AI for Net Zero
DIGITAL TWINS: ENERGY & TRANSPORT

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WHITE PAPER

Funded by UKRI

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PROJECT:

Real-time digital optimisation and decision making for energy and transport systems

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PROJECT OVERVIEW

We are integrating Digital Twins into different applications: wind energy, road transport, and Hydrogen safety. Digital Twins mimic real life environments to collect data, and this data is being used to optimise outputs in real-life scenarios.

Our research is improving the understanding in this field to help the UK in using AI to optimise energy and transport processes and ultimately achieve the national net zero aims.

AI for Net Zero: Energy and Transport is a research team made up of Principal Investigators and Post-Doctoral Researchers from four world leading academic institutes; Imperial College London, University of Oxford, University Cambridge, and EPCC - Supercomputing Centre, University of Edinburgh.

This White Paper provides a summary of the problems, solutions, and outcomes for each of the work packages in this research project. For further details on the project, updates, resources, and related publications, visit our website: aifornetzero.co.uk

DIGITAL TWINS FOR WIND ENERGY, ROAD TRANSPORT AND HYDROGEN SAFETY

DIGITAL TWINS

Our digital twins incorporate a pioneering approach to create models of complex systems capable of real-time behaviour prediction, paving the way for efficient modelling and control of engineering systems in real-world applications.

We have created a robust framework for real-time digital twinning and control by integrating sensor data with qualitative models, using advanced scientific machine learning and data assimilation techniques.

Virtual replicas of physical systems make it possible to monitor and analyse operations in real-time, enabling faster and more informed decision-making.

PROBLEM

The engineering systems that underpin key renewable or zero-emission technologies involve multi-physics systems, such as reacting hydrogen with multi-phase flows, the optimisation of wind farms' power output, and adaptive solutions to minimise aerodynamic resistance in road vehicles.

On the one hand, fast solutions to these problems are available through cheap models, but these solutions are not optimal. On the other hand, optimal solutions to these problems can be achieved (in principle) by simulation or experimentation, but the cost and time required are prohibitive.

SOLUTION

We are combatting this problem by combining the two essential disciplines: **physics-based modelling**, which is generalisable and robust but may require tremendous computational cost, and **machine learning**, which is adaptive and fast but not easily generalisable or robust. The intersection of the two spawns **scientific machine learning**, which maximises the strengths and minimises the weaknesses of the two approaches.

In other words, our project is creating **real-time digital twinning**—the creation of virtual counterparts that mirror the behaviour of complex physical systems—presents unique challenges in terms of accuracy, efficiency, and adaptability.

OUTCOMES & BENEFITS

Digital twins and modelling bring transformative benefits to society and the environment by providing more efficient ways to monitor, model and control complex engineering systems. These virtual replicas of physical systems make it possible to monitor and analyse operations in real-time, enabling faster and more informed decision-making.

As a platform for research and development, digital twins allow for quicker and more affordable testing of innovative ideas, reducing the need for expensive physical prototypes. By bridging the gap between theory and real-world application, digital twins are helping to create a more sustainable, safe, and efficient future for everyone.

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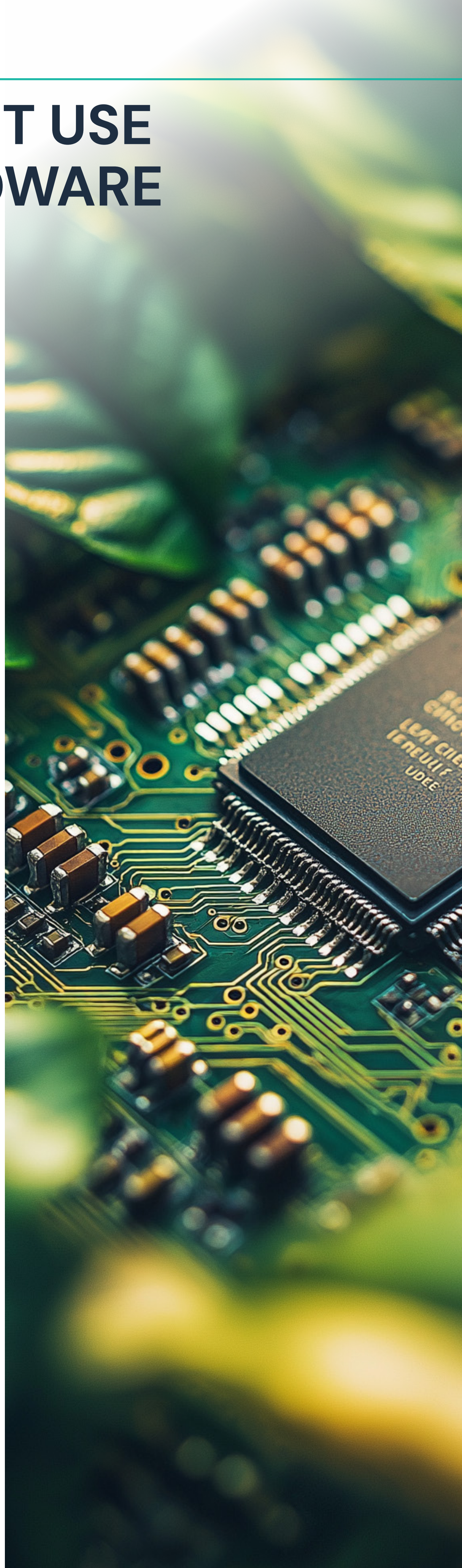
EFFICIENT USE OF HARDWARE



It is important to ensure that the use of AI for net zero solutions is going to be net beneficial for the UK. Therefore, we are assessing and exploring the energy efficiency of AI applications and propose recommendations that will improve and encourage best practices around **sustainable AI workloads on High Performance Computing (HPC) systems.**

This is a key element for the future because if we do not encourage or enforce sustainable practices, the environmental impact of AI could sadly undermine its intended benefits.

PROBLEM

The power demands of AI are growing exponentially at the risk of becoming unsustainable if its growth is left without intervention. The impacts could have wide ranging implications from the physical environment to societal. Some facts here show the potential environmental impact from the development of one AI system:

- Training of GPT-3 was estimated to have consumed 1,287 MWh (megawatt-hours), equivalent to the typical annual electricity usage of 477 average UK households. [1]

- Training the GPT-3 language model can directly evaporate 700,000 litres of clean freshwater, and further consuming 500ml of water for roughly every 10 – 50 medium length responses. [2]

This problem stems from the lack of **consistent or uniform energy metrics** across services to facilitate fair comparison. **Use of benchmarks for finding the optimal platform** is not always possible because it is not portable, and can end up being very costly and timely to work out the best place to run a workload.

The impact of simple hyperparameter tuning is huge, but there is a **lack of guidance** on how to tune for different architectures. It is simply too expensive to simply try everything. Furthermore, without guidance there is a **need to be careful of what you are optimising** reduction of time-to-epoch does not necessarily lead to benefits.

SOLUTION

We have been researching and assessing ways to maximise the efficiency of AI training and inference beyond hyperparameter tuning, and looking into bespoke low-power hardware as an alternative.
Benchmarking is also a big part of our research with the **aim to create a robust benchmarking system**, eventually coupled with thorough guidance, to support decision making of how to run workloads in the most sustainable way.

OUTCOMES AND BENEFITS

To ensure that AI can remain a sustainable solution is to increase awareness and understanding of energy requirements and environmental implications by publishing energy-efficiency data.
Through our research we can help the industry to be transparent about the **true monetary, environmental, and human costs of AI**. Our aim is to support informed decisions on the choices of AI technologies, from when to use it, to potential returns of investment.

References:

[1] E. Broadway, J. K. L. Lee and M. Weiland, "Sustainable AI: Experiences, Challenges & Recommendations" in #SC24-W: Workshops of the International Conference for High Performance Computing, Networking, Storage and Analysis, Atlanta, GA, USA, 2024, pp. 1805-1814, doi: 10.1109/SCW63240.2024.00227

[2] Li, P., Yang, J., Islam, M.A., & Ren, S. (2023). Making AI Less "Thirsty": Uncovering and Addressing the Secret Water Footprint of AI Models. ArXiv, abs/2304.03271.

WIND ENERGY

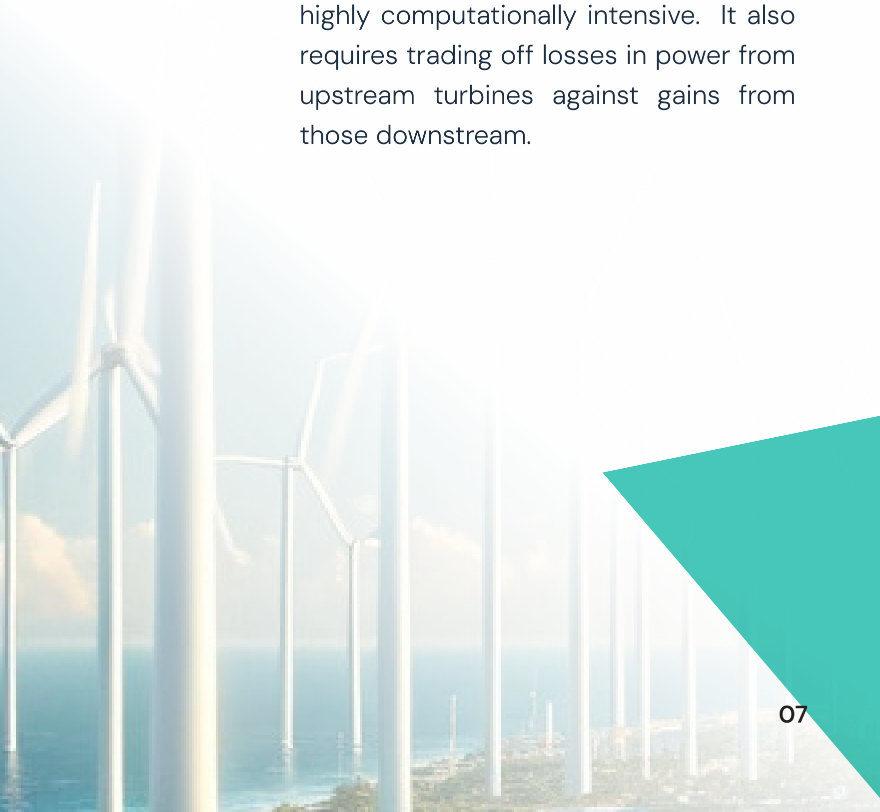
Current offshore wind farm configuration does not always allow for maximum power output due to its clustered arrangement. However, by implementing a simple technique such as wake steering, we can greatly optimise the energy production of offshore wind farms. Our research has been exploring wake steering as a control technique, that works by intentionally misaligning some turbines with the wind to deflect their wakes away from downstream turbines.

PROBLEMS

The problem of real time wake steering to maximise wind-farm performance is difficult because the system is highly dynamic - weather conditions change and steering an upstream turbine affects the performance of those downstream. Real time wake steering requires rapid, accurate prediction of each turbine's effect on the local airflow, which is highly computationally intensive. It also requires trading off losses in power from upstream turbines against gains from those downstream.

SOLUTIONS

Our solution is a model that uses a novel combination of an accurate digital twin of the wind turbines and the turbulent airflows around them with an AI controller. The controller learns how to **optimise windfarm performance** in the face of changing conditions, which it does through a trial-and-error process that adjusts based on feedback from the digital twin. This approach is called reinforcement learning.



OUTCOMES AND BENEFITS

Results from our research show that wake steering improves wind farm efficiency by redirecting turbine wakes, allowing downstream turbines **to receive stronger, less turbulent wind, which increases overall power output**. It has the potential to reduce mechanical stress and fatigue loads on downstream turbines, lowering maintenance costs and extending their lifespan. Overall, **wake steering enhances energy production and cost-effectiveness**, contributing to more sustainable and profitable operations.

- In 2024, wind power became the largest source of electricity generation in the UK. Wind power accounted for 30% of the UK's electricity.
- Surveys over a number of utility-scale wind farms have shown that wind turbine wake interactions are responsible for annual energy losses of up to 20%.
- Studies show **potential power output increases of 5–10% for optimised wind farms using wake steering** to mitigate wake interactions.

WAKE STEERING IMPROVES WIND FARM EFFICIENCY

HYDROGEN

The main mission of our research is to **revolutionise hydrogen research** with machine learning and computational fluid dynamics for a sustainable future.

Hydrogen (H_2) and its carriers, such as ammonia, are pivotal in the **global shift towards decarbonisation**. These fuels offer a cleaner alternative to fossil fuels, as they are carbon free, playing a critical role in reducing greenhouse gas emissions and powering a sustainable future especially in the hard to decarbonise domains such as marine, aviation and long haul transportation.

PROBLEMS

However, the potential of hydrogen is accompanied by significant challenges. H_2 must be stored under cryogenic conditions, making it highly complex to handle. Its extreme flammability adds another layer of risk, requiring meticulous safety measures during research and application. As a result, experimental work with hydrogen is not only resource-intensive but also fraught with challenges, leading to a scarcity of comprehensive data sets for engineers to optimise hydrogen-based systems. These challenges are reflected in data collection of on-site hydrogen release, which can be an expensive and dangerous operation.

SOLUTIONS

To maximise the reliability, safety and operational efficiency of hydrogen-based systems we have designed digital twins with surrogate modelling tailored to unintended hydrogen leaks. This thorough set of numerical tools for fast and reliable predictions of leak characteristics that we have developed can **achieve safer operations, minimise hazards, and reduce maintenance costs** in the hydrogen industry.

OUTCOMES AND BENEFITS

By implementing real-time safety measures, we can detect anomalies, mitigate risks proactively, and **safeguard both personnel and infrastructure**. This approach not only enhances safety but also builds trust in the reliability of hydrogen-based technologies, **accelerating their adoption for a sustainable energy** future.

Hydrogen is stored typically at high pressures and low temperatures. Also, typical hydrogen leaks have sizes of millimetres. Based on this consideration, we created a training database based on synthetic data from Computational Fluid Dynamics representative of hydrogen leaks, to characterise hydrogen stored at conditions typical of refuelling stations or tank storage.

We have developed a **framework based on machine learning models** to predict hydrogen leak characteristics, and a model to forecast the pressure and temperature signals following a hydrogen leak, that mimic what a sensor might read when tracking a hydrogen jet. These tools can be used to **create scenarios and prediction regarding safety** when hydrogen applications are developed.

ROAD TRANSPORT

The aim of our research is to revolutionise road vehicle aerodynamic performance by leveraging AI-driven decision making to enable dynamic, real-time control of aerodynamic features. With the objective to enhance energy efficiency, reduce emissions, and improve overall vehicle stability across a range of driving conditions and vehicle types, such as passenger cars and trucks.

IMPROVING EFFICIENCIES OF ROAD TRANSPORT

PROBLEMS

In addressing climate change, reducing emissions, lowering fuel consumption and extending the range in road transport is essential. Trucks contribute approximately 30% of total greenhouse gas emissions within the transportation sector. Overcoming aerodynamic drag accounts for roughly 50% of the energy produced by a truck's engine, irrespective of the type of fuel used, emphasising the importance of optimising aerodynamic efficiency and turbulent flows is essential.

Turbulence, the oldest unsolved problem in classical physics, is ubiquitous in systems that underpin the transition to net zero and is the main cause of aerodynamic losses. Enhancing efficiency therefore depends on predicting and controlling turbulent flows, even under limited information. However, the inherently complex, unpredictable, and high-dimensional nature of turbulence has thus far prevented the development of devices or algorithms that can reliably adapt to variable conditions in real-world turbulent environments.

SOLUTIONS

We are using **novel autonomous, dynamically adjustable flaps**, controlled by AI, on the rear of heavy road vehicles to reduce drag by **adapting in real time** to turbulence and changing external conditions. The flaps autonomously adjust to maximum drag reduction and enhance vehicle efficiency.

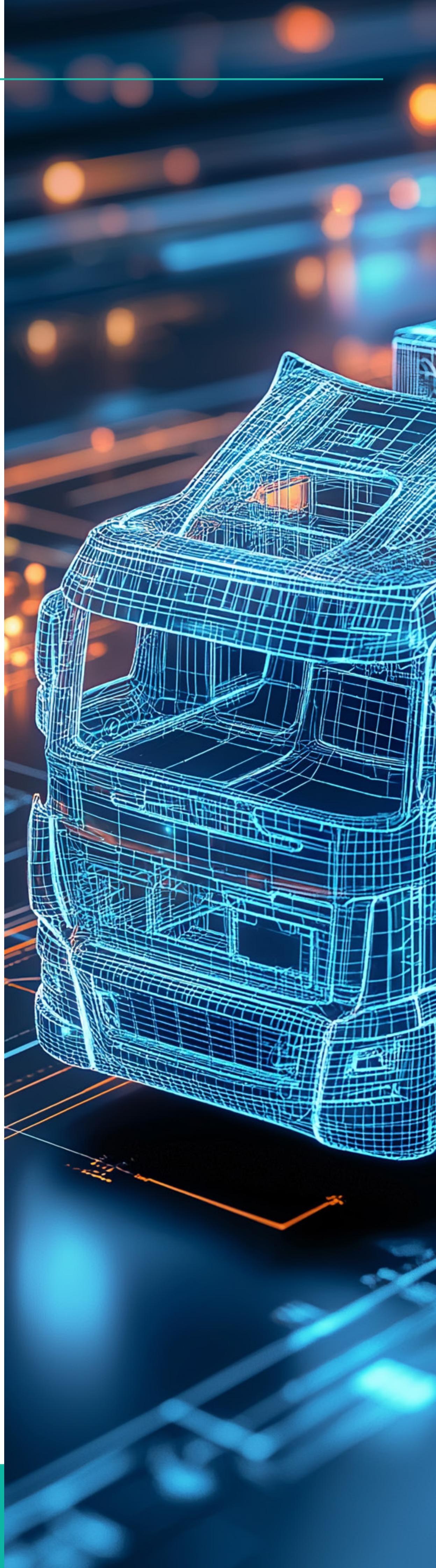
The state-of-the-art AI controller, based on a reinforcement learning technique, has been integrated into the flap system. This algorithm learns from limited observations to continually fine-tune the flap positioning and respond optimally to the complex, turbulent flow. We are creating real-time decision-making tools to enable active aerodynamic optimisation.

OUTCOMES AND BENEFITS

Current solution, static flaps, can reduce drag by 10% (at their optimised design point). When the external conditions are changed these devices become less efficient. Therefore, our solutions **improve the efficiency by 2 to 3 times** in respect to the static case (estimation from preliminary experiments). The adaptability of the mechanism guarantees the optimal configuration in variable situation.

It is estimated that 50% of the truck engine power is needed to overcome the aerodynamic drag of a Heavy Goods Vehicle (HGV) at a typical highway speed of 90-100 km/h1 (regardless of fuel type). A **drag reduction of 10% results in a reduction in fuel consumption of about 5%** [3]. With all this in mind, when we reduce fuel consumption and emissions, the consequent effect is a **reduction in the cost of the transportation of goods**.

References:
[3] Schoon, R., 2007. On-road Evaluation of Devices to Reduce Heavy Truck Aerodynamics Drag. SAE Technical Paper 2007-01-4294



COMMUNICATION IN POLICY MAKING

Communication is the driving interface between science and policy. Policymakers need to have access to, and understand, the scientific evidence resulting from the project which affects their policy areas. Our aim is to help fill the gap between new scientific findings and policymaking. We are creating versatile tools to inform research design and scientific evidence communication to facilitate their use in the real world.

PROBLEMS

There are still significant barriers to the knowledge exchange between scientists and policymakers as well as industry stakeholders. Improving the communication of research outputs is key. It is often the case that new scientific evidence and especially technical innovations do not find their way into the real world. The adoption of new scientific findings is key to maximise their scientific and societal value.

SOLUTIONS

We have created the **Evidence Communication Rules for Policy** (ECR-P) critical appraisal tool to help fill this gap. The tool can guide researchers to improve the communication of their scientific findings and help them formulate policy recommendations based on their research.
The tool can facilitate policymakers to assess scientific research outputs and enable them to critically appraise the quality of scientific evidence and accompanying policy recommendations.

OUTCOMES AND BENEFITS

The ECR-P critical appraisal tool can be used by policymakers, researchers and any other stakeholders interested in evidence-based policymaking and high-quality evidence communication. This work has the potential to influence how scientific outputs are developed and communicated in a manner that they can be readily accessed by the people that have the power to put them into practice.

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