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ARCNL - Advanced Center for Nanolithography

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1. Foreword by the committee chair

It is with great pleasure that I present this comprehensive evaluation report, a result of collaborative efforts of a diverse team of professionals. It is crucial to acknowledge the collaborative spirit of the committee during the evaluation. Throughout the evaluation process, the committee members demonstrated a commitment to impartiality, objectivity, and transparency.

The engagement and cooperation of all stakeholders, including ARCNL researchers, management team, contributing universities, NWO as well as ASML, played a pivotal role in the success of this evaluation. Their willingness to share perspectives, provide data, and participate in discussions reflects a shared commitment to continuous improvement and the realization of the organizational goals of ARCNL. It was a pleasure to communicate with the enthusiastic and committed research staff, PhD students and Postdoc's, and to get a tour of the outstanding research infrastructure.

This report not only highlights achievements of ARCNL, but also identifies areas for improvement, offering actionable recommendations that will undoubtedly contribute to the ongoing refinement and enhancement of the research centre. It provides valuable insights that enable strategic decisions within ARCNL.

On behalf of the committee, I would like to thank all participants involved in the reporting and on-site visit, for the open communication that was critical for obtaining insights in the way of working within ARCNL. I am very grateful to Meg van Bogaert, who acted as secretary on behalf of Academion and the support of Miriam Roelofs on behalf of NWO-I.

The purpose of this evaluation was multifaceted, seeking to assess and analyse the effectiveness, efficiency, and overall impact of ARCNL. May this report serve as a catalyst for positive change and inspire continued excellence within ARCNL.

Chair of the evaluation committee
Prof. Guus Rijnders
University of Twente

2. Executive summary

The main goal of the committee was to evaluate ARCNL considering its own aims and strategy. The committee did reflect and evaluate those topics, but also wanted to provide input and feedback to further strengthen the future of ARCNL.

The Advanced Research Centre for Nanolithography (ARCNL) stands as a unique model bridging the gap between fundamental research and practical applications, according to the committee's evaluation. Serving as a "win-win-win-win-win" for ASML, ARCNL researchers, universities, NWO, and the Netherlands, ARCNL exemplifies successful cooperation between diverse entities. As such, it also provides benefits to other entities by the inspirational example it sets. The committee was deeply impressed that such a unique and novel entity has achieved so much success in a relatively short period of time in a competitive, fast-paced research domain.

In the near term, efforts are required to plan the succession for the current director, emphasizing the need for a successor with a strong academic reputation, leadership skills, and industry experience.

ARCNL's flat organizational structure houses research groups with equal leadership roles, fostering a collaborative environment. The yearly strategy cycle, involving the Scientific Advisory Committee (SAC) and ASML, aligns stakeholders and promotes transparency. The mission emphasizes nanolithography, aligning with ASML's interests, while the strategy, continuously updated, mitigates research discontinuity risks.

The Human Resources Policy supports a balanced approach, emphasizing international recruitment and talent development. Looking ahead, challenges in tenure and promotion processes, especially for early-career PIs, call for optimized recognition of ARCNL's unique position by partner universities.

ARCNL’s academic culture focuses on community building, while inclusivity efforts are commendable. ARCNL demonstrates a proactive stance on diversity, with notable progress in female recruitment. However, gender disparities persist in leadership roles, requiring continued efforts, along with continued efforts to support all forms of diversity at ARCNL so it can attract from the broadest talent pool, and promote and retain that talent. Collaboration with partner universities and NWO and developing a next-generation strategy for diversity and inclusion could further enhance ARCNL's positive culture. Research integrity is a current priority, but external involvement in assessing integrity is recommended for objectivity.

ARCNL's PhD Policy and Training programme is laudable, marked by a thorough and quality-oriented approach. The commitment to a four-year standard for obtaining a PhD underscores ARCNL's dedication to high standards and timely programme completion. While the committee acknowledges the programme's strengths, it recommends enhancing post-PhD career development support beyond ASML-oriented paths, promoting a broader spectrum of opportunities.

The research quality at ARCNL, spanning Materials, Metrology, and Source themes, is exceptional. Researchers and PhD students demonstrate strength in addressing innovative and fundamental scientific problems. The interdisciplinary collaboration fosters groundbreaking advancements in highly charged ions, metrology methods, and contact dynamics. The committee encourages promoting these collaborations externally.

ARCNL's societal relevance is evident in its contributions to semiconductor technology, extensive patent generation, and impactful publications. The centre actively engages in outreach, conferences, and educational initiatives, effectively promoting science in society. However, there's room for improvement in entrepreneurial activities and fostering relationships beyond ASML for wider societal impact.

In embracing Open Science principles, ARCNL excels in open access publishing and FAIR data practices. With a commitment to over 90% open access publications, standardized data management plans, and active

participation in discussions on data sharing, ARCNL showcases its dedication to transparent and accessible research practices. The centre can leverage its leadership in Open Science as a model for other institutions, emphasizing tangible benefits and outcomes.

ARCNL's viability is well-established, contributing significantly to scientific excellence and societal impact in nanolithography. The mission remains focused on collaboration, flexibility, and innovation, aligning with the semiconductor industry's evolving needs. The strategic plan includes enhancing national and international collaborations, stimulating academic institutes, and promoting open science. ARCNL will continue to face challenges in the fast-paced nanotechnology field, warranting attention to stay ahead and remain sufficiently broad. While the close partnership with ASML is beneficial, increasing visibility and diversifying funding sources, such as European projects led by ARCNL PI’s, are crucial for sustained growth. Addressing vulnerabilities, optimizing stakeholder relationships, and showcasing ARCNL's uniqueness globally are recommended strategies for long-term success.

3. Procedure

3.1 Scope of the evaluation

This evaluation was carried out as part of the six-yearly evaluation of the nine research institutes of the Dutch Research Council (NWO). NWO asked evaluation committees of external peers to perform an evaluation of its research institutes over the period 2017-2022. Evaluation bureau Academion acted as independent intermediary to safeguard the quality of assessment, providing secretaries for each of the site visit and helping the institutes and evaluation committees prepare and execute the site visits together with NWO-I, the institute organization of NWO.

The evaluations were carried out according to the Strategy Evaluation Protocol 2021-2027 (SEP), the protocol for research evaluations in the Netherlands, agreed upon by NWO, the Royal Netherlands Academy of Arts and Sciences (KNAW) and the Universities of the Netherlands (UvNL). The committees were requested to carry out the evaluations according to a list of questions derived from the main assessment criteria of SEP (see appendix 1). The assessment was to include a backward-looking and a forward-looking component. The committees were asked to judge the performance of the institute based on the list of SEP questions and to offer its written conclusions as well as recommendations based on considerations and arguments. The main assessment criteria are Research Quality, societal Relevance and Viability.

During the evaluation of these criteria, the committees were asked to incorporate four specific aspects relating to how the institute organises and actually performs its research, its composition in terms of leadership and personnel, and how the institute is run on a daily basis. These aspects are: Open Science, PhD Policy and Training, Academic Culture and Human Resources Policy.

3.2 Composition of the committee

The committee for the evaluation of ARCNL was appointed by the Board of NWO, and consisted of the following members:

- Prof. Guus Rijnders (University of Twente, the Netherlands) – chair
- Prof. Friedrich Aumayr (TU Wien, Austria)
- Dr. Rogier Verberk (TNO, the Netherlands)
- Dr. Amelle Zaïr (King's College, United Kingdom)
- Prof. Robert Carpick (University of Pennsylvania, USA)
- Dr. rer. nat. Andreas Erdmann (Fraunhofer IISB, Germany)

The committee was supported by Meg van Bogaert, who acted as secretary on behalf of Academion. Miriam Roelofs was present during the site visit to support the committee on behalf of NWO-I.

3.3 Independence

Before the site visit all members of the committee signed the NWO Code of Conduct, by means of which they declared that their assessment would be free of bias and without regard to personal interest, and that they had no personal, professional, or managerial involvement with the institute or its research programmes. It was concluded that the committee had no conflicts of interest. The NWO-I coordinator present during the site visit did not take part in the evaluation but provided the committee with background information and context on the position of the NWO institute upon request.

3.4 Data provided to the committee

The committee received the self-evaluation report from the institute, including all the information required by the SEP. The committee also received documents on the following topics:

- ARCNL Strategy cycle;
- Data management
- Diversity and Inclusivity
- Employee survey
- Knowledge security
- Output analysis (CWTS)
- PhD Welcome booklet

3.5 Procedures followed by the committee

The committee proceeded according to the SEP 2021-2027. The secretary instructed the committee chair on his role in the evaluation. In its first meeting on 26 October 2023, the committee was briefed by the secretary on research evaluations according to the SEP 2021-2027, and by the NWO-I coordinator on the Dutch research landscape and position of the NWO institute therein.

Prior to the site visit, all committee members independently formulated a preliminary evaluation based on the written information that was provided before the site visit. During its preparatory meeting on 8 November 2023, the committee discussed the preliminary evaluations and identified questions to be raised during the site visit. It agreed upon procedural matters and aspects of the evaluation. The site visit took place on 9-10 November 2023 (see the schedule in Appendix 2). After the interviews, the committee discussed its findings and comments in order to allow the chair to present the preliminary findings and to provide the secretary with argumentation to draft a first version of the evaluation report. The final evaluation is based on both the documentation provided by ARCCL and the information gathered during the interviews with representatives of the institute during the site visit.

The draft report by the committee was presented to ARCNL for factual corrections and comments. In close consultation with the chair and other committee members, the comments received were reviewed to draft the final report. The final report was approved by the Board of NWO.

4. Evaluation of ARCNL 2017-2022

4.1 About ARCNL

The Advanced Research Center for Nanolithography (ARCNL) is a public-private partnership between the Dutch Scientific Research Institutes, three Dutch universities (University of Amsterdam (UvA), University Groningen (UG) and the Vrije Universiteit Amsterdam (VU)) and the semiconductor equipment manufacturer ASML. ARCNL is one of the nine scientific research institutes of NWO-I and employs approximately one hundred people. ARCNL was launched in 2014 and was initially housed at AMOLF. Since 2014 ARCNL has its own housing at the Amsterdam Science Park, and is independent of AMOLF since September 2015. Connections to AMOLF remain in the form of shared support services, a collaborative ARCNL-AMOLF research programme and collegial interactions.

The initiation of ARCNL was a response to an ASML request for basic research with a long-term application perspective. The choice was made to focus on ASML's advanced lithography systems that use extreme ultraviolet radiation (EUV, 13.5 nm radiation). By carrying out fundamental studies in the fields of physics, physical chemistry, and chemistry, ARCNL generates insights of benefit to lithography in general. The partnership with ASML requires understanding and implementation of challenges of the semiconductor industry. Such a high-tech industry is very dynamic and brings the need to understand and assess the technical readiness levels of subjects of study.

According to the committee, ARCNL serves as a unique example of a centre bridging the gap between fundamental research and practical applications. ARCNL is already a "win-win-win-win-win" for ASML, for the ARCNL researchers and PhD-students, for the universities, for NWO, and for the Netherlands. In general, ARCNL serves as an innovative and inspiring model where cooperation between multiple parties leads to value for basic science and technology, in contrast to the trend of declining investment in long-term research by industry in many other countries over the last two to three decades.

4.1.1 Governance

The management team (MT) of ARCNL consists of a scientific director, institute manager and three department representatives. The MT has weekly meetings, and the full staff meets approximately 8-10 times per year. In the first decade of existence, several phases have been gone through. In the first few years, the stakeholders had to get used to each other and mutual expectations had to be readjusted. This led, in 2019, to ARCNL 2.0 in which governance was adapted, leading to – among others – PIs now being appointed at the universities. Currently, all stakeholders are very positive about their interactions with and collaboration in ARCNL. The committee believes that ARCNL is going towards a consolidation phase. The transition in leadership is seen as very positive by all stakeholders and by ARCNL staff. The first director did a wonderful job in setting up the institute allowing the current director to continue with building bridges between all stakeholders. Some concern exists regarding the succession of the current director after his retirement in a few years. This asks for a candidate with a good academic reputation, leadership skills and understanding of and/or experience in industry. It is important that the new director is able to communicate with the different stakeholders involved. According to the committee, prolonged or even unsuccessful external searches indicated that the search process for leadership positions needs to be intensified. ARCNL and its stakeholders should be actively 'hunting' by soliciting ideas for candidates to approach globally; reaching out to and encouraging these people to apply and involving a professional talent-scouting firm. Should a candidate for the position of director be found, the committee is of the opinion that it would be beneficial if the current director gets the opportunity to act as mentor to the new director.

ARCNL has a flat organizational structure, with individual research groups sized 2-12 junior researchers, led by a single group leader. All group leaders have the same roles and accountability, regardless of being

employed at assistant, associate, or full professorship level. The founding partners have installed a Governing Board (GB) with members of all partners under chairmanship of the NWO-I representative. The GB discusses ARCNL progress, organizational and financial developments, and strategy.

ARCNL has a yearly strategy cycle, in which the Scientific Advisory Committee (SAC) discusses and assesses the scientific results, based on a self-evaluation of the group leaders. In addition, ASML writes an appreciation report, using KPIs which cover Scientific Output, Intellectual Property, the number of ARCNL employees with ASML as first next employer and Innovations from ARCNL adopted at ASML research or ASML D&E. The input by the SAC and ASML leads to a strategy day with all stakeholders, research groups and departments, resulting in a year plan. This cycle, although labour intensive, is appreciated by ARCNL since it makes all stakeholders aware of what is being done and leads to alignment. ARCNL is a best practice among the NWO institutes in the way it organises its yearly strategy cycle.

ARCNL receives funding from several sources: base budget from the ARCNL partners, external project and programme funding and PPP allowance (in Dutch PPS or TKI; from the Ministry of Economic Affairs via TKI-HTSM). The annual base funding amounts up to over 8 M€, of which 50% comes from ASML and 50% of NWO-I, UvA, VU and UG. The funding from universities is in-kind, meaning that they provide personnel and some infrastructure. ARCNL researchers acquire external funding from national (NWO) and international (HORIZON EU, ERC starting and consolidator) sources. Until 2024, ARCNL applies annually for the PPP allowance which is related to the contribution of ASML. As of this year, PPP allowance is competitive.

4.2. Mission, vision, and strategy

4.2.1. Mission and vision

The mission statement is: *ARCNL performs fundamental research, focusing on the physics and chemistry involved in current and future key technologies in nanolithography, primarily for the semiconductor industry. While the academic setting and research style are aiming for scientific excellence, the subjects in ARCNL's research programme are intimately connected with the interests of ASML.* The ARCNL vision is: *Push the capabilities of High-Tech industries by performing public fundamental research.*

The ambition of ARCNL, expressed in 2017, was to become a leading research centre with a clear focus on fundamental research in the context of nanolithography technology. ARCNL's goals and strategy take a balanced and forward-looking approach, positioning the centre as a key player in the future of the semiconductor industry and contributing to real-world scientific progress. The committee is highly impressed by ARCNL's dedication to advancing fundamental research in nanolithography through strong collaborations with ASML, universities, and its commitment to scientific excellence and open science. ARCNL's short and long-term goals align with the organization's mission and the semiconductor industry's broader objectives. By addressing industrial challenges, collaborating with ASML, and actively participating in the national and international research landscape, ARCNL is well-positioned to take a strategic and proactive approach.

According to the committee, the mission and vision statements have many positive attributes. ARCNL is unique, and thus the committee believes that it is important to have a concise and compelling mission statement, to provide a clear articulation of its vision up front, and to present these clearly and consistently at all appropriate opportunities. With respect to the mission and vision, the committee has two remarks, and one suggestion. The first remark is that the mission statement is not presented consistently in the documents provided. On several occasions, both in the documentation and the presentations, the second sentence of the mission statement was omitted. ARCNL should ensure the mission statement (pending any revisions, as discussed below) is known by all ARCNL members, and that they be encouraged to always present it in full whenever relevant. The second remark is that the vision statement could be clearer, and like the mission statement, it is not always presented consistently.

It may be that the inconsistencies indicate that the mission and vision statements could be improved or clarified. The committee recommends ARCNL to review the mission and vision statements with respect to them being clear, concise, and current. It is important that they clearly and commandingly point out the strengths and unique aspects of ARCNL, which are indeed highly meritorious according to the committee. Finally, make sure that they conform to what a mission and a vision statement should be. It might be useful to evaluate if the mission statement could be condensed to one sentence. ARCNL could undertake a process of improving the mission and vision statements. A subset of stakeholders could be asked to assess in the process of rephrasing vision and mission, e.g., with a simple survey and soliciting input from internal parties including through in-person discussions, and external parties through correspondence. In addition, this would be an opportunity to promote ARCNL externally more effectively and to ensure that internally the high-level goals are clear.

A new formulation of the mission and vision by itself would be a process to stimulate the stakeholders to talk about mutual expectations, alignment, long term vision, and strategy. It would also ensure ARCNL personnel being aware of the mission and vision statements, and that they can be easily found on the ARCNL website and in ARCNL documents and presentations. The committee believes that ASML and the universities would easily agree on many aspects, while keeping the statements broad enough to permit flexibility.

4.2.2. Strategy

The strategy of ARCNL seems well defined and aligned with ASML. It is continuously updated in the yearly strategy cycle. Both the continuous update of this strategy plan and the focus on mid- and long-term topics help to mitigate the risk of stopping major research activities at ARCNL. For example, the discontinuation of research activities on photoresist is a reason for the slightly lower level of maturity of the materials department compared to the other two departments. A more explicit definition of unique technical opportunities of ARCNL compared to other Dutch and international research institutions could be beneficial to focus specific research activities, to strengthen them by external funding (Dutch projects, EU projects, ERC-grants) and complement them by strategic partnerships with other institutions. To enhance the effectiveness of ARCNL's strategy, the centre may consider to continuously look further ahead than ASML does, to safeguard focus on fundamental aspects of EUV lithography, including researching innovative methods and physical processes.

The ASML application, which is leading for most of the research and researchers, creates a common ground and thereby a unique atmosphere of social connectivity and mutual support throughout ARCNL, plus some additional motivation for scientists that would like to see a future application of their work. This is a strength of ARCNL. The mission statement should give more clarity though, on what phases of development ARCNL should focus. This would reduce potential disappointment when a topic is transferred to ASML and would make clearer what ARCNL could be proud of.

As a public-private partnership, ARCNL is a unique organisation involving stakeholders from very different organisations; universities on the one hand and industry on the other. The committee is surprised that the stakeholders it met during the site visit do not seem to be fully aware of each other's intentions and expectations. Hence, the committee believes that better and explicit alignment between the stakeholders will promote mutual understanding and encourages joint focus. This would also create the opportunity to improve on some aspects that lead to pressure at the level of PIs as the result of different expectations from the stakeholders. This could perhaps be tackled alongside the process of reviewing the mission and vision statements.

The committee also believes that all stakeholders benefit greatly from ARCNL and its output. The committee believes that ARCNL therefore not only deserves longer-term commitments from its stakeholders, but also that stakeholders explicitly recognize that ARCNL has different needs from their own organisations. It

recommends that each stakeholder reconsiders any possibilities to optimize internal processes for the benefit of ARCNL, such as more tailor-made career support for PI's.

4.3. Human Resources Policy

The size of ARCNL, approximately 100 fte (including support staff housed at AMOLF), was chosen as an optimal balance between critical mass and allowing for a multidisciplinary-multigroup research approach with collaboration over the full centre. ARCNL research themes are fundamental and inspired by industrial applications. Group leaders are hired through an open international recruitment process, with the university as formal employer in the lead, involving ARCNL staff members and representatives from stakeholders (with the employer in the lead). Candidates are evaluated based on their competence and experience in collaborating with industrial partners and in flexibility to adapt scientific directions. Senior staff members, meaning (tenure-track) group leaders, have formal appointments with one of the partner universities. PhD students, postdoctoral researchers, technicians, director, and institute manager are almost all employed by NWO-I. The group leader initiates the recruitment of junior researchers, with the involvement of other ARCNL staff. Regardless of the formal employer, all research staff has annual appraisal discussions with the ARCNL director and a representative of the university. For PhD students, these discussions are part of the process to optimize the PhD trajectory. Each PhD student is directly supervised by the group leader, and benefits from a mentorship scheme with a mentor being external to the group, to address any mitigating circumstances. Such a mentorship scheme is not provided to the postdocs, the committee is of the opinion that the university partners could provide support in mentoring postdocs.

Group leaders generally start on a tenure-track (TT) assistant professor position and are expected to progress according to agreements with the employer university. To advance in their career, assistant professors and associate professors must demonstrate successful research, to instigate collaborations, to successfully guide PhD students and postdocs, to complete the University Teaching Qualification (UTQ), raise funding and contribute to the organization. ARCNL supports their development in the form of academic leadership courses and other professional skills training opportunities. A mentoring programme and InterVision support system is setup to provide additional guidance to the TT staff members. ARCNL furthermore supports researchers in applying for talent grants, such as ERCs and personal grants at NWO.

On paper, the requirements for tenure and promotion are similar at all three employer universities. In practice, however, the requirements appear more stringent at one university compared to the others. Teaching requirements are (officially) supposed to be a smaller part of the contract compared to university-based tenure track candidates, but differences in the amount of teaching reduction were reported by group leaders; the committee was unsure if this was mostly a perception, but regardless, it is a significant concern. As well, administrative tasks are dealt with differently between universities. Since the group leaders are doing their research fully at ARCNL, the director has continuous interactions with the universities that employ the TTs and that take decisions on tenure and promotion. Multiple group leaders noted positively that the director has instigated in-person meetings with their university Department Chairs for their formal annual reviews, which the committee commends as well. The committee notes and encourages the aims of university partners to formalize including an ARCNLs panel member in the tenure and promotion process to maintain equity of the process for ARCNL staff. For ARCNL, in particular for its director, it is a balancing act and a search to influence and stimulate the promotion/tenure of its group leaders, as it has no formal role in the decision making.

ARCNL has a substantial number of group leaders at an early career stage, who follow the tenure track path and aim to be promoted to full professors. The unique position of PIs at ARCNL, acting on the crossroad of multiple stakeholders, academy and industry, and significant responsibility by operating outside the walls of a long-standing institute like a regular university, makes them develop fast in aspects that are not part of a 'regular' university group. Concerning proof of quality, ARCNL is of the opinion that some talented PIs show

their scientific excellence faster than is rewarded by the university. Their development is measurable through their track record and accomplishment in obtaining very prestigious funding from NWO or EU as well as publishing high quality research and delivering consistent supervision and teaching. However, for tenure or promotion, the researchers also have organizational and (teaching) management duties. Group leaders noted - and the committee agrees - that substantially reducing the teaching and administrative tasks is crucial given the time and effort research staff must devote to other aspects, e.g., interacting with ASML, focusing on invention disclosures, and patenting activities, contributing to organizational service within ARCNL itself and needing additional time to stay connected to the university group. According to the committee, this should be recognized and rewarded by their (formal) employers.

The Recognition & Reward Initiative provides opportunities to take into consideration the unique position of ARCNL and its research staff. Recognizing that career development and talent management should encompass more than just research performance is an important step toward a more holistic work environment. By placing value on various aspects of an individual's contributions, such as teaching, outreach, and mentoring, ARCNL acknowledges the multifaceted nature of scientific careers. This approach can have several benefits like enhanced motivation, improved research culture and career development. The successful implementation of these measures relies on clear, transparent, and uniform criteria for recognition and rewards beyond research performance. The committee recommends to the partner universities to look for a formal, uniform, and transparent way to include ARCNL-specific input on the development of research staff for tenure/promotion decisions and be more flexible in recognizing ARCNL administrative and coordinating activities in these decisions.

Finally, to further help advance their careers, researchers should be encouraged and given flexibility and recognition for taking on activities such as: leadership roles in organizing conferences and symposia; being involved on committees and leadership structures of national and international professional societies; being involved on editorial boards or in editing special issues of leading journals; and pursuing opportunities to give invited talks externally. ARCNL and its stakeholder partners should make ongoing efforts to nominate their researchers for awards and honours from professional societies. This will benefit not only the individual researchers, but also ARCNL as a whole.

4.4. Academic culture and diversity

4.4.1. Academic Culture

Providing an optimal research environment for PhD students and postdoc is part of the strategic plan. ARCNL actively stimulates community building among all personnel. At centre level this is stimulated by bi-weekly plenary meetings and bi-weekly scientific colloquia with (inter)national speakers and a “pre-talk” by PhD students and postdocs. Junior researchers also organize bi-weekly poster sessions, in which they present their recent work. In addition to academic activities, the personnel club organizes social events.

PhD students are part of a research group and participate in regular group meetings, to ensure interaction with colleagues. Junior researchers also have regular bilateral meetings with their formal group leader. Some junior research staff informed the committee that they miss part of the atmosphere of working at a university, e.g., the students and interactions with non-physicists. This is not something ARCNL can easily change, but the committee encourages the centre to pay attention to this.

4.4.2. Openness, social safety, and inclusivity

ARCNL's academic culture, as described in the self-evaluation report, reflects a proactive and positive approach to fostering openness, (social) safety, and inclusivity. Its commitment to creating an open and transparent atmosphere is evident through its willingness to address issues such as cultural and gender differences, along with promoting various layers of scientific integrity. The centre's approach of including these aspects in yearly discussions with employees indicates a proactive stance toward open dialogue and

the resolution of potential concerns. Openness can lead to a more robust exchange of ideas and collaboration among researchers.

Overall, research staff feel comfortable and respected, including staff representing minorities and female research staff. According to the committee, support and communication on support is very important to continue to feel included. The acknowledgment of (social) safety as a crucial component of academic culture is commendable. The committee is of the opinion that ARCNL does well by prioritizing respect for differences and fostering an environment where individuals can address concerns irrespective of hierarchy, the centre promotes a sense of safety for all its members. The committee appreciates the undertaking of several actions, such as the discussions on psychological safety, performing employee surveys and then assessing and acting on the findings; recognition of the value of the flat structure of ARCNL in supporting diversity and the plans to embark in 2023 on a strategy for making ARCNL "a safe place over the full diversity spectrum and to remove biases". The dedication to inclusivity is a positive sign of ARCNL's commitment to creating a diverse and equitable research environment. By focusing on addressing cultural and gender differences, the centre is taking steps to ensure that all individuals, regardless of their background or identity, feel welcome and supported in their academic pursuits. According to the committee, this dedication and approach should be continued, and moreover, be further strengthened.

4.4.3. Diversity

In 2016 a Gender Equality Plan was drafted, including specific actions to recruit more female research staff. In the evaluation period, this led to an increase in female junior research staff, now approaching 30%. In addition, an active bystander workshop was organized for all personnel. According to the committee, ARCNL has made very impressive progress regarding the hiring and supporting of female researchers and has been successful in obtaining WISE Fellowships. Further mentoring and supporting those employees, paying attention to retention, career growth, and networking with other women (within ARCNL, its partners, and beyond) will be important. During the site visit, ARCNL shared that a diversity committee has been formed and that the centre is committed to further actions. ARCNL has consulted with AMOLF on this aspect, which is beneficial since AMOLF has a well-developed, community-centred Diversity and Inclusion Plan, and won an award for diversity efforts in 2022.

The increase in female research staff is impressive and commendable. At this time, the overall percentage of female PIs is improved but still low (18%) and the number of female PhD students is 22%. The committee sought to compare this to the national average; the closest comparison found were data from the Universities of the Netherlands (UNL, 2022)[1] which reports that, in engineering and the natural sciences, females make up 37% of PhD students and 28% of professors (at all three levels). The numbers may be less when considering the fields populated by ARCNL researchers (mostly physics) but suggest ARCNL remains below the national averages, and so improving these numbers is desirable. ARCNL may also benefit from seeking further statistical data to enable benchmarking of their numbers.

One of the challenges mentioned in interviews is that, already at the bachelor's level, the number of female students is low, creating a limited influx. Another aspect mentioned by female junior staff is the limited number of female role models that can act as informal or formal mentors. The committee suggests that ARCNL collaborates with its partner universities to look for role models with seniority who can help junior female staff in this respect. Additional efforts could bolster the recruitment and retention of women at all levels in ARCNL by enhancing awareness, understanding, and community, including inviting female seminar speakers (from academia and industry) to speak about their research and their experience as women in science; fostering discussions, workshops, or training session for all ARCNL personnel on bias (conscious and

[1] https://www.universiteitenvannederland.nl/en_GB/f_c_ontwikkeling_aandeel_vrouwen.html

unconscious); and working to ensure that D&I issues are integrated in appropriate ways throughout the mandatory PhD courses.

The self-evaluation report mentioned very limited other axes along which underrepresentation and bias can be manifested. This is important as such issues inhibit the recruitment, retention, and advancement of individuals from groups underrepresented in science in terms of race, ethnicity, religion, sexual orientation, gender identity, disability status, and economic background. According to the committee, ARCNL has an opportunity to distinguish itself from others and attract outstanding candidates from minority groups by offering a superior culture in terms of diversity, equity, and inclusion. The small size of ARCNL has the advantage of fostering a sense of cohesiveness and community, with staff using terms like “like a family” and “team atmosphere,” and reporting that they are glad that they all are able to get to know each other. Larger entities cannot match this. To capitalize on opportunities to recruit diverse talent, the committee encourages ARCNL to prioritize its nascent efforts to develop a strategy to address this. Including students, staff, and younger researchers in a bottom-up, community-based approach coupled with clear statements from ARCNL leadership of support for diversity, inclusion, and a commitment to address bias has potential to yield significant progress.

4.4.4. Research integrity

The description of research integrity at ARCNL portrays a centre that places strong emphasis on maintaining high ethical standards and fostering a research culture based on honesty, transparency, and accountability. The fact that topics related to research integrity have become a standard part of yearly discussions with employees is a positive indication of ARCNL's dedication to ensuring that all researchers are aware of and uphold the principles of research ethics. No concerns were raised on this issue during any of the committee’s discussions with ARCNL personnel, leadership, or stakeholders and the committee takes this as a positive sign. Regardless, given the importance of this issue, it may be advisable for ARCNL to survey its personnel on these issues; the self-evaluation report mentions scientific integrity as being covered in the employee survey, but the committee did not see specific questions on this topic in the employee survey report.

The committee noted that one of the Department Heads has been appointed as Scientific Integrity Ambassador. However, the committee was uncertain about the definition of this role and was pleased to learn that , to ensure objectivity and avoid even the perception of conflicts of interest, there are two independent NWO-I trust persons for scientific integrity.

4.5. PhD Policy and Training

ARCNL's PhD training programme is highly commendable, characterized by a comprehensive and quality-focused approach. ARCNL prioritizes strong supervision and instruction, emphasizing joint responsibility between PhD students and ARCNL staff. The presence of a PhD committee highlights a commitment to supporting students at every step. The centre has recently implemented a transparent ARCNL-PhD booklet to introduce students to policies, guidelines, and practices and to be transparent on the expectations for PhD students. The committee is very positive about the booklet but emphasizes the importance of regularly updating the booklet, to keep the information current. A new PhD student is introduced to ARCNL by their group leader, including meet-and-greets and support programmes. PhD students and postdocs are employed via NWO-I and defences take place at one of the partner universities. Usually, the ARCNL group leader is formally employed by one of these academic partners. Annual evaluations follow standardized NWO-I forms. The university partners differ in terms of formal requirements for obtaining a PhD degree. VU and UG require PhD students to collect 30 EC in professional development (e.g., courses, conference attendance and network activities). The UvA does not have such requirements, but in practice all ARCNL PhD students take these credits.

The policy of ARCNL to aim at a PhD degree in four years as the standard, reflects ARCNL's commitment to maintaining high standards and ensuring timely completion of PhD programmes. This focus on quality assurance is vital in maintaining the research centres reputation and the value of its academic programmes. Increased emphasis on post-PhD career development support, including also academic (and not ASML-oriented) pathways, could further enhance the overall quality of the centres' PhD training. For postdoctoral scientists no active programme is in place, but group leaders regularly engage in discussions on next career steps. The committee is positive about the plan to implement coaching for the next step in their career, be it academic or industrial. The committee also suggests placing additional emphasis on post-PhD career support, encompassing diverse pathways beyond ASML-oriented careers. Providing a broader spectrum of career development assistance would enhance the overall quality of the centres' PhD training.

Based on the discussions with PhD students and postdocs, the committee has a very favourable impression on the culture and environment at ARCNL. The community of PhD students is small, and everybody knows each other. The PhD-supervisors are considered excellent, the PIs high motivation, the open atmosphere, and the flat organisational structure of ARCNL were very positively mentioned by the students.

PhD students regularly present their work, both at ARCNL and at the university they are connected to. This latter also results in external interactions, which is very positive. The fact that the PhD students work at ARCNL, and their work might be useful for ASML is considered very positive. As an example, one of the PhD students filed an IDF within the first year and was very proud of this. Some minor complaints were mentioned, like very slow financial administration and problematic time sheets. PhD students and postdocs did mention that they notice and feel stress of their supervisor when he/she is in the tenure track.

Recently, a mentoring programme was initiated, in which a group leader other than the supervisors acts as a mentor. The mentor can provide feedback and support and discuss issues that the PhDs run into, for example with their own supervisor. The committee is very positive about this development and stimulates ARCNL to also setup a mentoring programme for postdocs as well. A minor point of attention is the fact that in the young ARCNL population - with many TTs - it must be recognized that PIs are under pressure requiring ARCNL to have an active policy to prevent this stress to work down to the level of PhD students and postdocs.

While there are many positive aspects, there are also some opportunities for improvement. One suggestion might be to enhance the interdisciplinary collaboration between PhD students, enabling them to work on projects that span different research departments at ARCNL. Furthermore, ARCNL could also consider establishing collaborations with a wider range of national and international universities, thereby providing PhD students with an opportunity to further broaden their education and training.

In summary, ARCNL's approach to PhD policy and training is comprehensive and well-structured. As the committee reflects on the PhD training provided by ARCNL, it notices, that there are certain areas where the programme already excels, but there is of course always room for improvement.

4.6 Research Quality

The ARCNL research programme covers three major research themes: Materials, Metrology, and Source, which are directly linked with the aspects of the modern EUV lithography tool. At the time of the site visit, the three themes housed a total of eleven research groups. In the evaluation period eight new groups started while three other groups were terminated or phased out due to various reasons. The three themes are:

- *Materials research* encompasses surface and interface chemistry in relation to (avoiding) the degradation of materials used in EUV machines. The ARCNL approach uses experimental techniques as well as theoretical methods. The Materials theme includes three research groups: Contact Dynamics, Materials & Surface Science for EUVL, and Materials Theory & Modelling.

- *Metrology research* develops experimental means to look at sub-wavelength structures with few nm-precision. In addition to the AMOLF-ARCNL programme, the Metrology theme includes five research group: EUV Generation & Imaging, Light Matter Interaction, Computational Imaging, HHG &EUV Science, and Nanoscale Imaging & Metrology.
- *Source research* deals with EUV generation challenges. The theme houses three research groups: EUV Plasma Processes, Plasma Theory & Modelling, and Ion Interactions.

According to the committee, the research at ARCNL is outstanding. Researchers and PhD students are viewed as very strong, and the scientific problems chosen are exciting, innovative, appropriate long-range and fundamental. The quality of the research can stand comparison to top university groups world-wide. Frequent evaluations by ASML and the SAC make researchers self-critical, modest, and stronger. The team of relatively young PI's is a major asset to ARCNL and its stakeholders.

Source

In the field of highly charged ions, ARCNL has played a pivotal role in advancing the understanding of the complex electronic and atomic processes governing the behaviour of ions under extreme conditions. Its groundbreaking research on the emission of EUV radiation from highly charged tin plasma sources, as published in Nature Communications, revealed a previously overlooked phenomenon—the contribution of multiply excited states in highly charged ionic states. This insight has had profound implications for EUV lithography, a most advanced and critical technology for the semiconductor industry. By identifying this high density of states between multiple excited ionic states, ARCNL has opened new avenues for more accurate theoretical predictions and enhanced EUV emission spectra.

ARCNL's expertise in ion-surface interactions has yielded critical insights into preventing contamination of silicon and metals in EUV conditions. The research on surface engineering, which focuses on mitigating contamination by preventing oxidation, is essential for maintaining the cleanliness of materials in extreme lithography environments. This research highlights ARCNL’s commitment to resolving practical challenges faced by the semiconductor industry while advancing fundamental knowledge of surface chemistry.

Metrology

ARCNL's work on new metrology methods will lay the foundation for more advanced tools in the semiconductor industry. The research achievements include results with high potential impact on future ASML technologies, e.g., digital holographic microscopy for overlay measurement. Earlier ideas sprouted from this group have been taken up by ASML engineering departments.

Given the growth of semiconductor metrology in general and the excellent infrastructure of ARCNL, there are unique opportunities for the Metrology Department to address future requirements of research and industry. Recent results from the department on the use of ptychography for HHG wavefront sensing, photoacoustic imaging of buried features and investigations on light induced damage of metallic, and dielectric surfaces showcase the very good research output of ARCNL and its potential impact on future metrology solutions for semiconductor fabrication. Other, more fundamental results could have an impact beyond semiconductor industry, e.g., the application of computational techniques for nanoscale imaging beyond the (spatial) Abbe limit.

Materials

The Materials Department is well situated with young, dynamic, expert talent leading its three groups. The Contact Dynamics group for example through its own work and its collaborations with others, has rapidly established itself as a world leader in contact mechanics and tribology, with the work being performed having broad implications across and beyond tribology and contact mechanics. The Materials Theory & Modelling group is innovative and versatile, with notable openness to pursuing a range of problems collaboratively with experimental efforts and industry researchers. They use forefront, cutting-edge

methods. Their work and impact will be significantly advanced by the planned acquisition of a high-performance computer cluster. The Materials & Surface Science for EUVL group has taken on the study of complex and difficult challenges of relevance to EUVL but also beyond and has set up impressive laboratory facilities. Overall, the published output and the conference presentations of these groups are excellent. Moreover, the impact clearly goes well beyond semiconductor equipment problems.

Research accomplishments

The research groups bring fundamental knowledge, new technologies and inspirations to ASML as well as contribute to fundamental, academic knowledge. ARCNL has made a significant and multifaceted contributions to the body of scientific knowledge, with notable achievements in the fields of highly charged ions, extreme ultraviolet (EUV) sources, computational imaging including ptychography, surface physics and chemistry, tribology, and several other areas of fundamental and applied research. Overall, the publication and patent statistics are impressive. The academic reputation and leadership of ARCNL staff within their respective fields are outstanding. This expertise is evidenced by the numerous publications in widely recognized journals, including Nature Communications and Physical Review Letters, as well as the impressive number of prestigious ERC starting, and consolidator grants awarded to them. Beyond the scientific contributions, ARCNL's involvement in the organization of the International Highly Charged Ions Conference in 2024 and the EUV Source Workshops exemplifies its leadership and commitment to advancing knowledge and technology in these fields. The contributions to fundamental science and technological advancements have positioned ARCNL as a leader in nanolithography research, benefiting the semiconductor industry and the broader scientific community.

The interdisciplinary dynamic between researchers is not only seen between different groups in the departments, but between in different departments, and is a strength that has potential to continue to spark unexpected discoveries and advancements. The collaboration between researchers from different groups seems to be well established. Within each of the three departments, clear and structured collaboration and joint projects were shown. Cross-departmental collaboration is also taking place, e.g., in projects with joint PhD students. To an outsider, these many connections and types of collaboration are less visible, which is unfortunate and, according to the committee, collaborations may further increase. The size of ARCNL and the stimulation by management, allows group leaders and junior researchers to spontaneously find each other and come to collaborations leading to beautiful and unexpected discoveries. The committee believes that ARCNL and the group leaders can do a better job of advertising this strength of the centre to the outside world, including to ASML. The unique feature of this centre should be reflected by all PR, culture etc.. The visibility of the high-level research at ARCNL could be even further increased by the involvement of ARCNL researchers in committees of international research conferences, e.g., in the SPIE Computational Optics conference, which covers many of the computational imaging activities of ARCNL.

One example of cross-cutting activities of ARCNL is the application of machine learning activities by several research groups. The leaders of modelling groups are fully aware of the potential and limitations of machine learning for their activities. The application of physics informed neural networks (PINNs) could be beneficial for source modelling and other activities of ARCNL. Most group leaders not only collaborate with other groups within ARCNL, but also interact with research groups at the university they work for, creating a broader network. There are also connections to other institutes and universities, although the committee is of the opinion that these collaborations could be further stimulated and structured.

4.6.1. Connection to ASML

The activities of the Metrology Department and of the Source Department are driven by experienced and highly motivated researchers. Considering this close connection to industry, the groups achieved a remarkable output of high-level scientific publications. Other groups like Nanoscale Imaging are focused on more fundamental aspects of optical metrology and are more loosely connected to ASML. Some of the

methods and techniques, which are developed in these groups of the metrology department, could be interesting for alternative lithography and patterning applications such as advanced packaging, Si-photonics, and 3D integration.

Despite the outstanding research, it was stated to the committee that the relation to ASML in the field of materials science in the context of EUV scanners is more challenging on a fundamental level compared to metrology and source. Fundamental material challenges have to be addressed to improve materials for various parts of EUV scanners and lithographic ecosystems including multilayer mirrors, absorber materials on masks, scanner stages and patterning materials. Ongoing experimental activities on contact dynamics of wafer clamps and on contamination and degradation of multilayer mirrors could be complemented by more fundamental investigations of material properties, which are relevant for other parts of the scanner and lithographic ecosystem. This could include novel methods for the characterization and modelling of material properties, which are relevant for lithography. More interactions with national and academic partners, and experts and ASML, could be helpful to identify the most interesting problems and topics, to be addressed with the expertise of ARCNL. The expertise of the materials modelling group could also be extended to explore the potential of novel patterning materials and processes such as self-assembly. Furthermore, although the photoresist research line has been stopped, the performance of patternable materials is of key importance for the achievable resolution of future lithography systems. One of the major limiters is given by the achievable line-edge roughness (LER), which depends on optical effects (photon noise and finite contrast) and on material inhomogeneities. The optical aspects of LER are relatively well understood. The very good background of the material modelling group could help to complement activities of imec and other partners of ASML to explore fundamental origins of material inhomogeneities and possible mitigation strategies using self-assembly and similar approaches. The committee was impressed by the ARCNL-ASML workshop held at ARCNL just before the committees visit on “Tribology Challenges for Nanolithography Programme 2023”. It was jointly organized by two ARCNL group leaders in the Materials Department and a group leader at ASML and featured international invited speakers, strong attendance by ARCNL and ASML researchers, and a brainstorming session to identify opportunities for research. The committee encourages further efforts like this and others to strengthen ties and communication between ASML and ARCNL, particularly for the Materials Department due to the intrinsic challenges it faces as mentioned above.

4.6.2. Facilities

The facilities at ARCNL are state-of-the-art and a basis for the groundbreaking research and innovation conducted there. They are providing ARCNL researchers with all the tools and environment necessary to make significant contributions to the field of nanolithography and related fields. The laboratories are well-equipped and maintained. The digital holography microscopy (DHM) setups exemplify the very positive impact of the close cooperation with ASML on the research infrastructure of ARCNL. These setups were developed in close collaboration with optical design and algorithms experts at ASML and have produced a number of very relevant results including the first experimental demonstration of 4D aberration correction (recently published in Optics Express).

The environmental XPS system in the Materials Department is one of only a handful of such lab-based capabilities and offers the opportunity to perform both cutting-edge scientific research and research uniquely beneficial to the specific vacuum environment in EUV systems. The tribology apparati in the Materials Department are impressive by the use of customization, which is often needed for meaningful experiments in this area. An area of need, but which is slated to be addressed, is the lack of an in-house computer cluster for materials theory calculations.

4.7. Societal Relevance

Concerning the economic sectors, ARCNL plays a crucial role in advancing semiconductor technology, fostering innovation, and enhancing industry competitiveness through close collaboration with ASML and the development of numerous patents. The scientific quality and innovation are large in ARCNL, and the relation with ASML is not hampering the output. This was considered a potential risk in the first years, but the development of ARCNL has proven better. On the academic front, ARCNL's publications in prestigious journals significantly contribute to the global body of scientific knowledge, providing valuable resources for researchers worldwide. The centre actively participates in outreach programs, conferences, and educational initiatives, effectively promoting science in society. ARCNL's research, therefore, has a significant impact on business and academic sectors, while maintaining an active engagement with the community and academic world.

ARCNL is the first Advanced Research Centre of NWO in collaboration with industry, which works surprisingly well. Industry (ASML) has profited not only from direct problem-solving but from the broader understanding of the scientific basics learned from ARCNL. The public-private partnership status of ARCNL is not used to equate the research as automatically relevant to society. Projects address fundamental questions of low technical readiness levels inspired by ASML challenges. The collaboration of ASML and academia in ARCNL does shorten and facilitate the transfer time from research to application. The impact of semiconductor tool improvements on day-to-day life is large, and the research at ARCNL leading to semiconductor tool improvements has impact.

During the visit, the committee talked to stakeholders about integrity aspects of the Public-private partnership. The agreement between stakeholders and ASML sets out clearly and in detail how IP, patents, spin-out opportunities, and collaborations with other (commercial) parties will be handled. Collaboration with other parties is possible and takes place, with the condition that it cannot be a direct competitor of ASML. The committee believes this is well organised where both ASML and the universities benefit from the collaboration.

The number of IDF and patents is high with nearly fifty patents generated in less than 10 years of existence. Unlike regular universities, focus lies on fast filing of IDFs. The threshold for IDF is very low and most ideas are being sent out. All PIs and PhDs mentioned that the applicability of their research is a positive aspect of working for ARCNL. All stakeholders initially co-own the IP. After publication of the patent, ASML has the option to get it transferred and pays a one-time revenue for the use of patents to ARCNL. The committee encourages ARCNL to look not only at patents applied for when assessing these activities, but also count the number of patents issued, and the number that are licensed externally or made use of by ASML.

Other aspects of societal relevance include the training of future employees of ASML in problem solving, problem analysis, data analysis, instrument building and reporting into articles and presentations. These skills are appreciated in industry and employment at ASML of PhD students and postdoctoral researchers as first job is an indicator of societal impact.

Although formally possible, most PIs are not showing entrepreneurial activities, e.g., start-ups or spinouts. Junior staff the committee talked to was not even aware of any possibilities to do so, or the possibilities to work with other companies. This leads to the committee conclusion that the policy on this aspect is not yet matured. It is possible that for most research staff the collaboration and interaction with ASML is sufficient and within their comfort zone. According to the committee, now might be the time to start thinking about this aspect.

ARCNL could optimize its impact on society by making more work from developing relationships with other companies and making suggestions in public about potential applications of its scientific results other than lithography. This would do right to public investments, academic development of staff, and visibility of

ARCNL. Some examples were provided during the site visit, e.g., with Tata steel, but not yet a strategy at ARCNL level.

Relating outreach activities, which are important to – among others – attract female researchers, ARCNL makes use of the AMOLF structure. Although the committee appreciates the fact that ARCNL – as a small centre – uses an existing structure, a disconnect is noticed between the AMOLF outreach activities and what would best fit ARCNL. Thus, the committee stimulates ARCNL to become more proactive in outreach activities.

4.7.1. Open Science

ARCNL strives to adhere to the principles of Open Science and FAIR data. Together with AMOLF a standardized policy has been developed on open access publishing and research data management.

One step to open science is open access (OA) publishing, for which ARCNL is committed to the key objectives of *Plan S*. Nearly all articles are published open access, of which Gold where possible. In 2021-2022 over 90% of publications appeared with ARCNL having full ownership of the rights. Articles accompanied by a replication package is growing in number (over 75% in 2022), allowing reproduction of the results. The publication process is aligned with the industrial stakeholder ASML. Research outcomes are reviewed for relevant intellectual property by ARCNL and ASML prior to publication. This might lead to a small delay in the publication, but ARCNL research staff (including PhD students) do not consider this delay problematic. In the future, ARCNL strategy will be to use gold open access and generate replication packages for papers. Together with AMOLF and NWO-I generic data sharing schemes will be discussed.

Data management has been professionalised in the evaluation period, with e.g., guidelines for handling and storage of research data, data management plans for PhD students and postdocs, documentation in standardized logbooks. In 2017 a data management plan was written, and a second updated edition has been made in 2023. Further, ARCNL participates with all NWO-I institutes in a Digital Competence Centre, DCC. ARCNL recognizes the importance of proper data management and storage. Its engagement in discussions with NWO-I and AMOLF about generic data sharing schemes indicates its dedication to handling research data responsibly. This approach ensures that research data is organized, preserved, and made accessible, contributing to the FAIR (Findable, Accessible, Interoperable, Reusable) principles in research data management.

ARCNL has a strategic focus on open access, aiming for an implementation rate of over 90%. According to the committee, this commitment to open access ensures that research outcomes are readily accessible to the scientific community and the public. This approach aligns with the principles of transparency and knowledge dissemination. The theme of cybersecurity and knowledge security has gained attention in the last years of the evaluation period. For protection of ICT infrastructure, ARCNL is connected to a so-called SOC-SIEM service. ARCNL also trains its personnel in several aspects of information security.

The committee found that ARCNL actively demonstrates its commitment to open science through various means, including the involvement of stakeholders, accessibility of research, and robust data management practices. This indicates a strong commitment to transparent and accessible research practices. The centre appears to be on the leading edge of open science topics compared to many other academic institutions worldwide. ARCNL has an opportunity to communicate this externally and serve as a model and guide to others, especially if some concrete examples of the tangible benefits/impact/outcomes of these policies can be shared.

4.8. Viability

ARCNL's plans and resources provide a solid foundation for continued scientific excellence and societal impact. ARCNL's viability is well established in the research community and is an important contributor to

the broader societal and institutional context. ARCNL is actively engaged in important areas such as lithography and metrology to meet the evolving needs of the semiconductor industry. A more explicit definition of unique technical opportunities of ARCNL compared to other Dutch and international research institutions would be beneficial to focus certain research activities and complement them by cooperation with others.

The mission statement remains unchanged with respect to the previous evaluation period and defines the ARCNL research strategy for the upcoming period. The strategy contains a significant measure of flexibility, needed for programme changes resulting from the yearly strategy cycle. Strategic plans for the next period are provided in the self-evaluation report:

a. Give content to the national role of ARCNL as one of the NWO-I institutes by stimulating and inspiring academic and other institutes to take up a role in boosting high tech roadmap challenges.
b. Take up a coordinating role in the public-private landscape, connecting to other partners.
c. Create ARCNL research roadmaps to help identify and define scientific breakthroughs and progress/milestones in the upcoming years.
d. Simulate collaboration within and outside the centre to increase excellence by a multidisciplinary project approach.
e. Develop and equip ARCNL groups to allow growing to excellence in a short time.
f. Initiate an incubator programme to prepare for changes in the scientific programme and for connections with other private stakeholders.
g. Take measures to keep ARCNL a dynamic research centre in the present situation where the agreed sized is approximately reached.

According to the committee, the aims and strategy are highly appropriate and well-articulated. ARCNL provides a unique example that shows how fundamental research can have impact far beyond the application areas of interest. This has, according to the committee, global importance for industry, academia, and science in general. The foresight is well-articulated and considered, with good feedback mechanisms and a clear commitment to frequent assessment, feedback, and implementation of change. The centres' clear focus on fundamental research in nanolithography and its collaboration with ASML reflect a forward-looking approach that directly addresses real-world challenges. The core competence of the centre lies in attracting competitive research funding, and in successfully realizing the bridge to industrial application. In doing so, ARCNL proactively addresses the needs of the scientific community and industry, thus consolidating its role as a valuable research institute in the field of nanolithography. From the NWO perspective that the NWO-I institutes play a national role, the committee believes that this is an important part of the upcoming strategy. Although ARCNL significantly differs from other NWO institutes, for example being a public private partnership and not directly having employed the research staff, the national role could be strengthened within the limits of this relatively small centre.

The goals of ARCNL for the upcoming coming period are scientifically relevant for application in nanolithography and well in line with the needs of the industrial partner ASML. The current management is fully aware of the role of ARCNL towards next generation nanolithography, and the overall management with the leadership of the current director seems optimal to reach the goals.

The plans and resources within the three research lines are perfectly implemented within ARCNL, although the visibility of the collaboration between the research lines could be stronger. The committee feels that the viability in the wider context of the centre might need attention. Developments within the field of nanotechnology are going very fast, for instance connected to wear in wafer stages and EUV power generation. In the latter one, for instance, new technologies to generate more power using single laser sources are being studied at ARCNL and the first results look very promising for next generation tools. The

decision to substantially invest further in such technologies seem to be decided mainly at ASML and this might hamper reaching goals within this theme.

The close partnership with ASML provides cutting-edge resources and industry insights, while global participation in conferences such as the Highly Charged Ions Conference underscores the company's commitment to knowledge sharing. Intellectual property management, with numerous patents from basic research, secures valuable resources. Inclusive policies and employee welfare reflect the focus on human resources. The transfer time between scientific discovery and industrial innovation has been substantially reduced by regular meetings between ARCNL and ASML staff. While there is an intimate relation between ARCNL and ASML, other universities and institutions collaborating with ASML might not know and understand the extent and scope of the research within ARCNL. It might be important to take the lead, as ARCNL, to increase such visibility, at least at the national level.

Societally, ARCNL's research enhances the semiconductor industry's competitiveness, impacting the global economy. Additionally, the outreach, public engagement, and local university collaborations signify a commitment to knowledge sharing and community enrichment. This dual relevance underscores the viability of ARCNL's goals.

ARCNL's plans and resources are well-designed, robust, and aligned with its mission. The centre addresses strengths and weaknesses, utilizes opportunities and mitigates threats based on the SWOT analysis. Throughout the site visit, the committee identified several vulnerabilities of ARCNL, e.g., the natural inflow of students from the region being too small, several very small research groups (sometimes even as small as one parttime PI from ASML), no clear activities related to entrepreneurship/spin-off and societal transitions like energy/climate which are important aspects to large groups of potential future employees. ARCNL should look for opportunities to become more resilient. Some important topics for the future of ARCNL are highlighted in the following sections:

Funding

According to the committee, it may be beneficial to further explore sustainable funding models for the long term. Given the importance of stability and predictability in scientific research, ARCNL could consider diversifying its funding sources to reduce over-reliance on one big funding source (ASML). In this respect the ERC grants, obtained by several members of the centre, have an increasingly important role. Furthermore, many of the PIs are relatively young and focus on the application of personal grants. Overall, ARCNL research staff has been very successful in the evaluation period, which is an important step in their academic career. At the same time, the committee noticed that ARCNL is not (yet) exploiting its unique interaction with ASML in funding opportunities. For example, funding in European Pathfinder projects requires industrial partners, making ARCNL an excellent candidate. European projects might seem large for a small organization like ARCNL, though the committee considers such directions and opportunities important in the future strategy. Not only will it potentially lead to external funding, but it also creates visibility for ARCNL.

Partnership with ASML

The focus on the relationship with ASML – including the significant funding - makes that ARCNL researchers seem not all fully aware of activities at other research institutes (in NL) that work for/with ASML. The committee is of the opinion that ARCNL could play a national role in orchestrating these activities. The activities related to ASML also have the unintended effect of pushing less directly related topics to a lower priority. Some topics are even interrupted by lack of PhD students. The committee suggests to finding means to secure a steadier attention and progress on such topics as they are important to the academic and scientific development of the PI's. The committee recommends reflecting on what ARCNL wants, if the current partner (ASML) is sufficient, or does the centre want more.

Stakeholders and governance

As mentioned in this report, ARCNL is clearly of great value for all stakeholders. To a certain degree, these stakeholders acknowledge this. At the same time, the committee notices that the multiple stakeholders have not made all intentions and expectations explicit to each other. According to the committee, it will further strengthen ARCNL, as well as mutual trust and understanding between the stakeholders, if the future perspectives are collectively drafted and disseminated. Furthermore, ARCNL is different from other NWO institutes, university research groups, and industrial partners. In return for the benefits that ARCNL brings to all stakeholders, stakeholders should be willing to introduce substantial flexibility into their relevant internal procedures.

Visibility

According to the committee, ARCNL has much to gain by making its uniqueness and excellent research more visible to the outside world. This is partly in the direction of the stakeholders, who see the added value of ARCNL, but - according to the committee - do not yet see the full potential of this unique centre. ARCNL could also gain reputation in the international academic community. Although small, the committee believes the centre has added value, and could even play a leading role, in international consortia, networks and collaborations. The PIs and their research are internationally known as outstanding, so should ARCNL be.

5. Conclusion and recommendations

Overall, the committee was impressed by the outstanding research that is performed at ARCNL. From the perspective of ARCNL being an excellent research centre, the committee not only evaluated ARCNL on the SEP-aspects and criteria but looked for ways to help ARCNL strengthen its future. The committee felt a lot of trust in the open discussions on important topics during the site visit. All participants showed ambition and enthusiasm, which led to the conclusion by the committee that ARCNL has become a mature research centre focussing on fundamental and long-term research, inspired by and relevant for nanolithography.

The three research lines are very well chosen, and all perform excellent research. The academic excellence is clearly visible and evidenced by the high number of personal grants as well as high impact publications. The size of the institute seems to be a good balance between focus and mass in research, while at the same time stimulates collaborations within ARCNL and maintain its unique character. The committee was furthermore impressed by the remarkable transformative aspects at ARCNL.

The committee got evidence for a collaborative spirit, at management level, PI level and junior scientist level. The flat hierarchy and strong communication between departments and groups strengthen the exchange of ideas and methods. PIs play a very important role in building bridges between ARCNL and ASML. More importantly, ARCNL PIs stimulate ASML to think about important future issues, challenges, and opportunities in nanolithography, such as new concepts for EUV sources, new concepts for metrology, digital holographic microscopy, and understanding wear in wafer stages.

The PhD training programme has a comprehensive approach and strong supervision and guidance of PhD students by young, knowledgeable, and motivated PIs. The committee appreciates the ambition to a transparent and supportive PhD system, with the development of a PhD booklet and structured introduction process. PhD students were positive about the culture and environment at ARCNL. The small, close-knit community and excellent supervision contribute to a positive atmosphere.

From this very positive perspective, the committee has a number of recommendations for the future:

1. The **succession of the current director** will not be easy, the candidate is required to have a good academic reputation, leadership skills and understanding of and/or experience in industry. The director has to be able to communicate with the different stakeholders involved. The search process should be intensified, with stakeholders actively soliciting for candidates.
2. The uniqueness of ARCNL could be better reflected in the **mission and vision statements** and in how consistently they are communicated. The process of reviewing and improving the mission and vision statements will stimulate the stakeholders to talk about mutual expectations, alignment, long term vision, and strategy. Clarification and explicit goals and ambitions will not just help the management team but will clarify expectations and processes for especially junior staff members.
3. The university stakeholders should take pride in their role in ARCNL and would support ARCNL and its research staff by working towards a formal, uniform, and transparent way to include ARCNL input on the development of research staff for **tenure/promotion decisions** and be more flexible in including ARCNL administrative and coordinating activities in these decisions.

The three recommendations above should be addressed in a focused series of joint working meetings of all stakeholders. A working premise of this process should be to recognize the uniqueness of ARCNL and the benefits it brings to all stakeholders. From that, a joint commitment to coordinate in an aggressive search for a director can emerge. A shared understanding of the Mission and Vision of ARCNL can be solidified. More flexible HR policies and alignment between university partners can be established. An improved understanding with ASML regarding the value of broader research goals and more entrepreneurial pursuits

can be stimulated. A recognition by NWO that the national role of ARCNL is different compared to other institutes can be cemented.

4. ARCNL's dedication to **diversity** and **inclusivity** is very positive, this dedication and approach should be continued and further strengthened. The challenge to achieve gender balance already exists at the bachelor's level and also the number of female role models to act as mentors is limited. The committee suggests that ARCNL collaborates with its partner universities to look for role models with seniority that can help junior female staff in this respect. The committee also supports ARCNL proceeding to develop and execute plans to address issues beyond gender for which underrepresentation and bias are manifested.
5. **PhD students and postdocs**:
    a. The PhD students would benefit from increased emphasis on post-PhD career development support, including academic (and not ASML-oriented) pathways.
    b. The committee is very positive about the mentoring programme for PhD students and stimulates ARCNL to also setup a mentoring programme for postdocs as well.
    c. The committee recommends enhancing the interdisciplinary collaboration between PhD students, enabling them to work across research departments.
    d. Some PhD students miss the buzzing academic culture present at universities. Together with the university partners, a solution might be found.
6. ARCNL has been very successful in acquiring competitive grants but could work on further diversification of its **funding**, to increase long-term sustainability. The connection to ASML provides unique opportunities, for example funding in European Pathways projects requiring industrial partners. European projects might seem large, though such directions and opportunities are important in the future strategy.
7. The connection and interaction with ASML are very good but might limit the **entrepreneurial** activities of many PIs, at least compared to university environments. To increase its impact on society, including sustainability challenges, ARCNL could develop relationships with other companies and make suggestions in public about potential applications of its scientific output other than lithography. **Outreach** activities could be more strongly tailored to ARCNL's research to increase impact.
8. ARCNL is a relatively young institute and has matured in recent years. It could be further strengthened by making its uniqueness and excellent research more **visible** to the outside world, both to the stakeholders and to the international academic community. This requires ARCNL to be less modest and aim at leading roles in Europe, e.g., in international consortia and networks.

Appendices

Appendix 1: SEP Questions Evaluation NWO institutes

The three main criteria:

1. Research quality

- How does the assessment committee assess the scientific quality of the institute, in light of its own aims and strategy? Central in this assessment are the contributions to the body of scientific knowledge. The assessment committee is asked to reflect on the quality and scientific relevance of the research. Finally, the academic reputation and leadership within the field is assessed. Looking ahead into the future, which recommendations can the committee give to the institute regarding their research quality?
- How does the committee assess the institute's place in the national and/or international research landscape? Is the institute a frontrunner or a follower in its field? Does the committee see untapped opportunities?

2. Societal relevance

- How does the committee assess the societal relevance in terms of impact, public engagement, and uptake of the institute's research in economic, social, cultural, educational or any other terms that may be relevant? The assessment committee is asked to reflect on societal relevance by assessing an institute's accomplishments in light of its own aims and strategy. Looking ahead into the future, which recommendations does the committee have for the institute regarding its societal relevance?

3. Viability

- How does the committee assess the extent to which the goals for the coming six-year period remain scientifically and societally relevant? It is also asked to assess whether its aims and strategy as well as the foresight of its leadership and its overall management are optimal to attain these goals. Finally, the assessment committee is asked to assess whether the plans and resources are adequate to implement their strategic plan. The assessment committee is also asked to reflect on the viability of the institute in relation to the expected developments in the field and societal developments as well as on the wider institutional context of the institute.
- How does the committee assess the way the institute fulfils their national role and does the committee have any recommendations regarding this?**1**
- How does the committee assess the way the institute contributes to the vision on 'Dutch research in 2030' as is written down in the NWO Strategy 2023-2027 and does the committee have any recommendations?

1 *With respect to the reports from the PCNI, the portfolio committee and (where relevant) the exploration reports.*

In addition, there are also four important aspects contributing to the success of the institute:

4.1 Open Science

The assessment committee is asked to consider to which extent the institute opens up its work to other researchers and societal stakeholders in the context of its strategy and policy. Furthermore, the committee is asked to consider whether the institute reuses data where possible; how it stores the research data according to the FAIR principles; how it makes its research data, methods, and materials available; and when publications are available through open access. The committee is specifically asked to give the institute and NWO-I recommendations on their Open Access and FAIR data and software policy. The assessment committee is asked to reflect on the current policies, and the practices with regards to the open availability

of the publications, research data and methods and assess them in light of NWO's high ambitions (e.g. is the institute a frontrunner in its field with regard to Open Access and FAIR data and software?).

4.2 PhD policy and Training

The assessment committee is asked to consider the supervision and instruction of PhD students. Furthermore, the committee is asked to consider whether the quality assurance system is functioning properly. The committee is asked for recommendations on how to enhance the supervision and education of PhDs (together with the universities), also in light of the three main criteria.

4.3 Academic Culture

Openness, (social) safety and diversity & inclusivity: The assessment committee is asked to consider the openness, (social) safety and diversity & inclusivity of the research environment. The assessment committee is also asked to evaluate the actions and plans for the future of the institute with regards to (social) safety, diversity & inclusivity.
Research integrity: The assessment committee is asked to consider the institutes policy on research integrity as well as the way the institute facilitates the relevant actions and requirements formulated in the Netherlands Code of Conduct for Research Integrity. For both themes: Looking ahead into the future, which recommendations does the committee have for the institute regarding their academic culture, also in light of the three main criteria?

4.4 Human Resources policy

Talent Management: The assessment committee is asked to consider the institute's policies on talent selection and development in relation to its aims and strategy. More specifically, it is asked to evaluate the institute's recruitment policies, opportunities for training and development, coaching and mentoring, as well as career perspectives for researchers and research support staff in difference phases of their career. An important aspect of this is the (inter)national cultural change regarding recognition and rewarding in academia that NWO-I is implementing. What are the institute's plans to further the desired cultural change and which recommendations does the committee have for the institute and NWO-I?

Appendix 2: Programme of the site visit

Wednesday 8 November 2023, Working dinner 19.00 - 21.00 hours.

18.00 – 18.30 Welcome and installation SEP Committee by representative Executive Board NWO

18.30 - 21.00 Working dinner: preparation site visit

Thursday 9 November 2023, 09.00 - 18.00 hours

09.00 - 09.15 Welcome by director ARCNL

09.15 - 10.00 Self-assessment ARCNL, dashboards

10.00 - 11.00 Interview 3 departments, group leaders

11.00 - 11.30 Coffee break, reflections

11.30 - 12.30 Speed dates junior researchers

12.30 - 13.45 Lunch, informal meetings staff

13.45 - 14.30 Reflection on interviews, additional questions

14.30 – 16.00 Lab-tour - informal contact SEP with group leaders and researchers

16.00 - 16.30 Coffee break

16.30 - 18.00 Closed session, preliminary findings, follow up questions

18.30 - 21.30 Dinner SEP with ARCNL staff

Friday 10 November 2023, 09.00 - 17.30 hours

09.00 - 09.45 Follow-up questions

09.45 – 11.45 Individual discussion with the ARCNL stakeholders

11.45 - 12.45 Closed session

12.45 – 13.30 Lunch, informal meetings staff

13.30 - 15.00 Closed session, finalizing draft SEP report

15.00 – 15.30 Presentation preliminary findings by SEP chair

15.30 – 16.00 Drinks

Appendix 3: Quantitative data

Input of research staff, support, technical staff

	2017	2018	2019	2020	2021	2022
Group leaders	6,7	7,6	10,5	9,5	12	10,9
Postdocs	8	9	8,4	11	17	16,8
PhD candidates	27,7	34,2	32	32,8	35	39
Researcher (others)	7,5	6	7,5	8	6	6,5
Total research staff	**49,9**	**56,8**	**58,4**	**61,3**	**70**	**73,2**
Support staff ARCNL	9,4	9,3	10,6	11	11	11,3
Support staff AMOLF	13,1	13,8	13,5	14	15,3	15,1
Total support staff	**22,5**	**23,1**	**24,1**	**25**	**26,6**	**26,4**
Total staff	**72,4**	**79,9**	**82,5**	**86,3**	**96,3**	**99,6**

Researcher (others) include MSc students and visiting fellows. Support staff ARCNL includes research technicians, ARCNL secretariat, shared Occupational health advisor and institute manager. The group leaders are employed at VU (Witte, Versolato, Kraus, Amitonova, Sheil), UvA (Planken, Bliem, Weber, Olsson), and RUG (Hoekstra). Den Boef is employed at ASML and extraordinary professor at the VU. Koenderink is fully employed by AMOLF (NWO-I) and is not counted as one of the group leaders here.

Funding

	2017	2018	2019	2020	2021	2022
FUNDING						
Direct funding	7.496	7.477	7.778	7.592	8.320	8.767
External funding	99	437	1.076	1.284	1.866	2.731
PPP-allowance	84	443	853	788	806	755
Other	0	142	0	0	0	0
Total funding	**7.679**	**8.499**	**9.707**	**9.664**	**10.992**	**12.253**
EXPENDITURE						
Personnel costs	4.166	4.903	5.252	6.147	6.633	7.435
Other costs	4.244	3.773	3.748	4.244	3.639	3.990
Total expenditure	**8.410**	**8.676**	**9.000**	**10.391**	**10.272**	**11.425**

The direct funding was initially distributed as follows: ASML 50%, NWO-I 33%, UvA and VU 18% (in-kind). In 2022, by the accession of the RUG the contribution of the public partners increased.
External funding includes NWO, ERC and other funding sources, except PPP-allowance.
The numbers reflect the turnover (as spent during the year) and does not reflect the total project budget allocated when a proposal is granted.

PhD success

				Duration start date until graduation in months						
	M #	F #	Total	≤ 4 years	between 4-5 years	between 5 - 6 years	> 6 years[3]	Total	Active	Dis-continued[1]
Starting year										
2012	1	0	1	0	1	0	0	1	0	0
2013	1	0	1	0	0	1	0	1	0	0
Start of ARCNL										
2014	5	2	7	0	3	1	1	5	0	2
2015	8	2	10	0	5	2	1	8	1	1
2016	7	1	8	1	3	0	2	6	0	2
2017	5	1	6	0	3	0	1	4	2	0
2018	6	3	9	1	3	2	1	7	1	1
2019	6	0	6	0	2	0	0	2	4	0
2020	7	2	9	0	0	0	0	0	8	1
2021	6	3	9	0	0	0	0	0	9	0
2022	8	3	11	0	0	0	0	0	11	0
Total	**60**	**17**	**77**	**2**	**20**	**6**	**6**	**34**	**36**	**7**