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Addressing Challenges in Long-Term Strategic Energy Planning in LMICs: Learning Pathways in an Energy Planning Ecosystem

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Abstract: This paper presents an innovative approach to addressing critical global challenges in long-term energy planning for low- and middle-income countries (LMICs). The paper proposes and tests an international enabling environment, a delivery ecosystem, and a community of practice. These components are integrated into workflows that yield four self-sustaining capacity-development outcomes. Planning long-term energy strategies in LMICs is particularly challenging due to limited national agency and poor international coordination. While outsourcing energy planning to foreign experts may appear to be a viable solution, it can lead to a reduction in government agency (the ability of a government to make its own informed analysis and decisions). Additionally, studies commissioned by external experts may have conflicting terms of reference, and a lack of familiarity with local conditions can result in misrepresentations of on-the-ground realities. It is argued here that enhancing national agency and analytical capacity can improve coordination and lead to more robust planning across line ministries and technical assistance (TA) providers. Moreover, the prevailing consulting model hampers the release and accessibility of underlying analytics, making it difficult to retrieve, reuse, and reconstruct consultant outputs. The absence of interoperability among outputs from various consultants hinders the ability to combine and audit the insights they provide. To overcome these challenges, five strategic principles for energy planning in LMICs have been introduced and developed in collaboration with 21 international and research organizations, including the AfDB, IEA, IRENA, IAEA, UNDP, UNECA, the World Bank, and WRI. These principles prioritize national ownership, coherence and inclusivity, capacity, robustness, transparency and accessibility. In this enabling environment, a unique delivery ecosystem consisting of knowledge products and activities is established. The paper focuses on two key knowledge products as examples of this ecosystem: the open-source energy modeling system (OSeMOSYS) and the power system flexibility tool (IRENA FlexTool). These ecosystem elements are designed to meet user-friendliness, retrievability, reusability, reconstructability, repeatability, interoperability, and audibility (U4RIA) goals. To ensure the sustainability of this ecosystem, OpTIMUS is introduced—a community of practice dedicated to maintaining, supporting, expanding, and nurturing the elements within the ecosystem. Among other ecosystem elements, training and research initiatives are introduced, namely the Energy Modelling Platform for Africa, Latin America and the Caribbean, and Asia-Pacific as well as the ICTP Joint Summer School on Modelling Tools for Sustainable Development. Once deployed via workflows, the preliminary outcomes of these capacity-development learning pathways show promise. Further investigation is necessary to evaluate their long-term impacts, scalability, replication, and deployment costs.

Keywords: U4RIA; OpTIMUS; OSeMOSYS; IRENA FlexTool; energy planning; energy system modeling; teaching; capacity development; self sustained; climate change; energy policy; accessibility; open-source; e-learning; sustainable development goals; low-carbon technologies; climate policies; ecosystem

1. Introduction

The global climate crisis requires the urgent decarbonization of energy systems. This is especially important in low- and middle-income countries (LMICs); however, these countries face particular challenges due to competing priorities, such as fostering economic expansion, securing reliable energy supply, promoting ecological sustainability, and fulfilling social advancement needs. The capacity for LMICs to drive nationally owned energy planning is fundamental for developing coherent, robust, transparent, and accessible strategies. Effective energy planning forms a key pipeline component of a 'Data-to-Deal' process that can mobilize the large-scale climate finance required to enable national development and decarbonized systems. Data-to-Deal (D2D) is a way of thinking about how to use data to make a difference. It starts with gathering data, then analyzing it, and finally using it to mobilize financial resources. The goal is to develop transparent workflows that can be replicated or used to inform similar efforts in other settings [1].

Transitioning to low-carbon energy systems has thus become an increasingly critical policy priority [2,3]. However, developing long-term energy planning strategies is complex. It requires an enabling environment that supports a dynamic ecosystem, in which key elements (knowledge products and activities) and their suitability need to be provided, regulated, and supported by a community of practice. If properly enabled, such an ecosystem might provide pathways to effective outcomes that can be scaled. A key outcome would be to enable national agency (the ability of a government to make its own informed analysis and decisions). Appropriate bodies should help ensure national ownership, robustness, transparency, and accessibility—underpinned by institutional capacity and self-sustained skill development. This is further complicated in situations where international technical assistance (TA) elements are fragmented. TA can inadvertently focus on siloed outcomes, thereby ignoring the upstream needs of the government to support the achievement of those outcomes. The difficulty is compounded by the requirement for LMICs to harmonize conflicting objectives (often overseen by different ministries). Lack of policy coherence and inclusivity can lead to distorted outcomes, which can be addressed by fostering competent national bodies and promoting international cooperation.

Long-term strategic energy planning in LMICs cannot be met with superficial assistance. It requires a comprehensive understanding of each country's energy mix, the available technologies, the policy landscape, and the socio-economic and political structures that underpin national energy systems. In short, a solid understanding of the context is critical for implementing robust and meaningful low-carbon development plans [4]. This requires in-country capacity.

1.1. The Challenge

There are critical weaknesses in many LMICs: limited national ownership, incoherency and exclusivity, inhibited local human capacity, low analytical robustness, limited transparency and accessibility. Each of these weaknesses is outlined in further detail below:

Limited national ownership: external consultants may not understand the local context in which the energy systems analysis occurs [5]. In contrast, national experts will better understand a country's decision-making process, governance structures, system requirements and limitations, needs, and political economy landscape [2–4]. As a result, national experts are likely to design more realistic scenarios and ask more relevant questions to help inform decision-makers. There is a pressing need for dedicated, in-country workforces with complementary skills and knowledge: on one side, the effective use of analytical tools to produce science-based evidence for policy; on the other side, an understanding of the institutional setting and processes of the country or region in question and the ability to communicate meaningful results to the right policymakers [4,6]. It is common to find either skill set on its own; however, it is a challenging task—and therefore rare—to acquire and incorporate both skill sets into institutional-level operations as they differ significantly from each other. With the growing and pressing need for credible, high-quality plans, many government agencies frequently outsource the development and application of energy models to external consultancies instead of investing in developing in-house expertise through learning-by-doing to strengthen their local energy planning capacity [4,5,7]. If resources are limited, the challenge of improving local capacities may be overlooked by redirecting funds to external agencies. This can lead to issues regarding ownership, as external agencies frequently restrict the results behind a paywall, making it harder for local institutions to have full control of the analysis. In addition, support from donors is often disjointed, resulting in numerous studies with different technical approaches and a lack of coherence and strategic planning for the entire energy system. Capacity-strengthening efforts can be similarly disjointed, and they are often not aligned with government policy priorities and procurement protocols (for example, the terms of reference for technical studies). This makes it more difficult for datasets, tools, and models to be usefully shared with decision-makers and their advisers [8].

Incoherence and exclusivity: Crucial stakeholders, such as policymakers and investors, are less likely to support plans they were not adequately consulted on as part of the development process. Additionally, resource constraints are a common problem, and this hinders local institutions and decision-makers from conducting their own analyses. Decision-making processes that lack an evidence-based approach have a greater risk of failing to attract investors, as investors prefer projects with a solid foundation of information and data to underpin investment decisions. Furthermore, as mentioned above, planning often does not consider the energy sector as a whole, instead focusing on individual projects that are not necessarily aligned. In many instances, supply-side measures take precedence, which can neglect demand-side issues or comprehensive sector-wide planning. For example, cooking and heating challenges are often considered separately to overall electricity projects. This may stem from inadequacies in stakeholder engagement and workflows.

Inhibited human capacity: Engaging external consultants for energy planning directs resources beyond the LMIC's analytical workforce, thereby compounding the problem by reducing the in-country capacity to carry out effective planning.

Low analytical robustness: Energy planners and academics have increasingly turned to energy system modeling tools to make informed decisions about investments and policies related to low-carbon solutions [1,9,10]. These tools are used to assess alternatives for the development of a country's energy systems. Key challenges can be addressed by considering costs, environmental impact, and resilience to external changes and unexpected energy demands. However, models and, especially, datasets are not always adequate and available to address robustly the issues arising from global energy transition trends, including shifts to modern forms of cooking or heating, the integration of variable renewables, greater electrification in the economy, and the role of smart grids and distributed generation.

Outsourcing analysis does not allow for evaluation and review of the datasets and models employed, as the output from a consultant is usually a report with recommendations. Reviewing and running additional scenarios is often costly and therefore rarely done in a comprehensive manner.

Limited transparency and accessibility of data, tools, and analytical and stakeholder workflows: Consultancies frequently use proprietary tools that require expensive licenses and rely on confidential and non-transparent data sources [11]. These are generally embedded in analytical and stakeholder workflows that are not easy to retrieve. Once a consultancy contract ends, the national energy planning institutions and their technical experts have no internal knowledge of the assumptions and decisions made when these models were built; this is exacerbated when there is a lack of capacity to use the models or fund their continued use. This results in an intermittent analysis cycle with little national buy-in or scope for the emergence of in-country energy transition champions.

1.2. The Proposed Solution

In response, the authorship team introduces an initiative together with key partners in the international energy planning community. Together they co-created and endorsed the "Roundtable Principles for Supporting Strategic Energy Planning" in line with the 2005 Paris Declaration on Aid Effectiveness [12]. These principles create an enabling environment in which a support ecosystem can be developed. They aim to improve the effectiveness of support for energy planning in LMICs and ensure that strategic decisions align with broader economic, social, and environmental goals. The five principles, whose development was initiated by the UK government's Foreign, Commonwealth and Development Office's (FCDO) Energy for Economic Growth (EEG) Programme, and is now led by the Climate Compatible Growth (CCG) Programme, have been signed by over 20 international organizations, such as AfDB, IEA, IRENA, IAEA, UNDP, UNECA, the World Bank, and WRI. The signatories commit, through their programs, to enable these principles, which are quoted in full from the founding document [12]:

- **National Ownership**: Support country-led energy planning processes that work in partnership with key stakeholders (defined as governments, government agencies, consumers/citizens and civil society organizations, utilities, investors, project developers and international development partners) to achieve broad consensus on strategic objectives and plans. Help empower the relevant authorities at the regional, national, and subnational level to rally stakeholders to implement the plan, and push back on proposals that do not align.
- **Coherence and Inclusivity**: Assist Governments to ensure that strategic decisions taken in the energy sector are coherent with broader economic, social and environmental goals (including Sustainable Development Goals and Nationally Determined Contributions under the Paris climate change agreement) by committing to evidence-based, integrated, and inclusive energy planning processes that lead to fair and technically sound energy development programmes.
- **Capacity**: Support Governments in the definition of priority capacity building activities which strengthen the capability of national institutions to take the lead on strategic energy planning. And incorporate plans and evidence into decision-making and implementation processes. Commit to the coordination of Development Partners in line with the Government's vision, requests for support, and goals, and avoid fragmentation and duplication of efforts.
- **Robustness**: Promote the use of models, analysis and decision-support tools that have strong technical and economic foundations, are fit-for-purpose to deal with rapidly changing circumstances in the energy sector, are able to support flexible and adaptive approaches to energy sector planning, and can be easily and regularly updated.
- **Transparency and Accessibility**: Promote open access to and review of planning inputs (data, model design and assumptions) and encourage the accessibility of plan-

ning outputs to key stakeholders, subject to government restrictions and commercial confidentiality constraints [12].

The latter principle includes a focus on what are referred to as the U4RIA goals, with suggestions for their achievement. These goals aim to enhance Modelling for Policy Support (MoPS), which is a process that uses models and data to help inform decisions about policies and associated investments. This process affects many different communities, from the analysts who create the models to the people who are affected by the policies.

To improve the MoPS process, models and workflows must be user-centric, retrievable, reusable, repeatable, reconstructible, interoperable, and accountable (U4RIA). This means that they should be designed with the needs of the users in mind, easy to find and access, able to be used again for other projects, able to produce consistent results, able to be rebuilt from their inputs and outputs, able to communicate with other models and workflows, and able to be tracked and audited.

The U4RIA acronym stands for these seven goals. By achieving these goals, MoPS can be a more effective and efficient process that can be used to make better decisions about policy [13,14].

As summarized in the conceptual diagram in Figure 1, this paper builds, in this principle-based enabling environment, an ecosystem of elements, including knowledge products and activities. For those elements to be user-centric, retrievable, reusable, reconstructible, and provide repeatable analysis that is interoperable and auditable (U4RIA), the paper also introduces the application of the U4RIA goals, based on Howells et al. [14], to the ecosystem and its elements.

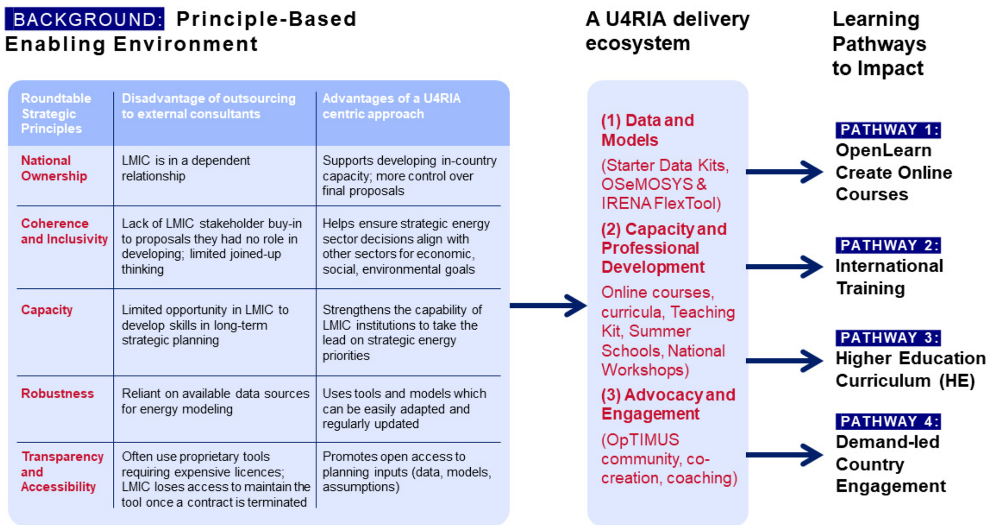

Figure 1. A conceptual diagram of the key components introduced in this paper: a principle-based enabling environment (Section 1), a U4RIA delivery ecosystem (Sections 2 and 3), and self-sustaining learning pathways to impact (Section 4).

To ensure that U4RIA goals are met, the paper introduces and employs a community of practice. That community serves the purpose of active provision, regulation, and support of key elements of the U4RIA ecosystem. Formed to provide this support, the Open Tools, Integrated Modelling and Upskilling for Sustainable Development (OpTIMUS) community (www.OpTIMUS.community (accessed on 13 May 2023)) consists of practitioners from a number of universities, programs, and international organizations that are aligned with strategic energy planning principles.

For example, this ecosystem can be used to create learning pathways for countries to develop self-sustaining national capacity to produce energy system models. It does this with **elements** including **knowledge products** that focus on (1) data and models; (2) capacity and professional development; and (3) engagement. Specifically, this paper focuses on the creation of four self-sustaining learning pathways with a focus on: (i) the open-source energy modeling system (OSeMOSYS) and the power system flexibility tool (IRENA FlexTool) with associated starter data kits; (ii) international summer schools, national capacity-development workshops, online fora, open learning courses and teaching kits; (iii) the OpTIMUS community's co-creation and coaching activities. Insights into the applicability and scalability of these approaches are partially explored and demonstrated.

Finally, conclusions and recommendations relevant to actors who support capacity development are provided. These begin to demonstrate how to build effective energy planning capacity in LMICs, including the measures and resources required to evaluate the long-term impact of these learning pathways, develop institutional strengthening, and make it scalable.

By engaging national experts, this approach leads to the development of more contextually relevant, accurate, and effective models. This ultimately leads to better country buy-in, as described in Section 4. Adopting this innovative strategy has begun to help several countries achieve self-sustainability and master essential skills for long-term success.

1.3. Paper Structure

The paper is structured as follows: Section 2 discusses the advantages and current use of selected open-source energy planning tools, specifically OSeMOSYS and IRENA FlexTool. These tools are presented as illustrative examples within the context of the U4RIA-delivery ecosystem. Section 3 expands on the description of the novel elements of the U4RIA-delivery ecosystem. It focuses on developing self-sustaining capacity, primarily in universities and research institutes, and emphasizes the importance of co-creating models with national experts. Additionally, it outlines the modular approach taken as part of this methodology and the role of international partners in developing this new energy planning ecosystem to support LMICs in improving their national capacity for long-term energy planning. Section 4 introduces new learning 'pathways' and discusses their key characteristics, such as duration, skill level, and resource requirements. OSeMOSYS and IRENA FlexTool are used as illustrative examples to showcase the potential of these pathways. Section 5 compares these four innovative pathways to reveal how they develop and maintain national capacity for energy system modeling in LMICs. Finally, the case is made for other development institutions to adopt similar strategies for strengthening capacity development programs in energy planning.

2. Background on Energy System Models for Planning

Energy modeling tools are widely used to support energy planning and decision-making. They provide a comprehensive and systematic approach to analyzing and evaluating different energy scenarios and ensuring energy policies are aligned with national (and or regional) energy needs, signaling where and how to invest in the energy sector [15–29]. These tools simulate and/or optimize energy supply and demand systems to determine cost-effective and sustainable energy mixes. They can be used to evaluate the impacts of various policies, regulations, and technological advancements on the energy system, considering economic, social, and environmental factors. Energy modeling tools are also helpful in identifying the potential for energy efficiency and renewable energy sources and developing comprehensive plans for energy system expansion and infrastructure upgrades. Overall, energy modeling tools play a critical role in energy planning by providing a rigorous and objective analysis of energy pathways, thereby supporting the development of informed and effective energy policies and investment decisions.

This article explores the use of a subset of the U4RIA-based ecosystem to deliver outcomes. Two open-source model generators (OSeMOSYS and IRENA FlexTool), together with supporting ecosystem elements, are used as two (of many) modelling tools examples. These modeling tools been used for financial mobilization, national development strategies, and national communications. OSeMOSYS is widely recognized for its ability to model the entire energy system or individual energy sectors—including supply, transformation, distribution, and end-use demand—and optimize the system to determine the least-cost energy mix [20–23]. IRENA FlexTool, on the other hand, is specifically designed to analyze power system flexibility. In doing so, it can evaluate the potential for renewable energy and the impact of renewable variability on the power system in order to support the integration of variable renewable energy sources into power systems. Studies have used these tools to evaluate the impact of energy policies on greenhouse gas emissions, energy access, and economic development and to identify opportunities for energy efficiency and renewable energy [24–26]. Sections 2.1 and 2.2 will delve deeper into the reasons behind choosing these tools as focal examples.

2.1. OSeMOSYS—The Open-Source Energy Modeling System

Primarily, OSeMOSYS is an energy modeling tool to evaluate long-term energy scenarios and inform energy planning decisions. It sits within the 'capacity expansion' modeling family and has several advantages over similar modeling tools. First and most critically, it is an open-source tool available to all and has the scope to be modified and expanded upon by users. Second, it is a highly versatile tool that can be applied to model various energy systems and scenarios. Third, OSeMOSYS is designed to be transparent and comprehensible to a broad audience. Fourth, OSeMOSYS is user-friendly and has been designed with straightforward input formatting as a feature facilitated by easy-to-use interfaces. An example is the clicSAND Interface based on Microsoft Excel [27,28], which simplifies the use of OSeMOSYS for non-experts and enables them to run scenarios and compare results without needing specialized software or technical skills. Finally, OSeMOSYS is designed to be interoperable with other modeling tools and data sources, facilitating integration into existing modeling frameworks and workflows. Some examples, of many, include the integration of OSeMOSYS with a computable general equilibrium model [29], with an input-output model [15–18], as a basis for the development of a widely accepted [19] integrated climate-, land-, energy-, and water-system approach, an optimization with OSeMOSYS-PuLP [20], with OSeMOSYS-OnSSET [21], and finally OSeMOSYS-FlexTool integration [22,23]. These advantages make OSeMOSYS a potent and accessible tool for modeling energy systems and assessing policy and investment decisions.

OSeMOSYS can be used to model the entire energy system or individual sectors, including supply, transformation, distribution, and end-use demand. The energy system model can be optimized to determine the least-cost energy mix. It considers a wide range of energy sources—including conventional and renewable—and allows for modeling different types of energy infrastructure, such as power plants, transmission and distribution networks (in a spatially aggregated fashion in most applications), and energy storage systems. Moreover, OSeMOSYS considers economic, social, and environmental factors—such as capital costs, fuel prices, greenhouse gas emissions, and energy access—to analyze energy options comprehensively. Finally, the tool allows the user to consider regulatory aspects and their impacts on the least-cost infrastructure development paths (e.g., taxation of emissions, annual or accumulated emission limits, renewable supply targets, constraints to capacity additions, and budget constraints [24]). The tool provides energy production and consumption outputs, costs, and emissions. These outputs can inform energy planning decisions and support the development of sustainable energy policies.

The tool's broad application in capacity-development and modeling activities, as evidenced by its use in numerous academic research papers, highlights its effectiveness as a tool for supporting energy planning (as shown in the paragraph above). Furthermore, the United Nations Department of Economic and Social Affairs has adopted OSeMOSYS as one of their supported modeling tools, indicating its potential for informing sustainable energy policy at a global level [25]. The comprehensive and rigorous analysis of energy options provided by OSeMOSYS can be leveraged to support the development of effective and sustainable energy plans. Overall, OSeMOSYS represents an effective tool for policymakers and energy planners seeking to address the global energy challenge and transition to a sustainable energy future. To make capacity-development activities self-sustainable in the future and accessible to a wider audience, previous work has developed simple exercises and case studies to teach OSeMOSYS, such as the UTOPIA [26] and ATLANTIS [30] models. Later work paved the way for the conceptual development of an OSeMOSYS teaching package framework [31]. However, these efforts did not materialize into actual online courses, full curricula for postgraduate courses, or new procedures for delivering technical assistance programs in countries; therefore, their impact has remained limited. This paper aims to demonstrate how capacity development for OSeMOSYS can be made more effective and sustainable over the long term by evaluating the lessons learned from the capacity-strengthening activities presented here. These activities include an online course on energy modeling using OSeMOSYS and IRENA FlexTool, training activities, and longer-term in-country engagement.

2.2. IRENA FlexTool

IRENA FlexTool is a power system modeling tool that provides detailed insights into the electricity grid operation and dispatch over a one-year horizon [32,33]. The tool was developed by the International Renewable Energy Agency (IRENA) and Finland's VTT Technical Research Centre. IRENA FlexTool is designed to support the optimal and cost-effective integration of variable renewable energy sources into power systems. This can is done by evaluating the potential for increasing the penetration of renewable energy in the electricity grid, assessing the impacts of renewable variability and uncertainty on the reliability of the electricity grid and identifying flexibility gaps in the system.

Despite being structured as a common electricity dispatch optimization model, it is focused on reporting flexibility indicators and power system flexibility, accounting for the flexibility capabilities of all the power system's assets. Moreover, it offers a simplified capacity expansion feature, enabling it to explore optimal investments in different options that support system flexibility in the long term [32,33]. Therefore, IRENA FlexTool can be used for either or both of the following analyses:

- Performing short-term optimal dispatch scheduling of the electricity grid (dispatch mode) at hourly or sub-hourly time scales and identifying flexibility gaps in the system, such as excess generation, loss of load, insufficient reserve, etc.
- Performing simplified investment planning analysis (investment mode) to identify a least-cost mix of different solutions to address insufficient flexibility issues in the system.

The main advantage of IRENA FlexTool over similar modeling tools is that it has a relatively detailed yet simplified representation of the electricity grid operation, reducing the computational requirements and lowering the learning threshold. IRENA FlexTool uses a Microsoft Excel interface and presents results in a user-friendly, concise, and informative manner, making it easy to use and accessible to a wide range of stakeholders. Further, it is also open-source (released under the GNU license), and the only prerequisite for its use is having Microsoft Excel installed [32,33]. These features make IRENA FlexTool a great option for conducting a quick but thorough flexibility assessment of the electricity system. Thus, it can complement OSeMOSYS by providing insights into the reliability and operability of different long-term capacity investment plans developed in OSeMOSYS. FlexTool has been used in different country case studies and capacity-development activities conducted by IRENA [34–39].

3. An Energy Planning Ecosystem

The methodology employed in this paper consists of a six-step procedure. First an enabling environment is introduced with the strategic energy planning process. Second, U4RIA design goals for the ecosystem elements are developed. Third, an OpTIMUS community of practice is assembled and used to provide ecosystem elements as well as support and maintain them. Fourth, these elements are mapped to provide routes for four distinct learning pathways. Fifth, members of the OpTIMUS community are engaged in co-creation and coaching activities that resulted in outcomes. Sixth and finally, to validate the assumptions made, testing is conducted to acquire insights and experience.

3.1. Key Elements of the U4RIA-Based Energy Delivery Planning Ecosystem

Divided into element types focusing on (1) data and models, (2) capacity and professional development, and (3) advocacy and engagement, the elements used in these pathway packages are described below.

(1) Data and Models

- Open-source modeling tools such as OSeMOSYS (with its user-focused Excel interface, 'clicSAND') and IRENA FlexTool, described earlier, are used for energy planning analysis.
- Starter data kits, which contain a base level of data which can be used to build models, can accelerate the modelling process described earlier. When developing a model, data must be collected. This can be time-consuming and laborious, reducing the time available for analysis. Thus, a set of starter data kits was developed. Together with Open University courses (see below), a new analyst can use these kits to develop an initial model much faster.

(2) Capacity and Professional Development

- A Teaching Kit: This is teaching material on the use of modeling tools to support strategic energy planning. This is adaptable, updatable by any contributors requesting editing rights, and open-access. Content is divided into a highly modular structure to allow the target users (i.e., teachers) to choose contents of interest and fit them within existing courses. An 'instance' of the set of material combined by the users can then be extracted for teaching in a university, an online course, and so on.
- Open University online courses (hereafter OU courses), hosted on the OpenLearn Create platform, are developed (as online instances of the teaching kit) so that anyone can enroll [40]. They have automatic grading, so those who complete them are certified. They cover theory as well as model development and usage. Certified users will have the capacity to engage in co-creation activities where interaction with tutors is focused on real-world country case study applications.
- Joint Summer Schools have been set up regionally in Latin America and Africa, and globally in Trieste, Italy. These schools require completed OU courses as a pre-requisite for applicants. This allows participants to initially focus on co-created case studies and teamwork and finish with a national starter model.
- In-country workshops and model co-creation and review can form an important component of capacity development and are a tested method many organizations use. Importantly, these can be useful events for analysts as they develop a starter data kit into a fully-fledged national model with specific analysis.
- Blueprints for:
    - (a) Universities can be a helpful starting point to understand how to use these elements to: extend an existing course, introduce a new course, develop a program, or set up a research unit or a center. These can provide insights and a set of texts that reduce the barriers and help understand how to be sustainable.
    - (b) Government planning units to help bolster existing or set up new activities and functions can be helpful. Elements such as the OU courses can help increase the speed of onboarding new analysts and improve internal knowledge management.

(3) Advocacy and Engagement

- Engaging stakeholder groups or communities that possess relevant data or are impacted by the modeling and its outputs is essential for promoting national representation and ownership of the analysis beyond the modeling team. Establishing dedicated and active engagement with "special interest groups", or SIGs, can play a pivotal role in this process. These are co-created and consist of regional experts and policymakers. By involving SIGs, an important step is taken towards incorporating diverse perspectives and ensuring inclusive decision-making throughout the analysis.
- Communities of practice of:

(a) Model developers: ensuring that willing and experienced experts have a space to help modelers and that modelers have access to experts can be important. Model debugging and learning are non-trivial. Thus, a large Google Group has been set up to encourage this interaction. Over time, the group has become a place for peer support, interaction, and feedback. Access to it reduces the need for specialized, in-country, and focused debugging by external consultants, which can be resource-intensive.
(b) Model insight users: it is important that the leaders of modeling teams, decision-makers, and experienced analysts have space to exchange insights that result from modeling. This can range from sharing academic papers to policy analysis. To facilitate this, online regional Energy Modelling Platform (EMP) groups have been developed on LinkedIn.

- Regional hubs can be useful to help root self-sustaining capacity development as they potentially serve either a larger demand (more people) or a deeper demand for a network of partner organizations. This can allow for critical mass to form where it otherwise might be dispersed.

Note that all the knowledge products in this ecosystem are open-source, open-access, and free. This is to increase transparency, accessibility, reduce costs, and allow for scaling.

Table 1 describes how these elements are adhering to the Roundtable Principles.

In conclusion, adopting ecosystem elements can help realize the Roundtable Principles for supporting strategic energy planning and, in turn, create an enabling environment for in-country national energy plans.

3.2. Different Methods of Integrating the Selected Elements into Self-Sufficient and Reinforcing Learning Pathways

In the pursuit of self-sufficiency in energy planning, it can be essential for countries to strengthen their energy planning capacity. This involves developing a comprehensive and integrated ecosystem that promotes sustainable energy planning.

In this paper, four learning pathways for supporting the strengthening of capacity are presented. These have been adopted and refined in several contexts, either in isolation or in combination. These make use of the "Key Elements of the U4RIA-Based Energy Delivery Planning Ecosystem" presented in Section 3.1. Each pathway has equipped analysts with skills and knowledge to help establish an aspect of a Data-to-Deal workflow that can be better 'self-sustained' [1]. These learning pathways could be progressive and tailored to the circumstances of national analysts (Figure 2). Section 4 will explore each learning pathway in detail, highlighting their critical components and applicability, so that development partners can start to set up capacity-development efforts in a similar fashion. The self-sustaining nature of each pathway is explored by listing current and resultant outreach and impact activities. Below, a brief overview of each pathway is given to highlight its main characteristics.

Table 1. Elements of an Energy Planning Ecosystem aligned with the Roundtable Principles.

Adhering Roundtable Principles → / Ecosystem Element ↓	Notes	National Ownership	Coherence and Inclusivity	Capacity	Robustness	Transparency and Accessibility
1. Teaching Kit "Climate Compatible Curriculum" [41]	Under development. A prototype has allowed for the development of courses offered in both English and Spanish	National analysts may develop tailored courses	International organizations can develop updates and their own translations	By selecting elements of the kit that are of interest, an 'instance' of part of a course can be extracted for use in capacity development	Robust Decision Making (RDM) materials are being developed, which will be added to the teaching material. In the meantime instruction is provided to develop sensitivity analysis	Open-source and open-access infrastructure
2. OpenLearn online Open University (OU) course [40]	Over 80,000 downloads of these courses have taken place. They include downloads of software, a percentage score, and a 'badge' to certify completion	Allows for onboarding of national stakeholders and for knowledge management	Features U4RIA workflows and is available to all types of stakeholders	Can be freely adapted and integrated into university teaching/ training, government onboarding/ knowledge exchange, and management programs	Includes initial models, assessments, and techniques	All openly available under creative commons licences
3. Starter Data Kits [42,43]	Openly accessible energy and transport data kits for numerous countries and workflows for how to develop them. There have been hundreds of thousands of downloads of these datasets	Provides a 'quick start' to developing a national model, but it does not add to national ownership per se	Allows for a basis for comparison and sense-checking and requires the involvement of analysts for improvement	Accelerates the process of developing a national starter model (and lowers the barrier to entry)	Provides the basis for developing faster testing and sensitivity analysis	Workflows are peer-reviewed and published, and data are open-access

Table 1. *Cont.*

Adhering Roundtable Principles → / Ecosystem Element ↓	Notes	National Ownership	Coherence and Inclusivity	Capacity	Robustness	Transparency and Accessibility
4. Capacity-Development Training [44]	A. Precursor OpenLearn online Open University (OU) course and certification	This needs to be successfully completed by nationals (and is a non-trivial achievement)	School applications are open to all. However, competition and entrance requirements are high	This element of the school provides basic capacity development with online clinics	To complete the OU course, the student must develop scenarios (which can be used for sensitivity analysis)	Candidate ranking is transparent
	B. Case-study teamwork	A nationally appropriate case study is developed with trainers, and a work plan is co-created	With coaching, model structure, data, and insights are developed and investigated. Those insights can move beyond the model to have implications across government sectors	Capacity development moves from coaching to co-creation, reducing dependency on external consultants	Various scenarios are created to understand output sensitivity	Candidates upload data, presentations, and posters into open repositories for transparency and easy future access
	C. National Starter Model	A final model is co-created and translated into policy-relevant national messages				
5. In-country workshops [45]	The national starter model is translated into a national model	All modeling (data, tools, and workflows) is nationally owned	Via stakeholder engagement, the national team develops coherent and inclusive scenarios	Deeper capacity is built, with a large national team(s) being developed	Work is afoot to develop an accessible 'Robust Decision Making (RDM) workflow' for translation	The national team is trained to apply and use U4RIA goals throughout their work, noting potential benefits
6. Special Interest Groups (SIGs)		SIGs are developed and driven from the ground up	SIGs provide a ready route to stakeholder engagement	SIGs can provide a basis for outreach and reach in the planning process, which is needed for information exchange	SIGs provide a basis to produce improved data, reality checks, scenarios, and sensitivity inputs	SIGs provide an interface between technical modelers and broader stakeholder groups. This provides the potential for enhanced transparency

Table 1. *Cont.*

Adhering Roundtable Principles → / Ecosystem Element ↓	Notes	National Ownership	Coherence and Inclusivity	Capacity	Robustness	Transparency and Accessibility
7. Communities of Practice	Google Group user group for model troubleshooting has been developed (with over 500 conversations and thousands of members) [46]	This ensures that skills are being developed	Active conversation and community support increase potential reach and inclusivity	The group accelerates capacity development as it reduces the need for focused or in-person debugging	Access to feedback and peer-reviewed studies provides potential insights to improve robustness	These fora are open, allowing for transparent access and information flows
	Two recently created LinkedIn communities [47,48], one for Latin America and one for Africa (with over 300 and 100 members, respectively), focus on higher-level studies, outputs, lessons, and job adverts	This aims to help facilitate South–South learning to enable a Southern-centric agenda to be developed		Sharing of 'higher level' analysis and policy insights that are regionally specific and help build and develop a critical body of knowledge and experts		
8. Blueprints for unit development (currently under development with several trials)	University Center (courses, curricula, business, and partnership model)	The adoption and adaption of the blueprints is by the country itself which allows for faster development of national human capacity and ownership of analysis	The blueprints allow for a coherent starting point, that builds on trialing, monitoring, evaluation, and learning.	This accelerates capacity strengthening in national institutions for conducting energy planning	The blueprints are based on trialing and learning, which are in turn based on sound evidence and analysis	The blueprints are open to review and accessible to all stakeholders
	Government Planning Unit Knowledge Management program					
9. Regional hubs (currently under development with several trials)	Regional hubs are being developed. Starting with the hosting of the Energy Modelling Platform (EMP) Schools, this has included the University of Namibia, Costa Rica, Cape Town, and Mauritius	Regional hubs may help support regional agencies, which are easier to access for partners than international hubs in very different contexts	Regional centers can help improve access for local analysts who may find access to international centers difficult and more expensive to access	A regional hub can provide a critical mass of human capacity where it is otherwise dispersed and relatively weak	Allows for the development of locally appropriate analysis and longer-term national capacity development	Local educational centers that promote U4RIA principles are more accessible to local students and analysts

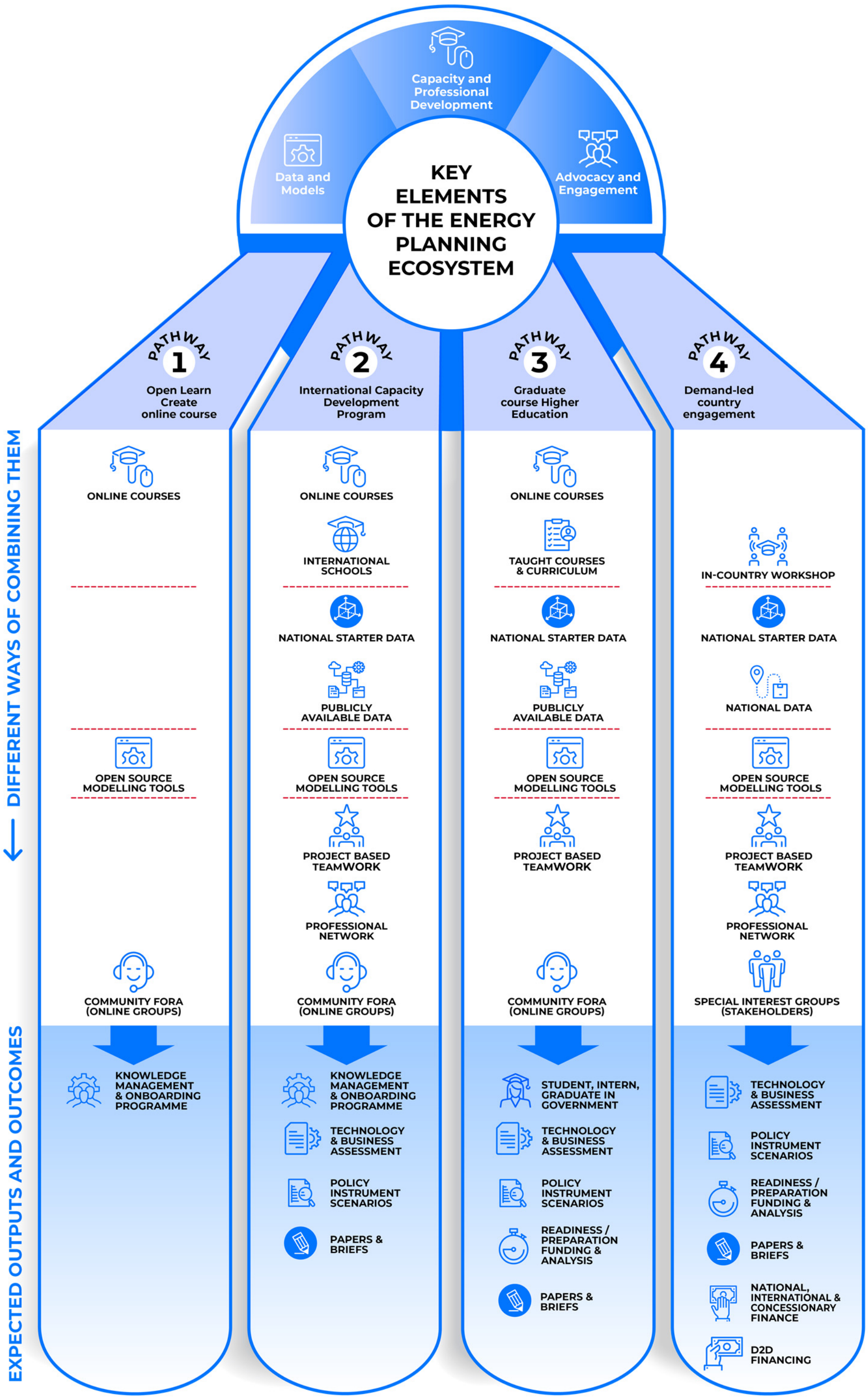

Figure 2. The four Learning Pathways that have taken up different ecosystem elements.

- **Pathway 1—Developing the basic skills through the OpenLearn Create online OU course (Section 4.1)**: An example of Pathway 1 is the OSeMOSYS and IRENA FlexTool learning path, which involves completing a free online course provided by the Open University's OpenLearn Create platform and engaging communities via open Google Groups. Although this paper focuses on OSeMOSYS and IRENA FlexTool, there is a suite of energy planning models, tools, and courses that is already available as part of this growing and continually delivery ecosystem. The OSeMOSYS and IRENA

FlexTool course (and others like it) is designed for beginners and covers the basics of energy planning and modeling by using predefined scenarios to create simple case studies. The course materials are presented in an easy-to-follow format with lectures, quizzes, and practical exercises. Learners have the flexibility to complete the course at their own pace, and upon successful completion receive a certificate. The course is designed to be accessible and affordable, requiring minimal resources from developers. It has successfully attracted a wide range of participants, including government modelers and International Energy Agency (IEA) technical assistance program participants.

- **Pathway 2—International Capacity-Development Programs (Section 4.2.)**: These summer school programs aim to develop participants' energy and resource modeling skills using open-source modeling tools for sustainable development pathways. Participants must complete the OU course of their choice (among the ones from the OpenLearn Create Climate Compatible Growth Programme collection) and attach the certificate of completion to their application form. Attendance at the schools is free of charge, and there are often subsidies for travel costs. The training lasts for three weeks and is jointly organized by the OpTIMUS community [49], international agencies, and a selected leading university in the region where the training occurs. The OpTIMUS community provides provisioning, regulating, and supporting services to the U4RIA ecosystem. The schools equip participants with skills, tools, and teaching materials for higher education teaching or government knowledge management. After the school, some participants have gained the skills to do independent research studies, which has led to several papers being submitted for peer review to journals. This learning pathway, applied to various international capacity-development programs, has successfully established a knowledge-sharing network that benefits all involved, and its output is published on an open-source repository.
- **Pathway 3—Teaching OSeMOSYS in Higher Education (Section 4.3.)**: Attending a postgraduate course at a university that offers this module is an established way to deepen knowledge of these tools. This paper showcases the example of Loughborough University's master's degree module that incorporates OSeMOSYS in its two climate change master's courses. The module has two blocks, one focusing on bottom-up energy policy initiatives and the other on OSeMOSYS modeling. This module examines different sustainable energy and climate policies and their impacts at various levels. The course is designed to cater to various skill levels and provides deeper levels of training. However, this pathway is more expensive than Pathway 2, as it requires students to pay university fees and has a longer duration, spanning a full semester.
- **Pathway 4—Demand-led country engagement (**Section 4.4.**)**: Building upon previous learning pathways, once a government expresses a commitment to long-term engagement, the team collaborates with an interdisciplinary team to co-create a workplan. This collaborative work includes tasks such as developing models and datasets that could inform country strategies. At this stage, creating institutional arrangements for embedding the use of modeling tools to support the country's policymaking processes is essential. This pathway has, therefore, the longest time frame, up to several years. Coordination teams can support and implement these efforts to convene relevant stakeholders and facilitate engagement activities. Importantly, the coordination units are run by boundary spanners [50] who understand the country's decision-making processes. Subsequently, this learning pathway could lead to attracting financial resources to support the implementation of the co-developed models, and, at this point, interfacing with the Finance Ministry and International Financial Institutions (IFIs) is essential. Furthermore, proactive engagement with external parties, including IFIs, will result in a comprehensive national planning analysis that can lead to financing and concessional funding, accelerating the country's low-emission future.

Our approach equips countries with the essential tools and resources to establish a sustainable and self-reliant energy planning ecosystem. By using different pathways that suit the specific needs of individuals and institutions, countries can establish an efficient workflow that prioritizes self-sufficiency and has a long-lasting positive impact. In the following section, the paper delves deeper into each pathway, examining their unique features, including their duration, skill level, and resource requirements. The paper uses OSeMOSYS and the IRENA FlexTool as examples, but the methodology outlined can be, and has been, adapted to other modeling tools. These learning pathways aim to establish a knowledge-sharing network that benefits all involved and promotes sustainable energy planning.

4. Learning Pathways

In Section 4, the learning pathways and their unique features are examined. Their specific characteristics are highlighted, such as the duration, skill level, and resource requirements, to provide concrete examples of effective capacity-development programs. For illustration, real-world case studies involving OSeMOSYS and the IRENA FlexTool are used. However, the methodology outlined in this section can be, and has been, adapted to other modeling tools.

4.1. Pathway 1: Developing the Basic Skills through the OpenLearn Create Online Course

This learning pathway starts with the OSeMOSYS and IRENA FlexTool online course hosted on the Open University's OpenLearn Create platform (henceforth called the OU course) [40]. The course provides the means for a beginner user to develop knowledge of the theoretical concepts behind energy planning and the use of models by creating simple case studies from predefined and fictitious capacity expansion and flexibility assessment scenarios. This is done through step-by-step lectures linked to practical hands-on exercises and quizzes, encouraging students to practice what they have learned. This approach to teaching follows the pedagogical framework that argues constructivist 'discovery' learning is most effective when also complemented with guided methods of instruction, hence the blend of more open-ended hands-on exercises with lectures and quizzes [51]. The structure of the OSeMOSYS and IRENA FlexTool courses is outlined in Figure 3. The theoretical concepts are introduced through lectures, each consisting of four mini-lectures of equal length.

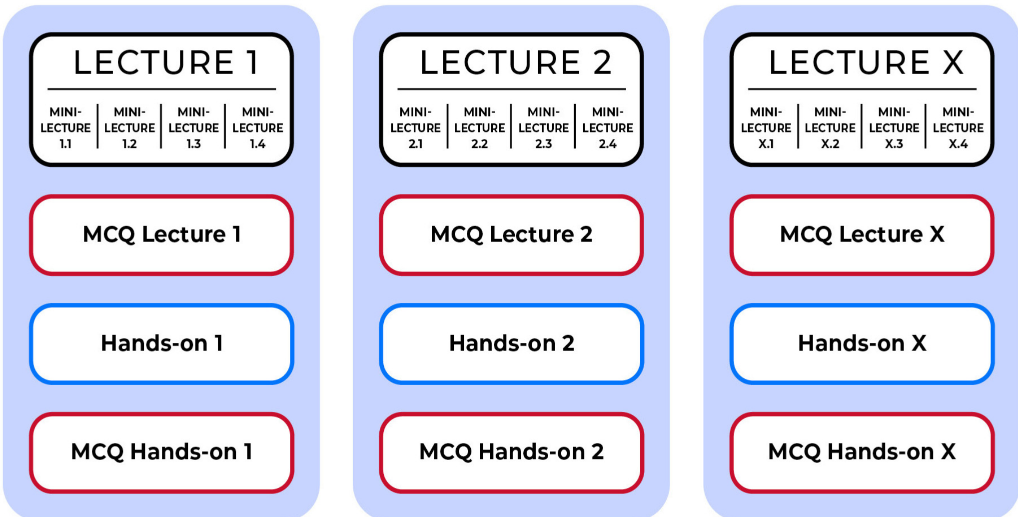

Figure 3. OU Online Course Structure made of Lectures, Multiple Choice Quizzes (MCQ) and Hands-on Exercises.

These key features make such courses unique and suitable for widespread capacity development:

Affordability and Accessibility: The OpenLearn Create platform provides user-friendly, high-quality educational resources without barriers. The OU course is free of charge and accessible to users in almost all countries worldwide. This online course is available in English and Spanish (a French translation of the course is currently being developed) for Windows and Mac operating systems. Additionally, the platform has a user-friendly interface that allows users to track their progress and work towards a free certificate of completion. The course material is presented in a way that is easy to understand, with read-only PowerPoint lectures that include embedded audio and speaker notes to improve accessibility. To increase student engagement and focus on the material, each lecture is divided into four mini-lectures, followed by a graded multiple-choice quiz to test students' understanding of the concepts. Practical user-guided exercises are provided in PDF format, with detailed step-by-step instructions and screenshots of the software and user interface. This makes it easy for students to apply the theoretical concepts they have learned. Furthermore, explainer videos on YouTube are available to support the understanding of the course and minimize the need for instructor intervention [52]. Indeed, for users to leverage the capabilities of the open-source modeling code of OSeMOSYS and IRENA FlexTool, the course has to be accompanied by materials and resources (including user-friendly interfaces like the one used to teach OSeMOSYS, called clicSAND [27,28]) that allow users to adopt them easily. Otherwise, if a tool is not easily understood by users, its value as an open-source resource becomes reductive.

Time frame: The OU course in OSeMOSYS and IRENA FlexTool can be completed at the learner's own pace and is not time-limited. Learners can take as much time as they need and start and finish the course at their convenience. This is especially useful for people with time, context, or family constraints and other commitments and opens the path for use in life-long learning. Referring to the community of inquiry framework for learning by Hrastinski [53], the flexibility allowed by this pathway positively influences cognitive presence, but it comes at the expense of teacher and social presence. In a sense, these are mitigated by using online forums (see the following) and are complemented by the other learning pathways.

Skill levels: The core focus of the OU course is to build up the basic knowledge (for the beginner user) of OSeMOSYS and IRENA FlexTool rather than acquire mastery. In other words, this pathway is aimed at entry-level students and does not require specific prior knowledge of the subject; the other pathways described are focused more on higher-level skills.

Outreach and Impact: The OU course is a valuable resource for reaching a large user audience. More than 400 people had already completed (i.e., received a completion certificate) the OSeMOSYS and IRENA FlexTool online course over the period of two years: from March 2021, when the course was first published online, to May 2023. Users need to complete all the activities on such courses to receive a certificate, meaning the number of certificates obtained from this course is a good indicator of the course keeping high interest throughout. Academics or government modelers have used the OU course to train their staff in research groups or modeling units and enhance their professional development without resorting to external consultants. The International Energy Agency (IEA) has mandated the completion of this online course as a prerequisite for participating in its technical assistance program in Africa [34]. This measure is intended to equip participants with the necessary knowledge and skills to contribute effectively to the projects. Successful course completion is required for participants to obtain a certificate, which attests to their competence in the subject matter. By implementing this policy, the IEA aims to ensure that technical assistance projects are conducted to the highest standards of quality and expertise. The selection process for the projects is highly competitive, with numerous candidates from each country. The final marks obtained on OU course certificates are among the criteria for selecting successful candidates. Furthermore, the certificate is also used as a mode of assessment in Pathway 3 (higher education) as a means to evaluate students' early comprehension of the modeling tool towards the beginning of the course [35].

Resource Requirements and Self-sustainability: A key feature of this pathway is that maintaining the online course requires little effort/resources from the course developers' perspective compared to other training activities. All assessment—done through multiple-choice quizzes—is done by the OpenLearn Create platform and is designed so that participants do not necessarily require external assistance to complete the course. That said, to aid participants who have difficulties understanding the course or get stuck, there is an option for participants to post their queries online via the OSeMOSYS Google Group [46]. Currently, the online OSeMOSYS Google Group has 767 members, all with different levels of expertise, ranging from first-time users to experts in the field. The heterogeneity of the community promotes high-quality peer support, which allows for teacher and social presence to an extent while limiting the need for dedicated trainer resources. In addition, by searching the group discussions, users can check whether their question has already been answered in the past and thus avoid overlapping discussion topics. As more users join the forum, the responses to frequently asked questions increase in number and quality, creating a self-reinforcing loop. A continuous improvement process ensures that regularly updated versions of the course are available. The improvements range from minor corrections to updating the teaching material when, for example, a new software version is released (e.g., update to the hands-on material) or a new module is introduced (e.g., update to the lectures).

Once students have gained basic knowledge through the OU course (Pathway 1), they can take additional courses to deepen their modeling skills. The aim is to provide participants with practical experience using these modeling tools in a real project/case study. In this regard, the authors designed two additional pathways. Pathway 2 is a dedicated and intensive 3-week international capacity-development training.

Pathway 3 is an alternative option to deepen modeling skills in the context of a university postgraduate program (i.e., a master's degree). While in Pathway 1, the scenarios and case studies were predefined in the online course, in Pathways 2 and 3, participants are trained to use the tools in applied projects, such as an actual country case study. This transition between the fictitious models of the OU course and the "real world" country is a key moment in the course where trainers need to intervene and focus on problem structuring or conceptual modeling. This needs to happen to guide how the modeling tools can be used appropriately, namely, to choose what research or policy questions are appropriate for the modeling analysis. Compared to Pathway 1, Pathways 2 and 3 have the advantage of helping users reach a higher level of competence. Unlike Pathway 1, these subsequent pathways require far higher resource input (i.e., increased funding, personnel, and logistics) to ensure the teacher's presence.

4.2. Pathway 2: Gaining Proficiency with the Tools by Using Them in a Case Study—International Capacity-Development Program

Currently, three operational international capacity-development training opportunities (hereafter called 'Schools') have formed part of the methodology of this approach; these are under the umbrella of the Energy Modelling Platform (EMP), which is a training and research initiative that provides capacity strengthening in energy modelling for countries in Africa (EMP-A), Latin America and the Caribbean (EMP-LAC), and Asia-Pacific (EMP-APAC) (www.EnergyModellingPlatform.org (accessed on 13 May 2023)). These are hosted by local, regional universities. They build off the Abdus Salam International Centre for Theoretical Physics (ICTP) Joint Summer School on Modelling Tools for Sustainable Development (SDSummerSchool.com (accessed on 13 May 2023)), offering training on various modules in the OpTIMUS ecosystem, including, but not limited to, OSeMOSYS and FlexTool. With each platform, a LinkedIn group is created to allow hundreds of alumni to stay connected. They are organized by the OpTIMUS community of practice. These schools are annual, hybrid, and last three weeks.

Affordability and Accessibility: To participate in a School, participants must first complete the OU course of their choice (for example, the OSeMOSYS and IRENA FlexTool course) and attach the certificate of completion to their application form. Attendance at the School is free of charge, and there are often subsidies for travel costs for in-person attendance. To apply, a candidate must demonstrate that the results of the study are in demand by the country they come from or represent, that the skills, tools, and teaching materials acquired will be used in higher education teaching or government knowledge management, or that the results produced at the end of the School will be used in policy-relevant research published on a visible platform. Priority is given to participants from countries with a demonstrable need and ability to apply the training to policy development.

Time Frame: These training events occur regularly throughout the year and last three weeks. The training is jointly organized by the OpTIMUS community [49], international agencies, and a selected leading university in the region where the training takes place; this can be in person or in a hybrid format [36–39,44,54]. The first two weeks of the School include interactive modules which are taught by relevant experts. Participants, with expert support, will create a country case study using the tools and skills learnt on the module. This is then developed into a poster and a brief PowerPoint presentation tailored to high-level energy sector stakeholders and decision-makers, which are presented during the third week of the training event. Feedback is given based on these presentations, and the participants who have created the best presentation are invited to present their work at a high-level strategic dialogue. Indeed, the last two days of the School are usually dedicated to a high-level strategic dialogue on energy planning and policy for sustainable development under the 2030 Agenda, with relevant experts and representatives from government and international organizations taking part. All participants attend as part of their training to become more familiar with energy planning discussions and meet and interact with key stakeholders. The teacher and social presence are, therefore, strong in this pathway and facilitate deep learning.

Skill Levels: The School equips participants with applied energy and resource modeling skills, using open-source modeling tools to create pathways conducive to sustainable development. Required prior knowledge includes following Pathway 1, that is, taking an OU course on the tool of interest is mandatory. During the School, participants receive guidance from leading academics and researchers in evidence-based energy development strategies. An induction session is conducted after acceptance, introducing participants to the geopolitics/political economy of the energy transition and the importance of long-term energy planning. Coaching and problem-solving sessions are scheduled throughout the School to deepen the participants' modeling skills. The training events include lectures to enhance theoretical knowledge of systems modeling, problem-solving sessions, and trainer support. This builds confidence in using the tool for different case studies and designing scenarios. Participants improve their communication skills by learning to report and use results for policymaking and preparing posters and presentations. Networking and teamwork opportunities are also available.

Outreach and Impact: Since June 2021, over 200 individuals have been trained in the OSeMOSYS and IRENA Flextool courses across various educational institutions. Most participants have been academics and government analysts, with a smaller proportion of students also attending. At the end of each training session, participants are asked to provide feedback through a survey. The survey responses are analyzed and used to continually improve the teaching activities and materials. Remarkably, when analyzing the survey results from the last three events held [36,37,44], 100% of participants who completed the survey (86% of the total) would recommend this training to a colleague, and 90% affirmed that the knowledge and tools acquired are pertinent for supporting their respective country's policymaking processes and daily work. Due to the success and high quality of the Schools, they are used by leading international organizations such as IRENA, UNDESA, and WRI. For example, the IEA uses two of these capacity-development programs for their African technical assistance program [34].

The process has become more self-sustaining as a result of publishing the School's output on an open-source repository. This is because future participants interested in working in a country that has been studied previously can access the repository and gain insights into where their predecessors previously reached. This enables them to have a benchmark for the types of results their own work could produce and build on previous work rather than starting the analysis from scratch, thus saving time and effort. For instance, the outputs from the June 2022 School held in Trieste, Italy, featured work on various countries, including Kenya [55], Tunisia [56], Cameroon [57], the Democratic Republic of Congo [58], Nigeria [59], Libya [60], Egypt [61], the Philippines [62], Indonesia [63], South Africa [64], Morocco [65], and Zambia [66]. Similarly, the Latin America edition of one of the Schools (called the Energy Modelling Platform (EMP) in Costa Rica) produced OSeMOSYS and IRENA FlexTool outputs for Ecuador [67], Brazil [68], Guatemala [69], Bolivia [70], Colombia [71], Dominican Republic [72], Uruguay [73], Cuba [74], and Suriname [75]. The publication of such outputs on Zenodo has helped establish a knowledge-sharing network that benefits all involved. It is an excellent example of the value of open data and collaboration.

After these Schools, some participants gained the skills to do independent research studies later, which led to several papers being submitted for peer review to journals [23,76,77]. In addition, the OSeMOSYS course was part of a capacity-building and knowledge-sharing plan for officials of the Government of Goa under a "100% RE action plan for the State of Goa" (RE standing for renewable energy) under the IGEN-Access II program funded by the German Federal Ministry for Economic Cooperation and Development (BMZ, Bonn, Germany) and implemented by GIZ India and the consortium led by The Celestial Earth in partnership with KTH, Sweden, and PTC, India [78].

Furthermore, a university lecturer from Makerere University in Uganda introduced OSeMOSYS and Model for Analysis of Energy Demand (MAED), two tools learned during one of the capacity-development Schools, into a new master's course called "Master of Energy Economics and Governance", using these tools and the teaching materials of the OU course (Pathway 1). The same lecturer also gave a presentation on renewable energy and economic growth strategies for Uganda at a high-level forum on 13 January 2022, and the recommendations from the forum were included in a confidential cabinet paper submitted to the Ministry of Finance. In addition, after completing training programs as per Pathway 2, a lecturer from the University of Sierra Leone started master's modules on energy systems modeling in two universities in Sierra Leone, featuring the use of OSeMOSYS as a modeling tool, and co-authored a publication on the advancements and limitations in the underlying capacity-development effort 8].

Resource Requirements and Self-sustainability: This pathway offers deeper training to fewer participants. It requires the active presence of trainers compared to the OU course (Pathway 1), which provides basic training to many applicants without the involvement of trainers. Therefore, a selection process is carried out to identify the best candidates for the training, as there is a limit on applicant places. If the training is conducted in person, a suitable venue must be secured, and a team is required to coordinate the event logistics. Additionally, funding challenges may be associated with covering the costs of travel, visas, and accommodation for trainers and trainees. A reliable internet connection is essential for hybrid training models, and dedicated online support must be provided for remote participants.

To ensure that Pathway 2 leads to self-sustaining capacity strengthening, a 'train-the-trainer' process is implemented. After the School, participants who have excelled in their tasks are invited to contribute as trainers to future capacity events. In this way, the training is delivered by people from the region where it occurs. The aim is to establish an annually recurring School in Africa, Latin America and the Caribbean, Southeast Asia, and a European-based global School (currently based in Italy). Ideally, these Schools would eventually become self-perpetuating, staffed with trainers local to the region with limited input from the OpTIMUS community—currently the chief organizing force behind them.

To address the demand for follow-up training or longer-term support, online alumni communities were recently established for Africa, Latin America, and the Caribbean, which currently have 367 and 128 members, respectively. Feedback received at the end of each School indicated a significant demand for such support. The online communities provide a platform for professionals to share job opportunities and research findings, access webinars and lectures, and establish new partnerships and collaborations with peers in the same country or region.

One significant challenge lies in ensuring long-term motivation among participants to continue working on their models after the training. This challenge often arises when knowledge acquisition remains predominantly at the individual level rather than being institutionalized within the organization, sector, or enabling environment. This issue is discussed in the levels of capacity framework [79] and further elaborated by Ramos et al. [80] or in the theoretical setting [81].

To address this challenge and move towards institutionalization, efforts were made to establish a special issue journal after the Energy Modelling Platform for Africa 2021. Participants in the School will benefit from reduced fees for submitting their work to the special issue. Additionally, a prize system will soon be introduced to recognize outstanding contributions, and an extracurricular writing course will be offered to support participants in publishing their research in journals. These initiatives aim to enhance the self-sustainability of the training process and foster the establishment of energy excellence centers in various regions. By sharing and publishing the work of students, the authors aspire to inspire and guide future participants while promoting the growth of energy excellence centers globally.

4.3. Pathway 3: Teaching OSeMOSYS in Higher Education Institutions

Knowledge of OSeMOSYS modeling tools and practices can also be deepened by attending a postgraduate course at one of the universities currently offering this module to their students, which is referred to in this paper as Pathway 3. As an illustration of this approach, this paper highlights the integration of the OSeMOSYS modeling tool into the master's degree module offered at the Department of Geography at Loughborough University (UK) as part of its two climate change master's courses. Another example, not described in detail in this paper, is at the Centre for Environmental Policy of the Imperial College London, where master's students are trained in the use of OSeMOSYS and IRENA FlexTool.

There are some similarities between Pathway 3 and Pathway 2, as they both provide guided learning structures for students to become comfortable with modeling tools. Both pathways share a similar structure, as students from both will participate in open university courses and engage in project-based training to develop their skill set. They also have comparable aims, focusing on mastering the tools' functions and using a selected country's starter data kit to develop a country case study.

However, there are notable differences in the time frame, resource requirements, affordability, and accessibility. Pathway 3 has a longer duration, lasting a full semester, compared to Pathway 2, which spans only three weeks. The resource requirements for Pathway 3 include a lecturer providing close supervision for the entire semester. In terms of affordability and accessibility, Pathway 2 is offered free of charge, while Pathway 3, being a university module of a master's program, requires students to pay university fees.

In Pathway 3, students may produce a poster, a PowerPoint presentation, and a term paper, which contribute to obtaining an official university degree. Additionally, the commitment level for both trainer and participant is different; an instructor for Pathway 2 delivers training for three weeks, whereas a teacher/lecturer for Pathway 3 should be present longer—though with less intensity and no need for traveling beyond the workplace—and maintain a closer relationship with students (Pathway 3). To enhance the self-sustainability of the human resource pool needed to train master's students, a significant focus is placed on retaining student capacity within the university where they have been trained. Some students expand their module assessment case study and work on a master's thesis based on OSeMOSYS and IRENA FlexTool. Subsequently, there is potential for these students to become teaching support, serving as university teaching or research assistants for a new cohort of students.

Module Overview: The teaching of OSeMOSYS at Loughborough University is part of its two climate change master's courses and is integrated into the 'Economics and Politics for Sustainable Development' module that the programs share. The module is divided into two blocks: the first focuses on bottom-up energy policy initiatives and the second on OSeMOSYS modeling. This energy modeling aspect of the module focuses on policy options and their economic implications for sustainable development, emphasizing greenhouse gas (GHG) mitigation and adaptation in the energy sector. Indeed, it covers aspects of sustainable development policy and economics, focusing on GHG mitigation as a Sustainable Development Goal (SDG), with the energy sector playing a crucial role as the largest source of emissions. The module aims to examine different sustainable energy and climate policies and their impacts at various levels. It includes a cost-benefit analysis (to generate a cost curve for mitigating GHG emissions) and a long-term emissions scenario using linear programming techniques with an input–output model, namely the OSeMOSYS modeling tool. The assessment for the module is divided into three assignments: the preparation of a policy brief (30%) based on the material taught in the first (non-OSeMOSYS) block; the successful completion of the OU course on OSeMOSYS (Pathway 1, 10%); and the development of a final report, involving scenario building for their country case study (60%). The intended learning outcomes concentrate on developing knowledge of energy policy concerning climate change issues and developing decision-making skills related to policymaking. Participants also gain practical skills focusing on analyzing the data generated by the OSeMOSYS modeling, transferable skills in general modeling knowledge, and the ability to communicate the modeling results (see [82] for more details).

Affordability and Accessibility: The affordability of this pathway is limited due to the fees for the entire master's program, currently at GBP 11,100 for domestic students and GBP 22,500 for international students (typical costs for a UK context). From the lecturers' perspective, the OSeMOSYS aspect of the course uses open-access teaching materials and tools jointly developed by the OpTIMUS community, reducing the preparation time required for module design. With the help of these resources, in the form of open-source datasets [42,43] and country models, students can effectively learn about energy policy and climate change issues while having direct tutelage and assessment feedback.

Time Frame: The module with the energy modeling element lasts for one semester, approximately four months, and has an assessment weight of 7.5 ECTS credits (the full master's degree is 90 ECTS credits). This translates to 150 working hours (self-study plus lectures and practicals). Each block in the module has 15 hours of contact time between the lecturer and the students. In the OSeMOSYS block, most of the 15 hours focus on practical laboratory work where students apply the OSeMOSYS model (using the clicSAND interface [27,28] and the OSeMOSYS Cloud platform, an online cloud service platform for OSeMOSYS [83]) to an energy model of a country case study (using the starter data kits [42,43]).

Skill Levels: The course is designed to cater to various skill levels. With the course located in the Department of Geography and Environment, most students approach the course content without experience in coding, modeling, or advanced Excel or IT skills. Thus, students start with a structured learning program that teaches the basics of OSeMOSYS modeling, followed by practical sessions using the clicSAND interface [27,28]. As students advance, they transition to a more learner-centered approach, where they can apply their knowledge to real-world country models using the starter data kits [42,43]. The course aims to develop students' practical and transferable skills, regardless of their initial skill level.

Outreach and Impact: Several students of the master's module have continued their work on energy transition by developing their master's thesis and subsequently open-source papers—in collaboration with the Energy Transition Council across various countries such as the Philippines [84], Kenya [85], Democratic Republic of Congo [86], Morocco [87], Laos [88], Egypt [89], India [90], Nigeria [22], and Indonesia [91].

Resource Requirements and Self-sustainability: To teach OSeMOSYS at a postgraduate level in higher education, several requirements must be met and resources found to ensure a successful and effective learning experience. First and foremost, skilled educators with expertise in energy policy, sustainable development, and OSeMOSYS modeling techniques are crucial. A comprehensive curriculum is essential, including lecture slides, practical exercises, case studies, and access to open-source teaching materials like the OU course (Pathway 1). Students will require access to the OSeMOSYS modeling tool, OSeMOSYS Cloud, clicSAND interface, and OU course materials. Using the starter data kits [37,38], which include open-source datasets and country models for 70 countries worldwide, has facilitated the application of knowledge to real-world scenarios. A well-equipped computer lab with internet access and properly functioning software is necessary for practical sessions. This may constitute an entry barrier in developing contexts if the internet connection is unstable and the computer infrastructure is not in place. In such cases, the realization of this pathway requires funding and institutional arrangements at the higher education institution where the course is proposed. If the institution does not have the resources to support the creation of a lab, international support can come, provided agreements (such as memoranda of understanding) between the university and the supporting organizations are in place and an application for funding is submitted. Similar arrangements may be needed if the national government is to support the establishment of the lab.

Assessment methods and materials, such as policy briefs, the completion of the OU course, and a final report, should be developed to evaluate students' understanding, progress, and achievement of the intended learning outcomes. Time needs to be set aside to offer guidance and support to students as they work on their projects. Indeed, the opportunity for students to share their ideas so that feedback can be provided is required to ensure their projects are appropriate and feasible. For added value, the master's course should have in place the means to foster connections with other institutions, organizations, and experts in the field. This will enhance the learning experience—and make it more relatable—and provide students with opportunities to engage in research, internships, and other activities related to energy policy and OSeMOSYS modeling.

The OSeMOSYS master's module at Loughborough University has evidence of empowering students to make a lasting impact in the energy policy world and create a self-sustaining cycle of capacity development. In the inaugural year of the course (academic year 2021/22), four of the sixteen participants assisted instructors at the ICTP Joint Summer School on Modeling Tools for Sustainable Development in Italy [38] one year into the program. This kind of hands-on experience consolidated the students' skills and allowed them to impart their newfound knowledge to others. This ripple effect of sharing knowledge and skills is critical to creating a sustainable future where LMICs can run their own OSeMOSYS courses and work towards locally specific and culturally relevant goals without relying on external experts. One of these students, who was part of the master's module and later wrote a thesis with the Energy Transitions Council [92], has now taken on a formal role as an advisor, delivering OSeMOSYS-based courses in various summer Schools. This demonstrates how a single student's involvement in the program can lead to a career in energy policy and is suggestive of how this self-sustaining capacity can multiply.

The value of the flexibility of the teaching material in this master's module is that it can be adapted to other curricula at different universities according to their time constraints and specific country needs. This can be achieved, for example, by using the Teaching Kit platform, which is a repository for all the necessary teaching resources for a higher education OSeMOSYS-led module [41]. Establishing regional centers of excellence/hubs in LMICs is of the utmost importance as it enables the coordination of capacity-development efforts and facilitates the promotion of open-source tools, data, and teaching materials to tackle energy transition challenges in the region. These hubs have the potential to foster collaboration and facilitate knowledge exchange among professionals and institutions within the region. Currently, several master's programs are being implemented in universities in low- and middle-income countries (LMICs) that leverage the U4RIA-based delivery ecosystem. Notable examples include the University of Sierra Leone (USL) and the University of Cape Town (UCT). The annual student fees for USL and UCT are about USD 520 and USD 1300 (25,000 Zar), respectively. In addition to building much-needed national capacity that draws lessons from the experiences of institutions like Loughborough University and Imperial College London, sponsoring student scholarships can serve as a powerful yet cost-effective incentive to expedite the development of graduate-level expertise.

4.4. Pathway 4: Demand-Led Country Engagement

The country engagement pathway takes a demand-led, long-term approach to strengthening the in-country energy system modeling capacity for energy planning. The primary objective of this learning pathway is to ensure that the training and capacity-building activities provided are fit for purpose and designed based on a request from the countries (i.e., demand-led). To ascertain the request, a series of activities, including facilitation, relationship building, and partnership formation with government organizations and national institutions, are conducted to ensure (i) the offering clearly matches the request of the government and various stakeholders involved and (ii) the level of ambition from the partner institutions is robust. That is, they are committed to a long-term engagement (see Figure 4) and the implementation of the tools as an outcome of the collaboration. To exemplify Pathway 4, this section uses an ongoing capacity-development activity. In this example, it is between the National Partnerships team under the Climate Compatible Growth (CCG) Programme (www.climatecompatiblegrowth.com (accessed on 13 May 2023)) and the Government of Kenya (GoK).

Figure 4. Example of a demand-led country engagement co-creation process, which typically takes approximately 18–24 months to complete.

The Ministry of Energy and Petroleum (MoEP) of the GoK requested assistance from development partners to improve their modeling processes and co-investigate the least-cost scenarios for the country's power system planning. Furthermore, the government called for capacity-development workshops on modeling tools that fit the criteria of OSeMOSYS and IRENA FlexTool. Following the request, in-depth discussions with the MoEP were organized to create a work plan that meets the needs of the stakeholders involved as well as verify their commitment to the training program.

To ensure the smooth running of the work plan and the achievement of the partnership goals, in this example, each party (GoK and CCG) appointed a coordinator. The coordinators work closely together to facilitate the implementation of the work plan. The government-based energy planning coordinator's main responsibility is to identify the relevant stakeholders to join the training program, ensure that the team commits to undergoing the intensive training process, and communicate the requests from the MoEP to CCG. This is key to ensuring that the program has buy-in from different parts of the energy planning sector (e.g., different utilities, government, and academics) and to enabling the program's impact. For the latter, the identification of the relevant stakeholders is a crucial step. The selected stakeholders need to have the right background to undertake the training so that the new knowledge acquired via the training can flow as seamlessly as possible into their daily tasks without requiring additional commitments. On the other hand, CCG's Kenya-based coordinator is responsible for fostering an enabling environment where communication and data flow between the trainers and the government team are open, collaborative, and inclusive, as well as ensuring that the activities abide by the work plan.

While the country engagement learning pathway has a flexible training structure based on requests from partner countries, similar to previous learning pathways, it relies on the three key elements of (1) data and models, (2) capacity and professional development, and (3) advocacy and engagement. This pathway is distinguished from the other learning pathways by its direct engagement with key country stakeholders and its target goal, which is to strengthen future scenario planning and practices within a country (rather than specific individuals), which ultimately requires a high level of engagement and a long-term approach. The following are some of the key features of Pathway 4:

Affordability and Accessibility: Attending the training events in the country engagement pathway is often free of charge to the participant, with external partners and local organizations often able to provide contributions in kind. However, attending these workshops is limited to invited groups of experts from relevant stakeholder groups in the country. The goal is to build a strong community of local experts who can continue to refine and use the models beyond the workshops. Coordinating the different stakeholders involved in the process is critical to its success. The government-based coordinator manages this process, ensuring the right group of experts is selected for the workshops. The affordability may be limited not for financial reasons but due to organizational resources; the experts must be given time to attend the training and consolidate the acquired knowledge into their daily tasks. This indirectly requires an investment from the organization the experts work for.

One key difference between the country engagement pathway and other learning pathways is that this collaboration may provide access to proprietary national data, which can be used to develop more robust country models that can then feed directly into national energy planning. However, as a result, the models and data used may not be publicly available.

Time frame: Compared to previous learning pathways, the country engagement process has a much longer time frame. In the case of the partnership with Kenya, the first phase of country engagement, which aimed to train local experts in using OSeMOSYS and IRENA FlexTool for power system modeling, took approximately 24 months. During this period, eight workshops were planned, as depicted in Figure 4. The prolonged duration of the training process allowed for more advanced and in-depth training of local experts, more opportunities for troubleshooting, and collaborative discussion on how to tailor models to better represent the country's power system. This will allow for the co-development of detailed and high-quality country models and datasets with local experts during workshops; such input from local specialists is essential for incorporating the country's energy planning priorities into the scenarios and model assumptions.

Skill level: The country engagement workshops provide comprehensive and in-depth training to local experts, enabling them to become comfortable with the tool and conduct complex studies. The experts also learn to conduct more complex scenarios and case studies with the tools, fill data gaps, and adapt to new versions of the tools. The training also works closely with local experts to assist them in using the tools in the policy development cycle. The goal is to build a strong community of national experts who can take ownership of the models and datasets and continue to use them beyond the workshops. Once the local analysts are comfortable with the tools, the interaction with the country transitions from direct engagement to more collaborative efforts. This means that local experts will have the necessary skills to independently implement the tools for addressing the energy planning challenges within the country, with external support decreasing over time.

Outreach and Impact: While the number of individuals trained in the country engagement pathway may be fewer than other pathways, the program's high level of engagement and demand-led nature ensure that the developed models and datasets are tailored to the country's specific needs, energy requirements, and priorities. This makes them more effective in impacting policymaking and attracting international finance. One concrete example of this impact was in Kenya, where the engagement with CCG led the country to use OSeMOSYS and IRENA FlexTool in its national medium-term planning.

Resource Requirements and Self-sustainability: The country engagement process is a long-term commitment that requires significant resource allocation from all parties. This involves mobilizing resources in the partner country for training and coordinating stakeholders to release their experts for the training. Therefore, compared to other learning pathways, country engagement is very resource-intensive. The country engagement pathway leads to a high level of skill development and knowledge acquisition, resulting in self-sustainability. Participants can become trainers, passing on their expertise to other modelers in their country by holding their own workshops. Some participants have even progressed to become trainers for other modelers in their country and other African nations. This train-the-trainer approach ensures the program's long-term sustainability and creates a self-sustaining model for knowledge transfer and skill development. The program's success is evident in the ongoing collaboration in Kenya and the formation of a core modeling team with expanded capabilities.

5. Discussion and Conclusions

In this section, the benefits and challenges of Pathways 1–4 are compared by analyzing the number of people trained, training resources required, and depth of learning skills acquired. Finally, future research directions aimed at improving the self-sustainability of these pathways are discussed.

5.1. Learning Pathways Comparison

This subsection compares the different pathways and offers insights into their applicability, scalability, and limits for development partners engaged in capacity-development activities. Knowledge uptake may be improved depending on the type of engagement and learning experience desired or required. When comparing the different pathways (Figure 5), several factors should be considered, such as affordability, skill levels, outreach and impact, resource requirements, and self-sustainability. To evaluate the performance of each of the four learning pathways discussed in Section 4, a self-assessment based on the authors' knowledge and lessons learned from the presented activities is conducted, using a score of 1–3 based on the aforementioned factors. It is worth noting that the scores are relative, not absolute. That is, 1 represents the lowest or worst score among the four pathways, and 3 is the highest or best. In the self-assessment, the experiences from implementing the pathways are collected in the aforementioned contexts and with reference to OSeMOSYS and IRENA FlexTool. Partners implementing these pathways in other contexts and using different tools may score them differently with respect to each other, obtaining different insights on their applicability in their context. Figure 5 presents the results of the comparative evaluation under these assumptions.

Affordability and Accessibility: Pathways 3 and 4 are targeted to a specific closed group of participants (students at specific master's courses and selected stakeholders from the engaged country) and their accessibility is scored 1. Additionally, Pathway 3 may require the payment of university fees, and Pathway 4 may require investments by the receiving organization to allow resource and time for taking the courses. As for Pathway 2, applications are open and free, but only a specific number of participants are eventually selected, thus a score of 2. Finally, Pathway 1, being open to everyone interested and free of charge, is the most affordable and accessible, and hence it was evaluated with a high score of 3.

Skill Levels: The skill levels are based on an assessment of the depth of learning across the samples of learners discussed in the previous sections. Taking that into account, Pathway 1 has the lowest score of 1, since it provides only core levels of learning, such as understanding of key concepts and their application to stylized problems under strict guidance. Pathways 2 and 3 have medium scores of 2 since they require a certain degree of critical application of the concepts and analysis and discussion of the results. Pathway 4 is the most advanced pathway, bringing participants to a level where they can ideate and construct complex analyses with a high score of 3.

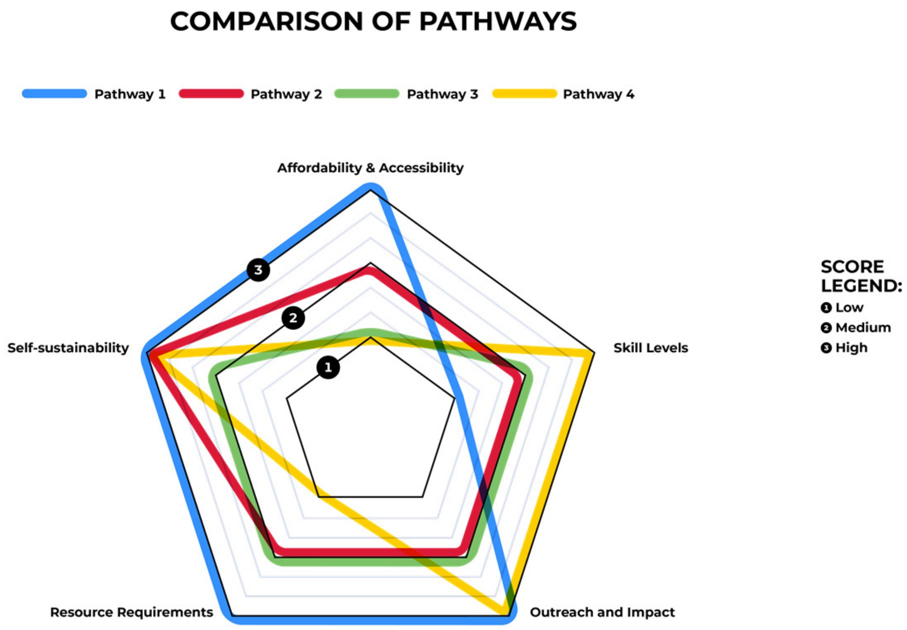

Figure 5. Learning pathway comparison based on their main features. On the diagram, numbers 1–3 represent scores, with 3 being the highest or best score.

Outreach and Impact: Pathway 2 has been assessed to have an intermediate impact, mostly reflected in the published open-source repositories with the results of courses and the journal publications of independent analyses conducted by trained participants after the Schools. Pathway 3 has a similar (medium) level of impact, as many students have conducted and published their master's theses using the models taught in the courses. As such, both Pathways 2 and 3 are scored at 2. As for Pathways 1 and 4, they are deemed to have a greater impact and are scored with a high score of 3. Pathway 1 results in a very wide outreach, serving as a starting point to reach a larger number of participants and get them involved. At the same time, Pathway 4 appears to be the most effective in supporting robust strategic energy planning since the analyses conducted are tailor-made and can meaningfully influence the engaged country's policy.

Resource Requirements: Pathway 1 has the highest score of 3, as it requires the fewest resources to create and maintain the online course. Pathways 2 and 3 require an intermediate number of resources, as skilled trainers are needed in both cases (either for three consecutive weeks in the International Capacity-Development Program events or regularly within the academic context), resulting in a score of 2. Pathway 4, requiring a long-term commitment from stakeholders from multiple parties, is the most resource-intensive, with a score of 1.

Self-sustainability: In terms of self-sustainability, Pathway 3 is scored with a medium score of 2 because it is teacher-based, and it cannot be ensured that the trained students will keep on working with the models, and become available support for future teaching activities, after the training ends. The remaining three pathways are evaluated as the most self-sustaining and are scored with a high score of 3. Pathway 1 enables the creation of online communities around the models through the course's dedicated group discussions and it doesn't require ongoing support. While Pathway 2 and 4 underpin the train-the-trainer approach, which supports and encourages participants who excelled in a training event to become trainers in future international development programs and in their respective countries.

Finally, in terms of **Time Frame**: Pathway 1—a relatively short self-paced online course to gain basic skills—has the shortest time frame; Pathway 2 has a medium duration of 3 weeks, while Pathways 3 and 4 have longer time frames, extending over several months. The timeframe factor was not quantitatively scored as the quality or effectiveness of different pathways cannot be solely determined by how quickly they can be completed.

In summary, several factors are considered when comparing the learning pathways, including affordability, time frame, skill levels, outreach and impact, resource requirements, and self-sustainability. Pathway 1 is a free, self-paced online course open to everyone, focusing on basic skills and fostering self-sustainability through the creation of online communities. Pathways 2 and 3 (which typically involve Pathway 1 and go beyond it) are more intermediate in terms of skill level, with Pathway 2 being a selective three-week program and Pathway 3 involving academic courses within a master's program. Pathway 4 is the most advanced and resource-intensive pathway, tailored to stakeholders from a specific country and intended to have a significant impact on that country's policies.

Key takeaways from this comparison are that:

- The learning pathways are complementary in almost all dimensions. If the aim of implementing them (within a project or a program) is to nurture an ecosystem for strategic energy planning in a determined context, it may be important to implement actions that pursue all four pathways in that context, involving each of the key actors (the broader community for Pathway 1, stakeholders with relevant expertise, motivation, and aims for Pathway 2, the academic community for Pathway 3, and government institutions for Pathway 4). A progression from Pathway 1 (with low resource requirements, less deep learning, high outreach, and high self-sustainability), through Pathways 2–3, up to Pathway 4 (high resource requirements, but deep learning, high impact, and equally high self-sustainability) may be the most effective and have the greatest long-term impact in some contexts.
- In terms of impact, all pathways can score from medium to high, but for different reasons and with different target audiences: Pathways 2 and 3 have longer-term impacts related to the creation and sharing of knowledge; Pathway 4 has a longer-term impact on a country's strategic energy planning; and Pathway 1 has a more immediate impact in terms of outreach.

The authorship team emphasizes in the paper the importance of offering a variety of these pathways to the wider community so individuals and organizations can choose the most suitable option based on their needs and preferences. Some pathways are less demanding, while others are more involved; however, all the pathways are accessible and can be built upon to progress energy planning at all levels.

5.2. Conclusions

To conclude, and as summarized in Figure 6, this paper has presented four innovative learning pathways that offer a comprehensive and integrated approach to promoting effective strategic energy planning. The insights, impacts, and limitations of the application of these pathways to global capacity-development efforts were discussed. The largest impacts from all learning pathways are as follows. Pathway 1 achieves broad outreach. Pathway 2 upskills LMIC analysts, produces new country-specific scientific knowledge, and creates regional communities of practice. Pathway 3 upskills higher education students and produces academic scientific peer-reviewed outputs (papers, briefs, theses, etc). Pathway 4 empowers local experts to use acquired skills and tools in country energy planning (such as policymaking or finance mobilization documents) and establishes SIGs. Key limitations emerge in that the affordability of Pathways 3 and 4 is somewhat limited in some cases: it can be limited in Pathway 3 where courses are given in an academic context where the university fees are significant; it can be limited in Pathway 4 where the government needs to invest time and resources, both of which can be scarce, to embed new ways of modeling and analysis into its policy cycles and organizational workflows.

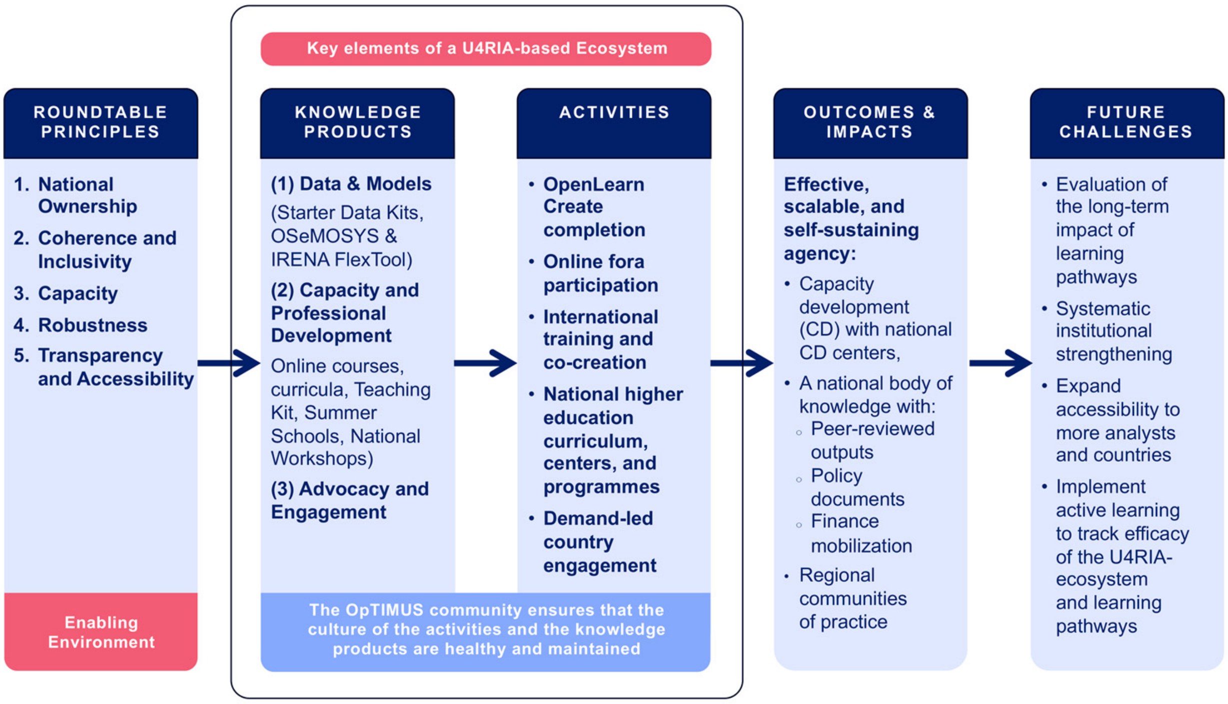

Figure 6. Conceptual diagram of the paper showing the interaction between the enabling environment, the U4RIA-based ecosystem, and its knowledge products and activities. All of these create outcomes, have an impact, and pose future challenges.

The authorship team compared the pathways and assigned them scores relative to five dimensions: affordability and accessibility; skill levels; outreach and impact; resource requirements; and self-sustainability. The main insight from the comparison is that the learning pathways are complementary in addressing needs across these five dimensions. Applying them in tandem in a national context over the lifetime of a project or program, each targeting different main audiences, can nurture the country's energy planning ecosystem.

To truly maximize the potential of these pathways and unlock their transformative power, further research is needed to make them more accessible and scalable to a wider set of contexts, each with its own specific challenges. This will help ensure that people from all countries are not left behind in this journey towards a sustainable energy future. To maintain this aim, measures and resources need to be put in place that can evaluate the long-term impact of these pathways and develop institutional strengthening. This is also crucial in refining and optimizing the effectiveness of these pathways in capacity development. To ensure self-sustainability, it is critical to provide appropriate support and resources to the communities formed around these pathways. This encompasses access to cutting-edge information and materials, regular training sessions that foster continuous learning, and opportunities for networking and collaboration, thus creating an interconnected web of empowered individuals. Establishing partnerships with relevant organizations or institutions is also essential to ensure that the models are seamlessly integrated into existing programs and initiatives. This collaboration can act as a catalyst for the wider reach and increased impact of the models and provide a robust support system for their continued use.

In essence, achieving self-sustainability in the capacity-development process for sustainable energy planning requires a multifaceted and dynamic approach. One route is to focus on striving for the Roundtable Principles for Supporting Strategic Energy Planning of improving national ownership, coherence and inclusivity, capacity, robustness, and transparency and accessibility. By prioritizing ecosystem elements such as creating and maintaining vibrant communities around the models, providing ongoing support and resources, and establishing partnerships with key organizations or institutions, a foundation for building a more robust and well-informed community of climate experts is established. These experts, armed with the knowledge and skills acquired through the learning pathways and applying them to their own local contexts and needs, will be better equipped to confront the challenges of climate change, enabling them to contribute to a sustainable energy future that can begin the process of safeguarding our planet for generations to come.

Future Research Direction—Next Steps to Improve the Self-Sustainability of the Process

This paper highlights the essential components and resources suggested for effective capacity development in energy planning, which can support developing nations in implementing energy planning strategies in a self-sustaining manner. The components work together to provide the foundation for modeling and analysis, local expertise, and the exchange of knowledge and best practices. It is recommended that policymakers prioritize these components to ensure future energy planning exercises are nationally owned, inclusive, robust, and transparent. However, further work is needed to explore how to make the presented learning pathways more accessible and scalable to wider audiences. To this end, future research and practices should focus on the following directions to improve the self-sustainability of the process and promote low-carbon futures for low- and middle-income countries (LMICs):

Expanding the Availability of Programs: High rates of downloads for the OU courses and oversubscription to existing capacity-development activities suggests a need to expand the availability of programs. This may include offering courses in multiple languages, collaborating with various educational institutions to incorporate climate data and modeling into their curricula, leveraging online platforms to deliver content to a wider audience, and developing platforms for cross-institution collaboration in the creation and updating of open access teaching material. By expanding the reach of these programs, a larger and more diverse pool of participants can benefit from the training, ultimately leading to a more inclusive and well-informed community of climate experts.

Evaluating the Long-Term Impact: It is crucial to evaluate the long-term impact of these learning pathways on participants and their contributions to climate policy and decision-making. This could involve tracking the progress of participants post-training, assessing their continued engagement with climate models, and tracking the use of these models in policy cycles. By understanding the long-term outcomes of these pathways, adjustments can be made to improve their effectiveness and self-sustainability.

Developing Institutional Capacity: To ensure that the acquired knowledge and skills are effectively used and sustained, it is essential to strengthen the capacity of institutions that work with climate data and models. This may involve building partnerships with relevant organizations, fostering collaboration between stakeholders, and providing ongoing support for the implementation and improvement of climate models. It will be critical for institutional strengthening to take into account that government institutions have limited time and resources with which to integrate open modeling practices into their policy cycles. Careful and seamless integration within the existing processes will be needed.

These strategies can help develop self-sufficient training centers alongside accessible open-source and certified teaching materials and will support knowledge management and the onboarding of new staff. This form of institutional strengthening will not only help to maintain the skills acquired by participants but also create a supportive environment for further learning and research. It will also be of great importance for the scientific community and development partners supporting capacity-development initiatives that successful models of institutional arrangements are widely shared and discussed.

Enriching Skill Sets: While the current learning pathways offer valuable knowledge and skills in climate data and modeling, future research should explore the potential of integrating additional skills into these programs. This may include incorporating data visualization techniques, advanced statistical analysis, and interdisciplinary collaboration. Work in this direction has already begun, as the next planned capacity development activity will integrate a course on "Modelling, policy and political economy", giving participants more overall context for the policymaking process. By offering a more comprehensive skill set, participants will be better equipped to tackle complex climate-related challenges and contribute to more effective policies and decision-making. Indeed, having dedicated workforces with an overlap of skills and knowledge will strengthen the effective use of analytical tools to produce science-based evidence for policy while also boosting the understanding of the institutional setting and processes to communicate meaningful results to the right policymakers and/or funders. The strength of any model comes down to its ability to communicate the results and transform them into implementation and action. Efforts will have to be dedicated to assessing the quality of learning and the level of acquisition of skills, especially in Pathways 1 and 2. This will mean developing modes of examination and assessment that go beyond the pass/fail criterion and a constructive alignment between the intended learning outcomes, the content taught, the activities carried out, and the assessment criteria.

In conclusion, effective capacity development in energy planning is crucial for developing nations to implement energy planning strategies that are self-sustaining. The recommended components and resources provide a solid foundation for modeling and analysis, local expertise, and knowledge exchange. To improve the self-sustainability of the process and promote low-carbon futures for LMICs, future research and practices should focus on expanding the availability of programs, evaluating the long-term impact of learning pathways, developing institutional capacity, and enriching skill sets. By prioritizing these areas, policymakers can ensure that energy planning exercises are nationally owned, inclusive, robust, and transparent, leading to more effective policies and decision-making.

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