ENANDES) (Chile, Colombia, Peru)

Activity: Conceptualizing a Climate Service Toolkit for Water-Energy-Food Ecosystem Nexus

Deliverable N°1: First report, including a comprehensive global review of existing platforms and frameworks for relevant climate information and services; Definition of the conceptual scope and objectives of the CST for Energy Services and WEF Nexus; and proposed table of content (ToC) for the final report

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ENANDES PROJECT

Climate Service Toolkit for Energy Services and the WEF Nexus

Deliverable 1: Comprehensive review of existing platforms on Climate Services for the Energy and Nexus applications and develop a conceptual scope of a Climate Service Toolkit for Energy

Version 5.0 - final version

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1. Introduction and Context

1.1 Background

Climate variability and climate change affect energy systems across two distinct but related pathways. The first concerns adaptation which linked to the physical infrastructure of energy production, transmission, and distribution is increasingly exposed to climate extremes, including floods, droughts, heat waves, and windstorms, whose frequency and intensity are projected to increase under continued warming [1] . Hydropower reservoirs are subject to altered inflow regimes and amplified drought risk; solar and wind installations face variability in resource availability and exposure to extreme events; and transmission infrastructure is vulnerable to temperature-driven demand peaks and weather-related disruptions. The second pathway concerns mitigation. The transition to low-carbon energy systems depends on an appropriate characterisation of renewable energy resources, reliable sub-seasonal to seasonal, annual, and interannual forecasts of solar, wind, and hydrological parameters, as well as climate-informed investments in new energy generation. In both cases, the quality, accessibility, and timeliness, and type of weather, water, and climate data, information, and services available to energy system actors, such as grid operators, decision-makers and planners, and investment sector, determine the quality of decisions that can be taken.

These challenges are particularly acute in South and Central America, where the energy systems of Andean countries depend heavily on hydropower. In fact, hydropower is contributing approximately 58% of generation in Colombia, 53% in Peru, 73% in Ecuador, and 30% in Chile (OLADE-SIE LAC, 2024, IEA, 2025).[2][3]Hydropower inflow in this region is strongly conditioned by ENSO-driven interannual variability, which produces marked contrasts in precipitation and glacier melt between El Niño and La Niña phases and generates substantial year-to-year uncertainty in reservoir management and grid planning. At the same time, the region is expanding solar photovoltaic and wind capacity at pace, particularly in Chile, Colombia, and Peru, creating a growing demand for operational climate services that existing global tools do not adequately provide. Existing global platforms such as NASA POWER[4] and the Global Solar Atlas provide long-term climatological data but do not offer the ENSO-conditioned seasonal services, regional calibration, and NMHS-oriented deployment design that operational energy management in this region requires.

National Meteorological and Hydrological Services (NMHSs), as WMO Member States, hold the mandate to provide operational weather and climate information, information, and services to all socioeconomic sectors, including the energy sector. The Global Framework for Climate Services (GFCS) formally recognised energy as a priority area for climate services alongside water, health, agriculture, and disaster risk reduction, establishing an institutional framework for the development of structured climate service toolkits tailored to the sector's specific information needs[5]). Despite this recognition, dedicated operational tools or platforms that bring together the full range of weather and climate information and services relevant to energy applications that are accessible to NMHSs in developing and emerging economies remain scarce. Existing global platforms, reviewed in detail in Section 4, address individual aspects of such a comprehensive and scalable platform; however, none of them constitute an integrated and fully NMHS-oriented climate service toolkit for the energy sector.

The ENANDES project[6], funded by WMO and implemented across Colombia, Chile, and Peru with extension to Argentina, Bolivia, and Ecuador (under the ENANDES+ project), addresses this gap directly. Under a dedicated activity and in consultation with all the ENANDES countries, a Climate Service Toolkit that consolidates and contextualises climate information and services for the energy sector applications in South and Central America is being conceptualized.

1.2 Objectives, scope, and methodology

The deliverable 1 presented here serves two related purposes. The first is to provide a comprehensive literature review and analytical foundation on which the Climate Service Toolkit (CST) for energy and nexus conceptualization will be based. This has been done through a systematic assessment of existing global and regional platforms, the definition of transferable design principles, and the identification of remaining gaps. The second is to present a proposed Table of Contents (ToC) and conceptual scope for Deliverable 2, which will set out the full CST architecture and implementation roadmap.

[1] Schaeffer, Roberto, et al. "Energy sector vulnerability to climate change: A review." *Energy* 38.1 (2012): 1-12.
[2] Organización Latinoamericana de Energía (OLADE), Panorama Energético de América Latina y el Caribe 2024.
[3] International Energy Agency (IEA). 2025. Electricity Profiles. Paris: International Energy Agency.
[4] https://power.larc.nasa.gov/
[5] Bloomfield, Hannah, and Oscar Martinez-Alvarado. "Integrated weather and climate services in support of net zero energy transition: best practices from the WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications." *Integrated Weather and Climate Services in Support of Net Zero Energy Transition* (2023).
[6] The ENANDES project (Enhancing Adaptive Capacity of Andean Communities through Climate Services) is funded by the Adaptation Fund and implemented by the World Meteorological Organization. Further information is available at: https://wmo.int/activities/projects/project-portfolio/enandes-building-regional-adaptive-capacity-and-resilience-climate-variability-and-change-vulnerable

The methodology combines two complementary approaches. The first is a systematic desk review of existing climate service platforms and toolkits across the energy, water, and agriculture sectors, covering both public and commercial environments, conducted against the nine assessment criteria defined in Section 3 and documented in the accompanying platform scan (Annex 1) The second draws on the outputs of the ENANDES co-design workshop held in Asunción, Paraguay in November 2025, which engaged national energy and meteorology experts from NMHSs and other stakeholders from across the region. The data has been collection through a systematic approach, following five structured facilitation methods: Meaning Mapping, World Café, Tree Method, User Journey Mapping, and Roadmap exercises (Asunción workshop results, 2025; interactive session facilitation guide, 2025).

Built on these exercises, we have conceptualised the CST for energy and nexus, contributing to the articulation of a shared platform definition, a consolidated set of user requirements, a candidate toolkit architecture, and a phased development pathway reflecting institutional readiness across the region. The outputs of the Asunción workshop are thus, co-design evidence which are not intended to substitute the systematic assessment conducted through the landscape review. Workshops participants converged on a definition of the CST as an operational, modular-based, decision support platform connecting regional and national services and bridging climate science with energy planning and operation. The outputs of the workshop and the conceptual scope are summarised in Section 7.

2. Taxonomy of Climate Services for Energy and the WEF Nexus

2.1 GFCS / RFCS / NFCS framework as the organising structure

Climate service provision within the WMO ecosystem is organised at three levels where each one corresponds to a distinct institutional layer. At the global level, the Global Framework for Climate Services (GFCS) is structured around five interdependent pillars: Observations and Monitoring; Research, Modelling and Prediction; the Climate Services Information System (CSIS); the User Interface Platform (UIP); and Capacity Development (GFCS[7]). These pillars describe the value chain through which scientific climate information is produced, quality-controlled, processed into usable products, delivered to decision-makers, and supported through training and institutional development. Energy has been subsequently added to the GFCS as a priority area alongside water, health, agriculture, and disaster risk reduction, in recognition of the sector's growing exposure to climate variability and its centrality to the low-carbon energy transition.

At the regional level, the Regional Framework for Climate Services (RFCS) coordinates service provision through WMO Regional Climate Centres (RCCs) and Regional Climate Outlook Forums (RCOFs), bridging global scientific production and national delivery capacity. Lastly, at the national level, the National Framework for Climate Services (NFCS) provides the coordination mechanism through which NMHSs bring together sectoral ministries, service providers, and end users. Experience from NFCS implementation across Europe demonstrates that sustained multi-stakeholder coordination at this level is necessary for translating climate information into services that are scientifically reliable and operationally relevant (Golding et al., 2025).

It is important to note that the CST for energy and nexus is structured around the full GFCS value chain. It is based on the Observations and Monitoring and Research, Modelling and Prediction pillars for its data and services layers, positions its user-facing components within the User Interface Platform pillar, and incorporates the Capacity Development pillar as a distinct architectural layer. . As such, the CST constitutes an integration of the GFCS value chain applied to the energy sector and platforms reviewed in Section 4 are assessed against this framework to identify transferable design lessons and institutional precedents.

2.2 Taxonomy by technology, timescale, and decision context

The taxonomy applied in this review organises weather, water, and climate services for the energy sector across four dimensions. The first is by energy sub-sector, including solar PV, wind energy, and hydropower, with biomass and hydrogen-based systems identified as directions for future development. The second organising dimension is the temporal scale of services. Based on the classification set out in WMO (2023), five service timescales are relevant to the energy sector:

- The first is the characterisation of past weather, water, and climate conditions using historical data, including reanalysis and observational records, which provides the baseline for assessing current risks and opportunities in energy production and distribution.
- The second is nowcasting and short-term weather forecasting, covering timescales from seconds to a few hours, which supports load balancing and the maximisation of usable power generation.

[7] Global Framework for Climate Services (GFCS), World Meteorological Organization. Further information available at: https://gfcs.wmo.int/

- The third is sub-seasonal to seasonal forecasting, spanning weeks to months, which supports infrastructure maintenance scheduling, reservoir management, and resource risk planning.
- The fourth is decadal forecasting, extending the seasonal forecast range to approximately ten years, which supports multi-year resource risk management.
- The fifth is multi-decadal climate projection, which supports infrastructure risk assessment, long-term planning, and system design under different emissions scenarios.

These five timescales correspond to three levels of weather, water, and climate provision. At the data level, raw observational and model outputs are produced and made available. At the information level, quality-controlled and processed products are generated from those inputs. At the services level, co-designed, decision-relevant products are delivered to sectoral users. The CST for energy and nexus operates primarily at the services level, integrating data and information from the levels below into decision-relevant products for energy sector actors. The third organising dimension is decision context. The taxonomy distinguishes four contexts: operational energy system management, renewable resource assessment, long-term infrastructure investment, and policy support. The first two represent the primary operational target of the CST for energy and nexus in its minimum viable product, consistent with the prioritisation framework in Section 6.

The fourth dimension distinguishes services by their function in climate change responses. Adaptation services support early warning and risk management for energy infrastructure exposed to climate hazards, including droughts affecting hydropower inflow and extreme weather affecting grid operations. Mitigation-supporting services provide climate information to optimise dispatch scheduling across the energy generation portfolio and to support demand forecasting and demand management.

2.3 The WEF Nexus as a scalability illustration

The CST for energy and nexus in this work is primary designed as a climate-energy-sector platform. The water-energy-food (WEF) Nexus is introduced here to illustrate the platform's scalability across sectors. This extension requires targeted adaptations to three specific components. The first is the selection of observational inputs relevant to water and food applications. The second is the design of analytical workflows suited to those sectors. The third is the configuration of decision-support outputs for the respective user communities. The core architecture, interoperability standards, and deployment model remain unchanged across all three sectors. Floating photovoltaic (FPV) installations on reservoir surfaces in Chile illustrate this nexus in practice (Cáceres González et al., 2025[8] ￼. Solar energy generation and reservoir evaporation reduction yield co-benefits driven by the same climate variables that underpin the CST's energy services, namely solar radiation, temperature, wind speed, and humidity, across a range of Chilean climate contexts. At the regional level, ENSO constitutes the dominant interannual climate driver across the ENANDES countries, conditioning both hydropower inflow regimes and renewable energy generation variability from season to season. ENSO dynamics are addressed within specific analytical modules, particularly the seasonal forecasting component, and do not determine the platform architecture.

2.4 User typology and decision contexts

The CST for energy and nexus is designed within the service-provider and service-user distinction established by the WMO institutional framework. National Meteorological and Hydrological Services (NMHSs) and Regional Climate Centres (RCCs) function as service providers. They operate the platform, co-produce its sector-specific products, and deliver services to energy sector actors through their respective mandates. Energy sector actors constitute the service-user community and are differentiated by application context rather than by a single typology.

Four application categories are identified, each with a distinct user profile and information requirement. The first is the operational management application, in which grid operators and utility dispatch teams require near-real-time monitoring and sub-seasonal to seasonal outlooks to manage generation portfolios and reserve scheduling. The second is the feasibility and resource assessment application, in which renewable energy developers and project finance teams require historical climatological baselines and interannual variability characterisation to support site selection and project design. The third is the planning and investment application, in which national energy ministries and infrastructure investors require multi-annual to multi-decadal climate information to guide capacity expansion decisions and assess climate risk exposure. The fourth is the policy support application, in which regulators and multilateral institutions require aggregated and interpreted climate-energy indicators to inform energy transition policy frameworks.
The CST for energy and nexus prioritises the first two application categories in the minimum viable product, consistent with the feasibility assessment in Section 6. The third and fourth categories are addressed in later phases as the institutional capacity to produce and sustain the required products is developed

[8] Gonzalez, Rodrigo Caceres, et al. "Exploring climate-driven performance of floating photovoltaic systems: Energy production enhancement and evaporation reduction." Applied Energy 386 (2025). https://doi.org/10.1016/j.apenergy.2025.125556

2.5 WMO regional and national implementation arms

The CST for energy and nexus operates within the three-level WMO institutional structure for weather, water and climate service delivery. At the national level, NMHSs hold the mandate for weather, water, and climate data, and are the primary institutional home for CST deployment in NMHSs, operating within their respective NFCS coordination mechanisms. At the regional level, WMO RCCs, particularly CIIFEN for the ENANDES region, provide technical support, regional weather and climate information and services , and capacity development. The seasonal forecast consensus for western South America is coordinated through the Regional Climate Outlook Forum for Western South America (COF-OSA[9])At the global level, the GFCS Secretariat and Global Producing Centres define the standards, frameworks, and normative structures that regional and national levels implement and contextualise. The global level does not operationally supply data to regional and national services as it establishes the authoritative basis on which those services are designed, governed, and assessed. Then, data products such as ERA5 reanalysis, ECMWF ensemble seasonal forecasts, and CMIP6 climate projections are produced by their respective institutions and accessed independently by regional and national services in accordance with globally defined standards and data policies. The present work of conceptualising the CST for energy and nexus operates at this same global normative level since it defines the standards, protocols, and architectural principles that regional and national implementations will apply, in the same way that the GFCS defines the framework within which NMHSs and RCCs develop and deliver their services. This institutional architecture informs the user typology in Section 2.4 and the deployment model to be developed in Deliverable 2.

3. Assessment Framework

3.1 Assessment criteria and comparison matrix

The landscape review in Section 4 applies a structured assessment framework to evaluate existing weather and climate service platforms and toolkits. The process proceeded in two stages. In the first stage, a comprehensive scan was conducted across five sector clusters, namely WMO and GFCS operational frameworks and platforms, European Union (EU) and Joint Research Centre (JRC) tools, global renewable energy data services and energy policy portals, regional platforms in South and Central America, and food security, water, and commercial systems, yielding a total of 48 platforms documented in the accompanying platform scan annex (which can be accessed here). In the second stage, nine assessment criteria were defined and applied systematically to all scanned platforms and the resulting scores were used to select 12 platforms for detailed case study assessment in Section 4.2. The nine criteria were developed through a process that combines the findings of the landscape review with the five GFCS pillar structure and the priority requirements identified in the Asunción co-design workshop. An initial set of candidate criteria was derived from the GFCS pillar definitions and validated against the functional requirements articulated by workshop participants. Criteria were refined following discussions with the CIIFEN team to ensure both technical and institutional dimensions were captured and giving priority given to the two characteristics most directly relevant to CST design, namely modularity and interoperability, and open access with programmatic data availability. This design in turn ensures that the shortlist is transparent and grounded in an explicit rationale. The nine criteria are as follows as shown in Table 1:

Table 1. The nine assessment criteria and their correspondence to the GFCS pillars (C: Criteria)

No.	Criterion Name	Description	GFCS Pillar Correspondence
C1	Modularity and Interoperability	Assesses whether the platform's architecture permits independent deployment of components and standardised data exchange with external systems.	Climate Services Information System (CSIS); User Interface Platform (UIP)
C2	Open Access and API Availability	Assesses whether the platform and its data are freely accessible and whether a documented programmatic interface exists, including machine-readable output in standard formats.	User Interface Platform (UIP)
C3	Data Source Range	Assesses the breadth of observational inputs integrated by the platform, including the capacity for source-level substitution to ensure resilience to outages in any single data stream.	Observations and Monitoring
C4	Temporal Range of Services	Assesses whether the platform covers the full spectrum of decision-relevant timescales, from historical reanalysis through real-time monitoring and sub-seasonal to seasonal forecasting to multi-decadal climate projections.	Research, Modelling and Prediction
C5	Operational Accessibility for NMHSs and RCCs	Assesses whether the platform is designed for and accessible to operational hydrometeorological services in developing country contexts, including co-design processes and infrastructure requirements.	User Interface Platform (UIP); Capacity Development
C6	Capacity Development Support	Assesses the availability of training, documentation, and institutional support associated with the platform,	Capacity Development

[9] Further information at https://crc-osa.ciifen.org

		and whether operational independence is specified as a deployment success criterion.	
C7	GFCS Alignment and Institutional Deployment Model	Assesses the extent to which the platform reflects GFCS principles and has a documented model for national or regional deployment within the WMO institutional structure.	Cross-cutting across all five pillars
C8	Multi-Sector Scalability	Assesses the range of sectors and energy sub-sectors covered by the platform, including whether it serves all three primary energy technologies and whether the architecture can extend to adjacent sectors such as water and food without rebuilding the core infrastructure.	User Interface Platform (UIP)
C9	Sector-Oriented Navigation and Interface Design	Assesses whether a non-expert user from the energy sector can navigate directly to relevant products, and whether content is organised by sector and decision type rather than by data variable or processing level.	User Interface Platform (UIP)

The assessment applied a global scoring approach in which all 48 platforms were rated against all nine criteria. Each criterion was scored on a three-point scale (H for High, M for Medium, L for Low, corresponding to values of 3, 2, and 1 respectively), yielding a maximum total score of 27. Global scores determined the primary shortlisting threshold. Within the analytical report in Section 4.2, the two or three platforms scoring highest on each individual criterion are presented as flag cases to illustrate the range of design approaches and identify the specific design elements transferable to the CST for energy and nexus. This combination of global scoring for shortlisting and criterion-specific flag cases for design learning ensures that the report captures both overall platform strength and the specific best practices applicable to individual components of the platform architecture.

The shortlisting of 12 platforms from the universe of scanned followed a sequential process. Platforms were ranked by total score, and those scoring 17 or above out of 27 were treated as strong candidates for detailed assessment. Platforms scoring below 13 were retained in the scan for gap analysis purposes but excluded from the case studies. Within the intermediate range, inclusion was determined by the diversity of institutional models and sectors represented, ensuring that the final selection spans WMO operational frameworks, EU and JRC platforms, global energy data services, regional South American platforms, and a national deployment precedent. Also, if needed additional platforms are retained in the shortlist below the score threshold. The full scoring matrix and shortlisting rationale are documented in the platform scan, Annex 1.

4. Global Landscape Review

4.1 Cases collection process, regional context, and shortlisting

The landscape review is based on a systematic scan of 48 platforms across five sector clusters: WMO and GFCS operational frameworks and platforms; EU and JRC tools; global renewable energy data services and energy policy portals; regional platforms in South and Central America; and food security, water and nexus. The scan was deliberately extended beyond the energy sector to include the wide nexus perspective. This extension serves two analytical purposes, the first one allows design lessons to be learned from operationally mature systems in adjacent sectors; and second, it provides the multi-sector comparative base needed to identify which capabilities are specific to the energy domain and which are general-purpose features transferable across sectors.

Platforms were identified through WMO institutional knowledge, the GFCS partner registry, and targeted searches within each sector cluster. All 48 platforms are documented with existing names, owners, URLs, descriptions, and WMO affiliation status in the accompanying platform scan Annex 1.. Each platform was assessed against the nine assessment criteria defined in Section 3.1. The regional context for South and Central America shapes both the selection criteria and the interpretation of results throughout this section. In several ENANDES countries, as noted in sections above, hydropower represents a large share of electricity generation, and reservoir inflows are strongly influenced by ENSO-driven interannual climate variability. The importance of these climate–energy linkages was highlighted during the 2023-24 El Niño, which contributed to hydropower deficits across parts of South America and reinforced the sensitivity of hydro-dependent electricity systems to precipitation anomalies and temperature extremes (WMO–IRENA, 2025)[10]. Yet, the nature of ENSO influences is not uniform across the region. In the Pacific-facing Andean catchments of Peru and parts of Chile, El Niño events are generally associated with reduced precipitation and inflows, while La Niña events tend towards the opposite. In Colombia and in the Amazonian catchments of Ecuador, teleconnections are more spatially variable, and the 2023–24 El Niño in particular produced inflow behaviour in several Ecuadorian Amazonian catchments that did not follow the typical Pacific-coast pattern. Looking ahead, these dynamics remain highly relevant, as the latest

[10] WMO–IRENA (2025), 2024 Year in Review: Climate-driven Global Renewable Energy Resources and Energy Demand.

WMO outlook indicates an approximately 80% probability of El Niño conditions developing during June-August 2026, rising to around 90% in subsequent seasons. Nevertheless, regional hydrological impacts will depend not only on ENSO conditions but also on the interaction of ENSO with other regional and local climate drivers (WMO, 2026)[11].

This spatial heterogeneity of ENSO teleconnections is a defining feature of the region and a primary argument for a regionally and nationally calibrated seasonal forecasting capability. So for example, seasonal forecasting at the one-to-four-month horizon is the operationally critical temporal scale for energy system management across the region, regardless of the local sign of the teleconnection. Simultaneously, solar PV and wind capacity are expanding in Chile, Colombia, and Peru, creating demand for operational monitoring and resource assessment services that existing global tools provide only in static climatological form. As result, absence of ENSO-conditioned seasonal services packaged for energy sector operators, and the absence of accessible climate projections for long-term energy infrastructure planning, are the two most consequential gaps motivating the CST for energy and nexus.

It is important to situate seasonal forecasting within the full architecture of the CST for energy and nexus. The CST for energy and nexus is conceived as a modular system organised around the five GFCS pillars, in which the climate information and services component encompasses a range of service types spanning monitoring, resource assessment, seasonal forecasting, and climate projections, each relevant to a different decision timescale and user application. Seasonal forecasting addresses the operationally critical one-to-four month planning horizon and is one service type among several that the platform is designed to host, produce, and deliver. The platform's architecture is defined by its capacity to integrate and standardise multiple service types through modular components, not by any single service. This framing is reflected in the criteria structure applied in Sections 3 and 4 and in the four-layer architecture described in Section 7, and the four main components of the CST for energy and nexus and their correspondence to the five GFCS pillars are presented Section 7.5.

As such, from the 48 scanned platforms, 12 were selected for detailed case study assessment as presented in section 4.2. Selection followed a straightforward rule for most platforms, a score of 20 or above out of 27 combined with direct geographic relevance. Five platforms scored well but were still excluded, and two platforms were included despite falling outside the geographic relevance filter. These seven exceptions are explained individually in Table 2. The complete scoring for all 48 platforms, including the 10 platforms not covered by either the 12 case studies or Table 2, is documented in Annex 1.

Table 2. Platform requiring a documented exception to the standard shortlisting rule

Platform	Score (out of 27)	Reason for exclusion or retention
GFCS CST generic framework	21	Governance and documentation reference and it is not a deployable digital platform. Design lessons cited in Section 5 but not included as a comparable case study.
Flash Flood Guidance System (FFGS) programme	21	Governance and documentation reference and it is not a standalone deployable digital platform. Design lessons cited in Section 5 but not included as a comparable case study.
WMO Early Warnings for All (EW4All) initiative	20	Governance and documentation reference and it is not a standalone deployable digital platform. Design lessons cited in Section 5 but not included as a comparable case study.
Copernicus Climate Data Store (CDS)	22	Data infrastructure portal, not a decision-support platform. Serves as an essential data source for the CST for energy and nexus rather than a design model. Limitations in decision-support orientation cited in Section 5.2.
World Bank Climate Change Knowledge Portal (CCKP)	19	Below shortlist threshold of 20. Limitations in operational depth and operational accessibility for NMHSs cited in gap analysis in Section 5.2 rather than in a dedicated case study.
FEWS NET (Famine Early Warning Systems Network)[12]	21	Geographic coverage limited to regions outside South America. Retained as a design reference specifically for its co-design methodology and sector-first navigation model, which are directly transferable to the CST for energy and nexus.
US National Integrated Drought Information System (drought.gov)	21	Geographic coverage limited to the United States. Retained exclusively as a design reference for criterion C9, Sector-Oriented Navigation and Interface Design. Identified by CIIFEN during preparatory consultations as the interface standard the CST for energy and nexus should aspire to for energy sector users.

[11] WMO (2026), El Niño/La Niña Update, May 2026. Forecast probabilities and impact caveats from the latest WMO ENSO assessment.
[12] https://fews.net/

4.2 Analytical report on selected cases

The following subsections each address one assessment criterion. For each criterion, two or three flag cases drawn from the shortlisted platforms illustrate the range of approaches taken and identify the specific design elements transferable to the CST for energy and nexus. Each subsection closes with a concrete design implication directed at the functional requirements and architecture work in Deliverable 2.

4.2.1 Modularity and Interoperability (C1)

Three platforms illustrate the range of modularity approaches relevant to the CST for energy and nexus; the JRC Climate Station (eStation3), GloFAS, and the NREL RE Data Explorer.

JRC Climate Station (eStation3)[13]

Feature	Relevance to CST for energy and nexus design
50+ thematic products organised as independent processing chains, each activatable, updatable, or replaceable without affecting adjacent products	Establishes the reference standard for product-level modularity. Each thematic module in the CST for energy and nexus must be independently deployable without platform reconfiguration.
Standardised WMS and REST API endpoints allow external systems to query specific products without accessing the full platform environment	Enables interoperability with national NMHS operational systems and with CIIFEN's regional infrastructure without requiring full platform adoption.
Designed for replication across multiple RCCs in different bandwidth and capacity contexts	Directly analogous to the ENANDES deployment scenario, where the platform must function across NMHSs with varying infrastructure capacity.
Products from different data sources (CHIRPS and ERA5) can coexist on the same installation, toggled by the operator	Confirms that source-level substitution is architecturally feasible within a modular design, supporting the CST's resilience requirement.

GloFAS[14]

Feature	Relevance to CST for energy and nexus design
Real-time flood monitoring and seasonal streamflow outlook components operate on independent update cycles and can be queried independently	Illustrates modularity at the functional layer as an NMHS needing only the seasonal hydrological outlook for reservoir scheduling does not need to engage with the flood monitoring layer at all.
Components driven by different data sources without structural interdependency	Confirms that functionally independent modules can be built upon different data sources within the same platform without structural conflict.
Usable at different levels of engagement depending on institutional capacity and decision context	Directly relevant to ENANDES NMHSs, where the platform must accommodate a range of operational capacities across participating countries.

NREL RE Data Explorer[15]

Feature	Relevance to CST for energy and nexus design
Solar, wind, and complementary resource datasets independently accessible via API	Demonstrates modularity at the data source level since institutions can access individual datasets without adopting the full platform interface.
Visualisation interface decoupled from the data retrieval layer	Allows ENANDES NMHSs with existing national portals to ingest external energy data without redirecting users to an external platform.
Developed with attention to lower-bandwidth connectivity	Directly relevant to NMHS infrastructure constraints across the ENANDES region.

Design implication for D2. The CST for energy and nexus must implement product-level modularity following the eStation3 precedent, with each thematic module covering solar resource, wind resource, hydropower inflow, seasonal forecasting, and climate projections independently deployable. A country-level deployment in a minimal

[13] https://estation.jrc.ec.europa.eu/eStation3/
[14] https://global-flood.emergency.copernicus.eu/
[15] https://nsrdb.nlr.gov/

configuration during Phase 1 must be extendable to the full product suite in Phase 2 without requiring platform reconfiguration or reinstallation.

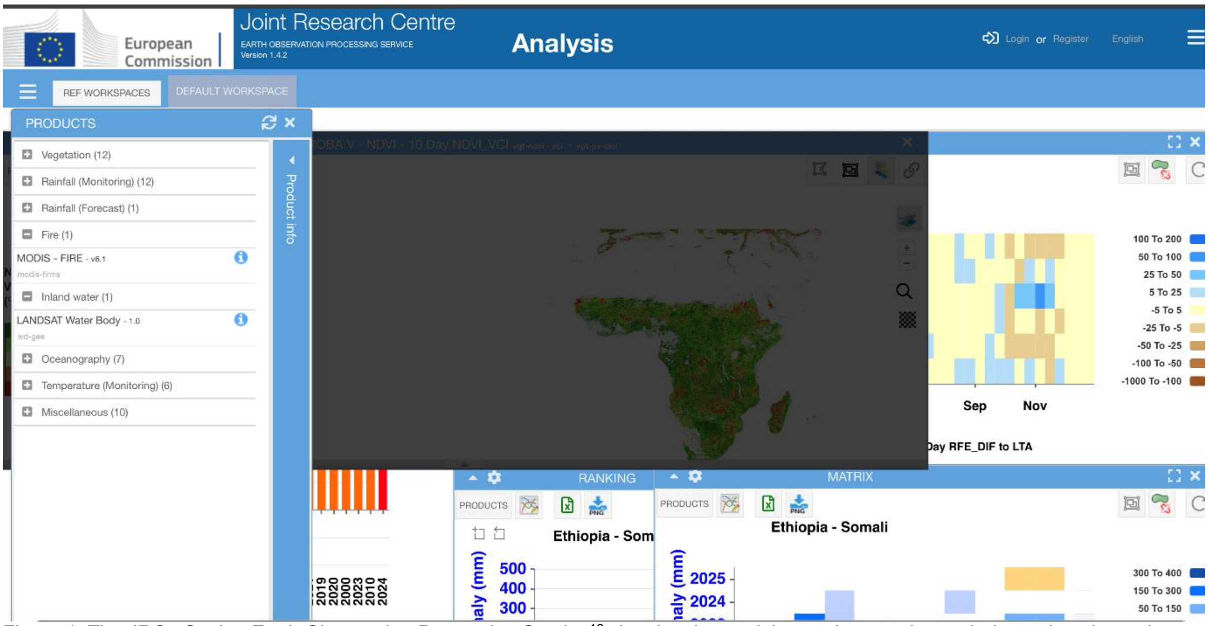

Figure 1. The JRC eStation Earth Observation Processing Service[16] showing the modular product catalogue. Independent thematic categories such as Vegetation, Rainfall, Fire, Inland Water, Oceanography, Temperature compose this platform and each contain versioned products drawing on specific data sources. The expanded Fire category shows MODIS-FIRE v6.1 as a self-contained module that can be activated, updated, or replaced without affecting adjacent products. This product-level modularity is then the suggesteed primary design precedent the CST for energy and nexus adopts for its service layer architecture.

4.2.2 Open Access and API Availability (C2)

Three platforms define the benchmark for open access and programmatic data availability relevant to the CST for energy and nexus: NASA POWER, the NREL RE Data Explorer, and the IRI Data Library.

NASA POWER[17]

Feature	Relevance to CST for energy and nexus design
REST API requires no registration and imposes no rate limits for standard queries	Registration-free access is critical in developing country NMHS contexts where institutional email addresses may not be recognised and reliance on personal accounts creates operational continuity risks.
Returns machine-readable output in JSON, ASCII, and CSV	Ensures compatibility with the range of data processing tools used by ENANDES NMHSs.
Comprehensive documentation includes Python code examples for renewable energy and agricultural use cases	Reduces the technical barrier for NMHS teams to integrate the API into operational workflows.

NREL RE Data Explorer

Feature	Relevance to CST for energy and nexus design
Bulk data download requires no registration	Extends the NASA POWER open access model with explicit attention to lower-income country deployment contexts.
API documented in both Python and R	Accommodates the range of programming environments in use across ENANDES NMHSs.
Developed with attention to lower-bandwidth connectivity	Directly addresses the infrastructure constraints of NMHS environments in the ENANDES region.

IRI Data Library[18]

16 https://estation.jrc.ec.europa.eu/eStation3/
17 https://power.larc.nasa.gov/
18 https://iridl.ldeo.columbia.edu/

Feature	Relevance to CST for energy and nexus design
INGRID query language allows programmatic subsetting, aggregation, and format conversion of climate datasets without downloading full files	Demonstrates open access for seasonal forecast data, enabling bandwidth-efficient data access for NMHS operational workflows.
Historical seasonal forecast archives available programmatically with tercile probabilities for precipitation, temperature, and derived variables	Allows skill assessment and calibration of CST seasonal products against a long record of regional forecast performance, which is a practical requirement for NMHS adoption.

Design implication for D2. The CST for energy and nexus must provide a fully documented REST API with no registration barrier, machine-readable output in standard formats, and code examples in at least Python, R or others as agreed. As such, low-bandwidth compatibility and the capacity to serve both full platform users and data-layer API users are design requirements from Phase 1.

An example of this implication is shown below:

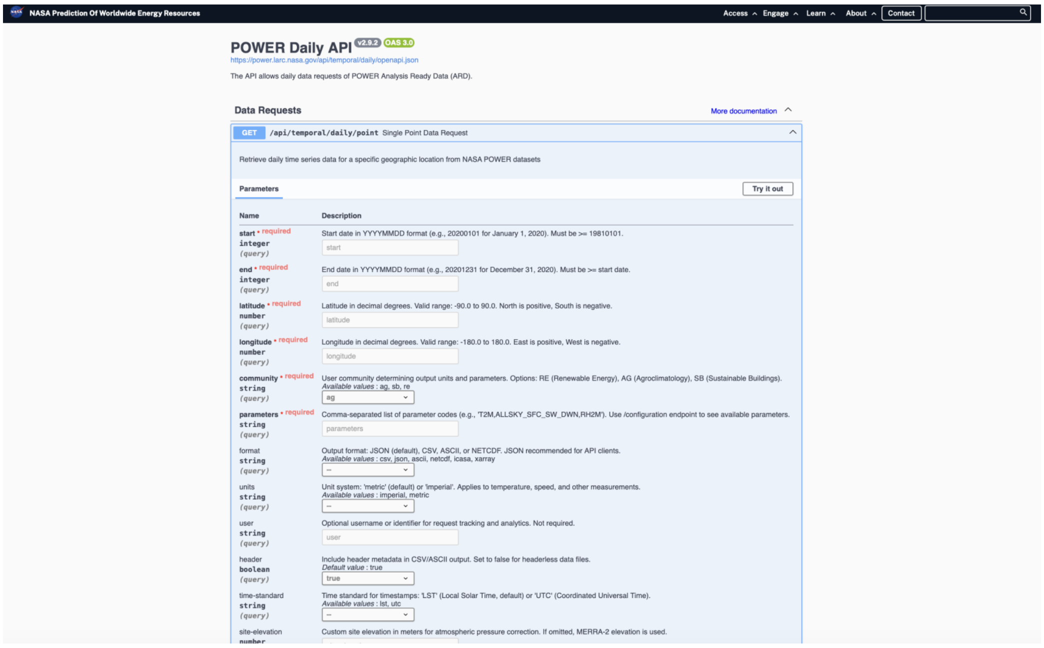

Figure 2. The NASA POWER Daily API[19] expanded endpoint showing the full parameter set for a single-point data request. Output formats include JSON, CSV, ASCII, and NetCDF. The user field description states explicitly that a username is optional and not required. The API is executable directly from a public browser session with no login or registration which needs to be the open access standard the CST for energy and nexus adopts for its own data layer.

4.2.3 Data Source Range (C3)

Three platforms show the range of approaches to multi-source data integration relevant to the CST for energy and nexus: the JRC Climate Station (eStation3), HydroSOS, and FEWS NET.

JRC Climate Station (eStation3)[20]

Feature	Relevance to CST for energy and nexus design
Integrates ERA5 reanalysis, CHIRPS precipitation, ECMWF SEAS5 seasonal forecasting, MODIS land surface products, and Copernicus Global Land Service for soil moisture and surface albedo	The broadest range of observational inputs in the scan. The multi-source architecture ensures product availability is resilient to outages in any single data stream.
Data management layer abstracts source complexity from the user,	Directly applicable to CST design as users should not need to know which data source underlies a given product.

[19] https://power.larc.nasa.gov/api/pages/#/Data%20Requests/daily_single_point_data_request_api_temporal_daily_point_get
[20] https://estation.jrc.ec.europa.eu/eStation3/

presenting consistent product interfaces regardless of which underlying data stream is active	
Products can be cross-validated against independent observational sources	Supports quality control and confidence-building for NMHS teams adopting the platform.

HydroSOS[21]

Feature	Relevance to CST for energy and nexus design
Combines in-situ station data, GRACE and GRACE-FO satellite gravimetry, and global hydrological model outputs to produce standardised hydrological status indicators	Demonstrates that usable indicators can be generated in data-sparse environments, directly relevant to ENANDES Andean and Amazonian catchments where monitoring infrastructure is uneven.
Satellite gravimetry provides regional-scale water storage context where ground networks are sparse, complementing rather than substituting in-situ networks	Establishes an appropiate cdesign principle for high-altitude Andean basins as satellite data as complement.

FEWS NET[22]

Feature	Relevance to CST for energy and nexus design
Integrates CHIRPS rainfall, MODIS vegetation, USGS streamflow estimates, commodity price indices, and livelihood zone classifications derived from household surveys	Demonstrates that data source breadth does not require a monolithic technical backend.
Integration is an analytical synthesis by expert teams into a unified regional outlook, not a technical merger of datasets	The CST for energy and nexus does not need to ingest all relevant data sources into a single database. It needs an architecture that allows products from different source combinations to coexist and update on independent schedules.

Design implication for D2. The CST for energy and nexus must integrate at minimum ERA5 reanalysis, CHIRPS or IMERG precipitation, ECMWF SEAS5 seasonal forecasting, and CORDEX-SA climate projections as its core data sources. The architecture must support source-level substitution so that if a primary data stream is unavailable or degraded, an alternative source can be activated at the product level without platform-level reconfiguration.

An example of this implication is shown below:

[21] https://wmo.int/activities/hydrosos
[22] https://fews.net/

Figure 3. FEWS NET's food security outlooks[23] are produced through the synthesis of multiple independent analytical streams (climate monitoring, remote sensing, hydrological information, market intelligence, and livelihood assessments) combined through a structured scenario-development process[24]. Each evidence layer can be updated, refined, or substituted independently without requiring redesign of the overall system. The CST for energy and nexus adopts this architectural principle. Sectoral products are derived from independent source layers and analytical modules that can each evolve separately, which is what allows new data sources and new service types to be added without rebuilding the core infrastructure.

4.2.4 Temporal Range of Services (C4)

Three platforms illustrate the temporal service coverage relevant to the CST for energy and nexus, the Copernicus Energy Hub, the IRI Data Library, and GloFAS[25].

Copernicus Energy Hub[26]

Feature	Relevance to CST for energy and nexus design
Provides ERA5 reanalysis from 1940, ERA5T near-real-time data with approximately five-day latency, and ECMWF seasonal forecast products	The most developed dedicated energy-sector climate platform in the scan, yet it does not cover the full temporal range.
Does not currently integrate a multi-decadal climate projections layer	The single most significant finding from this case is that the CST for energy and nexus must close this projections gap deliberately rather than assuming an existing energy platform can be adopted. The projections module must be specified in D2 from the outset and positioned as a Phase 2 delivery.

IRI Data Library[27]

Feature	Relevance to CST for energy and nexus design
Seasonal forecast products available programmatically with tercile probabilities for precipitation, temperature, and derived variables	Provides the most operationally relevant seasonal layer for the ENANDES region.
Historical seasonal forecast archives allow skill assessment and calibration against observed outcomes	Allows the CST for energy and nexus to validate its seasonal products against a long record of regional forecast performance, which is a practical requirement for NMHS adoption.
ENSO-conditioned South American seasonal outlook products produced through two decades of collaboration with regional NMHSs	The closest existing operational service to the seasonal forecasting component the CST requires for hydropower management.

GloFAS[28]

Feature	Relevance to CST for energy and nexus design
Streamflow-specific seasonal outlook at seven-month lead time, available as probabilistic ensemble output at 0.1-degree resolution	Corresponds to the operational planning horizon for reservoir scheduling in many ENANDES catchments. The most directly actionable seasonal product for hydropower operators in the scan.
Queryable by river basin or grid cell via REST API	Programmatic access design directly applicable to NMHS operational workflows and CST API architecture.
Natural complement to the atmospheric seasonal layer from IRI	Together with IRI, covers the atmospheric forcing and hydrological response dimensions of ENSO-conditioned energy system management.

Design implication for D2. The CST for energy and nexus must cover all five temporal modes defined in WMO (2023): historical characterisation using reanalysis and observational records, near-real-time monitoring, sub-seasonal to seasonal forecasting, decadal forecasting, and multi-decadal projections. Note: The seasonal layer, integrating ECMWF SEAS5 and ENSO-conditioned regional products following the IRI methodology, is operationally critical and must be present in the minimum viable product. The projections layer, retrieving on CORDEX-SA, is a Phase 2 delivery but must be architecturally anticipated in Phase 1.

[23] https://fews.net/latin-america-and-caribbean
[24] https://fews.net/global/guidance-documents/january-2018/print
[25] https://global-flood.emergency.copernicus.eu/
[26] https://energy.hub.copernicus.eu/
[27] https://iridl.ldeo.columbia.edu/
[28] https://global-flood.emergency.copernicus.eu/

An example is shown in the Figure 4 below:

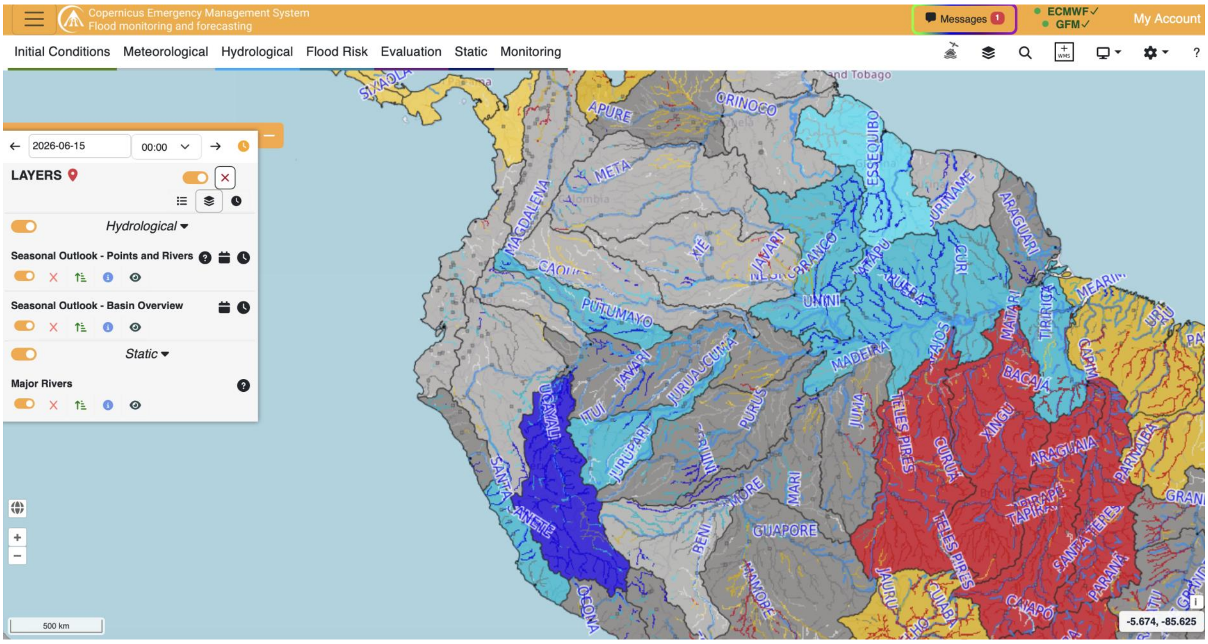

Figure 4. The GloFAS[29] Seasonal Outlook Basin Overview[30] showing the probability of unusually high (blue) or low (red and orange) river flows over the coming months. Darker shading indicates higher probability. The spatial heterogeneity of the seasonal signal across the ENANDES region illustrates why seasonal services for hydropower management cannot apply a single regional signal and must be calibrated or aligned to individual catchments.

4.2.5 Operational Accessibility for NMHSs and RCCs (C5)

Three cases illustrate the range of approaches to NMHS operational accessibility relevant to the CST for energy and nexus: the Bhutan CST, HydroSOS, and the ENANDES CST v1.

Bhutan CST[31]

Feature	Relevance to CST for energy and nexus design
Complete national deployment by an NMHS in a lower-income country context, co-designed through a structured process spanning needs assessment, product design, technical training, and operational handover	The only platform in the scan documenting the full deployment lifecycle. Defines what successful CST deployment looks like for the ENANDES context.
NMHS team participated in selecting the product suite and validating outputs against local observational data before the platform was considered operational	Co-design and local validation are non-negotiable deployment requirements, not optional quality measures.
After deployment, the NMHS operates the system independently, with RIMES providing remote technical support on request	Operational independence is the correct definition of successful deployment. Technical installation alone does not constitute delivery.

[29] https://global-flood.emergency.copernicus.eu/
[30] https://global-flood.emergency.copernicus.eu/react/map
[31] http://cst-bhutan.rimes.int/

HydroSOS[32]

Feature	Relevance to CST for energy and nexus design
Positions NMHSs as producers within a global hydrological status system rather than as passive users	Inverts the conventional NMHS-as-user model. ENANDES NMHSs should be positioned as contributors of locally observed and validated data that improve regional product quality.
National hydrological status assessments feed into a regional synthesis coordinated through WMO	Gives NMHSs institutional ownership of the system rather than dependency on it.

ENANDES CST v1[33]

Feature	Relevance to CST for energy and nexus design
Product suite limited in energy-sector depth; ENSO-informed seasonal services absent	Documents the current operational baseline and the depth of the service gap to be addressed.
Interface designed primarily for climate specialists rather than energy sector operators	The gap between the existing baseline and the operational requirement defined in Section 2.4 is the primary design motivation for the new CST for energy and nexus.

Design implication for D2. Operational accessibility requires co-design of the product suite with each country's NMHS team, training integrated into the deployment process rather than provided separately, documentation and interface in Spanish, and a platform that functions under the infrastructure conditions typical of ENANDES NMHSs. The Bhutan CST[34] co-design process is the reference model for country engagement planning in D2. Operational independence of each NMHS team must be specified as a formal deployment success criterion.

An example is shown below:

Figure 5. The product tiles show the operational functions performed by the NMHS team, including seasonal outlook products, weekly observation uploads, sub-seasonal forecasting, and sector-specific data exports. The platform is operated without external assistance after deployment. Operational independence of this kind is the deployment success criterion the CST for energy and nexus adopts from this precedent.

4.2.6 Capacity Development Support (C6)

[32] https://wmo.int/activities/hydrosos
[33] https://crc-osa.ciifen.org/CST/
[34] http://cst-bhutan.rimes.int/

Three references establish the range of capacity development approaches relevant to the CST for energy and nexus, they are the the Bhutan CST, CIIFEN's existing Regional Climate Centre infrastructure, and drought.gov.

Bhutan CST[35]

Feature	Relevance to CST for energy and nexus design
Training structured across three phases corresponding to distinct operational competencies, basic product use and interpretation, sector-specific application, and system administration for routine operation and updates	Capacity development must be an integral component of the deployment process itself, structured across phases rather than delivered as a standalone event.
Platform not considered successfully deployed until the NMHS team demonstrated operational independence	Operational independence must be formally adopted as an exit criterion for the ENANDES deployment and specified in D3.

CIIFEN Regional Climate Centre[36]

Feature	Relevance to CST for energy and nexus design
Established training activities, national focal point relationships in each ENANDES country, and technical support channels across the ENANDES region	The CST for energy and nexus deployment does not need to build a capacity development mechanism from scratch. CIIFEN's Regional Climate Centre infrastructure already provides one.
WMO mandate for systematic capacity development for NMHSs in western South America	Pre-existing institutional infrastructure is among the most significant enabling factors for the Task 5 pilot. This positions CIIFEN as the natural delivery partner for the CST training programme.
Existing training cycle and capacity development calendar already operating across ENANDES NMHSs	The CST training programme can be integrated into CIIFEN's existing cycle rather than running in parallel, avoiding duplication and leveraging established NMHS relationships.

drought.gov[37]

Feature	Relevance to CST for energy and nexus design
Decision calendar maps the annual cycle of energy management decisions to the relevant climate information products at each point in the year	Functions as just-in-time capacity development embedded in the interface, reducing the training burden on NMHSs.
Guidance embedded in the interface itself rather than provided through separate documentation or training events	Extends platform accessibility to energy sector users who engage with climate information episodically rather than continuously, without requiring formal training attendance.

Design implication for D2. The CST for energy and nexus must integrate sector-specific decision calendars into the user interface from the minimum viable product phase. The formal training programme must be delivered through CIIFEN's existing Regional Climate Centre capacity development infrastructure rather than developed as a parallel activity. D2 must specify how the CST training programme integrates into CIIFEN's existing capacity development calendar, including the sequencing of training phases relative to platform deployment milestones. Operational independence of each country NMHS team must be specified as a formal deployment success criterion in D2.

An example of this feature is shown below:

[35] http://cst-bhutan.rimes.int/
[36] https://crc-osa.ciifen.org/
[37] https://www.drought.gov

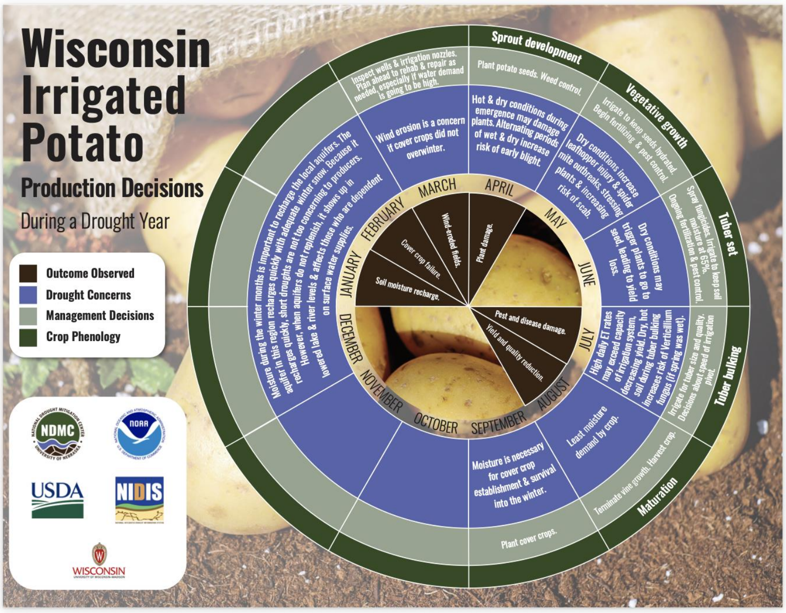

Figure 6. The Midwest Crop Production Decision Calendar on drought.gov maps management decisions to the annual cycle by month[38]. The CST for energy and nexus could adopt this format (e.g. decisions indexed by month and linked to relevant climate information) applied to the annual cycle of energy sector decisions (rather than crop production).

4.2.7 GFCS Alignment and Institutional Deployment Model (C7)

HydroSOS provides the strongest model for institutional legitimacy and GFCS alignment in the scan and serves as the primary reference case for this criterion.

HydroSOS[39]

Feature	Relevance to CST for energy and nexus design
Approved by WMO Congress through Resolution 25 of Cg-18 and overseen by the WMO Hydrological Assembly	Institutional grounding through formal WMO governance signals durability and long-term commitment to member states, independent of any individual project cycle.
Governance foundation translates into NMHS confidence that contributing to and using the system is a long-term operational investment	For the CST for energy and nexus, the equivalent signal of permanence is formal GFCS endorsement and integration into the CIIFEN Regional Climate Centre mandate.
Positioned within the standard WMO weather, water, and climate service delivery chain rather than as a project output	The CST for energy and nexus must be formally positioned within the GFCS three-level structure from the outset, with CIIFEN's Regional Climate Centre mandate as the regional institutional anchor.
WMO approval pathway documented and initiated during the operational phase, not after	The WMO endorsement pathway should be specified in D2 and the endorsement process initiated during the D3 pilot phase.

An example of this feature is shown below:

[38] https://www.drought.gov/documents/midwest-crop-production-decision-calendars-and-fact-sheets
[39] https://wmo.int/activities/hydrosos

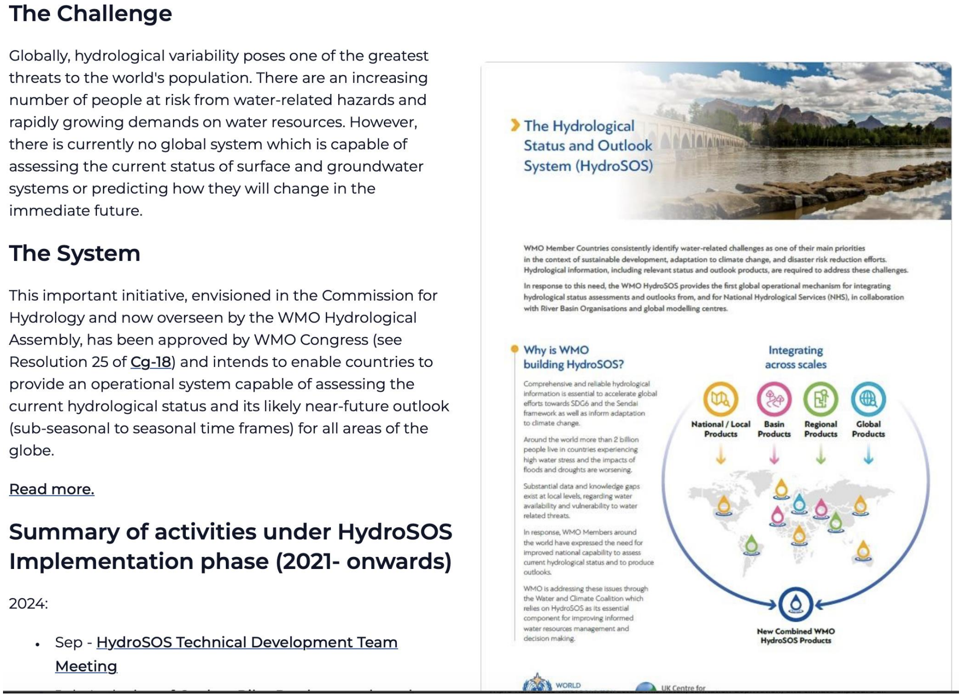

Figure 7. The WMO HydroSOS page on the WMO Community Platform[40] showing formal approval through Resolution 25 of the Eighteenth World Meteorological Congress (Cg-18). Institutional grounding through WMO governance is the design element transferable to the CST for energy and nexus.

Design implication for D2. The CST for energy and nexus should be formally positioned within the GFCS three-level structure from the outset, with CIIFEN's Regional Climate Centre mandate as the regional anchor. Formal GFCS endorsement is the mechanism through which the platform becomes a permanent component of the WMO weather, water, and climate service delivery chain rather than a project-dependent output. The WMO endorsement pathway must be specified in D2 and the endorsement process initiated during the D3 pilot phase.

4.2.8 Multi-Sector Scalability (C8)

Three platforms illustrate the range of approaches to multi-sector and multi-technology coverage relevant to the CST for energy and nexus: the Copernicus Energy Hub, NASA POWER, and FEWS NET.

Copernicus Energy Hub[41]

Feature	Relevance to CST for energy and nexus design
Solar, wind, hydropower, and energy demand products all available from a single platform with a consistent interface and data standard	A grid operator managing a mixed generation portfolio can access climate information for all technologies without switching platforms or converting between data formats.
Each product uses ERA5 as its observational backbone, ensuring methodological consistency when comparing across technologies	Product coherence across technologies is as important as breadth. Consistency in the underlying data methodology allows cross-technology comparisons that are not possible when different products using on different sources.

NASA POWER[42]

Feature	Relevance to CST for energy and nexus design

[40] https://community.wmo.int/site/knowledge-hub/programmes-and-initiatives/global-hydrological-status-and-outlook-system-hydrosos
[41] https://energy.hub.copernicus.eu/
[42] https://power.larc.nasa.gov/

Same MERRA-2 reanalysis backbone feeds both the renewable energy product suite and the agricultural meteorology product suite with modest additional computational overhead	A shared observational infrastructure can serve multiple sectors with targeted product packaging, amortising the investment in a high-quality data backbone across multiple user communities simultaneously.
Sectoral differentiation occurs at the product layer, not at the data layer	Confirms the core architectural principle: the data and infrastructure layer is sector-agnostic; the climate information and services layer is sector-specific.

FEWS NET[43]

Feature	**Relevance to CST for energy and nexus design**
CHIRPS rainfall, MODIS vegetation, and USGS streamflow products feed food security, pasture condition, and water access analyses simultaneously from a shared data layer	Demonstrates that multi-sector coverage does not require a monolithic backend or separate data ingestion pipelines for each sector.
Sectoral differentiation occurs entirely at the product and interpretation layer	The data layer is shared and sector-agnostic; the product layer is specialised. This separation is the architectural principle that allows extension to adjacent sectors without rebuilding the observational infrastructure.

Design implication for D2. The CST for energy and nexus architecture must treat the data and infrastructure layer and the climate information and services layer as explicitly separate components. The data infrastructure, built on ERA5, CHIRPS, ECMWF SEAS5, and satellite Earth observation, is sector-agnostic and can serve energy, water, and food sector applications simultaneously once established. Sectoral differentiation occurs at the services layer through the definition of energy-specific indicators, thresholds, and visualisations. This separation is the technical mechanism that allows new sectors to be added in future phases without modifying the core data infrastructure, and it is the architectural basis for the platform's long-term extensibility.

An example of this, is observed in Figure 7 below:

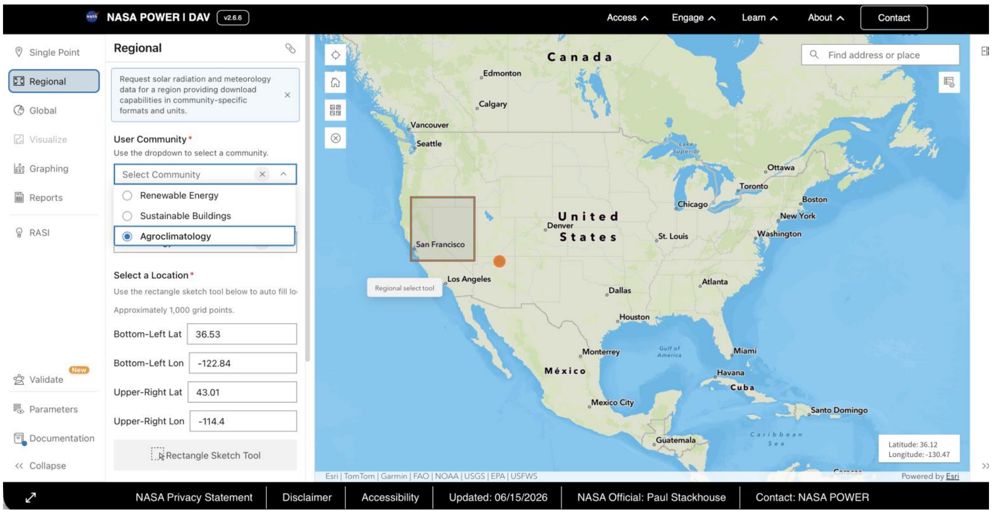

Figure 8. The NASA POWER Data Access Viewer[44] showing three distinct user communities: Renewable Energy, Sustainable Buildings, and Agroclimatology. They are served by the same underlying data infrastructure. The User Community selection filters the parameter catalogue to sector-relevant variables without changing the data backbone

4.2.9 Sector-Oriented Navigation and Interface Design (C9)

Three platforms define the interface design standard for the CST for energy and nexus: drought.gov, the NREL RE Data Explorer, and the Copernicus Energy Hub[45]. Drought.gov was identified by CIIFEN during preparatory consultations as the interface standard the CST for energy and nexus should aspire to for energy sector users.

drought.gov

[43] https://fews.net/
[44] https://power.larc.nasa.gov/data-access-viewer/
[45] https://energy.hub.copernicus.eu/

Feature	Relevance to CST for energy and nexus design
Topic-first navigation taxonomy: the user's entry point is a sectoral decision context, not a data variable. Persistent navigation menus maintain the user's sector context throughout the session	No prior climate expertise is required to reach energy-relevant content. The architecture reduces cognitive load for energy sector users by eliminating the need to understand the underlying data structure before reaching relevant products.
Decision-calendar format explicitly names the operational decisions each product supports and the months in which they are most relevant	Functions as capacity development embedded in the interface. Reduces the training burden on NMHSs and extends platform accessibility to energy sector users who engage with climate information periodically rather than continuously.

NREL RE Data Explorer

Feature	Relevance to CST for energy and nexus design
Map-first interaction model: the user's first action is a spatial selection, immediately returning location-specific resource data without requiring navigation of a data catalogue	Appropriate for resource assessment applications where the entry point is a geographic location rather than a dataset choice. Corresponds to the actual workflow of an energy developer conducting a site assessment.
The interface asks 'where' rather than 'which dataset'	Complementary to the decision-type model of drought.gov. Different energy user types enter from different entry points, and the interface must support both.

Copernicus Energy Hub[46]

Feature	Relevance to CST for energy and nexus design
Products organised by energy application rather than by the ERA5 variable from which each product is derived	A solar developer locates the photovoltaic yield product without needing to know it is calculated from surface solar radiation downwards in the ERA5 archive. Product names use the vocabulary of the energy sector user, not the climate data producer.
Application-oriented product organisation mediates between the technical climate data system and the practical energy decision context	This is the function of a User Interface Platform within the GFCS architecture. The Copernicus Energy Hub's application-oriented naming provides the vocabulary standard for the CST for energy and nexus interface.

Design implication for D2. The CST for energy and nexus interface must organise products by energy application and decision type, with distinct entry points for a hydropower operator, a solar or wind developer, and a grid manager. Drought.gov's decision-calendar structure and the NREL RE Data Explorer's location-first navigation together define the interface model. The Copernicus Energy Hub's application-oriented product naming provides the vocabulary standard. Ease of navigation is a first-order design requirement, not a cosmetic feature, and must be specified as such in D2.

An example of this functionality is shown below:

[46] https://energy.hub.copernicus.eu/

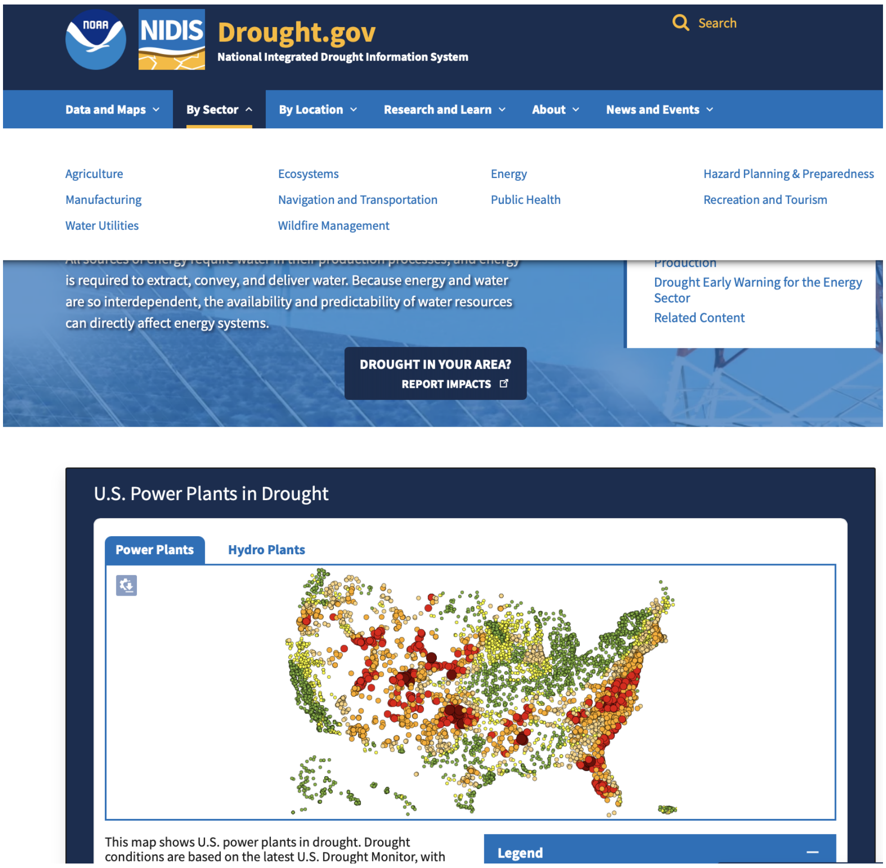

Figure 9. The drought.gov[47] top navigation showing sector-first organisation. Users enter through a decision context (energy, agriculture, water utilities). The URL structure (/sectors/energy) reflects this topic-first taxonomy throughout the site.

5. Synthesis of Best Practices, Gaps, and Enabling Factors

The landscape review supports the central finding stated in Section 2.2 that among the 48 platforms scanned, none covers taxonomy dimensions simultaneously across all three primary energy technologies within a single NMHS-deployable framework for the regional energy sector. Technically strong platforms exist for individual dimensions, but not for their combination within a single NMHS-deployable tool. The following synthesis extracts the specific design elements transferable to the CST for energy and nexus, identifies the consequential gaps, and notes the enabling factors that make the CST for energy and nexus both necessary and feasible.

5.1 Best practice design elements

Nine transferable design elements emerge from the case analysis, one corresponding to each assessment criterion. Table 3 below presents each element alongside the primary platform reference or references from which it is drawn and the specific lesson transferable to the CST for energy and nexus. The design elements are the analytical bridge between the landscape review in Section 4 and the prioritisation framework in Section 6.

Table 3. Best practice design elements by assessment criterion:

Criterion	Primary platform reference(s)	Transferable design element

[47] https://www.drought.gov/sectors/energy

C1 Modularity and Interoperability	**JRC Climate Station (eStation3)**[48]	• Product-level modularity with standardised API endpoints. Each module is independently deployable. • eStation3: 50+ independent processing chains, standardised WMS and REST endpoints, source-level substitution. • Designed for replication across RCCs with different bandwidth and capacity profiles.
C2 Open Access and API Availability	**NASA POWER** **NLR NSRDB Viewer**[49] **(formerly NREL)**	• Registration-free access via a documented REST API. Output in JSON, ASCII, CSV. • NASA POWER: no set rate limits, Python code examples included. • NLR NSRDB Viewer: low-bandwidth design, API documentation in Python and R, free API key via simple registration
C3 Data Source Range	**JRC Climate Station (eStation3)**[50] **HydroSOS**[51]	• Multi-source integration with source-level substitution. Resilient to single-source outages. • eStation3: consistent product interfaces regardless of which data stream is active. • HydroSOS: combines in-situ observations with satellite-derived precipitation, soil moisture, and snow cover data in data-sparse environments
C4 Temporal Range of Services	**Copernicus Energy Hub**[52] **IRI Data Library**[53] **GloFAS**[54]	• Full temporal coverage, historical to multi-decadal projections, per the five-mode WMO (2023) classification. • Copernicus Energy Hub lacks a projections layer. The CST must integrate the full range deliberately. • IRI Data Library: ENSO-conditioned seasonal methodology for the ENANDES region. • GloFAS: hydrological response layer, up to seven months lead time.
C5 Operational Accessibility for NMHSs and RCCs	**Bhutan CST**[55]	Phased co-design with NMHS teams. Operational independence as the formal deployment success criterion. • Bhutan CST: needs assessment, product design, training, handover, ending in independent NMHS operation. • Operational independence, not technical installation, is the exit criterion for ENANDES deployments.
C6 Capacity Development Support	**drought.gov**[56] **CIIFEN Regional Climate Centre**	• Sector-specific decision calendars embedded in the interface as built-in capacity development. • Drought.gov: decision-calendar format adopted for energy management decisions. The CST takes the approach, not the content. • CIIFEN's existing RCC infrastructure, training cycles and national focal points, delivers this.
C7 GFCS Alignment and Institutional Deployment Model	**HydroSOS**[57]	• Formal positioning within the GFCS three-level structure. CIIFEN's RCC mandate as regional anchor.

[48] https://estation.jrc.ec.europa.eu/eStation3/
[49] https://nsrdb.nlr.gov/
[50] https://estation.jrc.ec.europa.eu/eStation3/
[51] https://wmo.int/activities/hydrosos
[52] https://energy.hub.copernicus.eu/
[53] https://iridl.ldeo.columbia.edu/
[54] https://global-flood.emergency.copernicus.eu/
[55] http://cst-bhutan.rimes.int/
[56] https://www.drought.gov
[57] https://wmo.int/activities/hydrosos

		• HydroSOS: WMO Congress approval (Resolution 25, Cg-18) signals long-term institutional investment. • climateinformation.org[58] (SMHI, for WMO, WCRP, GCF): supplementary reference, general-purpose, not energy-specific.
C8 Multi-Sector Scalability	**FEWS NET[59]** **NASA POWER[60]**	• Data and infrastructure layer kept separate from the services layer. Sectoral differentiation happens at the services layer only. • FEWS NET: one data backbone feeds food security, pasture, and water access analyses. • NASA POWER: one reanalysis backbone feeds both renewable energy and agroclimatology suites.
C9 Sector-Oriented Navigation and Interface Design	**drought.gov** **NLR NSRDB Viewer[61] (formerly NREL)** **Copernicus Energy Hub[62]**	• Sector-first, decision-type navigation with distinct entry points per user category. • Drought.gov: topic-first URL taxonomy, decision calendars by month and decision type. • NLR NSRDB Viewer: location-first map interface. The user selects a site before any data catalogue. • Copernicus Energy Hub: products named by energy application, not by the underlying ERA5 variable.

5.2 Key gaps

The gap analysis is organised around the four main components of the CST for energy and nexus, aligned with the GFCS pillar structure. The central finding of the landscape review is that no platform in the scan covers all five temporal modes across all three primary energy technologies within a single NMHS-deployable framework. So, this finding reflects structural gaps across all four components.

Gap 1: Data and Infrastructure Component

The CST for energy and nexus is built after the operational launch of the WMO Information System 2.0, WIS 2.0,[63] in January 2025, which replaced the Global Telecommunication System as the WMO framework for weather, water, and climate data exchange across 193 Member States. WIS 2.0 uses MQTT publish-subscribe protocols for real-time data notifications, HTTP(S) for downloads, OGC API-Records for metadata discovery, and the WMO Core Metadata Profile for dataset description.

As such, the ambition is that the CST must conform to WIS 2.0 standards from the outset, specially since no platform in the scan was designed to do so, since most predate WIS 2.0's operational launch. Beyond WIS 2.0 compliance, no platform systematically references the WMO Observing Systems Capability Analysis and Review Tool (OSCAR[64]) requirements for energy-relevant physical variables (i.e. solar irradiance, wind speed at hub height, precipitation and runoff for hydropower) to characterise where regional observing network gaps affect product quality. Finally, no platform defines the technical and data exchange protocols that independently developed climate service modules must satisfy in order to be integrable into a shared modular architecture. It is thus the definition of these integration standards a primary deliverable of D2.

Gap 2: Climate Information and Services Component

A structurally important point for this component is that the platform does not itself develop climate services. It defines a structured and standardised format within which individually developed services can be integrated. Seasonal climate prediction is one service type among many that the platform must be capable of hosting. No existing platform defines this integration framework. The primary service-level gap is the absence of any operational platform providing ENSO-conditioned seasonal climate services packaged for energy sector operators in South America. The IRI Data Library provides the scientific foundation for such services but requires climate expertise to use and is not configured for energy decision contexts. GloFAS[65] provides seasonal streamflow outlooks at a four-month lead time but not within an energy management framework. Compounding this gap, the spatial heterogeneity of ENSO teleconnections across the region (documented in Section 4.1)

[58] https://climateinformation.org/
[59] https://fews.net/
[60] https://power.larc.nasa.gov/
[61] https://nsrdb.nlr.gov/
[62] https://energy.hub.copernicus.eu/
[63] https://wmo.int/activities/wmo-information-system-wis
[64] https://space.oscar.wmo.int/
[65] https://global-flood.emergency.copernicus.eu/

means a usable service cannot apply a single regional signal but must be calibrated to country-level and catchment-level responses. A second gap concerns climate projections: no platform bridges the CORDEX-SA data archive and an NMHS-usable energy sector projections product. Both gaps are manifestations of the underlying absence of being a platform that defines the standards for service modules and provides the framework within which they can be developed, validated, and delivered.

Gap 3: User Interface Platform Component

Existing tools in the scan, including the ENANDES CST v1[66] at CIIFEN, are organised around data variables and processing levels rather than energy sector decisions. No energy climate service platform operating in South America implements a sector-first, decision-calendar navigation model. Drought.gov demonstrates that this gap is solvable: its topic-first URL taxonomy, persistent sector-context navigation, and decision-calendar format show how a climate information platform can be designed so that energy sector users with no climate data expertise can navigate directly to operationally relevant products. The CST for energy and nexus must adopt this approach from the minimum viable product phase, applying the decision-calendar principle to energy management decisions (reservoir release scheduling, maintenance planning, dispatch strategy, and resource assessment) rather than drought management. The Copernicus Energy Hub[67] provides the complementary vocabulary standard as products named by energy application rather than by physical variable.

Gap 4: Capacity Development Component

No structured, phased training programme building NMHS operational independence for energy climate service delivery currently exists for ENANDES NMHSs. The Bhutan CST[68] precedent demonstrates what is required, namely training across distinct competency phases basic product use, sector-specific application, and system administration, with operational independence as the formally specified deployment success criterion. CIIFEN's existing Regional Climate Centre infrastructure provides the delivery mechanism; the gap is in the specification and activation of an energy-sector training programme within that infrastructure.

5.3 Summary of gaps by component

Table 4 below summarises the gaps identified above and their direct consequences for CST design.

Table 4. Summary of gaps by component

CST component	Gaps identified	Consequence for CST design
Data and Infrastructure Layer	No WIS 2.0-compliant data exchange architecture in regional platforms OSCAR observation requirements for energy variables not systematically referenced in any scanned platform No standardised integration protocols for connecting external service modules	CST data layer must comply with WIS 2.0 (MQTT, OGC API, HTTP(S), WMO Core Metadata Profile) and reference OSCAR requirements for energy-relevant variables. Integration standards must be defined in D2.
Climate Information and Services Layer	No platform defines standards for integrating independently developed climate service modules into a shared architecture No ENSO-conditioned seasonal climate services packaged for energy sector operators in South America No accessible climate projections product bridging CORDEX-SA data and NMHS energy sector use	D2 must define the technical and data exchange protocols that any climate service module must satisfy to be hosted on the platform. Seasonal forecasting and projections are individual service types to be specified as modules within this framework.
User Interface Platform Layer	Existing tools organised around data variables, not energy sector decisions No energy-sector decision-calendar interface in any South American platform	Interface must follow sector-first, decision-calendar model. Drought.gov provides the primary design reference for decision-type navigation. Copernicus Energy Hub provides the vocabulary standard.
Capacity Development Layer	No structured phased training programme building NMHS operational independence for energy climate services in the ENANDES region	Training programme to be specified in D2, delivered through CIIFEN's existing RCC infrastructure. Operational independence of each NMHS team must be a formal deployment success criterion, following the Bhutan CST precedent.

[66] https://crc-osa.ciifen.org/CST/
[67] https://energy.hub.copernicus.eu/
[68] http://cst-bhutan.rimes.int/

However, it should be noted that the gaps identified above, while relevant, are addressable. This is because, the primary data infrastructure needed to build the CST for energy and nexus is already operational and openly accessible. For example, ERA5 reanalysis and CHIRPS provide the observational backbone, ECMWF SEAS5 provides the seasonal forecasting layer, CORDEX-SA provides the projections layer, and the JRC eStation[69] modular architecture provides a proven technical deployment model. In addition, CIIFEN's WMO Regional Climate Centre mandate and its established relationships with NMHSs across the ENANDES region provide the deployment and capacity development infrastructure. Related to this, the Asunción workshop outputs provide validated user requirements. Taken together, the best practice design elements and the gaps identified in this section define the full scope of what a comprehensive CST for energy and nexus must address. Translating this into a deliverable platform requires the further step presented in Section 6.

6. Strategic Considerations and Prioritisation Framework

The landscape review in Section 4 and the synthesis in Section 5 establish what a comprehensive climate service toolkit for the energy sector and WEF Nexus could contain. It is important to note that no single platform reviewed achieves all nine criteria, and the design elements identified across the strongest cases, taken together, describe a platform of considerable scope.

The approach taken in this work responds to this comprehensive picture through two sequential steps. The first is to develop a conceptual framework that encompasses all main components of the CST for energy and nexus, covering the Data and Infrastructure Layer, the Climate Information and Services Layer, the User Interface Platform Layer, and the Capacity Development Layer, defined with sufficient generality to leave no technical consideration unaddressed. The intention is to characterise the principal features of each component and to define a concept that can accommodate emerging requirements and evolve as institutional capacities develop.

As such, the concept must contain all the features required for the platform's development and completion over successive phases, organised in a modular format with different maturity levels for gradual progression. Defining the platform at this level of conceptual completeness also enables it to function as a standards-setting framework. The standards and protocols established for the platform architecture allow any service provider, whether an NMHS, an RCC, a research institution, or an external partner, to develop climate service modules as self-contained components that conform to the platform's integration requirements and can be connected to it at any development phase. This standards-setting function positions the CST for energy and nexus as a replicable model for WMO Member States beyond the ENANDES region.

The second step, which follows from the first, is to define an initial minimum viable product from within that comprehensive conceptual framework. The prioritisation framework set out in this section serves this second step. Its purpose is twofold. It provides the strategic direction needed to scope the minimum viable product and the subsequent phases, and it establishes the explicit reasoning that will govern the assignment of functional requirements to implementation phases in Deliverable 2. Every inclusion or deferral decision in the CST design is explicitly traceable to this framework which then strengthens its credibility.

So the framework is based on three axes, which are operational criticality, feasibility, and foundational dependency. Each capability is assessed against all three, and its position across them determines its implementation phase, whether the minimum viable product, a later phase, or outside the scope of the current project.

6.1 The axis of criticality

This axis asks how central a capability is to the priority use cases defined in Section 2.4, and how acute the need is in the regional context. A capability is highly critical when it addresses a decision that energy sector actors in the region face routinely and cannot currently support with existing tools. The Data and Infrastructure Layer and the Climate Information and Services Layer, encompassing operational monitoring and seasonal forecasting of resource availability across the three primary technologies, score highly on this axis, because solar, wind, and hydropower generation in the ENANDES countries are all exposed to climate variability that operators must anticipate and manage on monthly to seasonal timescales.The regional climate drivers that condition this variability extend beyond ENSO to include, among others, the seasonal migration of the Intertropical Convergence Zone, the influence of the South American monsoon system, and Pacific and Atlantic sea surface temperature patterns, all of which affect the three technologies differently across the region. Capabilities that serve long-term planning rather than operational management, such as multi-decadal projections, score lower on this axis, because Section 2.4 has already defined long-term planning as an indirect application of the platform.

[69] https://estation.jrc.ec.europa.eu/eStation3/

6.2 The axis of feasibility.

This axis asks how large the gap is between what already exists and what the CST for energy and nexus would need to build, operate, and sustain. A capability is highly feasible when the underlying data, models, and access mechanisms already exist in mature and openly available form, so that the CST for energy and nexus's task is integration and contextualisation. In this way, the design intention is that now new invention is required. For the data and infrastructure component, the relevant standards are those already defined by WMO via WIS 2.0 and OSCAR, and the platform aims to conform to these. For the climate information and services component, individual service types are treated as self-contained modules that conform to the platform's integration standards and can be developed independently by NMHSs, RCCs, research institutions, or other relevant partners. This standards-based architecture means the feasibility question for any service type is not whether the platform builds it internally but whether a conformant module exists or can be developed by a capable institution and connected to the platform. For projection data specifically, several WMO RCCs already produce bias-corrected outputs derived from CORDEX-SA and comparable sources, so the platform connects to these existing sources. The specific access model, whether on-demand or locally cached, will be determined in D2. Feasibility is ultimately a question of whether a capability can be sustained by the institutions that will own it. A capability that cannot be sustained after delivery has not genuinely been delivered.

6.3 The axis of foundational dependency

This axis asks whether a capability must exist before others can be built upon it, independent of its own standalone priority because some components are infrastructural. The approach taken throughout is to design foundational elements so that they leverage the existing infrastructure and capabilities of the institutions that will own and operate the platform. Where WMO standards already define the relevant requirements, as WIS 2.0 and OSCAR do for the Data and Infrastructure Layer, the foundational layer conforms to these. Where NMHSs and CIIFEN already operate data portals, training cycles, and regional coordination mechanisms, the platform's foundational components build on these so that duplication is avoided.

Two capabilities rank highest on the foundational dependency axis. The first is the architectural separation of the Data and Infrastructure Layer from the Climate Information and Services Layer, upon which all service modules depend and which must be implemented from the beginning because modifying it later would require rebuilding core platform components. The second is the sector-first navigation architecture of the User Interface Platform Layer, which is foundational because a platform that its intended users cannot navigate delivers no operational value regardless of the quality of its underlying products. Both capabilities belong in the first phase regardless of their standalone operational criticality.

In this way, the three axes are applied together; a capability that is:

- Operationally critical, feasible, and foundational is clearly part of the minimum viable product.
- Foundational but only moderately critical still belongs in the first phase because other components depend on it and its absence would constrain subsequent development.
- Operationally desirable but has low feasibility is deferred to a later phase, allowing time to establish the technical, institutional, or data requirements needed for implementation.
- Neither critical nor foundational falls outside the scope of the current project.

The practical application of the framework proceeds in two steps, consistent with the approach established in the Section 6 introduction:

1. **Conceptualisation step:** The primary step is to define the full conceptual configuration of each of the four GFCS-aligned platform components. For each component, the three axes together determine which elements must be included from the first phase: the foundational dependency axis identifies what the architecture depends on, the criticality axis identifies what energy sector operations depend on, and the feasibility axis confirms what the operating institutions can build and sustain. This step constitutes the primary analytical effort of this work.

2. **Derivation of the Minimum Viable Product (MVP):** MVP specification is undertaken on a component-by-component basis and treating each GFCS-aligned layer as the unit of analysis. Budget allocations and implementation timelines fall outside the scope of this deliverable and will be addressed in D2.

The four GFCS-aligned platform components are described in Section 7. The framework will be applied systematically to all functional requirements in Deliverable 2, where each requirement will be positioned against the three axes and assigned to an implementation phase accordingly.

7. Conceptual Scope and Objectives of the CST for energy and nexus

The conceptual scope set out here follows directly from the prioritisation framework in Section 6. The vision, the user definition, the use cases, and the design principles below are not a comprehensive description of everything the CST for energy and nexus could become. They describe a deliberately scoped platform in which each element has been positioned against the three axes of operational criticality, realistic feasibility, and foundational dependency, and assigned accordingly to the minimum viable product or to a later phase. This scope is the foundation on which the technical specification in Deliverable 2 will be built.

7.1 Vision and definition

The CST for energy and nexus is an operational, modular- and component-based, open-access digital platform that has an automation standard approach for reading and analysing the required parameters from various internal and external datasets, is capable of running multiple independent processes to produce a specific type of service or product addressing a specific user (e.g. short term wind forecasting for wind power plants for dispatching problem, long-term climate projection for specific location for feasibility analysis for a solar power plant establishment, climate-risk assessment for the investment sector for a specific site), and is technically sound to communicate the produced results to the end-user through a user-friendly interface platform. The CST for energy and nexus has also featured as capacity development and help desk and provides a wide range of weather, water and climate data, information and services at different maturity and complexity level to multiple end-users and stakeholders. The open access feature of the CST for energy and nexus allows gradual development on any of these components over time that could be developed by any service provider and integrated by others due to the modular-based and scalable features of the platform. This of course requires clear definition of standards and protocols for the core concept of the platform for each component.

The defining architectural commitment of the CST for energy and nexus is being open-access, modular-based and scalable This means that the platform is conceived as a modular system in which new thematic modules, representing additional energy technologies, additional sectors, or additional temporal layers, can be added without restructuring the core infrastructure, and in which new user types can be configured as additional layers without modifying the Data and Infrastructure Layer or the Climate Information and Services Layer. This commitment follows the two-step approach established in Section 6. Because the platform is deliberately scoped at launch and expanded over time, its capacity to grow without being rebuilt is seen as a structural requirement; thus a platform that is delivered in phases must be flexible by design.

7.2 The four-layer architecture

The flexibility and modularity commitment described above is realised through a specific structural model. The CST for energy and nexus is conceived as four independent layers, each able to change and evolve without forcing changes in the others. The four layers, aligned with the five pillars of the GFCS, are the Data and Infrastructure Layer, the Climate Information and Services Layer, the User Interface Platform Layer, and the Capacity Development Layer This separation is the concrete mechanism behind the modularity principle, and it is the architecture that Deliverable 2 will specify in technical detail. The model is shown in Figure 10 and described below:

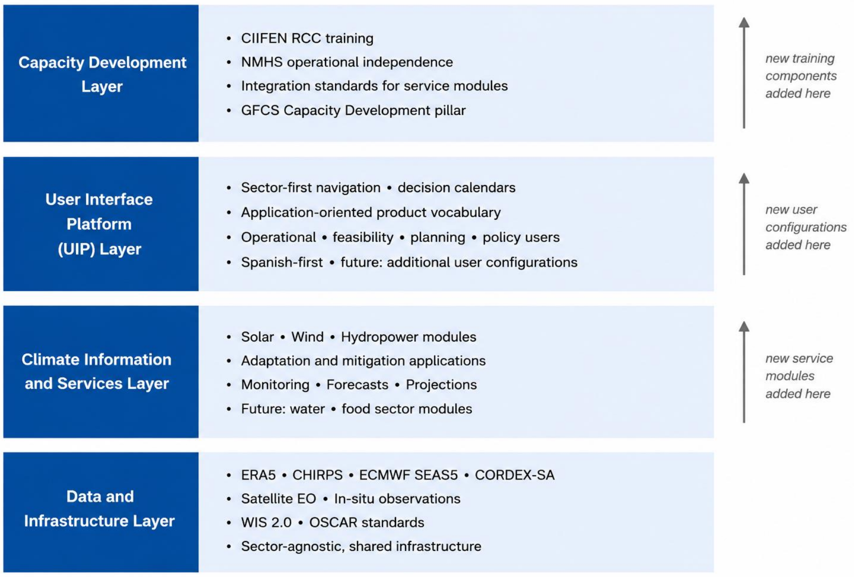

Figure 10. The four-layer modular architecture of the CST for energy and nexus. The Data and Infrastructure Layer establishes the shared observational foundation that supports all service modules, regardless of sector or technology. New service modules are added at the Climate Information and Services Layer; new user configurations at the User Interface Platform Layer; new training components and standards at the Capacity Development Layer. This separation is the structural basis for the platform's flexibility and phased growth.

Data and Infrastructure Layer. The data layer is the shared foundation of the platform. It comprises the full range of weather, water, and climate data sources relevant to the energy sector. It includes, among others, for example, reanalysis datasets including ERA5, in-situ observational data from station networks, satellite Earth observation products including MODIS land surface data, simulated outputs from global and regional modelling systems, climate projections from CORDEX-SA, and operational seasonal forecast products including ECMWF SEAS5. This layer is sector-agnostic since the same precipitation, radiation, wind, and temperature data that support energy applications also support water and food applications, so the data infrastructure is built once and serves all sectors that could be added to the tool. Importantly, this layer also incorporates source-level substitution capability identified in the landscape review, so that the unavailability of any single input does not interrupt the products that depend upon it. The detailed specification of WMO data standards applicable to each source will be addressed in D2

Climate Information and Services Layer. The Climate Information and Services Layer is where weather, water, and climate data are converted into decision-relevant services. It contains the thematic modules that process the shared data infrastructure into energy sector products, covering solar, wind, and hydropower technologies across the full temporal range of services. The latter include historical characterisation using reanalysis and observational records, real-time monitoring, sub-seasonal to seasonal forecasting, decadal forecasting, and multi-decadal climate projections. Services at this layer address both adaptation applications, including climate risk assessment for energy infrastructure and early warning for hydropower inflow, and mitigation applications, including renewable resource assessment and generation portfolio optimisation. Individual service types are developed as independent modules implementing the integration standards defined for the platform. So, they can be developed independently by NMHSs, RCCs, research institutions, or other partners and integrated into the platform at any development phase. Additional energy technologies and, in later phases, additional sectors are added at this layer as new module, without modifying the Data and Infrastructure Layer.

User Interface Platform Layer The User Interface Platform Layer corresponds to the UIP pillar of the GFCS and governs how different service users access and interpret the products of the platform. It comprises the sector-first navigation architecture, the decision calendars, the application-oriented product vocabulary, the language configuration, and the role-based access controls that shape the experience of each user type. Following the four application categories established in Section 2.4, distinct entry points and decision-calendar configurations serve operational management users, feasibility and resource assessment users, planning and investment users, and policy support users. The primary interface language is Spanish, with English as a secondary option. New user configurations can be added at this layer without modifying the service modules or the data infrastructure beneath.

Capacity Development Layer The Capacity Development Layer corresponds to the Capacity Development pillar of the GFCS and covers the activities required for NMHSs to develop and maintain the skills needed to operate the platform and deliver energy climate services. It includes the phased training programme delivered through CIIFEN's existing Regional Climate Centre infrastructure, the decision-calendar guidance integrated into the User Interface Platform Layer, and the operational independence criteria used to assess successful deployment in each country. Also, the layer also includes the platform's standards-setting function. By defining and publishing integration protocols, the platform enables external organisations to develop compatible service modules, extending its reach beyond the institutions directly involved in the initial implementation.

The value of the four-layer model is that it localises change, editions and additions. A new service type affects only the Climate Information and Service Layer, new user configuration affects only the User Interface Platform Layer. A new training component or integration standard affects only the Capacity Development Layer. Because the layers communicate through documented interfaces, the platform can grow along any dimension independently, which is what allows it to be scoped narrowly at launch and extended over successive phases. This is the structural foundation that the technical architecture in Deliverable 2 will elaborate, and it is the reference model against which the functional requirements will be organised.

7.3 Target users and priority use cases

The CST for energy and nexus is organised around a distinction between service providers and service users.

Service providers are the institutions that operate the platform and produce its services, they encompass:

- NMHSs operate the platform at the national level, co-produce sector-specific products, and deliver services to energy sector actors through their national mandate
- CIIFEN, as the WMO Regional Climate Centre for western South America, provides regional coordination, shared data infrastructure, and capacity development across national implementations
- At the global level, WMO sets the standards and frameworks that the platform conforms to, including WIS 2.0 and OSCAR.

Service users are the energy sector actors whose decisions the platform supports. They are defined by application context:

- **Operational management:** grid operators, utilities, independent power producers, O&M contractors, and market operators who need near-real-time monitoring and seasonal outlooks to manage generation portfolios, plan maintenance windows, and support dispatch decisions
- **Feasibility and resource assessment:** renewable energy developers, engineering consultants, financiers, and insurers who need historical climatological baselines and interannual variability characterisation to support site selection, project design, and financial risk assessment
- **Planning and investment:** national energy planners, development banks, and infrastructure investors who need multi-annual to multi-decadal climate information to guide capacity expansion, assess climate risk exposure, and support investment decisions
- **Policy support:** energy regulators and multilateral institutions who need aggregated climate-energy indicators to inform grid codes, capacity adequacy standards, and energy transition policy

The minimum viable product targets the first two categories, consistent with the prioritisation framework in Section 6. The full specification of user roles by energy project lifecycle phase is developed in Deliverable 2.

MVP use cases. From here, two use cases emerge in the minimum viable product:

- **Resource monitoring and assessment** across solar, wind, and hydropower. This answers the type questions users can already see in the climate record, such as *what is the typical solar irradiance in this part of northern Chile (the long-term climatological baseline), how is the wind regime in southern Peru behaving right now (near-real-time monitoring), and how variable is hydropower inflow in the Magdalena from year to year (interannual variability)?*
  These products serve both site planning and day-to-day operational management.
- **Seasonal forecasting of resource availability** across the same three technologies. This tells users what to expect over the coming one to four months since this is the timescale on which operators plan reservoir releases, maintenance windows, and dispatch strategy. Forecasts are calibrated to regional climate drivers and their location-specific and technology-specific effects.
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Notably, additional use cases are deferred to later phases as the platform matures and institutional capacity grows. These include multi-decadal climate projections for infrastructure planning, water-energy nexus analysis for reservoir systems, and cross-border market analysis under regional grid interconnection. Policy planners and long-term investment decision-makers access the platform's outputs indirectly, through the reports and briefings that NMHSs and operators prepare.

7.4 Geographical and thematic scope

The conceptual scope of the CST for energy and nexus is global. The platform is designed as a replicable standard that any NMHS can adopt. The ENANDES countries play the role of consulting and co-design partners during the conceptualisation phase. Colombia, Chile, and Peru form the core project group, with Argentina, Bolivia, and Ecuador contributing through ENANDES+. Their inputs retrieved from the Asunción workshop and ongoing national consultations then shape the platform's architecture without limiting its applicability to other regions or contexts. For the pilot implementation in Deliverable 3, a single-country deployment (to be selected in later phases) is the appropriate and desirable.

Thematic scope As such, the minimum viable product (MVP) covers:

- Solar PV, wind, and hydropower across historical characterisation, real-time monitoring, and sub-seasonal to seasonal forecasting
- Both adaptation and mitigation applications
- The operational management and feasibility and resource assessment user categories

The architecture is designed from Phase 1 to accommodate:

- Decadal forecasting and multi-decadal climate projections, delivered in Phase 2 through connection to existing RCC and research institution data sources
- Biomass and hydrogen-based systems as additional service modules in later phases
- Water and food sectors as additional service modules, consistent with the WEF Nexus scalability described in Section 2.3
- Planning and investment and policy support user categories in later phases

7.5 Key design principles and GFCS alignment

Seven design principles govern the CST for energy and nexus architecture. They are derived from the landscape review, confirmed through the co-design process and team consultations, and filtered through the prioritisation framework in Section 6. Each principle is tagged below according to its role. As such, Foundational Principles must be in place from Phase 1 because other elements of the platform depend on them. MVP Principles represent delivered operational capabilities in Phase 1. The Organising Principle governs the platform across all phases. The seven principles are:

1. **Flexibility and modularity (foundational)**

The architecture is modular at four levels and one for each platform layer. At the Data and Infrastructure Layer, observational sources are independently substitutable. At the Climate Information and Services Layer, service modules are independently deployable. At the User Interface Platform Layer, access and interfaces can be configured for different user roles. At the Capacity Development Layer, training components and integration standards can be adapted to different national contexts. Each layer communicates with the others through documented interfaces, so changes in one layer do not require changes in others. In D2, this principle is expressed through an architecture specification that formally separates the four layers with documented integration interfaces between them.

2. **Open access by default (foundational)**

All platform code, data products, and documentation are freely accessible. The API operates without a registration barrier. The codebase is open-source. Outputs are downloadable in standard formats consistent with WIS 2.0 data exchange requirements, including GeoJSON, NetCDF, and WaterML. No closed or commercial component is compatible with the NMHS institutional context or with the GFCS principles the platform embodies. In D2, this principle is expressed through a mandatory API specification, an open-source licensing requirement, and a data format standard aligned with WIS 2.0.

3. **WMO standards alignment and GFCS institutional legitimacy (foundational)**

The platform maps explicitly to all five GFCS pillars, as shown in Table 5. It conforms to WMO data standards, principally WIS 2.0 for data exchange and discovery and OSCAR for observing system requirements. It is developed with WMO endorsement sought through the GFCS framework, operated through CIIFEN's Regional Climate Centre mandate, and integrated into the National Framework for Climate Services coordination mechanism of each participating country. This alignment ensures the platform is a legitimate component of the WMO weather, water, and climate service delivery chain and not a standalone project output. In D2, this principle is expressed through an institutional architecture section specifying the endorsement pathway, the CIIFEN integration mechanism, and the country-level engagement protocol.

4. **Global standards-setting and replicability (foundational)**

The CST for energy and nexus is designed as a replicable standard that any NMHS can adopt, with the ENANDES deployment serving as the reference instantiation. The standards and protocols established for the platform architecture allow any service provider (eg. an NMHS, an RCC, a research institution, or an external partner) to develop conformant service modules as self-contained components that can be connected to the platform at any development phase. This standards-setting function is what makes the platform a contribution to WMO's broader goal of coherent, interoperable climate-energy service development globally. In D2, this principle is expressed through the definition of minimum technical requirements for service module development, covering data formats, API endpoint structure, metadata requirements following the WMO Core Metadata Profile, WIS 2.0 topic hierarchy compliance, and update frequency specifications.

5. **NMHS-centred co-design (MVP)**

Product definitions, interface design, and validation are co-designed with NMHS teams in each participating country. Deployment success is defined as NMHS operational independence, so the NMHS team can operate the platform, produce quality-controlled products, and deliver services to energy sector actors without external assistance after handover. The Bhutan CST[70] co-design process is the reference model, spanning needs assessment, product design, technical training, and operational handover. In D2, this principle is expressed through a country engagement plan specifying the co-design sequence, the validation process, and the operational independence assessment criteria.

6. **Sector-first, decision-oriented interface in Spanish (foundational and MVP)**

The interface organises products by energy application and decision type. Distinct entry points serve each of the four user application categories. Decision calendars map products to the annual cycle of energy management decisions, naming the specific decisions each product supports and the months in which they are most relevant. Product names follow the vocabulary of the energy sector user so that users can reach decision-relevant content without climate data expertise. The primary interface language is Spanish, with English as a secondary option. All decision-calendar content, documentation, and training materials are available in Spanish from the first deployment. This principle is foundational because a platform that its intended users cannot navigate delivers no operational value regardless of the quality of its underlying products. In D2, it is expressed through interface architecture specifications, annotated decision calendars, energy-sector product naming conventions, and a language specification supporting country-specific terminology.

7. **Phased implementation (organising principle across all phases)**

The platform is delivered in phases, with the first step being the comprehensive conceptualisation of all platform components and the second step being the derivation of a minimum viable product configuration for each component. Each phase is fully operational before the next begins. Phase transitions are governed by formally specified entry criteria derived from the prioritisation framework in Section 6. This principle ensures that the scope of the platform remains realistic and explicitly reasoned at every stage of its development. In D2, it is expressed through a phased functional requirements structure in which each requirement is assigned to a component, positioned against the three axes, and evaluated against defined readiness criteria.

Mapping to the GFCS value chain. The seven principles map to the five GFCS pillars as follows, and as shown in Table 5 below and as explained:

Table 5. Mapping of the CST for energy and nexus to the five pillars of the GFCS value chain

GFCS pillar	CST for energy and nexus component	Phase
Observations and Monitoring	Data and Infrastructure Layer ERA5 • CHIRPS • ECMWF SEAS5 • CORDEX-SA • satellite EO • in-situ networks WIS 2.0 data exchange standards • OSCAR observing system requirements	**MVP**
Research, Modelling and Prediction	Climate Information and Services Layer Solar • wind • hydropower service modules Historical characterisation • real-time monitoring • seasonal forecasting • projections Adaptation and mitigation applications	**MVP (monitoring and seasonal) Phase 2 (projections)**
Climate Services Information System (CSIS)	Processing and API layer Processing chains • product catalogue • REST API Integration standards for conformant service modules	**MVP**
User Interface Platform (UIP)	User Interface Platform Layer Sector-first navigation • decision calendars • application-oriented vocabulary	**MVP**

[70] http://cst-bhutan.rimes.int/

	Four user categories: operational • feasibility • planning • policy Spanish-first	
Capacity Development	Capacity Development Layer Phased training through CIIFEN Regional Climate Centre Operational independence criteria for each NMHS Standards for conformant service module development	**MVP**

As such, a description of each component:

- The Observations and Monitoring pillar corresponds to the Data and Infrastructure Layer. This layer draws on reanalysis, observational, satellite EO, simulated, and climate projection data sources. Data exchange and discovery conform to WIS 2.0 standards, and observing system requirements are referenced against OSCAR.
- The Research, Modelling and Prediction pillar corresponds to the Climate Information and Services Layer. This layer covers all service types from historical characterisation and real-time monitoring through sub-seasonal to seasonal forecasting to multi-decadal predictions and climate projections, addressing both adaptation and mitigation applications across solar, wind, and hydropower technologies.
- The Climate Services Information System (CSIS) pillar corresponds to the processing and API layer of the Climate Information and Services Layer. This includes the processing chains for each service module, the product catalogue, and the documented REST API, as well as the integration standards that define the technical requirements conformant service modules must satisfy.
- The User Interface Platform (UIP) pillar corresponds to the User Interface Platform Layer. This layer encompasses sector-first navigation, decision calendars, application-oriented product vocabulary, role-based access differentiated by user application category, and Spanish-first multilingual support.
- The Capacity Development pillar corresponds to the Capacity Development Layer. This layer encompasses the phased training programme delivered through CIIFEN's Regional Climate Centre infrastructure, the embedded decision-calendar guidance within the interface, the operational independence criteria that define deployment success for each NMHS, and the standards-setting function that enables external service module integration.

8. Conclusions

This deliverable set out to determine whether an adequate climate service platform for the energy sector already exists, and if not, what such a platform would need to contain. The landscape review answered the first question clearly. Twelve platforms were assessed against nine criteria spanning modularity, open access, data source range, temporal coverage, operational accessibility, capacity development, institutional alignment, sectoral scalability, and interface design, and none of them met the combined requirements that NMHS-deployable energy climate services in the ENANDES region demand. This is not a marginal shortfall. The platforms reviewed each solve a piece of the problem competently, modular architecture, registration-free access, decision-oriented interfaces, NMHS-led operation, but none solves more than one or two pieces simultaneously. That pattern is itself informative. It suggests the energy sector's climate service requirements are genuinely more complex than those the GFCS pillars were originally designed around, because energy decisions span multiple technologies, multiple temporal horizons, and multiple institutional actors at once, in a way that water or health applications typically do not. The pattern also recurs in the same way across the global platforms regardless of their country of origin or funding source, which suggests the gap is structural to the energy sector's information needs and not an accident of underinvestment in any one region or institution.

The second question, what such a platform would need to contain, is answered by the architecture developed in Sections 6 and 7. Four layers, Data and Infrastructure, Climate Information and Services, User Interface Platform, and Capacity Development, map onto the five pillars of the GFCS and organise the platform around where change happens in the system, new data sources, new services, new users, new training needs, so that growth in one layer does not force redesign in another. A three-axis framework orders the work that follows, separating what must exist immediately from what can wait and what falls outside scope entirely. Underlying all of it is a single architectural choice that shapes everything else: the platform exists to define standards that any qualified provider can build against, not to deliver a fixed set of services itself. That choice is what allows the platform to keep growing after this project ends, since its value lies in the protocols it establishes rather than in any particular thing built on top of them. The same choice also changes what success looks like for this initiative. Success is not measured by how many services the project itself delivers, but by how many qualified providers later choose to build against the standard once it exists.

Several conclusions follow from this work that bear directly on what Deliverable 2 needs to do.

- The case for building a dedicated platform, rather than adapting an existing one, is now established on analytical grounds, not just on the absence of a perfect match. The specific combination of multi-technology, multi-horizon, multi-actor complexity found in the energy sector does not exist in the platforms built for other GFCS priority areas, and adapting one of them would mean inheriting design assumptions that do not fit. Deliverable 2 can proceed from this conclusion without needing to re-justify the platform's existence.
- The standards-based architecture is the decision with the longest reach into Deliverable 2's actual content. It means the highest-priority work in Deliverable 2 is specifying what makes a service conformant for each layer, since everything else, which services eventually get built, by whom, and in what order, depends on that specification existing first and being precise enough to be tested against.
- The separation of the four layers is only useful if the boundaries between them are specified with enough precision that a real interface, not just an organisational label, sits at each junction. Deliverable 2's engineering task is to make that boundary explicit, what one layer is permitted to assume about another, so that the architecture's claimed flexibility is something the platform actually has, not something the diagram merely implies.
- The three-axis framework was built to make sequencing decisions traceable. Its value to Deliverable 2 depends entirely on whether every functional requirement that follows is actually run through all three axes and the result recorded, rather than the framework being cited once and then set aside while requirements get prioritised by instinct or convenience.
- The gaps identified in Section 5 were deliberately framed at the level of missing components, an interoperability standard, a sector-first interface model, a capacity development pathway tied to demonstrable operational independence, and not at the level of missing individual services. Deliverable 2 closing those gaps means producing standards that resolve them structurally. Producing a list of new services would not close them, regardless of how many services that list contained, and would in effect undo the central analytical move this deliverable made.
- The user typology developed in Section 2.4 and refined in Section 7.3, organised by application context rather than by institutional title, is a finding in its own right, because it means the same individual can occupy different positions in the platform's design depending on which decision they are making at a given moment, not a fixed position determined by their job description. Deliverable 2 needs to carry this logic through into the User Interface Platform layer's standards, so that interface design responds to the decision being made rather than to a static user category.
- The temporal range identified across the landscape review, historical characterisation, near-real-time monitoring, sub-seasonal to seasonal forecasting, decadal forecasting, and multi-decadal projections, was found nowhere assembled in a single energy-sector platform. This is a finding about the market, not only about the platform being designed here. It indicates that closing this gap has value that extends beyond the ENANDES region, and Deliverable 2 should treat full temporal coverage as a structural

requirement of the standard rather than as an optional enhancement to be added once core functions are stable.

- The repeated appearance of institutional legitimacy, formal WMO endorsement, RCC-level governance, integration into national climate service frameworks, as a determining factor in which platforms NMHSs actually trust and adopt indicates that technical quality alone does not predict uptake. Deliverable 2 should specify the institutional pathway alongside the technical one, since a standard with no formal route to recognition risks being technically sound and still going unused.