REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	Italy
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Project Title:	**H**ydrogen **E**mission **S**cenarios to drive Climate **P**rojections for **E**nvironmental and **RI**sk **A**ssessment (**HESPERIA**)

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☐	NO **X**

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	2.8 Million	10 Million	10 Million
Accumulated data storage (total archive volume)[2]	[GB]	4000	24000	48000

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 10,000,000 SBU should be more detailed (3-5 pages).

1. Project overview

Future climate projections conducted with state-of-the-art Earth System Models (ESM) are a key instrument in the hands of scientists and policymakers to advance our understanding of the climate system response to anthropogenic drivers and to assess and manage societal risks. Alternative greenhouse gas and aerosol emissions and land use scenarios generated by Integrated Assessment Models (IAM) on the basis of plausible future societal evolutions, are routinely used to drive climate models under protocol-driven coordinated efforts (e.g., ScenarioMIP; O'Neill et al., 2016) to inform the Inter-governmental Panel on Climate Change (IPCC) assessments. To adequately sample the range of possible future climates, different degrees of mitigation levels are accounted for in the design of individual scenarios, leading to accordingly divergent trajectories in climate evolution.
A promising avenue to accelerate the transition towards a decarbonized society is represented by the replacement of fossil-fuels with hydrogen (H2), as a carbon-free energy carrier. The potential large-scale employment of H2 in different sectors (including mobility, residential and industrial) may therefore contribute to a substantial reduction of CO2 emissions, provided that a consistently low carbon footprint is guaranteed in the H2 production process (specifically, by favoring "blue" and "green" hydrogen productions, that involve a reduced amount of, or zero carbon dioxide emissions; Ocko et al., 2022).
A factor that could significantly undermine the potential benefits of a transition to an H2-based economy is the issue of hydrogen leakages throughout the entire value chain. Although H2 itself does not directly contribute to radiative forcing, its presence can indirectly affect Earth's radiative balance by influencing the atmospheric concentrations of greenhouse gases (GHGs) such as methane (CH4), ozone (O3), and water vapor. For example, the introduction of H2 into the atmosphere prolongs the lifecycle of CH4 by reducing the abundance of OH, which serves as a key sink for methane. Given CH4's potent greenhouse effect, the release of H2 ultimately contributes to global warming. Additionally, the H2-induced reduction of OH radicals triggers a series of reactions that elevate ozone (O3) concentrations in the troposphere, further exacerbating warming trends. Furthermore, water vapor produced through the oxidation of H2 can persist in the stratosphere, leading to additional radiative forcing (Ocko et al., 2022).
In summary, emissions of H2 can have a significant climatic influence, necessitating thorough quantification to provide policymakers with a comprehensive understanding of the environmental implications associated with widespread adoption of H2 in the energy sector.

HESPERIA will rely on a state-of-the-art global climate model (EC-Earth; see Section 3) to advance current understanding of the possible climate impacts of a hydrogen economy.

The project will evaluate the effects of hydrogen emissions on Earth's radiative equilibrium and assess the climate implications of adopting a hydrogen economy, according to alternative scenarios spanning various levels of H2 deployment in different socio-economic sectors. The new H2-based scenarios will complement existing scenario-based assessments from previous Coupled Model Intercomparison Project (CMIP) efforts, providing an updated evaluation of possible future climate evolutions.

2. **Objectives**

In summary, HESPERIA will pursue the following objectives:

1. Estimate the effective radiative forcing (ERF) associated with the release of H2 in the atmosphere;

2. Assess the climate impacts of a future economy based on a large-scale deployment of H2.

These objectives will be tackled through a modelling approach, following well-established methodologies detailed in Section 3.

3. **Methodology**

3.1 Numerical experiments

The research objectives outlined in Section 2 will be addressed with version 4 of the EC-Earth climate model (EC-Earth4). EC-Earth4 is an evolution of the previous EC-Earth3.3 version, used for the Coupled Model Intercomparison Project 6 (CMIP6; Döscher et al., 2022). Compared to EC-Earth3.3, EC-Earth4 consists of the OpenIFS cy43 model for the atmospheric component (replacing IFS 36r4), coupled to NEMO4 as the ocean component (replacing NEMOv3.6) and SI3 sea-ice model (replacing LIM3). For the land surface, the H-TESSEL module is used, while the coupling interface is based on OASIS3-MCT software.
For HESPERIA, a standard Tco95L91-eORCA1 ocean-atmosphere (or atmosphere-only) configuration will be used, featuring a nominal resolution of approximately 100 km. This configuration does not include atmospheric chemistry and carbon cycle representations. Due to its lower computational demands, it is well-suited for conducting multiple century-scale concentration-driven simulations in either atmosphere-only (3.1.1) or coupled (3.1.2) configurations.

3.1.1 Effective radiative forcing simulations

The effective radiative forcing (ERF) resulting from the release of H2 will be estimated by conducting atmosphere-only simulations with prescribed sea-surface temperatures (SST) and sea ice cover. Following a well-established methodology (e.g., Andrews et al., 2021), the ERF is assessed as the energy imbalance at the top-of-atmosphere (TOA) caused by changes in greenhouse gas (GHG) concentrations induced by H2 emissions, accounting for stratospheric and tropospheric adjustments. ERF is practically estimated comparing results from two simulations: a control simulation with constant concentrations of GHGs and aerosols held at reference values; and a perturbed experiment where a specific forcing agent (e.g., all GHGs or single chemical species) is altered relative to the reference value, while all other parameters remain identical to the control simulation settings.
Since the EC-Earth model configuration for HESPERIA does not include an atmospheric chemistry component, the impact of H2 emissions on atmospheric composition (including CH4, O3, and water vapor concentrations; see Section 1) will be assessed through Chemistry Transport Model (CTM) simulations that will be conducted using observed and perturbed estimates of H2 emissions using resources external to HESPERIA. The GHG concentrations resulting from the CTM simulations will

be then used to force EC-Earth4 to estimate the ERF of H2. More specifically, the following ERF simulations will be performed:
ERF_CONTROL: Atmosphere-only simulation forced with observed seasonally varying SSTs and sea-ice fraction; land temperatures free to evolve; GHG and aerosol concentrations kept fixed to values representative of the present climate;
ERF_PERTURBED_GHG: As ERF_CTRL but with GHGs concentrations associated with a +10% increase in H2 emissions, with respect to present climate levels;
In addition to ERF_PERTURBED_GHG, the individual contribution of specific GHG species to the H2-induced ERF will be estimated via single-forcing perturbation experiments for CH4, O3 and water vapor (ERF_PERTURBED_[CH4, O3, H2O]).
All the ERF experiments will cover a common 30-year period under present climate conditions. The outcome of the experiments will be an updated estimate of the impact of H2 emissions on ERF, accounting for the cumulative effect of all GHGs as well as the contribution of single forcing agents, using a state-of-the-art global climate model.

3.1.2 Scenario simulations

Future climate projections for the years 2025-2100 will be performed with a coupled configuration of EC-Earth4 model under alternative forcing scenarios associated with an implemented hydrogen-based economy. The scenarios will be based on different GHG concentration pathways resulting from CTM simulations forced with future H2 emissions scenarios. Note that the design of the H2 emission scenarios and the corresponding CTM simulations of the future evolution for CH4, O3 and water vapor concentrations are not part of HESPERIA and will be delivered as part of a parallel effort.
The emission scenarios in HESPERIA will consider a baseline storyline (e.g., the CMIP6 Shared Socio-economic Pathway SSP3-7.0; O'Neill et al., 2016) plus several variants reflecting different degrees of H2 deployment, including a "limited", "medium" and "ambitious" scenario. Also, following the recommendations from the Scientific Steering Committee of ScenarioMIP (van Vuuren et al., 2023), for each scenario simulation a minimum set of 3 members will be run to reduce uncertainty.
To summarize, the following scenario simulations will be run in HESPERIA:

SCENARIO_BASELINE: 3-member ensemble of coupled simulations driven by SSP3-7.0 concentrations of GHG and aerosols and land use forcing;

SCENARIO_H2_LIMITED: As in BASELINE but with GHG concentrations accounting for the impact of a *limited* H2 deployment (i.e., H2 only used in the industrial sector as feedstock);

SCENARIO_H2_MEDIUM: As in BASELINE but with GHG concentrations accounting for the impact of a *medium* H2 deployment (i.e., H2 employed in the industrial sector as feedstock and for steel production, and in the freight transport sector);

SCENARIO_H2_AMBITIOUS: As in BASELINE but with GHG concentrations accounting for the impact of an *ambitious* H2 deployment (i.e., H2 employed in the industrial sector as feedstock, and in the passengers and freight transport sectors).

4. **Workflow**

As detailed in Section 3, two streams of numerical experiments will be performed in HESPERIA: atmosphere-only ERF simulations (Section 3.1.1) and coupled scenario simulations (Section 3.1.2). The experiments will be conducted according to the following work plan:

- Year 1: Experimental set-up and model testing. Modification of EC-Earth atmospheric module for the inclusion of an external source of water, simulating the H2-induced input of water vapor concentration.
- Year 2: Complete all AMIP runs. Start running coupled simulations (3-member ensembles of the baseline SSP3.70 scenario and one H2-variant)
- Year 3: Complete coupled simulations, finalizing the full set of H2-variant scenario simulations.

5. Resources and technical implementation

Based on scaling tests, each model year of EC-Earth4 in its atmospheric-only configuration (Tco95) costs around 9500 SBU, whereas each model year of the coupled EC-Earth4 (Tco95-eORCA1) costs around 19000 SBU (see Table 1).

Model configuration	SBU/model year
Tco95L91 AMIP	9500
Tco95L91/eORCA1	19000

Table 1. Summary table with estimated SBU cost per simulated year, for the EC-Earth4 model configurations to be used in HESPERIA.

The ERF experiments (described in Section 3.1.1) consist of 30-year AMIP-like simulations for each of the following experiments: ERF_CONTROL, ERF_PERTURBED_GHG, ERF_PERTURBED[CH4], ERF_PERTURBED [O3], ERF_PERTURBED [H2O]). After adding 50 years for testing and implementation, a total of 200 years of atmospheric-only simulation is reached, which costs 1.9 million SBU.

The coupled scenario experiments (described in Section 3.1.2) consist of 3-member ensembles of 75-year simulations (targeting years 2025-2100) for a baseline simulation plus 3 different H2-emission variants, covering 900 model years. We add 200 years for testing and implementation, reaching 1100 years which corresponds to 20.9 million SBU (see Table 2).

Regarding the storage, the requirements are around 35 GB/model-year for atmospheric standalone simulations (AMIP) and 45 GB/model-year for fully coupled simulations, implying 150x35GB = 5.25 TB and 950x45GB = 42.75 TB for AMIP and coupled simulations, respectively, totaling 48 TB in all.

Model configuration	Activity	Planned model years	Total Resource Cost
Tco95L91 AMIP	AMIP experiments for ERF estimation (all- and single-forcing experiments)	200	1.9 million SBU
Tco95L91/eORCA1	Coupled scenario simulations (baseline and 3 H2-emission variants; 3-member ensembles)	1100	20.9 million SBU

Table 2. Synthesis table for HESPERIA simulations and estimated computational costs. The total amount of requested SBUs is 22.8 million.

References

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