A comparison of the operational models of publicly funded open access nano research infrastructures

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Abstract: This study provides an empirical overview of nano fabrication and characterisation research infrastructures (NFCRIs), and uses this to gain an insight into the similarities and differences in the modes of operation. This will provide a context for future comparative studies of NFCRIs and will highlight parameters which are currently most frequently recorded by the NFCRIs and which may be suitable for evaluation as key performance indicators (KPIs). This study also aims to provide a reference document providing funding bodies and host organisations (universities and research centres) an overview of models employed for the operation of NFCRIS.

Keywords: benchmarking; clean room; international; nanolabs; nano research facilities; nano research infrastructures; nanotechnology; open access; operational models; public funding; research management; technological expertise; technology management; characterisation; nanofabrication.

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1 Introduction

Nanotechnology has long been recognised as relevance for addressing societal needs and as such a source of innovation and discovery. Efforts have been, and are continued to be made to leverage this potential by the formation of national or regional hubs, as mentioned by Roco et al. (2010) as research user facilities and test-beds for nano-enabled devices and system concepts.

Since the turn of the millennium there has been significant national and local investment in NFCRIs across the globe. An early overview was provided by Kautt et al. (2007). Typically public funded and established within universities and research centres, these RIs open their doors to external users in a spirit of open innovation (Chesborough, 2014). Many countries now have well-established national or regional NFCRIs which provide a significant resource in terms of portfolios of high-end equipment, requiring specialist trained personnel, which is on the one hand too expensive to be held by individual research groups, whilst on the other essential to complex scientific topics (National Academy of Sciences, 2005). Such RIs form a narrow band in a broad spectrum of large-scale facilities which span scientific disciplines covering themes from polar research ships to astronomical surveys (German Federal Ministry of Education and Research, 2016).

RIs have become recognised as hubs for innovation (European Strategy Forum on RIs , 2017), the European Commission (2016), recognises their position and importance 'at the core of the knowledge triangle of research, education and innovation and therefore play a vital role in the advancement of knowledge and technology and their exploitation'.

In spite of there being a recognised investment in NFCRIs and a noticeable widespread geographical distribution, there is little available in the literature which provides comparable information on their specific capabilities and operation. It is to be expected that the home organisation, or the respective funding provider, regularly evaluate the performance of individual NFCRIs, and require the provision of information in the form of KPIs and/or written reports. However, Technopolis (2015) has recognised that a comparative evaluation of NFCRIs, which would require a multi-dimensional and complex analysis based on simple metrics. has not been the subject of regular assessment. There are indications that future comparative studies of the impact are to be expected in the near future, and the OECD (2019) has recently described a reference framework.

The motivation of this study was to provide an empirical overview of NFCRIs, and to use this to gain an insight into the similarities and differences in the modes of operation. This will provide a context for future comparative studies of NFCRIs and will highlight parameters which are currently most frequently recorded by the NFCRIs and which may be suitable for evaluation as KPIs. This study also aims to provide a reference document providing funding bodies and host organisations (universities and research centres) an overview of models employed for the operation of NFCRIS.

2 Definitions

- RI: although there is no single definition of a research infrastructure, an RI is here to be understood to be a publically funded, organisational unit dedicated to offering access to equipment and possibly also expertise to users from academia and or industry (OECD, 2017). RIs may be single sited at a single geographical location or distributed with several participating organisations networked across a region. (Technopolis, 2014)
- NFCRIs are defined in this study as non-commercial RIs specifically offering access to nano fabrication and/or characterisation technologies to external users.

2.1 Types of user access

The European Commission (2016) recognises three types of user access;

1 Excellence-driven Access, which normally requires the selection of the most promising proposals from users requesting access

2 Market-driven Access: where access is offered as a service to paying users irrespective of the goals of the work

3 Wide Access where remote access is offered to RIs, e.g., data banks. There are recent indications that data management will cease to be limited to e-infrastructures as RIs seek to manage and make available increasing volumes of experimental data (OECD, 2017).

Users are those persons who access the facilities. *Internal users* are here defined as employed by the same organisation as the NFCRI, *external users* are from different organisations, *transnational users* are external users based in organisations in a different country to the host NFCRI.

3 Methodology of the study

The present study involved an initial internet search and preliminary screening of NFCRIs on international level, and the design and application of a questionnaire which was distributed to selected NFCRIs. The criteria set for the internet search were:

- non-commercial organisations with an R&D component to the service offer
- specifically offering access to nano fabrication and/or characterisation technologies to external users (pure nanoelectronic centres are included only if they have an overlap to nano system applications)
- established using public funding or sponsorship

The questionnaire was designed along the themes described in the conceptual background. The associated questions which were addressed to the NFCRIs are listed at the end of each theme.

4 Conceptual background

RIs aim to facilitate the cost effective implementation of limited funds by investing in equipment which is open for use by not only the home organisation but also to users from further afield.

4.1 Planning and establishment of NFCRIs

The importance of establishing and ensuring the long-term viability of research facilities has already been recognised in several sources, (e.g., National Academy of Sciences, 2005; OECD 2017; European Strategy Forum on Research Infrastructures, 2017). The planned establishment of NFCRIs is mentioned in several national roadmaps, examples here are the USA (2014), Australia (2014, update 2016), Croatia (2014), Czech Republic (2015, update 2019), France (2016), Lithuania (2011), Netherlands (2014, update 2016), Norway (2014, update 2018), Portugal (2014, update 2020), and Sweden (2012). It will however prove difficult to judge the relative importance of a NFCRI simply referring to it being mentioned in the respective national roadmap, since the roadmaps are the product of different national processes. For example; some countries only mention newly planned

RIs requiring more than a prescribed investment limit, while others also mention those which they continue to support; so clearly care needs to be taken when reaching a conclusion based on what can be read in the roadmap. Some national roadmaps mention the formation of networks of pre-existing NFCRIs. The establishment of such networks means that funding can be coordinated and specialist centres developed. The Australian government (2014) regarded this approach as a ‘light touch’ to ensure the accessibility of the facilities to a large scope of researchers. Within Europe France, the Netherlands, Sweden and Norway mention the establishment of networks. The benefits of a network also lie in the development of a complex, linked research infrastructure, and the many possibilities for knowledge and skill sharing. (Technopolis, 2011).

Questions relating to the planning and establishment of NFCRIs:

- When was the RI established?
- Is the NFCRI single sited or distributed?
- Is the infrastructure part of a network?
- Which technologies are offered to users?

5 Operation and monitoring performance

An RI offers a portfolio of capabilities which is more wide-ranging and requires more skilled personnel than those which can be afforded by a single investigator (National Academy of Sciences, 2005). The operation of a RI, is therefore different to the running of a research organisation or university institute and requires a different type of management (Technopolis, 2011) and depending on the size of the RI, a new organisation may need to be formed. Examples of additional tasks conducted by a RI are that user requests need to be handled in a fair way, the operation monitored and records on the use of equipment by user groups needs to be maintained. Finances need to be managed whether the user is charged for access or if the operation of the facility is provided for by a dedicated budget. In the case of international networks a dedicated management will need to be established to coordinate the consortium and the users. These are all aspects which influence the operational structure of a RI, and need to be designed to suit both the local environment of the organisation, and the requirements of the national funding body.

The selection of parameters to monitor the performance of an NFCRI will depend on the envisaged areas of impact. *Scientific excellence is* a paradigm on which RIs are founded and key to their long-term sustainability (OECD, 2017; European Strategy Forum on Research Infrastructures, 2017). Excellence driven access will be reflected in the chosen type of user access and the implementation of a selection mechanism for users will be based upon the criterion of scientific excellence. The transnational relevance of an NFCRI will be reflected in the percentage of users from different countries. The importance given to scientific excellence may be reflected in the requirement of the publication of results and the keeping of statistics on the number of publications. Whereas NFCRIs with *market driven access* would on the other hand focus on the acquisition of paying customers, and have a higher proportion of users from industry.

The *mode of operation* may influence the scientific output and generation of knowledge. Skilled scientists and technicians with many years’ experience possess tacit knowledge which enables the application of the technology for a specific user challenge

(Technopolis, 2015). Creativity within a research centre can be optimised by small group size, and by ensuring access to a sufficiently large variety of technological equipment and complementary skills Heinze et al. (2009).

a Questions relating to the access procedure and the performance of the NFCRIs:

1. Is there a central access point, e.g., user office?
2. Are user proposals selected? If so how (internal and/ or external review) and what are the selection criteria (feasibility, ability to pay, scientific excellence)?
3. Which users are served (internal users, external but from the same country, external and transnational national)
4. What type of access is offered? Access to equipment, expertise, combination of technologies, is collaboration between the user and host NFCRI encouraged, can users rent space and set up their own laboratory?
5. Number of users
6. Percentage of academic and industrial users?

b Questions relating to operational statistics:

1. How many staff are employed to operate the facility?
2. What are the operational hours?
3. What is the length of user projects

c Questions relating to Impact/scientific excellence vs. market driven/ IPR Knowledge/ publications and patents

1. Are users required to publish results?
2. Who owns the IP
3. What is the annual publication rate
4. How many patents per year?

6 Funding and financing user access

The sustained acquisition of funding is recognised as one of the biggest challenges facing RIs (OECD, 2017). Changes in government at a national level as well as developments in the priorities of the host organisation can lead to changes in, or increase the competition for available funding. Sustained funding is essential if the paradigm of scientific excellence is to be held throughout the lifetime of an RI. NFCRIs offer a portfolio of complementary individual technologies, and thus face the additional burden that new technologies are continually becoming available; consequently significant reinvestment in the latest equipment is often needed to maintain the state of the art and compete with new NFCRIs.

Related questions:

- Which are the most important sources of funding?
- What costs are charged for user access (full cost, subsidised rates, no cost) for internal, external, academic and industrial users?

- Are there other ways of supporting the cost of user access?
- What are the annual operational costs (without personnel)
- What funds are available annually for reinvestment?

Socio-economic impact (Multidisciplinarity, application relevance, social capital and knowledge flow)

The socio-economic impact of RIs lies in the spread of knowledge to a wider community. The user can take knowledge gained in the interaction with an RI home; this may, for example, be through the training of users, the experience gained by doctoral students and/or collaborative interaction between host and user. In turn; the host organisation gains or develops knowledge by the interaction with the user.

Socio-economic impact may also arise in the use of the NFCRIs. In addition to generating knowledge in fundamental sciences, the RIs are application relevant and the innovative potential of the technologies is reflected in areas of public importance, e.g., energy, health, optics and photonics and communication technologies. Application relevance implies a multidisciplinary approach and the creation of an environment where technological and application specialists can interact with the users. (Technopolis, 2011). Furthermore, the formation of technological hubs RI's with specific expertise, where scientists with multiple backgrounds converge may have a spin off effect (Battard, 2012; Technovation, 2012) since this raises the visibility of the home organisation increasing the opportunities to be visible among their competitors as expert in particular fields.

Questions relating to socio-economic impact:

- Are users trained to use the equipment?
- Is teaching on the capabilities offered, e.g., at user meeting or workshops?
- Is collaboration with local scientists encouraged?
- What are the most important channels for marketing the RI?
- Which application areas are served?

7 Discussion and results of the questionnaire

The defined scope of the survey was to address NFCRIs offering external users dedicated access to nano and micro technologies. This covered both structuring and characterisation methods. The centres were all public funded, non-profitmaking and located at universities or research organisations.

A total of 86 NFC RIs across the globe were identified as consistent with the criteria applied in the initial internet search. These 86 NFCRIs were written to individually by email and invited to complete an online questionnaire. In addition to the multiple choice questions, it was also possible to provide a comment. These comments were often helpful in that they provided the context of the reply. Since a relatively small number of facilities were approached it was possible to write individually and clarify replies when necessary.

28 completed replies were received from the participants in the survey corresponding to a response rate of 32%.

Notes on the results:

- The number of NFCRIs involved in the questionnaire is relatively low, however the consistency of the replies has enabled a general picture of the differing priorities and operating models to be formed.
- Since the aim of the survey is to gain a general overview of the operation of and challenges facing NFCRIs the names of the responding organisations have been omitted from the report.

8 The planning and establishment of the NFCRIs

A comparison of the NFCRIs with the national RI roadmaps revealed that approximately 30% of those identified as relevant to this study are mentioned in a national roadmap. These tended to be located in a relatively smaller country, e.g., Czech Republic (2015), Norway (2014), or mentioned in the context of the formation of a national network, e.g., the USA (2014), Australia (2014), France (2016), Netherlands (2014), and Sweden (2012).

We found that the RIs represent both single sited and distributed NFCRIs. 16 were based in European member or associated states, 8 in the USA, and responses were also received from Canada and Australia. About half were established before 2005 and the USA NFCRIs, except for one which is a new NNCI centre (http://www.nnci.net/), were established before 2000. It demonstrates that the USA led the way with establishing open access NFCRIs during the end of the last millennium, and since then there has been a gradual growth particularly noticeable in Europe (Kautt et al., 2007). This trend is still continuing both in the USA and Europe with new facilities being established also in the newer member states of the European Union. Half of the respondents mentioned that they are member of a network; and the survey includes members of NFCRI networks in the USA, France, Norway, Sweden, the Netherlands and Australia.

8.1 Technologies offered to users

As to be expected by the definition of NFCRI; all the infrastructures participating in the survey offer access to equipment and technical support. The output is dependent upon the offer of high-end, expensive and sometimes unique technologies which are not commonly affordable by the majority of universities or research centres. Most of the NFCRIs questioned dedicate their activities to fabrication methods, and relatively few solely to characterisation. Lithographic methods (e.g., e-beam lithography and photolithography) together with etching methods (e.g., dry and wet etching, reactive ion etching) and thin film methods (e.g., PVD and CVD based methods) are well represented by the majority of NFCRIs. Replication methods and back end processing, assembly and packaging are also much less common, which probably reflects the exclusion of nano-electronic facilities from the study. The offer of the synthesis of nanomaterials is limited, however approximately 50% of the respondents offer the preparation of carbon nanomaterials, carbon nano tubes and graphene. Similarly unusual is the availability of modelling, design and simulation (e.g., finite element analysis, optical modelling and design) (an overview of the technologies is given in Table 1).

Characterisation methods tend to be those required to characterise the fabricated structures; therefore microscopic methods (e.g., scanning electron microscopy (SEM), focused Ion beam microscopy (FIB) and transmission electron microscopy (TEM)) are those most frequently found. Spectroscopic methods such as X-Ray Photoelectron Spectroscopy (XPS), UV/Vis Spectroscopy and (tip enhanced) Raman Spectroscopy are also fairly widespread, as is ellipsometry. Much less common are methods solely used to determine the chemical composition or molecular structure such as Fluorescence Microscopy, 3D Atom Probe Tomography or powder or single-crystal X-ray diffraction. A few NFCRIs also offer mechanical testing methods such as for compression, straining, creep or have capabilities for application relevant testing such as for electrical battery testers, photovoltaics, semiconductor parameter analyser or biomolecular characterisation.

8.2 Operation and monitoring performance

Each NFCRI has an independent management structure, and there are many possible combinations and variations in the operational models which describe the precise nature of the access and the relationship between the host organisation and the user. About half the NFCRIs have a central access point such as a user office which handles enquiries and applications from users and/or customers.

8.2.1 Analysis of the access procedure, the performance in terms of publications and patents and the relationship with excellence and market driven access

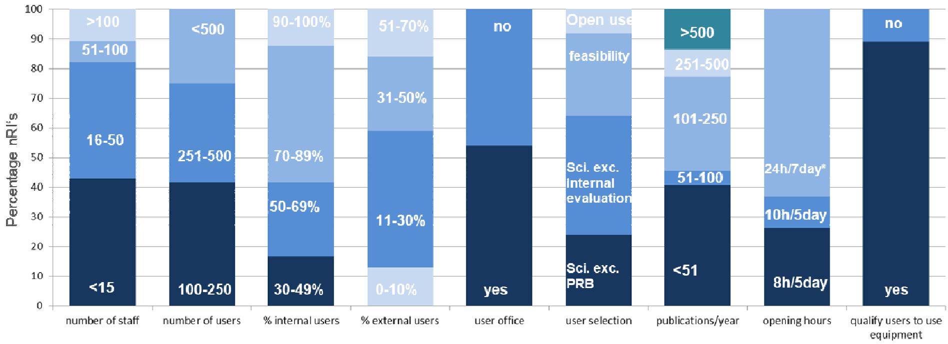
Use of the equipment at the RIs is awarded according to a variety of procedures, and the method of the selection of user projects is defined by the priorities of the host NFCRI Figure 1. In approximately 50% of NFCRIs scientific excellence is a key selection criterion. We found that the scientific excellence of a proposal can be evaluated by the host scientists and/or an internal or external review panel. About one in five NFCRIs review the user requests via an external peer review panel (PRB) and this criterion appears to correlate with a higher percentage of external users. In about 2/3 of NFCRIs the feasibility and/or the payment for access are the most important criteria, while proprietary access is also possible at the majority of NFCRIs. Industrial use generally accounts for between 10 to 25% of the total access time.

In addition to serving users, the majority (> 90%) of NFCRIs also offer the less structured approach of an open laboratory where equipment can be used as required by trained registered users who generally, but not always, come from the home organisation. Access to the equipment is not subject to a review process and may be used according to availability, and some have a central booking system. These NFCRIs, like those which assess only the feasibility, still claim to aim for scientific excellence, the supporting argument for this claim being the open provision of a portfolio of equipment for the scientific community promotes excellence.

Table 1 prevalence of fabrication and characterisation technologies

	Fabrication technologies		
	Present in most (> 60%)	*Present in some (20%–60%)*	*Unusual (< 20%)*
Lithographic and non-lithographic structuring methods	Optical photolithography; electron beam lithography focused Ion beam (FIB)	Direct laser writing; laser material processing	3D direct laser writing; deep X-ray lithography helium Ion microscope; ultraprecision micro machining; proton patterning or milling; dip-pen nanolithography, polymer pen lithography
Etching/cleaning	Wet etching, dry etching plasma cleaning; metal reactive ion etching (RIE)	Si Isotropic etching	
Thin film methods	PECVD; chemical vapour deposition (CVD)	LPCVD atomic layer deposition (ALD); physical vapour deposition (PVD)	Polymer deposition system; molecular beam epitaxy; MOCVD; pulser laser deposition
Replication methods		Electroplating/electroforming; thermal imprint lithography; Nano imprint lithograph; self assembly Technologies	Injection moulding; hot embossing; high precision 3D printing; screen printing; sol gel patterning
Back end processing assembly and packaging		Wafer bonding; wire and die bonding; dicing, sawing; thermal processing annealing, doping, oxidation	Anodic bonding; packaging; flip chip; adhesion bonding
Modelling, design and simulation			Optical modelling and design; finite element methods
Nanomaterials synthesis		Carbon (graphene, CNT)	Polymers; Biomolecular synthesis; SiC; metals and alloys; ferroelectrics; ceramics
	Characterisation technologies		
	Present in most (> 60%)	Present in some (20%–60%)	Unusual (< 20%)
Spectroscopy/ Spectrometry		X-Ray photoelectron spectroscopy; UV/Vis spectroscopy; (tip enhanced) raman spectroscopy	X-ray fluorescence; atomic emission; Auger; time-of-flight secondary Ion mass spectrometry; Infrared/THz; X-ray absorption; IR near-field; reflection absorption IR; time-of-flight mass spectrometry
Microscopy	Scanning electron microscopy (SEM); focused ion beam microscopy (FIB); transmission electron microscopy (TEM)	Fluorescence microscopy; confocal fluorescence microscopy	Helium ion microscopy; scanning near field optical microscopy; 3D atom probe tomography; photoemission electron microscopy; X-ray Tomography
Diffraction		Ellipsometry; powder X-ray diffraction (PXRD)	Single crystal X-ray diffraction; X-ray reflectometry; neutron diffraction
Mechanics		contact profilometer	Nanoindentation; bulk mechanical testing
Application related testing			Electrochemical battery tester; photovoltaic test station; biomolecular characterisation, LED characterisation, semiconductor parameter analyser; solar analyser; electro-optical characterisation; reverse engineering and failure analysis of electronic assemblies; reliability, environmental testing

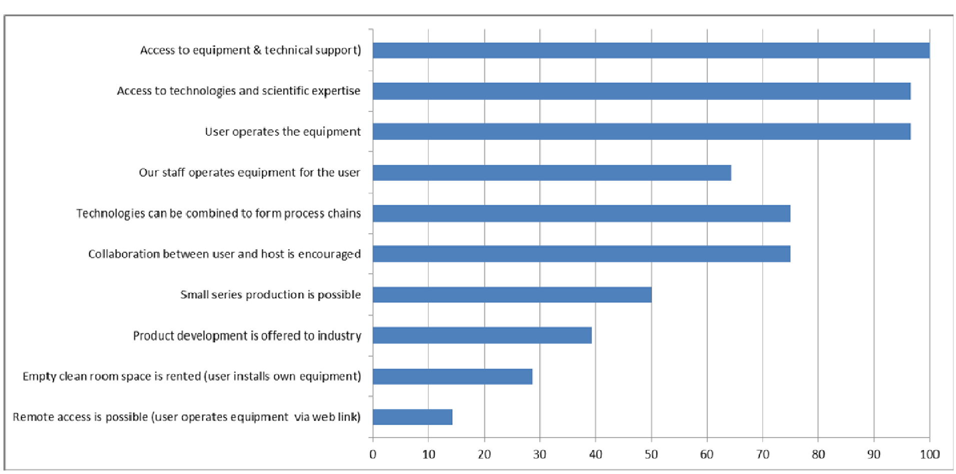
Figure 1 Summary of perfomance indicators against the percentage of NFCRIs (see online version for colours)



Although the NFCRIs selected for the study, following an internet search of their web pages, fulfilled the criteria that user access was offered to external users, the results of the questionnaire indicate that the majority predominantly serve users from the home organisation and it is usual that external users come from the same country. Replies here often required clarification in that home users who originate from different countries are sometimes counted as oversees users by their home organisation. The median number of users was found to be 300, the median for internal use lies at 75% Figure 1. We learnt also that whereas users from the home organisation are more likely to be able to operate the equipment themselves those from outside organisations are more likely to be assisted by the host's staff.

Technologies can be combined into process chains at all the NFCRIs. About half of them also offer small series production and product development to industry. In some cases clean room space can be rented to users to install their own equipment. Remote operation where instruments can be controlled over the internet is currently very limited Figure 2.

Figure 2 Types of access possible at the NFCRIs against percentage, most NFCRIs offer more than one type of access (see online version for colours)



The vast majority (only one replied negative) offer scientific expertise and encourage collaboration with local scientists.

8.2.2 Operational statistics

8.2.2.1 Staff numbers

Staff numbers do appear to be related to the nature of the NFCRIs. The majority have less than 100 scientific and technical staff dedicated to the users and nine have less than 15 Figure 1. The median is 20 and the average is 31. The ratio of the number of listed technologies to staff ranges from 0.1 to 5.3. Those with a smaller number of staff, and a higher ratio of technologies to staff, tend to house collections of equipment which can be used as required, in this case the role of the staff is primarily to maintain and keep the equipment operational. Those with larger numbers of staff, and technology to staff ratios of <1 tend to be NFCRIs where the user access programme is an integral part of the scientific activities.

8.2.2.2 Operational hours

About half of the NFCRIs operate 24/7 hours per day, others tend to be open for an 8 or approximately 10 hour day five days a week Figure 1. Maximising the usage of the equipment is clearly an important factor in the efficient use of expensive resources, however there are several conflicting priorities which affect the feasibility of 24/7 operation. Some instruments can run automatically and therefore can be operated full-time; others need an operator or trained user at hand. Discussions with the NFCRIs which operate 24/7 revealed that some have equipment which can be accessed at any time by trained users, and those that charge for access sometimes charge less for off peak times. However the 24/7 use of infrastructures is also restricted by safety considerations such as a strict 'buddy' rule and the out-of-hours prohibition of the use of wet benches or toxic and flammable gases. The NFCRIs where the host scientists carry out or strongly support the execution of the work are clearly most limited by the numbers and regular working hours of available personnel.

8.2.2.3 Length of user projects

There is a large variation (from 2hrs to 27 months) in the length of a user project which arises from the different types of users, e.g., in the case of PhD students, some carry out most of the laboratory work at the NFCRI and therefore have a longer length of project, whereas others need the facilities for specific tasks and carry out the majority of their work elsewhere, consequently the time taken for the work at the NFCRI is considerably shorter.

8.2.3 Scientific excellence vs. market driven priorities/ IPR Knowledge/ publications and patents

Although, as observed by Technopolis (2015), the performance of NFCRIs has hitherto not been compared in detail, the majority of NFCRIs do monitor the output in terms of publications and have regulations on the ownership of intellectual property (IP). Half of the NFCRIs request users to publish the results Figure 1 and this appears to correlate with having a single access point such as user office and monitoring the publication of results. The median value for the annual number of publications is 140, the median of publication per user is 0.2 and the ratio of publications per staff member is 5.7. Mainly the technologically relevant IP belongs to the user, or jointly to the user and host organisation. Only rarely does it belong exclusively to the host organisation. In the cases where the IP belongs to the user, the aim is still to make the specific knowledge gained in adapting the processes available for the benefit of users.

The number of patents is generally not recorded; the few which do monitor the number of patents tend to have up to 15 per year. At first glance, the lack of records may appear surprising however there are several logistical reasons which make it impractical. Firstly, although users are encouraged to inform the host NFCRI of publications, (this is sometimes a precondition for future use), patenting results relates to the transfer of knowledge gained by the users. The NFCRIs therefore have no record of the patents or indeed products arising from external academic or industrial users, and it would be a matter of good will and continued contact with users to be assured of gathering reliable statistics. A measurement of the impact on companies of the use of RIs would therefore require an investigation of the company users rather than the host facilities.

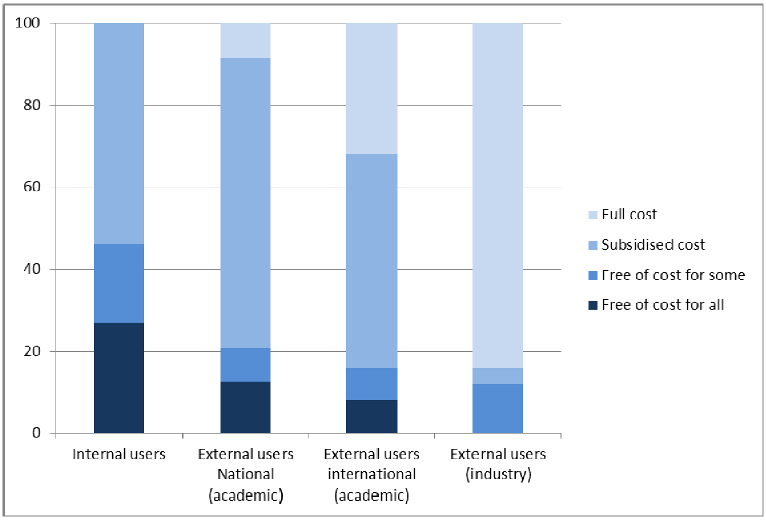
9 Funding and financing user access

The most important funding source is state funding and more than 50% of NFCRIs rank it as a primary funding source. Even though the NFCRIs in this study are all non-profit making; the income from users is the secondary most important source with five NFCRIs being dependent on this for their main source of funding.

All NFCRIs receive some funding to be able to offer internal users access to the equipment at no cost or at a subsidised rate which is often lower than that offered to external users. The cost of using the equipment is often subsidised by the NFCRI funding, or covered by the research grants of the users.

In the case of external users; national or regional financial support allows more than 60% of the NFCRIs to subsidise the costs of access for the external users. National academic users receive access free of cost at five of the NFCRIs which responded to the questionnaire (of these two have funds to be able to offer some no fee access) and subsidised access is available at 17 NFCRIs. External academic users pay full costs at two of the USA NFCRIs. International academic users receive free of cost access from only two of the respondents to the survey, (a large scale facility funded by the Helmholtz Association in Germany, and a Department of Energy funded centre in the USA) and a further two RIs have funds for a limited amount of free of cost access. The NFCRIs which offer no cost access tend to serve a higher percentage of users from external organisations, and encourage collaboration between staff and users. Subsidised access for international academic users is possible at approximately 50% of the NFCRIs, whereas 25% of the centres charge the full costs. Two of the NFCRIs offer some industrial users free of cost access and another one offers subsidised access, at all the others industry is charged the full cost Figure 3.

Figure 3 Indication of funding sources against percentage of NFCRIs (see online version for colours)



Several countries offer the users, rather than the NFCRIs, financial support to cover the cost of access by including this in the individual research grants, e.g., Sweden, the UK, Norway, the Czech Republic and Australia. Four of the European based NFCRIs are able to offer vouchers to industry and five (four European and one USA) are able to offer vouchers to academic users, these are not the same as those which offer vouchers to industry. Norway is an example of a country in which companies can offset the costs of access to an infrastructure against tax.

The annual operational costs vary widely, as indeed is to be expected with the differences in the cost of living between countries such as Norway and Moldova. It is also difficult to ensure comparable results since the context of the operational cost values varies from organisation to organisation. To obtain such necessarily detailed results would require a much more thorough and iterative procedure similar to that performed by Grimard and Jones (2013) for 12 facilities in the USA. The financial data described here is intended to illustrate, rather than provide an accurate comparison of, the annual operational costs and reinvestment in the NFCRIs. The average value of running costs excluding personnel costs lies at 2.9M€ and the median at 1.5M€. The minimum was 60,000€ and the maximum 8.4 M€. Most of the NFCRIs have an annual reinvestment of between 150,000 and 2 million euros per annum. Direct comparison is again not possible because additional to annual reinvestment budgets, there are irregular opportunities to compete for additional funds.

10 Socio-economic impact

The present study does not attempt to describe the socio-economic impact, but rather to provide an empirical basis for future impact studies.

10.1 Knowledge transfer

With only one exception, all the NFCRIs train users to use the equipment independently; the one exception does train some regular users with the host scientists carry out the work for the majority of the users. Approximately 60% of NFCRIs also offer teaching on the capabilities of the equipment, such as at workshops in conjunction with annual user meetings. The aim of the NFCRIs thereby is to increase the breadth of knowledge of the users by offering insight on how unfamiliar techniques can be applied and consequently to result in more ambitious and complex user projects.

The most effective means spreading knowledge to the wider community and of attracting new users is regarded to be the publication of results both in scientific literature and conference presentations. Up-to-date web pages are of high importance, however marketing activities such advertisements in scientific literature, exhibition stands at conferences or presence in the social media are not regarded as effective.

10.2 Application relevance

Application relevance can range from the investigation or proof-of-principle through to device development. The four most significant application areas served by the NFCRIs in this study are fundamental sciences, energy, health and optics and photonics, each being of relevance to more than 80% of the respondents. The next most important are Environmental (including safety), and information and communication technologies (ICT).

It is important that RIs facilitate advances in the fundamental sciences and this was observed in the majority (92%) of the NFCRIs. Areas include developing micro/nano engineering methods, investigation of surface-science, the increase of functionality of micro/nano structured materials, condensed matter, magnetic materials and quantum physics.

In the energy application area; energy harvesting and photovoltaics are the most relevant, followed by fuel cells, electrical energy storage, microreactors and micromixers and mechanical energy storage.

In the area of health, 75% of the NFCRIs are experienced in applications in biosensors, lab-on-a-chip and health monitoring systems, and two thirds of these are also active in either or both devices for medical implants and medical equipment.

It can be argued that optics and photonics is not strictly an application area, however it is considered here as such because the expertise of the infrastructures is often used to make structures and devices for application in optics and photonics. The results show the high degree of relevance of optics and photonics to the NFCRIs since 75% of the respondents to the questionnaire responded positively to this question. Of particular importance are; micro- and nano- scale photonics, optoelectronics, optics, lasers and nonlinear optics, integrated photonics, quantum photonics and plasmonic systems.

ICT is regarded as relevant to 60% of the RIs. Of particular importance are LED/OLED, data storage and telecommunication applications.

Environmental and safety applications are relevant to approximately 50% of the NFCRIs, with general environmental factors and water being top of the list. More than 25% also serve safety related applications.

10.3 KPIs: comparative context factors

The results described above provide an empirical overview of the peer NFCRIs which monitor their performance and therefore had the necessary figures available. However, in discussion with the participants of this study, and clarifying the results of their input to the questionnaire it became clear that there was a large variation in the understanding of the terms. When planning future comparative studies of NFCRIs as suggested by Technopolis (2015) and OECD (2019), it is therefore essential to carefully define each KPI; however, if done thoroughly this will greatly increase the effort required of the participating NFCRIs. Table 2 gives some examples of factors to be considered.

Table 2 Factors to consider to ensure the comparability of KPIs

KPIs	*Example factors to ensure comparability*
Number of staff	Management, scientific and technical staff. This should only include those dedicated to running the RI, not include research scientists at the home organisation.
Number of technologies available	How is technology defined? Some RIs count each piece of equipment individually, others group several pieces instruments together as a single technology.
Number of users	Does one user have access over a longer period of time, or does each use of a technology count as a user?
Origin of users	Some organisations count home users of foreign national origin as international users
Number of publications	Publications by in-house, and/or external users, comparison with relative size of the NFCRI. All publications/conference papers/journal quality
Number of patents	The number of patents is largely not recorded. For patents registered by external users, it would be necessary to interview the users rather than the RIs
Operational hours	Does the user carry out the work or the host organisation. Can equipment run automatically overnight or do samples need changing regularly?
Operating costs	Which individual costs are included, take account of variation in cost of living in different countries
Re-investment budget	Regular reinvestment costs, is there also internal competition for funds at irregular intervals, external funds
Cost of using equipment	Different national funding models lead to different costing procedures

11 Conclusions

The strategic planning of national investment to establish NFCRIs as named entities in larger public bodies (universities or research centre RIs), and the opening of the NFCRIs to external users, illustrates the importance of providing pooled and managed key resources for the benefit of a wider group of researchers.

*There is no single best practice mode*l for operating an NFCRI because the business models inevitably need to be consistent with the national funding mechanisms and local needs of the host organisation. Common to the NFCRIs is that the majority offer access to equipment and expertise, the possibility of combining technologies into process chains and encourage collaboration with local scientists. The main differences arise in the way access to the NFCRIs is managed and this is dependent upon the target user groups.

The modes of operation are consistent with observations in the literature known to be linked with improved scientific impact, and areas for a future assessment of socio-economic impact have been identified. The NFCRIs represented in this study mainly strive for *excellence-driven* access (as defined by the European Commission, 2016) which promises the rewards of high impact publications and scientific renown for the host NFCRI. Worthy of mention here is that excellence driven access does not necessarily imply no fee access, the costing mechanisms of the NFCRIs are dependent on the business model employed by the host organisation and their respective funding providers. Verification of scientific excellence would need, e.g., an analysis of the quality of the publications of the NFCRI. The results of the survey illustrate that a structured approach to user acquisition, e.g., by the operation of a central user office and the selection of the most promising user proposals by an independent peer review board is linked to a higher number of publications. This statement may however need qualification, in that NFCRIs with more thorough management practices may track the publications of the users more rigorously and consequently have higher recorded number of publication. A *market driven* model is generally not the prime means of operating user access to a publically funded RI, however contributions to the NFCRIs budget can be generated by the operation of a service facility for external organisations.

When considering future studies of the socio-economic impact of NFCRIs, in addition to analysing the ways in which knowledge is transferred within the NFCRI the flow and utilisation of knowledge by the users would need to be explored. Consequently, in addition to analysing the immediate output of the NFCRIs it will be necessary to investigate the valorisation of results by the users and subsequent industrial uptake by industry.

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