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Foreword

This report follows and complements recent work undertaken by the OECD Global Science Forum (GSF) on the establishment, management and sustainability of research infrastructures (RIs). It addresses the new challenges faced by managers, operators, funders and decision-makers in developing and supporting Very Large Research Infrastructures (VLRIs) and in establishing long-term strategies.

VLRIs are complex undertakings owing not only to their high technology requirements, scale, and long lifespan but also to the increasing diversity of partners involved, the number of physical sites over which they may be distributed and, of course, the increasing costs for their construction and operations, which necessitate elaborate business models to ensure their sustainability. Most VLRIs provide services to the international research community and are correspondingly funded, managed and operated by multiple stakeholders. In the context of limited research budgets, governments and funding agencies are confronted with the challenge of supporting increasingly large and complex RI portfolios and need to make selective decisions between supporting national projects and international VLRIs. Potential users of VLRIs are increasingly diverse, and their numbers are rising, particularly as the data produced by VLRIs become progressively more complex, varied, and widely distributed. The operation and use of these VLRIs therefore require careful optimisation. Furthermore, recent crises, such as the COVID-19 pandemic and associated global supply chain issues, have highlighted the need for enhanced risk assessment and management policies when embarking on such large enterprises.

This policy report presents a series of lessons learned on establishing VLRIs, options for improving their use and operation, as well as more strategic considerations that VLRI stakeholders should take into account in their planning of future projects.

A summary of the decision-making processes and strategic instruments used by countries on VLRIs for their investment policy is presented in a separate annex document: DSTI/STP/GSF(2023)5/ANN/FINAL.

This project was overseen by an international Expert Group appointed by GSF (appendix 1). The report was written by the Expert Group co-chairs (Heidi Bandulet and Willy Benz), the project consultant (Paul Dufour) and the GSF secretariat (Frédéric Sgard), with extensive input from Expert Group members.

It is hoped that this report will be informative and useful and comments from readers are welcomed. The Global Science Forum staff can be reached at gsforum@oecd.org.

The OECD Global Science Forum (GSF)

The GSF is a Working Party of the OECD Committee for Scientific and Technological Policy (CSTP). Its main objective is to support countries to improve their science policies and share in the benefits of international collaboration. GSF provides a venue for consultations and mutual learning among senior science policy officials of OECD member countries. It carries out analytical work on high-priority science policy issues.

The GSF's principal stakeholders are the government science policy officials who bring issues to the GSF for deliberation and analysis in an intergovernmental setting.

More information on the GSF mission and activities is provided at http://www.oecd.org/sti/inno/global-science-forum.htm.

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VLRI Acronyms

ARICE	Arctic Research Icebreaker Consortium
EAST	Experimental Advanced Superconducting Tokamak
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory
ELI	Extreme Light *Infrastructure*
ELIXIR	Not an acronym – European distributed RI for life science data
ELT	Extremely Large Telescope
EMBL-EBI	European Molecular Biology Laboratory – European Bioinformatics Institute
ESS	European Spallation Source
FAIR	Facility for Antiproton and Ion Research
Hyper KAMIOKANDE	Not an acronym – neutrino observatory in Kamioka
IceCube	Not an acronym - neutrino observatory in Antartica
IFMIF	International Fusion Materials Irradiation Facility
IODP	International Ocean Discovery Program
ITER	International Thermonuclear Experimental Reactor
JWST	James Webb Space Telescope
KAGRA	Kamioka Gravitational Wave Detector
KSTAR	Korea *Superconducting Tokamak Advanced Research*
LIGO	Laser Interferometer Gravitational-Wave Observatory
NICA	Nuclotron-based Ion Collider fAcility
SARAO	South African Radio Astronomy *Observatory*
SKA	Square Kilometre Array
TRIUMF	Not an acronym - Canada's particle accelerator centre
VIRGO	Not an acronym – European gravitational-wave detector
European XFEL	European X-ray free-electron laser

Executive Summary

This report is based on an analysis of publicly available documents and additional information collected from a group of 15 OECD countries and 3 relevant international bodies represented on an expert group, which oversaw the work. It also includes the outcomes of two dedicated international workshops. The report identifies and analyses good practices and presents a series of lessons learned regarding the establishment of VLRIs, options for improving their use and operation, as well as more strategic considerations that VLRI stakeholders should take into account in their planning of future projects. These analyses and recommendations relate to six main issues that were investigated in detail:

- Strategic planning
- Governance
- Financing
- Impact
- Data management
- Ecosystem

Strategic planning and priority-setting are becoming critical as research funders need to make increasingly tough choices about their investments. Many of the existing planning instruments have difficulties to integrate VLRIs because of their high cost and international dimension, and investment decisions are still very much taken on a case-by-case basis. National planning and decision-making instruments must evolve to fully capture their respective international contexts as well as societal and interdisciplinary dimensions. The necessary strategic processes and instruments need be developed at all relevant levels (international, national and RI level). These should enable closer collaboration among research communities and decision-makers and support a more comprehensive portfolio management approach that reconciles VLRI decision-making with the priority needs of scientific communities.

Governance models for VLRIs have always been a challenge, owing to the diversity of VLRI partners and differences in the culture and practices of these partners. Recent crises have demonstrated the need for robust mechanisms able to face unexpected events. Feedback from VLRI managers indicated a strong demand for stable and resilient governance models, balanced with an increased need for flexibility. Indeed, VLRIs usually involve many international partners, and their governance structures must allow for the participation of a diversity of stakeholders. Sustainability and inclusivity must be ensured through innovative governance models that can respond to different partner expectations and better manage the potential risks associated with VLRI projects.

The number, scale, complexity, and diversity of VLRIs are all increasing and each new generation of VLRIs is becoming more and more costly. New investments are routinely in the billions of euros for construction, and operation costs typically span decades. At the same time, many funders are reporting reaching a ceiling in their ability to support VLRIs. This not only means increased selectivity in their investments but also a demand for better and more efficient use of available resources. Funding pressure implies more cooperation among funders and improved strategic planning. There is need for a more accurate picture of the funding trends and anticipated demands at the global level in order to develop a more reliable and predictable funding environment that encompasses the entire life-cycle of VLRIs. In addition, the increasing complexity of VLRI partners and users calls for more inclusive and flexible funding models that will allow different forms of contributions and hence facilitate the participation of broader communities of stakeholders. Finally, the demand for efficiency in financial management requires better risk assessment and risk management procedures and related budget contingencies.

The primary expectation for impact from VLRIs is the production of breakthrough scientific knowledge, and this remains true for all recent initiatives. However, the potential socio-economic impact of VLRIs has become more important in the investment decision of funders and decision-makers. While socio-economic impact assessment is now imbedded in most RI projects, assessing value or impact beyond scientific production is much more challenging for VLRIs because of the diversity of their stakeholders, who often have different expectations and different approaches to impact assessment. Furthermore, VLRIs are increasingly expected to contribute to solving broad societal challenges, something that they were often not designed or prepared for. It is necessary that partners in new VLRI initiatives agree at the outset the full scope of the infrastructure, taking into consideration their different priorities. The selection of impact assessment methodologies and indicators should then respond to the needs of all partners and be flexible enough to adapt to new requirements.

VLRIs produce vast amounts of data. Data management is therefore a massive challenge. This has become an even greater issue as the demand for access to VLRI data has increased because of the growth and geographic expansion of traditional user communities. Many VLRIs have also seen a steep rise in the demand for data from expert users from other disciplines in order to address new scientific and societal challenges. This creates an extra burden and cost for VLRI management that is often not planned for nor sufficiently funded. There is a need for new approaches to provide data to experts and non-experts in different disciplines beyond the VLRIs' traditional user communities. This requires the development of new data access mechanisms, user-friendly data products and services and standardised interoperable data formats. It also require extensive training for new categories of users. All of the relevant costs need to be incorporated into the recurrent operational budgets of VLRIs, which is rarely the case at the moment.

Finally, although VLRIs are themselves complex structures that may be distributed over different sites and are connected to a diversity of research partners, there are often valuable opportunities for them to develop synergies with other RIs. There are three main drivers for the development of more integrated VLRI ecosystems: to enable researchers to tackle complex/interdisciplinary scientific questions; to rationalise and improve a VLRIs own activities; and, to avoid duplication of efforts. VLRIs also need to work together to develop their scientific and technological know-how and provide mutual support, training and career paths for the professional staff on whom they depend. However, the development of networks and synergies with other RIs is not yet fully integrated in the plans of many VLRI managers and funders. There is an opportunity to enhance collaboration at the global level to fully benefit from the potential of a broader diversity of VLRI stakeholders and develop more resilient efficient and effective VLRI ecosystems.

Policy Recommendations

The following recommendations emerged from an analysis of the responses from VLRI managers, funders and decision makers to surveys, and discussions held at two international workshops conducted as part of this project. VLRIs, in this context, are understood as RIs with a high degree of uniqueness and complexity, and a strong international dimension. While the recommendations focus on issues relevant to recent and emerging VLRI initiatives – some may also be relevant to other RIs. More specific and practical policy options and examples that relate to these recommendations are described in section 3 of this report.

Strategy and Planning

As the scale, complexity and role of new VLRIs increase, RI foresight and strategic planning instruments used for landscaping and decision-making must evolve to fully capture the international context and strengthen their societal and interdisciplinary dimensions. Such instruments should be developed at different scales (international, national and individual VLRI) and enable closer collaboration among research communities and decision-makers. Throughout their development, the following should be considered:

- Convening appropriate international discussion fora, to help identify opportunities, scan the horizon for emerging policy and research opportunities and threats, address challenges, and reconcile national interests and competition with the need for international collaboration;
- The implementation of a portfolio management approach by government and funders to assess the priority needs of their scientific communities and to achieve an appropriate balance between the various options for contributing to different VLRIs (i.e., as host, major or minor stakeholder, in-kind contributor, through access agreements etc.);
- Agreeing on the definition and actual scope of VLRI projects among stakeholders, taking into consideration their national and regional research landscapes and priorities. Joint scoping should define the scientific and societal domains to be addressed, while ensuring flexibility to adapt to emerging challenges and priorities;
- Developing policy awareness for all VLRI stakeholders within strategic planning processes that assess the changing global research context and landscape. This can help all actors anticipate the need for adjustments in their approaches.

Governance and Management

VLRIs are highly complex organisational structures with a need for specific rules and procedures to operate efficiently:

- A critical element for the functioning of VLRIs is their capacity to involve international partners. Hence, their legal status and governance structure must allow for the participation of a diversity of stakeholders. Innovative and flexible solutions should be developed to allow new memberships and partnerships to emerge and develop throughout the lifetime of a VLRI. This includes being open to partners who contribute in ways that do not involve direct financing;
- Expectations from each VLRI partner should be clearly expressed at the outset (and revisited at regular intervals) in terms of scientific impact, industrial/economic return (juste-retour), job creation, societal and environmental benefits. The potential risks associated with VLRI projects should be openly discussed among potential partners;
- Interactions between funders and members of a VLRIs' governing and management bodies must be efficient and based on mutual trust. Return on investment now incorporates many different metrics that should be selected with attention to the scientific, economic, social and environmental impacts and discussed regularly in an effort to ensure the satisfaction and motivation of all stakeholders;

- VLRI policymakers, funders and managers are encouraged to share experiences and exchange good practices internationally in the areas of RI policymaking and funding, road-mapping and landscape analyses, user strategies and access policies, governance and management, and monitoring and assessment, thereby feeding into strategy debates at both expert and political levels in relevant international fora. International cooperation should be based on balanced and reciprocal openness, and should promote a level playing field underpinned by fundamental shared values and ethics.

Business model and life-cycle funding

As the share and amount of funding for VLRIs is on the rise, many funders are reaching their maximum capacity and have therefore become increasingly selective in their investments. While alignment with national priorities remains a key driver in decisions to invest, budget limitations are pushing funders towards resource sharing and international cooperation to realise VLRI projects;

- Governments and funders should seek to develop a regular assessment of research funding/expenditures being allocated to VLRIs such that stakeholders benefit from a more accurate picture of the funding trends and anticipated needs at the global level;
- VLRI policymakers and funders are encouraged to treat VLRIs as long-term commitments in order to create a stable, reliable and predictable funding environment that encompasses the entire VLRI life-cycle and takes account of evolving user needs at the global level. The conceptual phase of a VLRI being considered particularly fraught with challenges, funders should ensure that resources and mechanisms are in place to adequately support this critical phase;
- VLRI policymakers and funders are invited to further develop inclusive and flexible international in-kind contribution and access models that recognizes different forms of contributions to facilitate the participation of broader communities of stakeholders and countries;
- VLRI business plans should integrate a comprehensive risk assessment framework that is shared among partners to ensure common understanding and awareness of risks, and help achieve consensus on appropriate mitigation strategies, including provisions for schedule and budget contingencies.

Impact

VLRIs are long-term enterprises which are developed primarily to produce frontier knowledge. However, they are also increasingly expected to deliver a broad range of societal and economic benefits. Responding to this wide range of objectives is challenging, especially as these emerge from a diverse mix of international stakeholders and stakeholders;

- VLRI stakeholders should define and agree, at the outset, the scope of their VLRI project, taking into consideration the different interests and priorities – e.g., what scientific, political and societal domains will be addressed; and what flexibility will be required to adapt to new challenges and priorities. An agreed impact assessment methodology should be developed from VLRI project inception, covering its entire life-cycle, and designed to meet the needs of different stakeholders.
- Where appropriate, VLRIs should have processes for keeping abreast of the evolving policy landscape in relation to major societal challenges such as energy security and addressing climate change. Furthermore, VLRIs should embed environmental impact assessments within their planning and design and take appropriate measures to minimise their climate footprints;
- VLRI strategies need to give greater consideration to training, education and skills development for the next generation of professional scientists, engineers and skilled technical workers, and integrate more creative public outreach strategies to ensure enhanced public policy and community support. This needs to be supported and valued by funders as part of the core activities of a VLRI.

Data management including data sharing and access

Increasingly, data management is becoming a major issue for VLRIs and there is a strong push for international data sharing and openness. However, there are a number of challenges that VLRIs need to address for optimising data management and data access:

- VLRIs should explore new approaches to provide data to non-experts and to experts in disciplines beyond their traditional user communities in order to respond to the increasing demand for VLRIs to have a broader impact on complex societal challenges. This requires the development of new data access mechanisms, user-friendly data products and services and standardised interoperable data formats. It also implies that new staff and resources will need to be allocated towards these activities, driving up operational costs − something that funders need to be fully aware of;
- As current policies and practices are heterogenous, a consensus on the implementation of open data, including access to software and codes, should be developed among VLRI stakeholders. This in turn needs to be translated into a data policy at the level of an individual VLRI and provide the basis for a fully costed data management and access plan that addresses human resources and training needs as well as technical requirements;
- Data management needs, including those related to open access and access for non-experts, should be fully integrated in VLRI operational costs to avoid putting an additional burden on VLRI management. Potential gains in efficiency and effectiveness in data management as a result of cooperation between VLRIs and other RIs, including cyber-infrastructures and data repositories, should be considered in assessing data management needs and costs.

Policy Support within the VLRI Ecosystem

VLRIs, as large enterprises that often include many in-house ancillary facilities and are invariably connected to a complex network of partners. There is an imperative to develop and maintain effective linkages with these partners and develop synergies with other RIs in order to fulfil broader scientific and socio-economic needs and expectations:

- VLRI policymakers and funders are encouraged to consider VLRIs as strategic investments and recognise that the establishment of VLRIs, embedded in regional and national development strategies, has potential to accelerate socio-economic development. A well-balanced geographical distribution of VLRIs, can help harness the full potential of the research and innovation excellence that exists around the world;
- VLRIs should be embedded in national and international networks as an integral part of the essential infrastructure, which is critical for mobilising science in responding to crises. All VLRIs have unique technical capacity and expertise that can be leveraged in this regard;
- VLRI policymakers, funders and stakeholders are encouraged to engage in dialogue using appropriate international fora to promote more effective international cooperation, including the sharing of strategies and good practices.

Introduction

Background and rationale

Very large research infrastructures (VLRIs) have been the focus of many reports and initiatives in recent years with a focus on improving their governance, efficiency and sustainability (OECD, 2017[1]; 2014[2]; 2010[3]; GSO, 2019[4]; ESFRI, 2017[5]). During this period, changes in the socio-economic and scientific contexts have been challenging earlier models for these ambitious scientific and technological projects and raise several issues:

- VLRIs are increasingly complex: this is linked not only to technological developments but also to the diversity of stakeholders involved and, increasingly, to their distribution over multiple sites; what are the impacts of this complexity on governance and financial models?
- VLRIs may be expected to generate new wider impacts alongside their main scientific aims that go beyond socio-economic benefits; these might include broad societal benefits such as social innovation, responses to challenges and crises, and positive impacts on the whole scientific ecosystem. The potential environmental impacts of VLRIs are also increasingly considered. How are these expectations affecting their management and operations?
- VLRIs are of interest to many countries, expanding beyond those traditionally leading in such scientific enterprises. What are the potential challenges in balancing increased competition and the need for both a collaborative approach to solving global issues and the pooling of resources among nations? How can national interests be aligned?
- There is an increasing policy emphasis on open science and inter-disciplinarity, linked with the rapid evolution of digital technologies. New challenges include ensuring fairness and equity, with regards to data sharing, as well as the requirements for sustainable data management and storage of very large amounts of data. What are the resulting consequences regarding the expectations and operating environment for VLRIs?
- Current crises, with the pressure they are exerting on public budgets, may require a more strategic approach to VLRIs from decision makers. How does this situation affect national investments (e.g. choosing between national or international RIs) and impact the overall research landscape? What are the action that could be undertaken to prevent and mitigate different types of risks?
- The potential role(s) and importance of these facilities to address major societal challenges has been highlighted during the COVID-19 crisis, which led many RIs to quickly re-organise their priorities and working processes to respond to new demands from both the scientific community and decision-makers. What are the lessons learned from this crisis that can inform optimisation of the future operation and use of VLRIs?
- Considering the impact and scale of VLRIs, how can the sustainability over their whole life-cycle, including their decommissioning or repurposing, be addressed?

Owing to the increasing complexity of these ambitious projects, their financial cost has been steadily increasing, leading to a need for funders and decision-makers to be more selective, and for VLRI managers to develop more robust and sustainable business plans. Considering these issues, the Global Science Forum authorised at its 44th meeting on 21-22 April 2021 a new activity focused on optimising the organisation and use of VLRIs, which was carried out by an Expert Group (listed in Appendix 1), nominated by interested delegations.

Terms of Reference and focus

The Terms of Reference for this activity were determined by a scoping group nominated by interested delegations, which preceded the formal launch of the activity.

The objective of this GSF activity is to provide options for facilitating the development, operation and use of VLRIs, to make these more responsive to global crises or major disciplinary shifts, and to provide long-term perspectives for their development worldwide.

While there is no consensus on the definition for what constitutes a VLRI, only those that had most, if not all, of the following characteristics were considered by the Expert Group for this activity:

- Uniqueness: The RI is unique or quasi unique worldwide and provides world-leading capabilities;
- Complexity: The RI is highly complex in its organisational structure, technology and/or operation. Its scale is usually very large in terms of the required human and/or capital resources;
- International dimension: The RI possesses an international dimension which is reflected in its governance, its operational footprint and user base.

The Expert Group established a list of VLRIs that meet these criteria, together with a few interesting cases that provided complementary information despite only partially meeting the criteria. A small subset of VLRIs were then further examined as case studies in support of this activity.

The activity was set up to include the following components:

1. A horizon-scanning exercise that included VLRIs in operation, under construction and in the planning stage, to provide a vision of the future landscape of research infrastructures. The activity considered VLRIs at different stages of their life cycle, i.e., new projects at the conceptual and design stages, VLRIs under construction, VLRIs under steady-state operations, as well as VLRIs towards their end (decommissioning or repurposed). The activity also explored different areas and disciplines, with financing aspects at the core, recognising that national budgets are finite and acknowledging the reality of a possibly lengthy post-covid economic recovery. This scanning exercise was completed by an analysis of existing strategic instruments used for decision-making, as well as contextual policy drivers, to identify emerging challenges for VLRIs.
2. A review of a series of key challenges, based on literature, questionnaire and interview surveys and workshop feedback. This included:
    a. The governance, financing and business models for VLRIs as well as implications on human resources management, partnerships and networking with other RIs. This review took into account the increasing diversity of partners involved and their expectations, the need for long-term sustainability and the lessons learned from the COVID-19 and other major crises, where appropriate.
    b. An analysis of data management and delivery challenges for VLRIs, investigating how these facilities can manage and provide access to extremely large amounts of data in the context of Open Science and of new and potentially non-expert user communities.
    c. An analysis of the evolution of expected impacts (and impact assessment methodologies) for these VLRIs.

3. This study was also an opportunity to address the topic of collaboration vs competition, i.e., how can governments work better together to jointly develop and decide on the needs for, and investment in, VLRIs by looking at the ecosystem of VLRIs at a global scale, taking into account both scientific and political drivers.

Methodology and definitions

This activity was supervised by an international Expert Group nominated by the OECD Global Science Forum (Appendix 1) and was co-chaired by Dr. Heidi Bandulet (Canada Foundation for Innovation) and Prof. Willy Benz (University of Bern). Experts from international organisations interested in RI policy were also invited. The Terms of Reference of the work were proposed by a Scoping Group and approved by the Global Science Forum in April 2021.

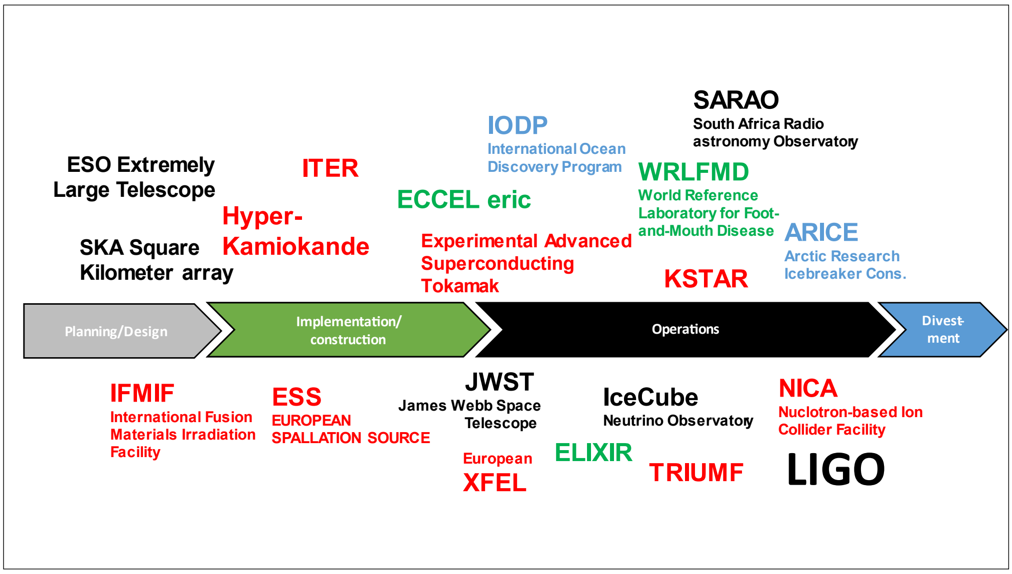
Preliminary fact-finding and discussion with the Expert Group were conducted to identify existing and upcoming VLRI projects worldwide (and agree on a set of common definitions) and identify existing challenges to provide a basis for the surveys. In parallel, a horizon-scanning exercise was carried out with the support of a consultant (Paul Dufour) to identify issues from existing national/regional research infrastructure roadmaps as well as upcoming challenges. The activity also examined emerging drivers behind institutional and national strategies for VLRIs. This revealed a large diversity of practices and approaches (see chapter 2).

Two surveys were carried out by the Expert Group

Two different surveys were designed to obtain detailed information, insights and feedback from VLRI managers, funders and decision-makers, the results of which were further discussed with relevant stakeholders at international workshops.

- Targeting RI managers, the first survey consisted of a detailed questionnaire focused on six key challenges and issues as identified by the Expert Group: Governance, funding and business models, data management, human capital, training and education, impact assessment, and VLRI ecosystems. A broad range of VLRIs was selected covering different scientific domains, VLRI types, geographical areas and life cycle stages (see Figure 1) to ensure appropriate representation and variety.

Figure 1. VLRIs included in the first (VLRI managers) survey



- Targeting funders and policy-makers, the second survey was conducted initially through a written questionnaire, followed up in several instances by interviews carried out by Expert Group members. The questions raised were complementary to those of the managers' survey and were distributed along four main themes: financing, VLRI portfolio and ecosystem, governance, management and operations, including data, as well as broad impact and benefits. Funders and decision-makers consulted in this activity (see Figure 2) were selected on the basis of their involvement in the choice to invest in VLRIs and their country's participation in supporting those VLRIs included in the managers' survey to obtain complementary feedback.

Figure 2. Funders and decision-makers consulted in the second survey

It is important to note that the two surveys were designed to be illustrative rather than statistically representative and were focussed on elucidating interesting cases from a diversity of examples. Survey responses do not reflect the full range of VLRI, but were deemed sufficiently diverse to capture both heterogeneities and commonalities in VLRI portfolios.

Two international workshops specific to this activity were organised, one held virtually on 15 June 2022, and another held in-person on 17 October 2022 in Brno, Czech Republic, as a satellite event of the ICRI2022 conference. The workshop programmes and participants are available on the GSF web pages (workshop 1[1], workshop 2[2]). Input was also garnered from a GSF panel discussion organised at the 2021 International Conference on Research Infrastructures (ICRI)[3].

Both workshops included case study presentations from VLRI stakeholders illustrating the challenges they face and providing some interesting and practical solutions and options. The first workshop discussed issues from the VLRI managers' perspective, and the second from the funders' and decision-makers' perspective. Stakeholder inputs from the surveys and workshops on practices and policies provided more detailed information on key challenges and good practices, which are included in the report.

Definition

As indicated earlier, stakeholders often have different definitions of what is a VLRI. Hence, throughout this activity, it has been important to provide the various stakeholders with a standard working definition to ensure a common understanding. The research infrastructures selected for the purpose of this activity have the following combined characteristics:

- Uniqueness: The RI is unique or quasi unique worldwide and provides world-leading capabilities.
- Complexity: The RI is highly complex in its organisational structure, technology and/or operation. Its scale is usually very large in terms of the required human and/or capital resources.
- International dimension: The RI possesses an international dimension which is reflected in its governance, its operational footprint and/or user base.

1. Policy context and horizon scanning

Priority-setting is a critical matter as the envelope for funding research and governance surrounding VLRIs is being scrutinised more closely for its returns – economic, as well as social and environmental. As a result, various strategic instruments ranging from decadal surveys to roadmaps and national research vision strategies are being re-imagined at the same time as the ongoing operation, planning and design of VLRIs.

International cooperation in big science projects and programmes became more imperative in the late 80s' as these were becoming more common in the forefront fields of research. As the OECD Ministerial meeting in March 1992 underscored, a central challenge was to make intelligent choices regarding both the science and the funding and management of such projects and programmes, When the OECD Megascience Forum (MSF) was launched in 1992, the ITER program had just approved its second engineering design phase. And in the first three years, the Megascience Forum examined six scientific fields in which international projects could play a larger role: astronomy, deep drilling, global change research, oceanography, neutron beams and synchrotron radiation sources, as well as particle physics. Most of these fields are still under active research today with new partners and increasingly ambitious projects–and science diplomacy along with shifting geopolitical issues play an increasing part in their development. Not to be overlooked as well are the built-in inspirational outcomes of large-scale science projects. As one commentator recently wrote[4]: *While megaprojects may well have huge economic and scientific benefits, they can also create a more aspirational and adventurous culture*. Indeed, a powerful case for more long-term funding has been demonstrated with the success of the Webb telescope and the new research horizons surrounding novel genomics and global health infrastructures.

Of course, the fast-moving, global geopolitical situation and policy challenges have meant that the issues facing the funding, design, operation, maintenance and ongoing governance of VLRIs are only becoming more complex. But at the heart of this is the continuous push and pull of international competition and cooperation to move discovery research forward (Smith, 2007[6]).

A Changing Research Landscape for VLRIs

Very large-scale research infrastructure collaboration occupies a highly complex and fast-moving, and at times, risky policy space. All large laboratories and research infrastructures need to be to proactive, as well as react to, and act within this evolving context.

VLRIs are not just national in scope— they often demand international partnerships with relevant governance and funding protocols. Science and its knowledge production is a global enterprise, and so too are the politics and geography of location. It has become so due to the increasing complexity and cost of the infrastructures needed to address evolving "grand challenges", often beyond the scope of even the largest countries. Another element to consider is the stability international collaboration produces. Stakeholders involved in VLRIs are very much aware that their long-term commitments are needed and that such collaborations are difficult to terminate, hence this introduces a stability element which is critical for the resilience in the research infrastructure, although unforeseen issues can affect such stability.

It is also important to bear in mind where these R&D investments are highly concentrated across the globe. While effort is underway to strengthen scientific excellence in many developing countries, new strategies are required to incorporate an inclusive and interdisciplinary approach to this funding, including the geographic spread of these facilities, easier mobility of their talent, along with access to their instrumentation and data.

The Research and Innovation Strategies Driving VLRIs

In the early 90s, many countries were struggling with how to develop strategies around the selection of large-scale or mega science research. Some of these were bottom-up activities initiated organically by small groups of individual researchers to pursue basic or fundamental science questions. Others were top-down arrangements with significant effort and expense required to sign formal international agreements where other goals were envisaged along with the advancement of knowledge. Criteria for decision-making were developed that essentially outlined key questions such as:

1. What are the prospects in terms of the advancement of knowledge?
2. What are the views of the research community using the facility?
3. How interdisciplinary will the user community be?
4. What opportunities exist for international links or collaboration?
5. What impact will the infrastructure have on education, training, applications and spin-offs?

Today, these criteria for choice are still with us – but they have evolved into more sophisticated policy and governance questions that require input from many stakeholders, both within and outside of the ecosystem of research. Ultimately, the scale and scope of approaches in supporting and funding VLRIs is dependent largely on the framing of these existing or new infrastructures within national or regional/multi-national strategies. Some countries have taken a strategic approach to this by integrating the research infrastructure within these frameworks. And they have evolved over time to address the shifting pace of research and its larger scale reach across the globe.

Moving Roadmaps from Rhetoric to Reality

Although national strategies to focus investment in science and technology are necessary exercises carried out in most countries, linking these seamlessly to the necessary research infrastructures and data platforms-both at home or in partnership with other countries is quite another challenge. One favoured approach is through the use of research infrastructure roadmaps.

Typically, roadmaps cover several key issues, including the scientific scope of the RIs; their geographic and/or administrative scope; their temporal scope, along with the size of considered RIs. Most roadmaps are framed within a larger context of a national strategy or approach to supporting the overall research and innovation ecosystem. VLRIs are included in a number of roadmaps but in a more heterogenous way as they present a number of specific challenges, often linked to their international dimension. The GSF 2008 report on Roadmapping of Large Research Infrastructures highlights some of these key issues around the methodology and process of these ' feuilles de route' (OECD, 2008[7]). That report noted other issues associated with roadmaps and relates to some work of the Group of Senior Officials (GSO) established in 2008 by G7 Science Ministries in recognition of the potential for increased international cooperation on global research infrastructures (Group of Senior Official on Global Research Infrastructures, 2017[8]). First published in 2006, with 35 projects, the European Strategy Forum on Research Infrastructures (ESFRI) has developed its own regional roadmap which has been regularly updated in 2008, 2010, 2016, 2018 and 2021, bringing the number of RIs of pan-European relevance to 63, and is now including a number of international RI initiatives of interest to European countries.

As existing VLRIs have evolved and new ones are being developed, there has been increased attention to larger, more complex shifts in the way in which research itself is funded and conducted.

In the early days of the CERN experiments for example (which date back several decades), physics and astrophysics ruled the science world and engineering was a much sought after expertise to ensure sound functioning of the facilities. But global approaches have now pivoted to the fast-moving pace and growing interdisciplinary nature of research and knowledge production.

Indeed, the organisational structures for international VLRIs can range from highly structured and centralized, like CERN, to decentralized and loose, like the LIGO collaboration. Some of these facilities may well become game changers, like CERN was over 60 years ago and will at times lead to Nobel prizes or other recognition. For example, ITER was born with an ambitious objective and, beyond its seven official members, represents a collaboration of 35 nations trying to prove the feasibility of fusion as a carbon-free source of energy.

Today, newer grand challenges for VLRIs have emerged centred on climate change, genomics, biodiversity, oceans management and environmental sustainability, cutting across scientific disciplines and statecraft. These VLRIs require multiple sites and mobile or virtual capacities. By their very nature, they are conceived and deployed at a global scale that strives to match the scope of the targeted problems.

Table 1. Roadmaps and Other Strategic Planning Platforms for VLRIs

National strategies	Roadmaps-decadal surveys	Landscape analyses	Integrated, regional fora	Metric and impact analyses
National strategic efforts designed to frame and fund emerging science, technology and innovation approaches through dedicated policy and public outreach processes Examples include the innovation and research strategies in the United Kingdom, Australia, the Netherlands	Blueprints that set investments for RIs within national STI priorities or decadal surveys working with various stakeholders both nationally while globally assessing and scanning the next frontiers for astronomy, astrophysics, ocean sciences, high-energy physics etc. Examples include NASA's Decadal Strategy for Planetary Science and Astrobiology 2023 - 2032, and the Canadian Space Agency's Science and Space Health Priorities for Next Decade and Beyond	Comprise a survey of all RIs that are accessible for researchers within the country; often mapping growing linkages among fields of research Examples include the French 'feuille de route" research infrastructure plans-latest in 2021	ESFRI- ERIC are key examples across the EU, but so too are geo-specific VLRIs requiring specialised sites or unique platforms and - or instrumentation such as in polar areas, icebreaker consortia or in specialized locations, Examples include ARICE on futures for polar research infrastructure	Emerging metrics and analyses to assess economic, social impacts as well as training and public outreach. These can involve grand challenge approaches such as linking to sustainable developmental goals (SDGs), health and genomics, climate change, green-clean energy impacts, etc.

Strong and effective roadmap-like visions have also been developed for research infrastructure within a narrower domain. For example, in astronomy and space science, decadal surveys are often the preferred approach. Such surveys are usually developed by national science and research bodies working with the various stakeholders nationally while globally assessing and scanning the next frontiers for the fields. The United States National Academies of Science, Engineering and Medicine and NASA have produced several of these reports to map emerging new frontiers in space and planetary science (Committee on the Planetary Science and Astrobiology Decadal Survey et al., 2022[9]). The European Space Agency has its own vision 2025 document[5] that defines five immediate priorities as well as working closely with the EU.

There are other more integrated approaches to link networks of VLRIs. Take the case of the ESFRI, the European Strategy Forum on Research Infrastructures. Established in 2002 to bring together the various national research approaches to RIs in Europe, it has now moved forward with its Roadmap 2021[6], which identifies vital new European research infrastructures in six thematic fields (energy, health & food, environment, physical sciences & engineering, social and cultural innovation, and digital platforms). With a vision to maximise the impact of pan-European investments in research infrastructures in terms of science, European and international collaboration and innovation, the updated roadmap includes a comprehensive analysis of the current infrastructure landscape. It reviews progress of ESFRI projects currently being implemented; and provides strategic guidance on issues of general interest to national governments and research infrastructures themselves.

On occasion, efforts are made to explore the state of the art of certain disciplines. This is the case currently with the long-range Snowmass review of particle physics. The Particle Physics Project Prioritization Panel (P5) recommends a 10-year research agenda for the United States Department of Energy and National Science Foundation[7]. In another case, the European Strategy for Particle Physics update[8] recommends a so-called Higgs factory as the highest priority to follow the LHC, while pursuing a technical and financial feasibility study for a next-generation hadron collider in parallel, in preparation for the long-term. Maintaining the existing European support for neutrino physics in the United States and Japan is also strongly recommended. A comprehensive report, it also covers areas of synergy with neighbouring fields such as astroparticle and nuclear physics, and it includes societal aspects ranging from training and knowledge transfer to minimising the environmental footprint of future facilities.

National multidisciplinary strategies for roadmaps that include VLRIs may also extend worldwide. The United Kingdom and Australia highlight examples of these. At times, certain countries or locales may have assets, geography or capabilities that larger countries may not possess— hence the need to expand the roadmaps to consider the importance of location such as the case of the Square Kilometre Array (SKA) project, the world's largest radio astronomy facilities in Southern Africa and Australia, or the South Pole for the unique ICECube neutrino facility.

In the landscape analysis offered by many of the roadmaps, a common thread is to consider how best to integrate the emerging fields of research, as well as ensuring equity, diversity and inclusion in the research capacity.

Table 2. Selected Roadmaps linked to National Strategies

United Kingdom	Australia	Netherlands
R&D Roadmap 2020 New funding offers investments to ensure the United Kingdom can further benefit from the opportunities of international scientific partnerships. Integrated with the 2021 United Kingdom Innovation Strategy	2021 Research Infrastructure Roadmap- national survey about how National RIs are used now, and how it can address future trends, needs and challenges	2021 Large-Scale Research Infrastructure Roadmap (updated from 2016) more alignment among science fields in NSE, Social sciences and Medical-Health, engagement and attention to Equity, Diversity and Inclusion
Provides long-term flexible investment into infrastructure and institutions managed through the UKRI portal as well as data and analytics research environments Builds on opportunities report and landscape analysis https://www.ukri.org/what-we-offer/creating-world-class-research-and-innovation-infrastructure/	Designed to drive a more integrated NRI ecosystem; improve industry engagement with NRI; develop a National Digital Research Infrastructure Strategy Prepares Australia to tackle future challenges in four key infrastructure areas: digital research; synthetic biology research; research translation; environmental and climate research infrastructures Will inform the 2022 Research Infrastructure Investment Plan https://www.education.gov.au/national-research-infrastructure/2021-national-research-infrastructure-roadmap	Builds on national strategy to strengthen research and innovation ecosystems- and links to the EU's ESFRI https://www.nwo.nl/en/researchprogrammes/national-roadmap-large-scale-research-facilities

Emerging Horizon Planning Issues and Policy Considerations

Roadmaps and their landscape cousins are evergreen in nature. They are continually being benchmarked, evaluated and updated. But they can run into roadblocks and detours from time to time. The impact of the current crisis in the Ukraine shifts cooperation from Russia among EU nations while affecting the evolution, funding and governance of their VLRI frameworks now in place. For instance, the VLRI under construction in Germany, Facility for Antiproton and Ion Research (FAIR), faces increased costs for the other members given the suspended cooperation with Russia. In the case of the European-XFEL, which is funded by

Russia for slightly more than a quarter of its budget, a statement from the stakeholder countries notes that they will not start new agreements with Russian institutions and will suspend existing ones, while respecting the legal obligations of the VLRI. In Arctic research and space cooperation, this too will have significant impacts to existing and planned VLRIs as sanctions and official science ties with Russia are cut or suspended and take hold across the globe.

Funding and sustainability remain critical. The pandemic has affected some of the planned VLRIs and their development. For instance, the Swedish government has stated that it will provide an extra 300 million kronor to address the delay caused by the Covid-19 pandemic to the European Spallation Source (ESS), a major international particle accelerator-based neutron research facility being built in Lund, Sweden.

New challenges and revised strategic orientations will be required. And emerging technologies are coming online that will offer opportunities for creative research platforms. A recent article has listed just some of the futures for RIs in the fields of gravitational wave observatories and the link with other physics RIs for example (Bailes et al., 2021[10]). Indeed, one of the new experiments involves the United States and India currently working together to build a detector in India, a collaboration between LIGO and three Indian institutes (Padma, 2019[11]). The United States is providing hardware, data, training, and assistance, while India is providing the site, infrastructure, labour, and materials.

The increased focus on climate change and biodiversity as well as meeting key SDG targets has impacted the roadmaps and vision for some VLRIs. For example, the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL) underscores the attention that is being given to addressing energy and climate[9]. A proposed North Atlantic Carbon Observatory (NACO) from a Canadian consortium is yet another distributed facility being put forth focussing on the carbon sinks in the oceans[10]. Yet another emerging, distributed model is the Global Ecosystem Research Infrastructure (GERI) (Loescher et al., 2022[12]). The GERI position paper indicates that: *"it is an integrated network of analogous, but independent, site-based ecosystem research infrastructures (ERIs) dedicated to better understand the function and change of indicator ecosystems across global biomes. Bringing together these ERIs, harmonizing their respective data and reducing uncertainties enables broader cross-continental ecological research. It will also enhance the research community capabilities to address current and anticipate future global scale ecological challenges. Moreover, increasing the international capabilities of these ERIs goes beyond their original design intent, and is an unexpected added value of these large national investments*."

The life sciences have also seen a boost in new distributed models for VLRIs, especially in the context of the global pandemic fallout. Genomics networks to track new variants of the novel coronavirus emerging across the globe are now well linked. The aptly-named ELIXIR[11] VLRI, with its 23 nodes across Europe, has made clear the need to pay attention to how the benefits of investment can impact many sectors of society, economy and policy.

Increasingly important is the need to address public and community outreach as well as effective communication of the impacts of VLRIs. This is especially hitting home in many countries where resources are constrained. Some attention is being paid to targeting policy-makers and elected officials in providing them with on-site visits in addition to explaining the potential for globally governed RIs as instruments of enhanced science diplomacy.

Australia's NRI report has examined new mechanisms for public education about the RIs through social media and surveys of users. ITER is marketing a digitized exhibit and providing digital materials to schools, universities and museums. CERN is moving forward on a large investment for a public education centre (CERN Science Gateway) to better inspire and inform students and citizens about the value of discovery research. LIGO maintains a K-12 educational program through a science and education centre at the Livingston Observatory and a new LIGO Exploration Center at the Hanford Observatory is designed to grow the engagement of students with frontier science. SKA has devoted some considerable effort to engaging the public on the value of astronomy, especially in the context of Africa's research developments and is currently engaged in building a SKA Exploratorium for the public.

A related issue is encouraging and supporting next generation talents to work in these new RIs. The pandemic had some impacts on the ability to retain and attract top talent in certain fields, and some of the RIs are exploring new incentives on how to address this challenge. South Africa's research minister has noted that the country: "has awarded about 2000 bursaries over the past 15 years for undergraduate and postgraduate studies in astrophysics, data science, engineering and artisanal skills. The bursaries are intended to develop a pipeline of skills that will grow the astronomy community to undertake scientific research through access to the telescopes that we have in Africa, as well as engineers to develop instrumentation and maintain the telescopes[12]."

Open science and the digital transformation are two powerful forces now impacting the shape and scope of VLRIs across the globe. Security issues on what data can be made available remain problematic for many VLRIs. Indeed, open science is facing its own challenges post-COVID-19 and in a changing geo-political environment. Some of these issues are discussed in the recently released GSF report on integrity and security in the global research ecosystem (OECD, 2022[13]).

Clearly, advancing the frontiers of knowledge will require a more joined-up interdisciplinary approach, in areas such as health, energy and biodiversity. But attention will need to be given to community engagement and public acceptance and trust. For example, in the stewardship case of the construction surrounding a Thirty-Metre Telescope and other telescopes in Hawaii, along with any future developments, a new authority with indigenous expertise membership has been established with a focus on mutual stewardship in which "ecology, the environment, natural resources, cultural practices, education, and science are in balance and synergy." It will administer rules that will establish limits on astronomical development and may limit commercial use and activities on Maunakea. In another case with the launch of the Square Kilometre Array Low in Western Australia, the site has been named Inyarrimanha Ilgari Bundara – an Indigenous name meaning 'Sharing the Sky and Stars'. The lessons learned from these and other similar cases can help shape a framework for ensuring greater success in garnering the public and policy attention and support for these critical research experiments.

Cooperation and complementarity can go hand in hand when designing VLRIs. While access to research results and exchange of data are clearly needed to move projects forward, there is often a need for complementarity in the design of new facilities. The current discussions in the United States over a new neutrino observatory—the Deep Underground Neutrino Experiment to be installed in the Long-Baseline Neutrino Facility (LBNF/DUNE), and the construction of the Japanese Hyper-Kamiokande VLRI— is an example where operators are making clear that the facilities can and need to work together. As the director of the DUNE VLRI underscored: "complementarity and confirmation of parameters is essential to our understanding" [13].

A strategic and international approach to VLRIs

The 2021 International Conference on Research Infrastructures (ICRI) hosted by the Canadian Foundation for Innovation in Ottawa[14] outlined some key issues that are emerging. Building on this, the 2022 ICRI conference in the Czech Republic[15] highlighted some of themes that are emerging around socio-economic benefits and impacts of RIs (including new metrics) as well as the multifaceted key challenges centred on sharing of data more globally.

But ICRI and other fora have made clear that there is a need for conversation space on emerging VLRIs issues (examples of existing fora are given in Table 3).

Table 3. International policy fora on RI policy

International fora	Mission-objectives
OECD Global Science Forum	Body of the OECD dedicated to science policy, originally created as "the Megascience Forum" to address specifically policy issues related to large international RIs, and which is producing regular analyses and recommendations on RI policy. The GSF is a platform where national science policy makers can debate issues and priorities.
Group of Senior Officials on Global Research Infrastructures	Body originally created by the G7 that has developed a set of criteria for defining Global RIs, which enables new facilities around the world to understand various access mechanisms and to join global networks.
International Conference on Research Infrastructures (ICRI) https://www.icri2022.cz/	Conference, every two years, bringing together experts from different fields to discuss challenges and trends for research infrastructures around the world.
European Strategy Forum on Research Infrastructures (ESFRI)	Forum set up by European countries to support a coherent and strategy-led approach to policy-making on RIs in Europe, and to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at EU and international levels.

Ultimately, it is important to recognise that there will be new, emerging science partners around the world that can be important scientific collaborators. Scientific talent and research capacity is rising around the globe as many countries invest in building a more robust S&T enterprise. While national interests will always play an important role in VLRIs decision-making, collaboration across borders can yield greater results for all involved. Many of the most pressing scientific questions are not defined by national boundaries and will clearly require enhanced global collaboration for advancement. Most VLRIs have been scientifically de-risked; that is, it is reasonably clear that the research to be undertaken is technically challenging but achievable—but will require more resources than any one nation is willing to commit. After all, no country is self-sufficient in any of the new emerging knowledge and research frontiers.

However, priority setting, governance and funding choices around these new experiments will face new challenges. Resiliency will be the new watchword. Efforts to enhance strategic foresight and attention to future-proofing risks will be required to anticipate any new futures for VLRIs. Critically, how can the VLRI research community engage more strategically with the policy level, its users, the social and outreach networks and the larger research networks? How can policy and horizon scans be integrated in these future experiments? Can the organisations conducting roadmap exercises exchange common lessons and learn from each other in a more deliberative fashion? These are some of the key issues on the horizon.

2. Analysis of challenges

2.1. Governance

As mentioned in the definitions, the term "governance" encompasses the set of structures, principles, rules and procedures through which a collaboration operates, and through which decisions are made by the parties to the collaboration. More specifically, this includes two major items:

- The VLRI's formal status and everything related to its membership, legal structure, foundation documents, link to the host country, etc.
- How the VLRI is run: administrative and operating structures, decision-making processes, role of funding agencies, secretariat structure and personnel issues, role of the host, etc.

The 2010 OECD report on large RIs largely addresses all the challenges raised by all these items, and this report provides some updates on emerging issues and options related to new VLRIs. The fundamental legal/administrative structure of a VLRI remains a very important element since it will drive the agreement characteristics that bind the various partners of the VLRI together and documents their commitment to the project. The surveys conducted during this work revealed a variety of legal structures currently being used by VLRIs, which are summarised in Table 4, and which each have various pros and cons.

Table 4. Existing legal structure models for VLRIs

International dimension	Legal statute	VLRI examples	Pros	Cons
Fully international	International organisation	ITER, ESO (ELT), CERN (LHC), JINR (NICA), SKA, ELIXIR	Long-term stability, resilience	Very long birthing process
	International agreement	IFMIF, IODP, ALMA	Flexibility	Lighter commitments
International with major national members	Non-profit company or foundation based on an international agreement	XFEL, ESRF	Stability	Vulnerability to the main member(s) difficulties; may be less acceptable for some partners
Regional with international partners	ERIC	ESS, ECCSEL, ELI	Stability, resilience	Difficulty to include non-EU members
	Consortium agreement	ARICE	Flexibility	Difficulty to secure long-term financial commitments
National with international partners	National Institute	Super Kamiokande KSTAR, SARAO, EAST	Stability	Restricted international participation
	University + national research funding agency	ICECube, LIGO, JWST,	Proven and flexible system, open to international collaborations	Mostly United States-specific, no real international governance
	Consortium of national stakeholders/not for profit organisation	TRIUMF	Stability	Restricted international participation

What this analysis indicates is that there is no obvious one-size-fits-all solution for VLRIs and that recent projects have been using various legal status according to their own specificities. Recent events (COVID-19, war in Ukraine, rise in energy costs) have served as crash tests for many VLRIs and have demonstrated the advantage that robust agreements have in the face of unexpected events. Feedback from VLRI managers indicated a strong demand for stable and resilient models and suggested that, despite their flexibility, loose collaboration agreement may not be suitable for ambitious and long-term projects. High-level agreement and a strong legal statute not only symbolise the strong commitment of the partners, but also help the management in developing a long-term vision for the project and may be useful when difficulties are encountered and the strength of the partnership is put to the test.

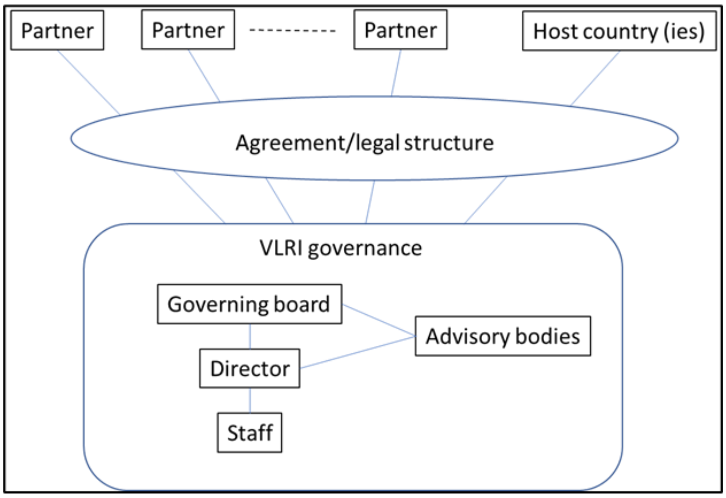
On the other hand, strong but rigid agreements may represent a liability when there is a need for adjustments or even major modifications. In the case of ITER, while the international agreement makeup leads to the incomparable richness of the project, it has also added a level of complexity to day-to-day management and, in some cases, to the misalignment of goals and incentives that has led to project delay and cost increases. It is also interesting to note that, for example, TRIUMF's model was changed in 2021, from a Joint Venture to a not-for-profit corporation. The changes that were made were intended to allow TRIUMF to operate more efficiently through a more streamlined Board structure, supporting more proactive decision-making, greater accountability, and a stronger focus on both the science and the stewardship of TRIUMF. This new model also accounts for geographic and diversity considerations. Overall, there is a need to include in the VLRI statutory agreements a mix of stability and flexibility.

For VLRIs, a critical element is also the capacity of the project to include international partners since those are usually a key requirement not only for financial reasons but also to ensure a maximum scientific quality and reach/usefulness to the scientific community. As indicated in Table 1, some legal structures and arrangement models are clearly more adapted to international partnerships, even though they often require longer preparatory and negotiation phases, and there may be legal barriers to the participation of some partners. For example, the European ERIC model allows, in principle, easy and flexible ways to increase participation from new (EU) member countries and / or new facility owners in current member countries, and there are significant efforts to welcome non-EU members. However, some countries have issues in obtaining the required signatories at the ministry level for becoming a member of an ERIC. Similarly, setting up a national non-profit organisation may also be challenging for some countries as this usually implies paying membership fees from government bodies to a nationally registered company. The European XFEL or ESRF avoided that obstacle by using a hybrid model whereby an international convention between partners was set up alongside their national legal structure.

There is an obvious link between the formal agreement and the legal structure: formal collaboration documents sometimes state explicitly whether the terms of the agreement are "legally binding" (or "not legally binding") on the signatories. International organisations will typically require binding agreements while consortia will often not. Even if the clause is adopted, the practical implications may be unclear, especially if the signing parties are governments, and in the absence of an international constraint or enforcement mechanism. In negotiating the agreement, a potentially useful strategy is to agree on concrete actions that would be taken in the event of explicitly specified departures from the terms (for example, if one of the partners wishes to leave the collaboration).

The governance organisation of VLRIs often follows a fairly standard model (see Figure 1) which is however adapted to the size and complexity of the project.

Figure 3. VLRI generic governance structure



Source: adapted from (OECD, 2010[3])

The governance structure plays a fundamental role in defining the strategy of the VLRI, in the decision-making process and in the overall management. Because of the complexity of many VLRIs, the simple generic structure described Figure 1 is often adapted to the diversity of stakeholders, to the possible distributed or mobile nature of the RI and to the science requirements (see IceCube governance model[16] as an example).

Furthermore, there may also be a transition of the governance structure between the pre-construction and the construction phase, or between the construction and the operation phase. In the SKA example, a legal status was required when entering the preconstruction phase of the project to bind partners within a 'interim' legal framework to facilitate major project decisions (site decision, headquarter decision, science case, project scope etc) necessary for the next (construction) phase; the interim governance structure was also used to prepare a more sustainable legal and governance structure (that of an intergovernmental organisation) for SKA's construction and operation phases.

The strategic directions of VLRIs are usually defined by a governing body representing the project partners. While this is, in theory, fairly straightforward for single-site and well-structured VLRIs, it may become more challenging for other more complex settings. For example, the strategic mandate of ECCSEL is codeveloped between its Operations Centre, the Research Infrastructure Coordination Committee and the country nodes.

In all cases, since the key strategic decisions are taken by the governing body, it is essential that the project partners define a proper procedure by which they will exchange their views (which can differ significantly) and come to decisions that all partners can accept. Generally, this involves some form of voting which can be done following the "one partner one vote" model or can be weighted according to some pre-defined scheme. Changing this later on as a result of the evolution of the VLRI might not be straightforward but is sometimes desirable.

Human resource management is another challenging issue connected to the VLRI governance structure. It is also one that is complex to address, namely because of the often-international nature of VLRIs and their distribution over serval sites and countries. The staff (whether full- or part-time) of a given VLRI, while paid by funds provided by its members, can often be hired and managed under a variety of statuses depending on the VLRI's legal statute and its operational structure. They may thus be directly employed by VLRI (under diverse types of contracts), or, as detailees/secondees, they may retain an affiliation with a national institution. Although VLRIs are very long-term enterprises, the nature of their legal structure, and sometimes lack of long-term financial perspective, mean that only a few of them (usually only those VLRIs that have the legal statute of an international organisation) can offer indeterminate contracts. Although a number of VLRIs are addressing this through close relationships with neighbouring research institutions or with other RIs to facilitate staff mobility, a number of VLRIs surveyed reported that the absence of long-term funding commitments created both stress for the management body and risks of there being gaps in expertise.

The international nature of many VLRIs may also lead to issues that relate to their governance: while no VLRI investigated established staff quotas for its members, the under-representation of some member countries in the overall staff structure is often problematic, and in such cases warrants pro-active measures from the human resource management.

An emerging issue that was raised during the survey is that of the legal structure and governance of networks of VLRIs. Indeed, even VLRIs increasingly work in networks or even consortia to exploit synergies and complementarities among the various facilities. For example, in the domain of gravitational wave observation, the three main existing VLRIs which are LIGO (in the United States), VIRGO (in Europe) and KAGRA (in Japan) have developed agreements between them (in the form of Memoranda of Understanding or Memoranda of Agreement), which have enabled sharing of data and the formation of meta-collaborations (collaborations of collaborations) that function as a single scientific entity that analyses all gravitational-wave data. This greatly enhances the scientific output of the network with respect to individual observatories. The structure of these agreements explicitly allows for future growth of the ground-based gravitational-wave observing network as new observatories are built and come online. While these agreements have been successfully implemented over a period of years, they have faced challenges when trying to ‘merge’ two functioning and independent projects/collaborations with separate and independent organisational structures, governance models, cyberinfrastructure platforms and policies, and funding sources. Thus, future generation international VLRI networks, such as the gravitational-wave observatory networks now under consideration (including the US Cosmic Explorer and the European Einstein Telescope) would benefit from establishing joint collaboration governance models and policies well in advance of the beginning of operations, even though the right governance model for such meta collaboration still needs to be properly defined (in the case of the Einstein Telescope, some preparatory work is being carried out to determine what formal connexions with other gravitational waves facilities may be set up[17]).

- VLRIs governance structures need to balance long-term sustainability and flexibility. The need for robustness has been underlined by the recent crises and should be a major criteria for VLRI stakeholders when deciding on governance structure. However, such structure should be able to adapt to the life-cycle phases of the VLRIs as well as to the international diversity of their members.
- As VLRIs increasingly need to work in synergistic networks, serious consideration should be given to develop governance models for large international collaborations between VLRIs, to improve their capacity to share or delegate some strategic decisions at the collaboration level.

2.2. Financing and business models

As discussed in previous chapters, the number, scale, complexity, and variety of proposed VLRIs are all increasing. Each new generation of VLRIs in the traditional 'big science' disciplines, namely physics, space science, and astronomy, in further pushing scientific and technology boundaries, is becoming more and more costly, with new investments routinely in the billions if not tens of billions of euros for construction, let alone operation costs which typically span decades. Meanwhile, the need, opportunities, and incentives for establishing VLRIs in other disciplines are also growing, especially when considering the trend towards integrating and consolidating facilities and data across multiple sites and establishing them as VLRIs. Two of the Extreme Light Infrastructures sites, while were originally funded as distinct projects, evolved into Europe's leading laser VLRI, with a third expecting to join. And while the lion's share of public investments into VLRIs still seem to be in those traditional disciplines, their proliferation in other domains (e.g., health, oceans) is adding significant pressure on national science budgets. This much is confirmed by the funders in this activity.

Governments, big and small, are thus confronted – to maintain or gain scientific leadership, or else to build research capacity - with having to make investment decisions that are more strategic. While budget constraints are nothing new, and strategic planning tools have become more sophisticated, many funders report reaching a ceiling in their ability to support VLRIs, and therefore anticipate having to become increasingly selective in their investments. For many, this is also because they themselves need to advocate for budget increases from their own governments to meet growing demand which is often difficult given the short-term line of sight of most governments, and the increased expectations of demonstrable returns that enhance national prosperity.

The flipside, as some have observed, is that this situation favours more cooperation among funders, even domestically, as well as more cooperation and strategic planning among science groups/disciplines – from joint priority setting to collaboration in design and use of research facilities. The NSF reports for example that this spurs more joint funding with other federal agencies (i.e., Department of Energy, NASA, United States Geological Survey, etc.) to improve financial models for support of VLRIs.

Moreover, the recent and emerging challenges stemming from the shifting geopolitical and science policy contexts, discussed in chapter 2, which can affect funding partners very differently, are, on the one hand, pushing decision-makers and funders to modify their approaches to funding VLRIs, and on the other hand, pushing those leading VLRI projects to adapt their business models towards becoming more resilient and sustainable. Unsurprisingly, the challenge of financing VLRIs, which by and large come from public funds pooled across domestic and foreign sources, remain at the top of the agendas of both funders and VLRI managers surveyed in this activity.

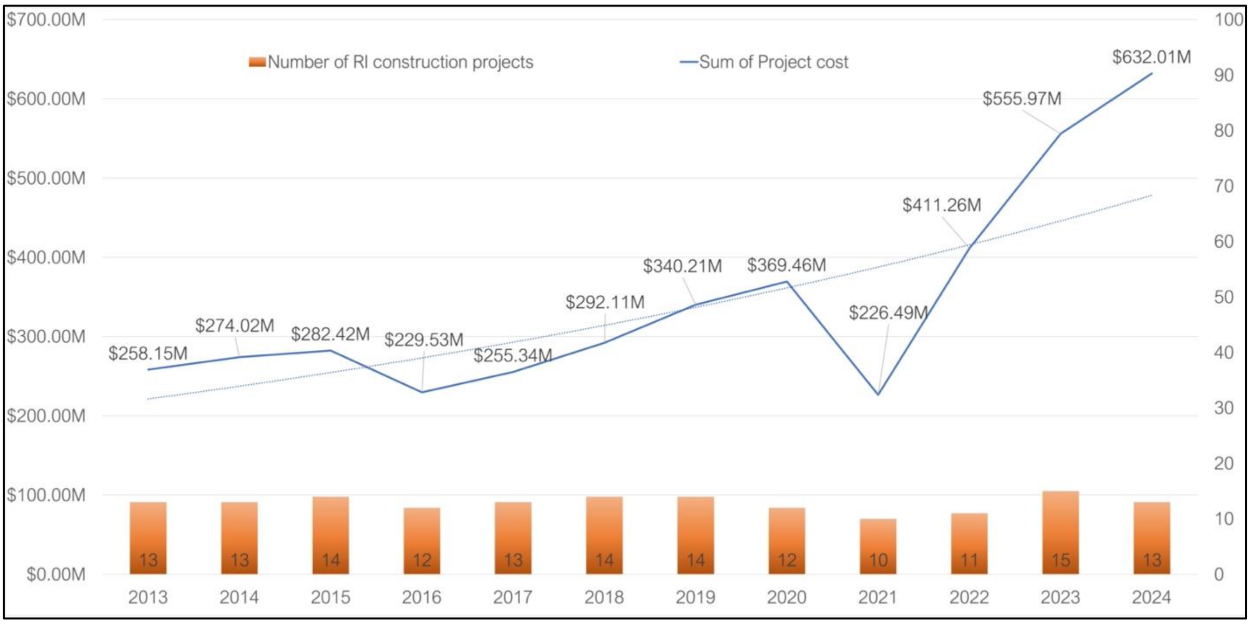
Although this report chiefly aims to draw attention to new challenges, improvements and lessons learned, it is clear from survey responses and case studies that many of the considerations and recommendations that were discussed at length in the OECD report on Large RIs (2010[3]) in sections regarding funding and contributions, as well as the negotiation of agreements remain as relevant today as they were a decade ago. It is worth noting that the funding schemes of a large number of facilities on the VLRI list predate the strategic tools and funding mechanisms presented here. These have evolved considerably since the time initial agreements for financing of these VLRIs were negotiated – for example the idea for the European XFEL was conceived in the 90s' but it became operational in 2017. Nevertheless, as they matured as VLRIs, several have shared valuable lessons during this work that can be useful to new projects. Inputs into this activity also highlighted the difficulty in identifying challenges that are particular to VLRIs; instead, most appear to overlap with those of other international and/or large RIs but where they distinguish themselves is in their scale and level of complexity. Hence this chapter will also reiterate some of the most prevalent and persistent challenges that ought to be considered by today's VLRI stakeholders, and by extension those of other medium to large RIs.

Investments into research infrastructure

According to OECD data[18], the Gross Domestic Expenditures on Research and Development (GERD) are growing in nearly all countries represented in this activity. In fact, the average GERD among OECD countries grew from 2.24% in 2010 to 2.67% in 2020. Several countries are setting aspirational goals; for example, the United Kingdom, currently at 1.71% aims to reach 2.4% by 2027[19], Germany to 3.5%, and Finland to 4% by 2030[20]. Similarly, the EU had set the goal to reach 3% of GDP[21] by 2010. The GERD, being normalised to the size of the economy, is not entirely telling of a given country's 'purchasing power': Germany's 2019 investments are 110B€ whereas those of Korea at estimated at approximately 70B€ despite its much higher GERD.

While data is readily available on total research funding in each country, the same cannot be said for the share of funding specific to RIs, and even less so to VLRIs. This activity revealed that only a few countries are currently able to provide rough estimates, and even in such cases, estimates do not always reflect the contributions from all domestic players. But the examples, however limited, do support the rationale for this activity in that RI investments are indeed increasing steadily. It is, however, unclear whether the share dedicated to infrastructure is growing commensurately or faster than total public investments into R&D. Data provided by the Federal Ministry of Education and Research in Germany, for example, shows that funding specific to VLRIs has grown by about 9% per year in recent years, this increase being largely driven by an increase in the cost of RIs. In Korea, the cost of large to very-large RIs built from 2013 to 2020 is expected to more than double by 2024 (see Figure 4). Total estimated funding for infrastructure by UKRI is also forecast to increase by about 15% per year for the next two years[22]. In Sweden, RIs have been representing over 30% of the Swedish Research Council spendings for several years, with a peak at 36,8% in 2021 (*source: Annual report Swedish Research Council 2021*[23]). In the Netherlands, one of trends in the national Research and Science Policy is that more attention is paid to research infrastructures in general and to the (increasing) costs of (new) memberships and upgrades, especially the further expanding European RIs portfolio. An additional (recent) source of governmental funding for big investments in knowledge development, research and innovation is the National Growth Fund (NGF)[24]. The Dutch government has earmarked € 20 Billion in total for the period 2021-2025 for project investments which have the highest potential for structural and durable economic growth. Although not directly designed for RIs, the NGF fund is enabling the Ministry of Education, Culture and Science to link the economical aspect to big investments in new VLRIs such as the upcoming Einstein Telescope.

Figure 4. Evolution of Korea's number of constructed large RIs and funding allocation for their construction



Source: Korea National Research Facilities and Equipment Center

The gathering of RI funding data (e.g., RI funding trends, possibly VLRI) alongside trends in research funding would enrich discussions around RI planning and financing for the international community. At the European level, ESFRI has recently set up a group working on the financing of RIs that will examine this question, although the issues extend beyond Europe.

Government and funders' decision-making approaches and funding instruments

The funders and decision-makers surveyed for this activity formed a mix of government ministries, departments and agencies (with varying degrees of independence in their decision-making) as well as entirely independent not-for-profits mandated by their government to coordinate and deliver funding (e.g., the Canada Foundation for Innovation). Survey questions on the financing of VLRIs probed on main domestic challenges, opportunities and barriers for investing in VLRIs, and the external challenges and opportunities for coordinating funding with other countries.

As discussed in chapter 2, in the last decade many research-intensive countries have developed strategic tools, such as national and regional RI roadmaps, and established or refined decision-making frameworks on large investments into RIs. The approaches used by funders and decision-makers who responded to the survey are summarised in a separate Annex document (DSTI/STP/GSF(2023)5/ANN/FINAL)

Whether it is a decision to partake in an operational VLRI via membership fees, or for setting up a new VLRI as host or funding partner, surveyed funders qualify their own decision-making as either top-down/centralized (strongly guided by government policies and priorities), bottom up/community-driven (with projects instigated by the community), or else a mix of the two. South Africa's National Research Foundation, although it also pairs its approach to a strong Science Engagement strategy with the wider community, is primarily top-down and strongly driven by regional capacity building, socio-economic development and skills. The United Kingdom and European countries, as well as Canada seem to adopt a more bottom-up approach. However, many agreed that the bottom-up approach in one country can be difficult to reconcile with partners whose approaches are top-down.

Not many countries have a decision-making framework specific to VLRIs. Funding mechanisms often make no differentiation between VLRIs and smaller RIs, and between national and international projects; projects often compete within a limited pool of funding, although funding for smaller RIs can be used to support VLRIs: in the Netherlands, for example, an RI's own funding may contribute to VLRI projects through upgrades, special projects, preparatory work, or even membership fees for an initial period. Many countries reported that balancing investments among domestic vs international RIs, and different size RIs, is a challenge that comes with various trade-offs. The Research Council of Norway resorts to continuous detailed cost-benefit analyses to help optimise its portfolio, for example to compare the value of continuing current memberships or embarking on new ones. And although most countries recognize the need and value of international cooperation around VLRIs, there is still a high degree of competition and national interests present, which can be misaligned between partners. Funding decisions are first and foremost based on criteria such as the potential gain in competitiveness, scientific leadership, and broad impact at the national level to justify use of tax-payers' contributions. There are also different requirements and risk assessments between VLRIs' hosts and participants, and between minor vs major partners that influence decision-making. Countries, or agencies, with budget limited VLRI portfolios, like the Canadian Space Agency, reported needing to be particularly strategic in selecting which project they engage in as they are then far more vulnerable to decisions taken by majority players.

Some funders are mandated to establish VLRI in a given priority area (e.g., the United States Department of Energy which has specific areas targeted for funding, like the Fusion Energy Sciences programme) while others support the full spectrum of disciplines out of a single budget envelope. This then poses a challenge in portfolio optimisation, for instance in Canada's, Netherlands' and Sweden's cases. The United States National Science Foundation attempts to assess balance within disciplines through conducting portfolio reviews but these only occur within programmes with so far no explicit attempt to achieve balance at the agency level.

As stated in chapter 2, for most countries, initial guidance in prioritisation comes from a national strategy for research, sometimes coupled with a strategy for international engagement, for example the United Kingdom's Research and Development Roadmap and UKRI's international strategic framework. Generally, the reliance on long-term strategies is found to be very important to building sustainable funding models. A partner's lack of such high-level strategies may be seen as a risk that reduces its attractiveness as a partner to others. In Canada, where funding decisions on large investments rely heavily on assessments made by international experts, many voices call for the development of similar tools that would help assess international opportunities, in light of Canada's needs and areas of strength and within the national and international landscapes.

There are different types of strategic tools specific to infrastructure most relied upon in VLRI decision-making and identification of priorities. Community plans continue to be widely used to prioritize and coordinate projects within specific disciplines. Some funders play the role of convenor in calling for communities to come together and develop a common vision of their future RI needs, including VLRIs. Dedicated funding programs support development of large international proposals for joint facilities (e.g. the arctic vessel network, ARICE, which seeks to integrate services and projects across multiple vessels worldwide). However, the sole use of domain-specific plans leaves out huge gaps of the actual needs in other disciplines. Therefore, many countries, even smaller economies like Denmark and Finland, engage in RI landscaping and road mapping exercises to identify broad needs, help anticipate future needs, prioritize their spending, and since there is rarely a single national funder, help galvanize domestic funding partners and institutions around opportunities.

These national exercises vary greatly in scope as well as in purpose. In the United Kingdom, although the landscape analysis presents as a guide to support strategic investment decisions, it offers no guarantee of funding for those in it. In Norway and Sweden, the calls for proposals for funding are held jointly with the road mapping exercise meaning that those who are selected to be on the roadmap also obtain financial support (or become earmarked for support as more funds are appropriated). In Australia, the roadmap is renewed every 5 years whereas investments decisions are made every 2 years. Similarly, in the Netherlands, there is a periodical update of the roadmap every 4 or 5 years and, in principle every 2 years, a call for funding for projects on the roadmap.

There are also joint road mapping exercises across multiple countries – ESFRI being the notable example - which are useful to determine whether national needs align with those of potential external funding partners. Such a transnational roadmap helps define areas of opportunity and of mutual benefit where the institutional, national, and communal roadmaps intersect. All EU funders surveyed affirmed that the ESFRI roadmap resulted in greatly enhanced cooperation. There has been at least one case where Germany did not participate due to differing prioritisation in the national process. In Norway, consolidating roadmaps involves drawing up an analysis document for decision-making and putting forth recommendations regarding Norwegian participation in individual research infrastructures on the ESFRI Roadmap.

Another advantage of road mapping is that it can decouple the roadmap qualification process from funding decisions and immediate budget constraints. The qualification process ensures that a rigorous vetting of the science case of the VLRI is realised, thereby acquiring a 'seal of quality. This decoupling allows for VLRI stakeholders to solidify the business case in the meantime. It avoids having to reassess the same proposals at each new round of decision-making as it is the case namely in Canada. It also signals to potential funding partners the funder's commitment. ELIXIR is good example of a facility developed from the original 2006 ESFRI roadmap which greatly benefitted from the process in building a successful consortium of partners over time.

Financial thresholds often appear explicitly in frameworks to determine the mechanism or process for decision-making and associated levels of decisional and signing authorities, namely for memberships and treaty agreements. As expected, processes tend to be more rigorous with the number and types of reviews (assessing, for example, the science case, technical readiness and feasibility, maturity of the project, socio-economic impacts, etc.) increasing as the investment value increases. Reviews typically involve several internal and/or external advisory and assessment committees. In France, VLRIs costing more than 100M€ are subject to a counter-expertise socioeconomic impact review mandated by top Government in addition to the ministry’s process. The United States, both the DOE and NSF, have had in place very detailed and comprehensive frameworks for a long time that are often referred to by other countries in establishing their own. Korea’s is recent: based on the experience of developing KSTAR (1995~2007), the completion of the first phase of development of RAON (Rare Isotope Accelerator Complex for Online Experiments) (2011~2023) with a total project cost of more than 1B€ in total costs, and the promotion of the construction of KPS (KOREA PHOTON SOURCE,2022~2027) from 2023. However, In Korea, 38 government ministries are involved in R&D, and this multiple investment structure adds to the complexity. Because large-scale investment decisions require coordination across multiple ministries, and the number of partners adds to the complexity and lengthens the process, several funders and VLRI managers cite the mismatch between decision-making timing and funding cycles as a significant challenge to international cooperation on VLRIs. In general, inconsistencies within and between national funding mechanisms are difficult to overcome.

Some countries established principles guiding respective roles and responsibilities, and signing authorities, among ministries and other funders, namely in Norway, which go as far as determining how Norway will be represented, by whom, on the governance bodies of facilities of which it becomes a member. Some legal structures impose strict requirements, for example, ministry level approval to join an ERIC facility as a member. In Canada, the lack of clearly defined authorities for facilitating negotiations, managing the interface with other funders abroad, and entering into agreements of some funders, like the CFI, while mandated to deliver on a decision-making framework, is often seen as an impediment to international engagement. This is in contrast, with funders like the United States DOE which defined a threshold-based authority and decision matrix. For most VLRIs, the final step in decision-making resides with the highest authority, for example parliament, cabinet, congress, etc., with allocations for such investments added as a permanent budget item in the national budget, outside the funder’s regular envelope. In the Netherlands for example, decisions for long-term commitments to VLRIs are taken beyond the regular funding procedures for roadmap projects and are taken on a case-by-case basis at the highest level, by cabinet/government – generally following a long and outstanding track record of Dutch scientific involvement and Dutch membership of the international science collaboration in that particular field of science and/or instrumentation/technology development.

While most countries strive to establish transparent review processes and criteria for decision-making, the survey revealed that there are often political considerations that will invariably influence final decisions. Sheer political will to move a project forward is sometimes the impetus for green lighting a VLRI project. In the reverse case, roadmaps offer a long-term view of VLRI needs that can shield against an unfavourable negative political climate or instability. For many EU countries, being included in the national or ESFRI roadmap is thus a critical element for the decision process.

- Although decision-making frameworks specific to VLRIs are rare, many countries establish financial thresholds for different decision-making processes. Many funders report reaching a ceiling in their ability to support a growing cohort of VLRIs, and therefore anticipate having to become increasingly selective in their investments and accordingly rely more and more on sophisticated strategic tools. Funders are confronted with balancing investments, often from the same pool of funding, among domestic vs international RIs, and different size RIs, which is a challenge that comes with various trade-offs.
- Most countries are guided by a national strategy for research, sometimes coupled with a strategy for international engagement. The use of national RI roadmaps is gaining momentum; they help galvanize domestic funding partners and institutions. Transnational roadmaps further help define areas where the institutional, national, and communal roadmaps intersect. Funders can play a role in convening communities to assemble around a common vision of their VLRI needs.
- Road mapping can also be useful in decoupling the qualification process – which attributes a 'seal of quality' to the project − from funding decisions and immediate budget constraints. Roadmaps offer a long-term view of VLRI needs that can shield against an unfavourable negative political climate or instability.
- The number of partners exacerbates the complexity of financing negotiations. Not only does each partner aims to get their fair share of returns, but they often have different funding approaches and conflicting approaches to decision making (top-down/centralized vs bottom up/community-driven).
- There are different requirements and risk assessments for VLRIs' hosts and other partners, and between minor vs major partners that influence decision-making. Sheer political will to move a project forward is sometimes the impetus for green lighting a VLRI project.

VLRI business models

An RI's business model refers to the financial arrangements (i.e., sources of funding and their management) as well as range of activities, and services, that allow the RI to meet its mission and strategic goals. Since it determines the way the RI structures itself, interfaces with stakeholders, approval of the budget and finances, reactions to external events, etc., the business model is intimately linked to the governance model, and both typically evolve conjointly. The considerations discussed in the Governance section 3.1 on the legal structures, nature of partnerships and agreements, evolution along the lifecycle stages of VLRIs are relevant in that they also carry implications for business models. For example, the loss of a major partner will affect both the governance and the financial stability of the VLRI. A useful way of regarding governance is that of 'custodianship of the business model'. As such, a well-adapted governance is key to ensuring the efficient use of financial and human resources and for weathering difficult times and crises.

Being relatively few, and with each possessing peculiar constraints and challenges, VLRIs require business models tailored to their unique circumstances. The business models of the surveyed VLRIs are therefore diverse and difficult to generalize but there are similarities in the funding challenges they face depending on their nature, their services offered, or their physical location, this in addition to their legal structures.

More than half of VLRIs surveyed are membership-based and therefore pool contributions from several governments and funders. In such cases, the number of partners usually equates with the number of main sources of financial support to the project's construction and/or operations, whether as in-kind and/or cash; although other revenue streams sometimes complement member funding, such as from industry, foundations, non-member countries, and funding for specific subprojects, e.g. via EU funding programmes.

Some VLRIs have subsidiary forms of membership as well (e.g., associate memberships) or receive contributions outside their convention, for example ITER's technical cooperation agreements with Australia and Canada, ESO's partnership with Australia. Not all these additional contributors will be represented in decision-making bodies but can be observers or participate in committees, such as ECCSEL's Industry advisory group. Agreements often have clauses setting requirements regarding the length of partner funding commitments: at least 10 years for ESO and 5 years for ERIC's, whereas to limit the risk of failure, ITER's constitution includes a 'non-quitting' clause for the construction phase. This explains why Russia remains part of the collaboration despite sanctions due to the military invasion of Ukraine. Even when there is no immediate funding shortage, many VLRIs actively seek new members (this despite sometimes adding complexity to financial management); a partnership strategy, clearly demonstrating benefits for each type of stakeholder, is said to be important in that regard. However, the process to become a new member being often very slow and complex - not from the VLRI's side but mainly due to national decision-making processes − is an oft-cited challenge.

Member contributions can be calculated according to a standard formula approved by the governing body, typically based on each country's net national income. This is the case for CERN, ESO and ECCSEL. For other VLRIs, like SKA and ITER, partners must negotiate the sharing of costs, a process which can be quite long, and delicate since each must be satisfied in getting their fair share of returns and benefits. Then, there are different requirements for a host vs participant: the host needs a solid business case and must be committed on the long-term, also carrying most of the risks. Typically, the host country will cover a larger portion, as a 'premium' for highest returns on investments. For example, Germany covered 58% of European XFEL's construction, and Europe, 45% for ITER, and the three hosts of SKA, 55%.

ESO and JINR, both intergovernmental organisations involving many member countries, are interesting cases because they oversee a portfolio of RIs and VLRIs, rather than a single RI. Membership fees are pooled into a central budget that is then used to fund several projects, in effect acting like their own funding organisation, with projects' priorities determined by its members according to a long-term plan. When a new country joins ESO, a special contribution is paid to reflect the new member's share of the accumulated net investment value and financial assets, including depreciation, already funded by the existing members. Although the convention stipulates that the contributions of acceding countries be used to decrease the payments of the existing members by default, thus far new contributions have instead been added to the baseline to allow growth of the RI portfolio. This type of model provides stability and long-term financial sustainability, but also gives central management the flexibility to quickly respond to a changing situation, such as project cost escalations.

In contrast, some VLRIs get majority support from a single funder. For example, TRIUMF, KSTAR, EAST, LIGO and IODP. While this comes with the advantage of simplicity, reliance on a single source can be a risk if the funder, for any reason, be it budgetary pressures, change in priorities, etc., fails to renew funding. Although revenue is often complemented with project funding from public and private sector sources domestically and internationally, it is often a marginal source of income. For example, the percentage taken up by government funds in the operating cost of a large research facility in Korea is around 80% of its operating cost; compared with 2/3rds for TRIUMF. Although for the latter, since the use of commercial revenue is unrestricted, it can help mitigate costs overruns and serve to fund activities unsupported by other means. For IODP, reliance on ad-hoc revenue sources for specific expeditions is proving too volatile in the recent global financial context, and a new model is being contemplated. A challenge for this type of funding model is that it is not always best adapted to the long lifespan of the facility, and its overall risk profile, especially if the funding cycle is short.

Distributed VLRIs, such as ELIXIR and ECSSEL, operate according to a mix of the above models, where the central hub or operations centre is funded through membership fees (in addition to in-kind personnel in the case of ECCSEL) whereas the nodes are largely funded through national- and EU-level investments. ELIXIR redistributes membership fees back to nodes for implementing its scientific programme with the aim of creating a coherent, pan-European research infrastructure for life science data[25].

Regional centres that are not part of the VLRI-organisation but which are nevertheless essential for the use of the facilities may also contribute in kind. This is the case for the SKA which is developing together with the international science community a collaborative ecosystem referred to as the global network of regional centres. This network requires substantial separate/additional national funding to establish and operate these centres in the member countries or regions[26]. Similarly, there are European ALMA Research Centre *nodes* in several member countries of ESO. This is an interesting concept, because the distributed centres bring additional benefits to the members of the VLRI. This nuances the dichotomy between single sited and distributed facilities and represent an interesting example of VLRIs ecosystems (see chapter 3.5), linking global/international to regional/national facilities.

- A VLRI's business model is intimately linked to its governance model, and both typically evolve conjointly. A well-adapted governance is key to ensuring the efficient use of financial and human resources and for weathering difficult times and crises. Choosing the right business and governance model early on can help setup the VLRI for sustainability.
- Business models for networks of regional centres that further add to the capacity of VLRIs should be further examined.

Managing cash and in-kind contributions

The financing of VLRIs usually involves some degree of cash and in-kind contributions. The latter come in the form of buildings, structures, components and systems, services, personnel, etc. However, there is no recommended ratio applicable to all VLRIs as each approach has its pros and cons that must be weighted in light of the VLRI's unique context, including the expectation of partners. But any VLRI manager today is preoccupied with striking the right balance. From the VLRI's included in this study, at one end, ITER is the example with the highest in-kind ratio, at 80-90%, while the ESO is essentially all cash as an organisation, but receives in-kind contributions towards building instruments.

A high ratio of in-kind contributions allows a project to capitalise on the strengths of the partners, thus favouring complementarities, and spreading the economic and societal benefits, often in the form of national procurement/contracts, all the while limiting partners' respective responsibilities to a more constrained portion of the project. In-kind contributions help distribute some of the risk and liability among partners, for example in protecting partners from operations costs beyond their responsibility. It is seen as an effective and natural mechanism for international partners to contribute their best to the project in terms of scientific and technical expertise, engineering resources, manufacturing capability, etc. It also avoids the undesirable situation where it is mainly the host that benefits from everyone else's investment. This type of arrangement can also be used to create lasting capacity in partner countries to support next phases or generations of the project, for example ITER and its next phase, DEMO.

Case study: ITER

ITER is largest nuclear fusion experiment in the World. Due to its complexity and degree of sophistication, it is still being used today by both VLRI funders and managers as a blueprint for managing collaborations. It constitutes a unique enterprise especially regarding the distributed construction with components being developed and built in three different continents; it therefore had to develop a robust mechanism for international technological cooperation and coordination.

Each domestic partner developed its own contribution to the project according to required specifications, as 80-90% of member contributions are provided in kind. Domestic agencies dedicated to the project were set-up by each member country. Specific agreements had to be developed to establish the contribution of each member to the various steps and parts of the project, taking into account the role of the host and that of other members.

Domestic agencies usually issued procurement contracts to their own contractors. In addition, all members are guaranteed access to 100% of the intellectual property. While in-kind contributions represent the majority of investment, a central reserve fund under the control of the Director-General was established in 2015 to empower the quick resolution of project change requests and to offset the risk that unavoidable design changes result in further delay to project execution.

As attaining a high degree of precision in executing each piece of the puzzle is critical, this model of in-kind procurement proved to be extremely challenging. This was especially the case for first-of-a-kind components given the immense technological challenges and associated risks. Plus, each major component had to be transported from one country to another to be completed before it could be shipped to the ITER site; steps for which the Fukushima nuclear incident and COVID-19 caused problematic delays. Also, the prohibition on cost and schedule contingencies imposed by some partners because of national rules has presented a major challenge.

Adopting an approach of continuous improvement is an imperative for ITER's success. The above scheme nearly failed until quality-control policies were reinforced, something which over the last seven years have proven successful. In fact, ITER is known to have one of the most refined 'Risk and Opportunity Management frameworks' as it has been substantially strengthened over the years, and includes risk assessments at multiple levels of the project. An interesting aspect of the framework is the active identification of opportunities to compensate for risks, a good example of which was the integration of a system called the Disruption Mitigation System that was not in the original design but was incorporated following its success in other projects. Overall, ITER's risk management practices are now on par with those of other large, complex undertakings outside science; for example, ITER uses industry-grade product lifecycle management.

ITER also regularly undergoes assessment of its management structure and practices. A sweeping organisational reform, addressing and correcting problems identified in one such review, was executed in 2015. This integrated the ITER Organization Central Team and several domestic agencies so that they could function as a single entity, thereby simplifying the decision-making process, reducing bureaucracy, and maximizing the efficiency of the project management.

On the flipside, in-kind contributions make project management much more difficult as they add other elements of risks related to quality control, schedule, integration of systems, and more. For example, the promised equipment may not be delivered on schedule, or at all, because of technical or financial obstacles, the responsible partner leaving the collaboration or because of global supply chain issues. This complexity tends to increase with the number of partners. Feedback from ESS management indicated that, for them, a ratio of 35% overall was just about manageable. In-kind contributions from members also need to be reliably valued. Therefore, adopting an in-kind contribution valuation methodology, shared among partners, is an important consideration. Normally, a formal assessment is carried out by an in-kind review committee.

While many partners expect a return on their investment in the form of supporting their own industry and and scientific capacity, other forms of return can be negotiated such as intellectual property, reciprocity in use of VLRIs, access to VLRI data. For the SKA, the large members were guaranteed 70% minimum of return on investment in procurement. However, such negotiations can be challenging if new partners are sought to fill a remaining funding gap even though nearly all of the procurement has already been allocated.

Sometimes collaborating through in-kind contributions is not the most cost-efficient way to proceed but is nonetheless pursued for other reasons, for example to build a working relationship with another country, as a means for diplomacy and/or international development.

Whatever the situation relating to in-kind support, centrally held cash is also important. Inevitably, a significant amount of cash will be spent in the host country, where local services and administrative/support staff can be obtained at the lowest cost and with the least effort. It also provides the ability to purchase a large, costly item that is not of sufficient technological interest to be an in-kind contribution from one of the partners, but which is critical to the operation.

While the financing of VLRIs usually involves a mix of cash and in-kind contributions, there is no recommended ratio as each approach has its pros and cons that must be weighted considering the VLRI's unique context, including the expectation of partners. In-kind contributions help distribute some of the risk and liability among partners and is seen as a natural mechanism for international partners to contribute their best to the project. Centrally held cash, however, remains important to provide a much needed flexibility and a capacity to respond quickly to unexpected events.

Evolution along the VLRI's lifecycle

While each phase in a VLRI's lifecycle is fraught with its own set of challenges, for both VLRI managers and funders, most respondents characterized the conceptual phase as one of the most challenging as it requires strong commitments, particularly from the host nation, and often the result of pooling resources from different domestic players. In some cases, early partners initially bidding to become the host site for a VLRI, or its headquarters, may retract from the project entirely (as did Canada in ITER) or lessen their support. Launching a new VLRI requires careful planning, and choosing the right business and governance model early on can help setup the VLRI for sustainability.

On that, Dr Womersley, the former CEO of the ESS, argued that "a lack of a credible funding plan − therefore rigorous lifecycle cost estimates − as well as inadequate stakeholder engagement are probably the worst pitfalls that can jeopardize the viability and sustainability of a VLRI, more so than any weakness in the science case". A solid business case should be developed from the start in addition to the science case. For ESS, assembling a consortium early on that could provide both the political mandate and funding took considerable time and inevitably influenced the business model of the project. ESS had the additional challenge that it was being constructed on a green-field site without the dedicated support of an established laboratory. However, industry partners were on board and advocating for the facility from the start, which made a more convincing case for attracting investments. For ELI, this process was quite difficult as it was initially proposed as a single-sited facility for which no single country was able justify such a large sum. Several initial partners withdrew and later the project was descoped into three smaller facilities.

Most national funders reported having mechanisms that consider most, if not all, lifecycle phases. However, where seed funding to explore a VLRI's feasibility at an early stage is not readily accessible, this was said to cause issues downstream, namely because it could mean locking in project costs at a later phase before they are fully understood, leading to unrealistic expectations by funders. Hence, a funding mechanism providing adequate resources for the early development phase of a VLRI was seen as critical.

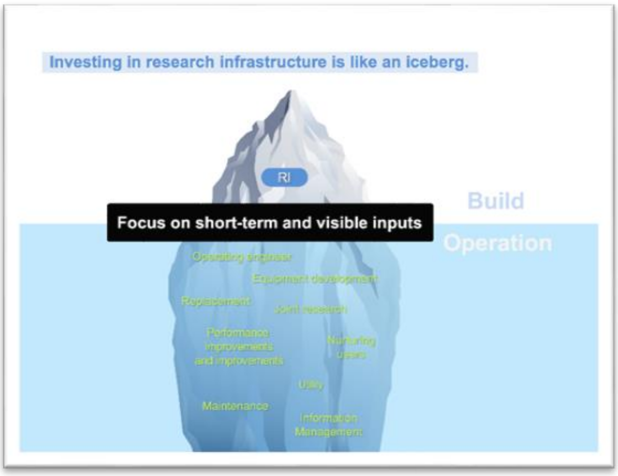
A recent example is the £3.2 million investment announced by UKRI to advance plans for its own XFEL facility[27].

Even the best planned projects can face unexpected cost overruns, such as the impact of the COVID crisis that required a re-baselining of ITER's costs. However, many issues can be mitigated by the setting of rigorous costs estimates, factoring in risks, using a standardized methodology and terminology that are shared by all stakeholders. As Figure 5 illustrates, the capital investment to build a VLRI is just the tip of the iceberg; most VLRI costs are 'under the sea', and a superficial approach will only look at short-term visible inputs. In other words, for decisions to be made based on complete information, stakeholders need to be made aware of the VLRI's lifecycle costs, reflecting the full range of activities deemed necessary to accomplish its mission. For its road mapping process, the French Ministry for Higher Education and Research developed and optimized such a methodology, including both direct and indirect as well as hidden costs, which it said proved useful in negotiating participation in international projects. Some VLRIs have implemented a methodology employed at CERN called "earned value management" which tracks the real progress and true cost situation of a project using performance indicators.

One cost that seems frequently overlooked or under-estimated is cyber-infrastructure. While an integral component of any type of modern VLRI (whether actually within the VLRI itself or as supporting facilities to the VLRI), this is an area that is still not always considered in budget planning. Many agreed that investment in computer resources for calculation, analysis, storage and digital communication, as well as in high-speed and high-volume networks, and in the personnel to manage those resources, needs to increase to meet rapidly growing data volumes, and expectations on data sharing.

Transnational physical access is also an area that several VLRI managers reported was underfunded. Many national funding programs only fund national access thus leaving out many potential users/researchers, especially those coming from underdeveloped countries.

Figure 5. Illustration of how VLRIs are perceived by decision-makers and of actual VLRI costs beyond the construction phase



Source: Korea National Research Facilities and Equipment Centre

The transition from construction to financing operations for the long term and in a sustainable way is a challenge for many VLRIs. For some, this is due to a disconnect between funding streams for construction, upgrades, and operations, with sometimes investment decisions made in isolation from each other, leading to inconsistencies. Or else completely flat operating budgets that do not allow the VLRI to operate optimally unless it seeks to diversify its sources of income. Predictability and timing of funding are concerns for those relying on a mix of contributions coming in a succession of short-sighted investments and investments covering the full scope with longer term engagement. This can hinder a VLRI's ability for long-term planning, and exacerbate staffing issues, for example.

It is also quite difficult to maintain the engagement of funding partners over the entire lifespan of the VLRI. Political instability and loss of funding partners are common challenges. There are also VLRIs that are built for a specific purpose, and efforts to extend that mandate can lead to complex negotiations, especially if major upgrades are required to keep it relevant. Others exceed the lifespan that was planned initially (e.g., space telescopes) and raise the issue of continued funding when the funders' budgets are constrained.

As with governance, the business model typically needs to adapt to its life phases to reflect the change in the makeup of partners, and broader stakeholders. Several reported a transition between the construction and operations phases, and/or sometimes between the planning and construction phases, such as ELI, and SKA. There can also be more intermediate steps, for example ESS is putting together a business model for the initial operations phase which will run in parallel to that of the construction phase. The overlap is planned to last for about 7 years. It then anticipates a change in model when it reaches steady-state operations. LIGO was in a similar situation when it managed two parallel but distinct budgets while it underwent upgrades for the Advanced LIGO. For member-based organisations, members' shares tend to change between construction and operations. ESS's host nations, Sweden, and Denmark, covered nearly 50% of construction costs, but only 15% of operations. For ELI, while the initial operations phase is covered at 90% by the three hosts, the aim is to recruit more members to reduce this to 50% during steady-state operations.

Models also evolve with the VLRI's mission, for instance towards increased industry support, or with changes in the landscape, for example when a next-generation project takes the lead, the original VLRI may redefine its mission or be repurposed entirely, if not decommissioned.

> The business model needs to adapt to a VLRI's life phases – often between the construction and operations phases – to reflect the change in the makeup of partners, and broader stakeholders. The conceptual phase of a VLRI remains one of the most challenging as it requires strong commitments, particularly from the host nation. Seed funding to explore a VLRI's feasibility at an early stage is important. It is also quite difficult to maintain the engagement of funding partners over the entire lifespan of the VLRI.

Managing contingencies, and risk

The scale and complexity of VLRIs makes them inherently risky, therefore sound risk management is a prerequisite for any VLRI project. NSF, DOE and some space agencies, for example, have developed robust risk and project management frameworks which are recognized as best practices worldwide. The risk and opportunity management system of ITER is considered one of the most, if not the most, sophisticated for a VLRI. However, given mounting global economic and geopolitical risks, there is broad agreement that risk management is an area that needs to be given particular attention moving forward by both funders and VLRI managers, and that more robust tools must be developed based on this experience.

Typically, schedule, budget and scope contingencies are used to manage foreseen risks, provided these risks are properly identified using sound methods. If costs escalate, there is always an option to descope the project, or else reduce the level of activity during the operation phase, but not without some loss or negative consequences. It is then critical that these contingencies be included as part of the risk-adjusted total project costs to set realistic expectations. Additionally, a mechanism should ideally be in place to allow coping with the consequences of unpredictable challenges, the so-called 'unknown unknowns'. Many funders and VLRIs hold a cash reserve, separate from the contingency, for that purpose, but not always.

The feedback from the surveys revealed that not all respondents have adequately protected themselves against the post-pandemic effects, and the crisis generated by Russia's war of aggression against Ukraine, and that their risk's analyses showed their limits. For instance, funders reported that most projects in the construction stage experienced delays and cost increases, which required re-baselining of their costs, such as in the case of the ESS. For the NSF, this meant additional funds were requested in the annual budget appropriation of the organisation to address these unexpected costs. These recent crises stressed the need for agility and flexibility from the part of funders to respond to unexpected events.

The survey also revealed incongruities in the approaches to risk management across partners which exacerbate challenges for projects with multiple partners – mainly in terms of tolerance to risk, mitigation strategies, flexibility towards allowing schedule, budget and scope contingencies and reserve funding in budgeting. Some partners are constrained by national rules that prohibit cost and schedule contingencies.

Developing frameworks using common terminology, with clearly defined responsibilities, which are well understood by all partners from the outset is seen as key to success. Furthermore, adjustments to the risk management strategy are necessary when transitioning from one phase to the other.

- Given mounting global economic and geopolitical risks, there is broad agreement that risk management is an area that needs to be given particular attention moving forward by both funders and VLRI managers, and that more robust tools must be developed. Schedule, budget, and scope contingencies should be considered as risk mitigating measures provided lifetime project costs are well estimated and risks are properly identified using standardized methodology and terminology that are shared by all stakeholders.
- VLRI cost estimates should factor in costs for the required computer resources for calculation, analysis, storage and digital communication, as well as in high-speed and high-volume networks, and personnel to manage those resources.

2.3. Data management

VLRIs produce vast amounts of data, and those are probably their most valuable output. But this bring its own set of challenges, not only for the management, curation and maintenance of these data but also for their access by various categories of users. Although these issues may seem common to all RIs, they are amplified and more complex for VLRIs.

VLRIs' approach to data management has been significantly refined over recent years. Not only as the result of the amount of generated data growing exponentially but also the fact that various regulatory and security constraints need to be integrated. For example, ESS has put in place a formal, codified scientific data policy in 2020. It covers the collection, access, curation, use, disposal and storage of scientific research data collected from the neutron beam instruments located at ESS under all access modes - except proprietary access - and fully embraces FAIR principles (i.e., findable, accessible, interoperable, and reusable). As VLRIs often work in synergy with many external laboratories, data mirror sites are sometimes set up in cooperative institutes, also ensuring robustness in data access. In the case of VLRIs which are more oriented towards external users, such users will often maintain research data sets under their own data access and management policies. There are also VLRIs that are in essence data RIs, in which case even more extensive guidance and policy rules are developed, such as for ELIXIR[28].

Based on the survey results, data management challenges for VLRIs can be grouped into four main categories:

- Data growth

- Data sensitivity
- Data access/ownership
- Data access for non-expert users

Data growth

Despite the extraordinary growth of data sets produced by VLRIs, our survey indicated that most had set up solutions for storing and processing the data. In some specific cases such as JWST, not only a high-capacity database technology and relevant database tools for the users had to be available but also a high data rate communication system had to be set up from the satellite's telescope to the earth, and this appears to work satisfactorily[29]. As data sets grow, some VLRIs such as KSTAR are considering updating their current file system to more advanced ones (hierarchical structure, partial data access) but there are no reports of real technical difficulties and, while these may be costly, they are usually well integrated into the financial requirements of the VLRI. These large amounts of data also create a challenge for data-sharing: a number of VLRIs report that transferring all raw data to users is nearly impossible, hence data analyses need to be performed on-site and only the digested data are being transferred.

Data sensitivity

The topic of the sensitivity of the data, whether for ethical or security reasons, is treated very differently between VLRIs. While this is also a challenge common to all RIs, the international dimension of the VLRIs adds a level of relevance. Ethical issues will mostly concern human-related data. Because national regulations are often different from one country to another, VLRIs that handle human-related data must develop specific secured storage and access policies. For example, as sensitive human data cannot leave the jurisdiction in which they were generated, ELIXIR has developed technological solutions to allow researchers to discover potentially useful data in other countries and then request access through the relevant channels. For example, the ELIXIR-operated Life Science Login[30] allows data access committees to verify the request comes from a bonafide institutional account, and ELIXIR's Federated European Genome-Phenome Archive[31] (EGA) provides solutions for sensitive data that cannot be transferred across national boundaries. This means that the same VLRI may have to develop several access policies to their data. The COVID-19 crisis highlighted potential difficulties in sharing sensitive but necessary health data and new policies are being developed to combine security and fast access to such sensitive data.

Other data may need to be protected for security reasons. For example, during the COVID pandemic many RIs were subjected to external unauthorised attempts to access their data[32]. Data theft may occur for economic reasons, as they may have strong intellectual property value. If data is prematurely or inappropriately released to the public without proper supporting information this can also lead to dangerous misinterpretation. Thus, a number of VLRIs that manage sensitive data have developed strong cybersecurity protection mechanisms, although this is not considered as a high priority issue for VLRIs in less sensitive scientific domains.

Data access/ownership

Most VLRIs don't just produce large amounts of data, they produce data from a structure which is composed of various national stakeholders, or at least that collaborate with many stakeholders from different countries, and their data are often produced for a very broad international community. These factors add a layer of complexity in the data use policy they need to set up. While most agree on general Findable, Accessible, Interoperable, Reusable (FAIR) principles, the reality behind is more complex and nuanced. Our survey reveals five main categories of policies among VLRIs, several different access policies being potentially developed for different types of data by a given VLRI:

- Open access to both the scientific community and the general public; this is usually for data produced by public funding, sometimes with a grace (embargo) period of 1-5 years that allows the scientists who produced the data to publish in scientific journals before the data being fully open.

- Open access in theory but restricted access in practice; this is often for data that require advanced skills and tools to be of any use. VLRIs may provide a "digested" version of these data for non-expert users (see next subchapter on access) but this is not always the case. Another case is when users need to apply for an access authorisation to the VLRI management (for example, for EAST); in this case, different user groups may have access to different data sets.
- Restricted to VLRI members and VLRI staff; this is a way to provide a return on investment to the VLRI funders who may have to support a very expensive RI or because the topic is highly competitive (such as fusion).
- Restricted/closed for IP reasons; this is typically the case for data generated by for-profit entities at the RI, and for subsets of data that can be used to produce patents and generate revenues.
- Restricted/closed for security reasons; while this is fairly rare in the field of VLRIs, some data sets may have dual use potential, be of use for national security and are thus fully classified, or else would compromise basic operations.

In addition, there may be specific access policies related to the host country of the VLRI, whose research community may benefit from a privileged or additional access capacity. For example, many astronomy VLRIs in Chile make provision for greater or earlier access to data for Chilean scientists as part of the agreement signed between the VLRIs governance and the host country.

Despite a trend towards open science/open data principles, VLRIs still have very different data access/ownership policies. This is partly inherited from domain-specific cultures (in astronomy, or some ocean sciences VLRIs, for example, the traditional practice has always been a grace/embargoed period followed by open access to the general community) but there is also an influence of the legal structure and international nature of the VLRI. Although embargo period tends to get shorter with the movement to open science, even the most recent VLRIs and those in development usually have/plan for some sort of restricted access to some data sets or embargoed access for a specific duration. VLRI stakeholders thus need to work towards achieving a greater degree of consensus on open data principles.

Data access for non-expert users

Providing access to the data controlled by VLRIs to non-experts (and experts in new disciplines) is probably the biggest challenge regarding VLRI data management. The pressure that arose in recent years for increasing the socio-economic impact of VLRIs as well as ensuring reproducibility means they are compelled to develop new data access mechanisms, user-friendly data products and standardized formats, all of which potentially entail costly technical solutions. This often implies that new staff and resources need to be dedicated towards these activities which drive up operational costs.

As discussed during the first GSF workshop on VLRIs[33], broadening access of VLRI data is often challenging when it implies having to compromise between the needs of the traditional experts and those of the new user communities. Experts, on the one hand, most often require access to high volumes of raw data, and benefit from the VLRI offering a system of tools and resources (e.g., application programming interface or API) enabling them to create their own software applications. Non-experts, on the other hand, face barriers in making sense of the data and therefore require more data services and support from the VLRI, as well as data in accessible formats.

Case study: LIGO

According to LIGO, opening up data access to non-experts is similar to the "last mile" problem in transportation: there are gaps in access, knowledge and resources that need to be solved. While lots of VLRI scientific data are, in theory, "open" and public, even when restricted access is not set up, there are practical obstacles to overcome:

- Are the data easy to find and download?
- Do I recognise the file format? Can I figure out how to open it?
- Can I load the data in a spreadsheet or text file?
- Are there "secret steps" to processing the data?
- Can I find the software? Can I get it installed on my computer?
- Once the software is installed, can I figure out how to use it?
- Do I know where to ask for help when I get stuck?

To solve this data gap, LIGO has set up a diversity measures. The Gravitational Wave Open Science Center (GWOSC) ensures FAIR public data release, through an accessible web server, standardised formats between LIGO, Virgo and KAGRA data, and open-source software. The open data policy has encouraged data use, with about 6000 visitors per month to the GWOSC and 250 publications in 2020-2021. Open data workshops have encouraged non experts to use the available data. The GWOSC event portal includes a cumulative catalogue of all LGO-Virgo-KAGRA detections which can be picked up by astronomers to follow up discoveries using different instruments. And a strong effort has been developed to support the user communities through discussion forums, help desk, online course, web apps, tutorials and workshops: in 2022, open data workshops gathered over 1000 participants in 15 locations and virtual events.

Another challenge is that of matching data access to new science, such as multi-messenger astronomy. In the case of gravitational wave VLRIs, gravitational wave detectors now share publicly data and results from low-latency analyses within minutes that can be picked up by telescopes for follow-on observations. External users just require the location of the signals and not the actual data. It is striking that 90% of the science in this domain was probably achieved using 1% of the data. This illustrates the overall challenge for VLRIs with non-experts requiring a small amount of "digested" data and support while experts still require large amounts of data to conduct detailed analyses. This requires from VLRIs an additional effort (and relevant resources) to provide what non-experts require, something which is not yet integrated into many VLRIs financial and operational models.

Despite the strong external push for providing access to VLRIs' data to non-experts (for example, to encourage VLRIs to respond to SDGs), many VLRIs do not consider this a high priority and still have strong barriers in their data access policies and mechanisms. Furthermore, up to now, there has been relatively little direct incentive or directives from funders and decision-makers to remove those barriers or to support data sharing to non-expert users. VLRIs stakeholders need to provide the necessary incentives and resources to enable new approaches to open up data to non-experts and to experts in other disciplines in order to fully unlock the potential of these facilities.

2.4. Impact assessment and expectations

VLRIs are long-term scientific initiatives developed to produce frontier knowledge. While this is still very much at the core of the strategic objectives of even the most recent VLRIs, there are growing expectations that they also deliver a broad range of societal and economic benefits. These benefits include spreading knowledge to the public, strengthening and expanding scientific networks, training future scientists, engaging with society, creating jobs and boosting economic growth in local communities, fostering innovation through technology development, and collaborating with other scientific organisations and industry. Some VLRIs also include in their missions the contribution to public policies and, more widely, to solving major societal challenges. This wide range of objectives, especially if they were not clear at the outset, creates a number of challenges for the VLRIs. The situation is all the more complicated as VLRIs must meet the needs and expectations of a diverse mix of international stakeholders and stakeholders.

Assessing impact

Assessing the impact of an RI is always strongly related to the vision and objectives that have been established by its funders and community. VLRIs typically collect a range of scientific performance and output metrics (e.g., publications), in line with their core mission. The duration of usage of the infrastructure by the different stakeholders can be monitored as an indicator of the interest of the corresponding community. Contracts and procurement metrics are often used to monitor individual stakeholder industrial return, where applicable, and there is also a growing interest/emphasis by policy makers and stakeholders for VLRIs – industry collaboration and technology transfer, e.g., investments and support for co-design and co-development of advanced (key)technologies and scientific instrumentation through collaborations between VLRIs and industry[34].

However, many VLRIs have yet to develop formal assessment procedures for broader socio-economic impact. This is because these additional expectations are more recent and the metrics by which such impacts can be measured may vary among stakeholders, making a clear definition difficult. As a result, VLRIs often periodically assess this broader impact by commissioning external studies from specialised consultancy firms.

A number of VLRIs also take a dual approach to impact assessment. A regular/annual exercise related to expected deliverables/milestones, and a more in-depth assessment, often conducted externally, that can be linked to a proposal for upgrades or other significant life-cycle events. For example, TRIUMF conducts a specific assessment every five years prior to its funding renewal. Through a formal evaluation, which takes over a year to complete, TRIUMF is comprehensively assessed against a range of key measures, including scientific excellence, socio-economic impact, relevance, capacity, and governance. These external assessments often come with specific recommendations that the VLRIs must address in subsequent years.

The impact assessment methodology is more challenging for VLRIs that are spread over multiple sites. To meet this challenge, for example, ELIXIR has set up a two-pronged approach: (1) a high-level impact assessment at the level of the entire infrastructure and (2) another at the level of individual nodes thereby strengthening the capacity of country nodes to carry out assessments related to their own national situation and particular set of stakeholders (namely those funding the node’s activities, and other influential stakeholders at the national level). In some cases, some of the ELIXIR nodes are supported by expert impact evaluators who are able to produce ad-hoc assessments of a more limited scope.

More recently, however, some VLRIs have adopted a more systematic approach to impact assessment, using new tools and methodologies such as those described by the OECD (OECD, 2019[14]) or by the EU RI-PATH project[35]. The European spallation source, for example, has developed an impact assessment model that takes into account the whole impact pathway throughout the full life cycle of the infrastructure.

Case study: ESS

The European spallation source (ESS) has in its mission goals to produce research outputs that are best-in-class in terms of scientific quality as well as in terms of socio-economic impact. Contrary to many VLRI projects, ESS decided to develop an impact assessment mechanism starting from the conception phase, and that would be progressively adapted as the life-cycle evolved. This makes it possible to evaluate in detail the impact during each phase with, for example, 42 impact indicators and metrics for the construction phase, and 41 for the operation phase, with only a partial overlap.

The metrics had to be developed in response to the expectations of the different stakeholders and therefore regroup indicators that assess the overall impact of the ESS globally as well as a number of indicators that provide feedback of interest to individual ESS members. Selected key indicators include co-publications among member countries, new partners in grant projects, the number of new suppliers, the innovation level of products and services supplied to the ESS, their origin and nature (in-kind…) etc.

The experience of developing of a specific impact assessment methodology for the ESS which was initially based upon the assessment framework developed by the OECD and the EU RI-PATH project yielded a series of important lessons:

- Socio-economic indicators (SEI) can be measured from the concept phase through the complete lifecycle of a RI
- SEI parameters should not be static and need to be fine-tuned:
    - When phase milestones are achieved
    - If context or surrounding parameters have changed
- SEI should be seen as a continuous project for a RI with reporting dates e.g., on an annual basis
- SEI does not have the same shape and form for all RI stakeholders:
    - ESS created narratives for each member country
    - SEI were “translated” along the lines of “what does it mean for you”

However, the ESS return on experience also indicated that stakeholders had very different expectations and interpretation of impact indicators, and that a more consensus methodology and philosophy might be needed for future VLRIs.

Broadening the scope/new demands

The impact on training and education, both at the expert level and for a wider audience, is one of the key impacts of VLRIs that has taken an increasing importance in recent years. Due to their unique nature and their international dimension (CERN facilities are a good example), VLRIs have traditionally played a role in the training of both scientists and engineers, but this has escalated in priority for several reasons:

- VLRIs are constantly evolving with different project phases requiring different staffing profiles and competencies in an international environment. Several VLRI managers reported difficulties in recruiting during the survey given that VLRIs require highly trained staff in specific domains, who are not easy to find on the traditional job market. VLRIs thus need to develop training for their own internal needs but also to build up a broader workforce that can operate in different RIs. In response, ITER has for example created a “ITER ACADEMY” Training Programme that addresses the capacity-building and development of staff competencies and organisational needs that are required to achieve the Project's goals. Similarly, XFEL set up a PhD school to increase cohesion and attractiveness, with about 50 positions. ESO introduced a 3-year Engineering & Technology research fellowships to develop engineers that contribute to building and operating state-of-the-art facilities for the advancement of astronomical research. The main impact has been the creation of an internationally networked community with shared standards of quality and excellence. Furthermore, demand for diversity and gender equality also means that VLRIs need to provide attractive training to under-represented groups. Distributed VLRIs also face specific challenges to maintain expertise throughout the whole infrastructure; ELIXIR has for example developed an internal staff exchange programme[36] to respond to that need.

- Stakeholders increasingly expect VLRIs to deliver impact in the form of training, both for the country's own human resource requirement but also as a means of conveying the country's attractiveness. In Canada, TRIUMF is for example is expected to play a critical role in the training of the next generation of innovators and leaders from across the country and beyond. VLRIs provide education across a unique multidisciplinary high-tech workplace, bringing together talent from a wide range of institutions. VLRIs often provide training from the undergraduate level to the highest expertise for established professionals, thus playing an important role for the VLRI stakeholders. This is often developed in close association with local universities and academic centres but also with academic partners of the various stakeholders for international VLRIs: JINR has for example developed partnerships not only with the local Dubna University but also with the departments of leading Universities of the member states associated with JINR. In some cases, training is actually one of the main purposes of the VLRI; this is the case for IFMIF which was set up not only to test materials but also as a place for training in the design, construction, maintenance and operation of future fusion and accelerator facilities.
- An increasing number of VLRIs are located, or have some of their facilities located, in less scientifically productive countries. Training local scientists and engineers is "part of the deal" agreed with the host countries and hosting VLRI facilities may also spur national education systems in STEM areas. Typical examples are in the astronomy domain where many new facilities are located in the Southern Hemisphere in Chile, Argentina or South Africa. When South Africa submitted its expression of interest to host the SKA in 2003, there were fewer than five radio astronomers in the country. Since then, over 1400 grants at various levels have been awarded by the South African Radio Astronomy Observatory (SARAO) - a significant return on South Africa's investment in the international SKA effort. In Chile, ESO also funds (via its Joint Committee) post-doctoral programmes in astronomy at Chilean academic institutions.
- As VLRIs progressively broaden their user-base to non-expert communities, there is a need for training these new users. As described in chapter 3.2, considerable efforts were for example developed by LIGO to provide tutorials and specific training for non-experts users.

New demands have also emerged in recent years, often linked to the societal role expected of VLRIs. Hence, VLRIs in the field of environment or health are expected to contribute to the Sustainable Development Goals (SDGs) or to support national or regional decision-making in these areas. For example, ECCSEL is expected to have a positive impact on the EU Green Deal climate focus areas, and for the first time in the history of the conference, nuclear fusion had a seat at the table during the COP26 in Glasgow, with ITER playing a significant role. The Republic of Korea has also placed greater emphasis on the fusion energy program recently to meet the needs of its energy mix in 2050 with minimal carbon production. This has led to new expectations for KSTAR facilities that come with an anticipated budget increase. Various VLRIs in the physical sciences (e.g., TRIUMF) contribute to societal demands through life sciences and materials science programs, conducting research with direct applications to society and industry. Breakthroughs in life sciences facilitated by RIs can dramatically improve health care outcomes and other RIs support the production of medical isotopes and development of radiopharmaceuticals – critical tools in the treatment of cancer. The COVID-19 pandemic illustrated the potential of many RIs to mobilise effectively in crises. Many non-health related VLRIs have responded quickly to the emergency needs by allowing fast-track projects related to COVID-19 (such as providing synchrotron facilities for structural analyses) or by providing access to their high-capacity computing facilities to support modelling projects. This has highlighted the potential role of VLRIs in addressing global challenges, which usually requires a multidisciplinary approach.

Despite these very positive examples, societal expectations are currently rarely translated into formal impact assessment exercises and do not benefit from established/robust methodologies mixing quantitative and qualitative indicators.

Beyond specific outputs, momentum is also being given to mobilizing VLRIs – including their staff and students – to help address systemic issues not only within research communities, but in society at large. For example, some VLRIs such as IceCube have created a Diversity, Equity, and Inclusion Working Group to respond to and monitor these aspects.

Responding to stakeholders' expectations

As the most recent VLRIs have been established through complex agreements involving a wide variety of stakeholders, potential differences and even conflicts can arise from differences in expectations, which the VLRI management need to address. To begin addressing these issues VLRIs need to develop high-quality, targeted communications to ensure strong working relationships with their partners and stakeholders. Target audiences include member country decision-makers, domestic agencies communication offices, industrial suppliers, national laboratories, scientific conference organisers, professional associations and educational organisations, each requiring a specific communication policy.

Managing different stakeholders' expectations requires extensive dialogue. For example, the European XFEL is developing performance indicators that include measures related to training, patents, procurement and development of specific equipment from companies and technology exchanges, as a response to a strong demand from stakeholders. This is not just taking into account the value but also the nature of knowledge and technology transfer to member countries. In order to manage the different expectations from different stakeholders, the European XFEL organises annual meetings to analyse their relative expectations.

Diversity among partners also affects the definition of success. For example, the scientific impact for gravitational wave VLRIs is optimized by network success, i.e., achieving the maximum possible sensitivities and uptime for each detector in the network. Hence, having common configurations of detectors in the network would lead to a more efficient maintenance and offer the development of greater sensitivity. However, this level of commonality often clashes with funding, proposal-review, and career progression values. Originality and innovation as a measure of individual performance are often at odds with uniform procedures and configuration controls that promote efficiency and robust performance. This diversity of values has made it more difficult to effectively collaborate between VLRIs operating in different funding and accountability environments. Thus, complex membership can negatively affect the impact of a VLRI, and this is even more true for networks of VLRIs as discussed below.

Multi-sites VLRIs need to consider both their overall impact for their stakeholders, and the specific impact of their various facilities located at different sites and hosted by different countries. The national bioinformatics infrastructures that are part of ELIXIR develop and operate hundreds of bioinformatics resources which are funded through a myriad of public and charitable sources, and in some cases the private sector. Funders all have individual missions and associated strategic objectives, and hence specific requirements in terms of evidence to support of them. Increasingly, ELIXIR (its coordinating secretariat and its national nodes) is being asked to provide such evidence, through a diverse set of questions, to demonstrate public value. ELIXIR's approach has been to progressively develop its understanding of funders' expectations and needs and, on this basis, to proactively gather a body of evidence (Martin et al., 2021[15]).

Providing such an impact assessment to stakeholders is also a challenge for some astronomical observatories which have their headquarters and telescopes spread over several continents. For example, the SKA is distributed at two main sites situated in South Africa and Australia, with the main headquarters in the United Kingdom, and several additional sites in different African countries are foreseen for the next phases of the project. As SKA is now starting its construction phase, survey feedback indicated that while SKA plans to use the OECD framework to establish appropriate assessment metrics, they are still in the process of aligning the expectations of the different countries in terms of impact assessment.

VLRIs' impacts are necessarily diverse and evolve during the life of the project and VLRI managers are facing a stream of demands and expectations from their stakeholders which can be difficult to address. This illustrates the need to define and agree at the start of any VLRI project what are they expected to deliver during their life-time, what are and will be the priorities, and robust impact assessment methodologies. VLRIs stakeholders and managers should also anticipate that VLRIs may need to adapt to new expectations and thus agree on a level of flexibility given to management to adapt operation to new priorities.

2.5. VLRIs ecosystems

While VLRIs are themselves ambitious and complex structures , they are also imbedded into an even more complex ecosystem of regional and national RIs, research institutes, universities and private sector organisations allowing for complementarities and synergies. VLRIs are connected to a complex network of partners and are increasingly developing synergies with other RIs.

Responses to our survey indicate that for VLRIs there are typically four main drivers for developing and fostering networks with other RIs and research organisations:

- to look for opportunities of collaboration for the exchange of knowledge and allow researchers to tackle complex/interdisciplinary scientific questions
- to lobby for resources and rationalise their own activities and avoid duplication of efforts
- to provide scientific and technological know-how and human resources capable of supporting them in their tasks
- to provide the necessary computing network and capacity required

Broadening scientific impact

Despite their capacities, even VLRIs may not host all the equipment and resources required to address complex scientific challenges, particularly when these are multi- or inter-disciplinary in nature.

Many VLRIs have forged partnerships to develop or invite joint research proposals, and this is of course facilitated when VLRIs are situated in the same geographical area (such as the European XFEL and DESY in the Hamburg region, or EAST with other RIs in the Hefei city area). Similarly, VLRIs often develop partnerships with other RIs of the same domain that have complementary equipment and modalities to allow for more complex experiments. IceCube, the neutrino observatory, for example, formed collaborations on topics of common interest with other neutrino telescopes deployed in the Mediterranean and in Lake Baikal through cooperative agreements. Recognizing that it cannot by itself meet all scientific needs, SKA partners with several national and regional facilities such as LOFAR, the VLBI network, and the Event Horizon Telescope, itself a network of observatories. The magnetic-confinement fusion research community of RIs is also very closely linked and there are strong collaborations among fusion facilities (EAST in People's Republic of China, hereafter "China", DIII-D in United States, JET in EU, etc.) as well as joint experiments dedicated to address issues critical to ITER such as fusion material facilities to test whether chosen materials can sustain the extreme conditions. Similarly, around the two neutron VLRIs in Europe, ESS and ILL, there is a vibrant ecosystem of small, medium and large facilities used by European researchers which are critical to the productive functioning of the flagship facilities. In this domain, the VLRI community in Europe has self-organised in a network (the European Synchrotron and Free Electron Laser User Organisation37) together with users to enable various kinds of experiments in fields ranging from physics through life sciences to cultural heritage. There are, however, limitations to networks, that can negatively affect their potential impact. This has been the case for gravitational wave VLRIs where there is a diversity of national efforts and legal frameworks to accomplish similar goals. Working together has been hindered by different national regulations regarding export controls, intellectual property, privacy, etc. Responding to the demands of stakeholders across several dozen nations, each of which could change its regulations at any time, is a massive legal challenge and there is a need for stronger international efforts to create uniform standards for scientific collaborations.

There is also an interest in close cooperation to develop synergies on key core technology research, as many of the instruments required are quasi unique and necessitate specific know-how that can be shared between RIs. For example, the ESO instrumentation is built by consortia of institutes (often including contracts to companies) in the member States. The networking among these ESO partners has allowed the emergence or reinforcement of centres of expertise and collaboration networks around specific instruments and technologies, which in the longer term may lead to various spill-over effects from ESO research and instrumentation to other fields and institutions. The effort spent by these partner institutes is reimbursed in guaranteed observing time. Going one step further, the ATTRACT project aims to harness the innovation potential of VLRIs and create a model by which innovative technologies can be brought to market. Using the technological and instrumentation communities fostered by organisations including CERN, ESO, EMBL, ESRF, European XFEL and ILL, the ATTRACT project provides seed funding and then scale-up funding for technology projects in the detector and sensor field.

The development of RI networks is also particularly important to provide support for interdisciplinary and frontier research. Multi-messenger astronomy provides a very good example. In this domain, cooperative agreements have been developed between IceCube, the gravitational wave VLRIs LIGO, VIRGO and KAGRA, the NASA Fermi satellite, the VERITAS ground-based gamma ray telescope, the new Cherenkov Telescope Array (CTA), the Zwicky Transient Facility (ZTF) and other astronomical telescopes and cosmic ray particle arrays. These agreements already foresee and plan for growth in order to absorb new observatories as they come online which is an interesting example of imbedded flexibility.

The COVID-19 crisis also accelerated the development and/or expansion of networks of RIs. Although there are relatively few VLRIs in the field of bio/health science, those that make available relevant data such as ELIXIR (and its Node EMBL-EBI) partnered with other data RIs to quickly establish a COVID-19 Data Portal that enabled the sharing of infectious disease data. Very recently, some COVID-19 portals were repurposed for the monkeypox virus[38], illustrating the how existing infrastructures can quickly be mobilised to tackle new threats.

Optimising resources

Considering the cost of VLRIs and the competition that exists to obtain funding, many VLRIs have established close network relationships with similar facilities to optimise their use and potentially lobby research funders as a community rather than as a single entity. In the domain of ocean research, the International Research Ship Operators network, which regroups the world’s leading marine scientific research vessels operators (including for polar research), will typically support the exchange of ship time and equipment between countries, foster benchmarking and co-operation in support of marine research and the developments in national research fleets. This promotes collaboration and avoids duplication of efforts. In some other domains, networks are set up to develop common strategies. For example, the League of advanced European Neutron Sources developed a landscape assessment of the European neutron source ecosystem to form the baseline for future discussion between funders, facility operators and other stakeholders about the new neutron ecosystem needed for Europe to remain competitive and actively engaged in resolving social-economic challenges facing society. The EUROfusion consortium is an even more integrated network which brings together most European fusion-related RIs through common scientific and technological projects and experiments.

Supporting operation

VLRIs do not just require important financial support but also a range of critical input for their operation. As described above, this is true for technological developments that may be common to different types of

Case study: EUROfusion

EUROfusion consortium was created in 2013 and is funded at 55% by the European Commission and the rest by its national members EUROfusion supports and funds fusion research activities on behalf of the European Commission's Euratom programme within 26 EU member states, while Switzerland, Norway and the United Kingdom participate in the activities with their national fusion budgets. It therefore brings together all the major European fusion laboratories and research infrastructures and also includes three majors VLRIs projects: ITER, IFMIF and the future DEMO.

The originality of this consortium is that it developed a EUROfusion roadmap with the ultimate goal to develop a functional fusion reactor, covering the whole developmental aspects from research to applications. Although developing this roadmap was met with some political resistance, it provides a dynamic and momentum to the consortium and a clear final objective. The initial phase serve to gain mutual trust between partners and the challenge was to build cohesion and solidarity between members of different sizes and priorities but it is now a major driving force for fusion. It is playing an important role in the ITER development through the development of many experimentations in the various national fusion RIs and has on board the whole EU industry as stakeholders, thus promoting innovation and competitiveness to EU industry and many spinoffs. It is currently developing public-private partnerships to expand its work programme.

The lesson learned from EUROfusion is that integration is key; this is very much a transdisciplinary effort that requires many different expertise, and there is a strong added-value in the network, which is expanding its connection at international level. The current energy crisis has in addition boosted the interest for fusion research and development.

VLRIs, such as in the domain of detectors, optics etc., but even more in their need for highly specialised human resources. Experts in some of the scientific or engineering disciplines required by VLRIs are scarce, and VLRIs may not be able to provide the stable contracts that would be required to attract and retain these experts. Networking among VLRIs and relevant RIs may help provide opportunities for skills and career development for these experts that single facilities alone might not be able to offer. Again, this exchange can be facilitated by close geographical proximity, such as between European XFEL, DESY and other RIs in the Hamburg region, or the ESS and the Max IV light source in the Lund region.

High-performance computing facilities

Although most VLRIs have developed their own advanced computing facilities to collect and analyse the vast amount of data they produce, several have also established partnerships with cyber-infrastructures to enhance these capacities. ESCAPE (European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures) brings together the European astronomy, astrophysics and particle physics RI communities in a common cluster with aligned challenges of data-driven research, with demonstrated capabilities in addressing various stages of data workflow, and establishes a functional link with these RIs and the European Open Science Cloud (EOSC). Similarly, ELIXIR works closely with other e-Infrastructures, especially in the context of implementing the European Open Science Cloud and is involved in a range of EOSC integrating projects.

Providing rapid access to VLRI data to all stakeholders and users is also a challenge that may require partnerships. For example, ITER uses the advanced pan-European backbone network GEANT that connects National Research and Education Networks (NRENs) across Europe, which offers broad geographical coverage, high bandwidth, and innovative hybrid networking technology. IceCube also makes extensive use of grid computing infrastructure, at the forefront of high throughput distributed and cloud scale computing, for example through the GPU Cloudburst Experiment[39].

> There is a growing development of networks and synergies between VLRIs themselves and with other RIs, based on common interests, but that this has only rarely been developed into more integrated cooperation such as in the case of fusion research in Europe. Indeed, as mentioned for gravitational wave VLRIs, there is a lack of governance models for effective meta-collaboration, which are needed to overcome barriers between very different and independent structures. Little incentive for the development of such synergies was found from the funders and decision-makers survey, which suggests that this is a policy topic whose importance should probably be better underscored.

3. Conclusions

RIs have been a major topic for analysis and discussion ever since the creation of the OECD Megascience Forum in 1992. They play a key role in enabling and developing research in all scientific domains and represent an increasingly large share of research investment. VLRIs present specific challenges to their stakeholders that are linked to their size, complexity and international dimension. They are increasingly expected to generate broader impacts alongside their main scientific aims, including playing a role in addressing major societal challenges. They are of interest to a growing number of countries, expanding beyond the traditional scientific power-houses, and they are increasingly expected to make their data and other outputs available to much larger and more diverse user communities.

This policy report presents a series of lessons learned regarding the establishment of VLRIs, options for improving their use and operation, as well as more strategic considerations that VLRI stakeholders should take into account in their planning of future projects. Considering the size and complexity of VLRIs and that many research funders are reaching their limit in funding capacity, these initiatives require growing synergies between the different stakeholders from their planning and inception stage to their operation. VLRI managers, funders and decision-makers will need to work together at international level to develop the strategies and synergies required to reap the full benefit of these large-scale investments.

The recommendations summarised at the outset of this report should allow VLRI stakeholders to address the emerging challenges that were identified by experts during this project. These recommendations are supported by a number of examples of good practices that are described in section 2.

Notes

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2 Very Large Research Infrastructures: issues and options - part 2 - OECD

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Appendix 1. OECD GSF Expert Group on VLRIs

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Canada	Heidi Bandulet (co-chair)	Associate Director for Research Facilities, Canada Foundation for Innovation (CFI)
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Czech Republic	Jan Hrusak	Scientific advisor at the Czech Academy of Sciences
France	Elena Hoffert	Mission officer, Department of Major Research Infrastructure, Ministery for Higher education and research
Germany	Simon Bohleber	BMBF
	Andrea Fischer	Head of division “Large International Research Facilities”, BMBF
	Lisa Sarah Fruhner	DESY Science manager
	Christoph Peshke	DLR project management agency
Japan	Takaki Hatsui	Team Leader, RIKEN SPring-8 Center (RSC)
Korea	Yong-Joo Kim	Policy team, National Research Facilities and Equipment Center (NFEC)
	Sun Kun Oh	Konkuk University
Netherlands	Patricia Vogel	Strategic policy advisor, NWO
Norway	Helmer Fjellvåg	Professor in inorganic materials, University of Oslo
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Spain	Inmaculada Figueroa	Vice Deputy Director General for the Internationalisation of Science and Innovation General Secretariat for Research Ministry of Science and Innovation
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	Linnea Avallone	Chief Officer for Research Facilities, NSF
G7 GSO	Patricia Postigo McLaughlin	Policy officer, DG Research & Innovation, Unit A.3
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OECD	Frédéric Sgard	GSF secretariat
	Paul Dufour	Consultant GSF secretariat
	Masatoshi Shimosuka	GSF secretariat
	Carthage Smith	GSF secretariat