X-Road Sustainability Improvement Study

Public Report

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Terms and Abbreviations

In the following table, the items are ordered in logical groups (i.e., not in alphabetical order).

TERMS, CONCEPTS	Explanations
Sustainability	▪ "System's sustainability describes how well it will continue to exist and function, even as circumstances change. ▪ Is multidimensional; the five key dimensions are economic, social, environmental, technical, and individual" [5] ▪ "Is systemic" [19]
Environmental sustainability	▪ "Concerned with the long term effects of human activities on natural systems." [19] ▪ "Covers the use and stewardship of natural resources. ▪ Ranging from immediate waste production and energy consumption to the balance of local ecosystems and climate change concerns." [5] ▪ "For software-intensive systems, this means addressing ecological requirements, including energy efficiency and creation of ecological awareness." [25]
Technical sustainability	▪ "Longevity of information, systems, and infrastructure and their adequate evolution with changing surrounding conditions ▪ Includes maintenance, innovation, obsolescence, data integrity" [19] ▪ "Refers to maintenance and evolution, resilience, and the ease of system transitions." [5] ▪ "long-term use of software-intensive systems and their appropriate evolution in a constantly changing execution environment" [25]

Social sustainability	▪ "For software-intensive systems, it encompasses
	  o the direct support of social communities in any domain, as well as
	  o activities or processes that indirectly create benefits for social communities." [25]

Sustainable Software Engineering	▪ "developing sustainable software through a sustainable software engineering process.
	  o A process where software products are developed in a way that mitigates the negative impacts, which result or are expected to result in a software product that throughout its life cycle is continuously evaluated, documented and used for additional optimization of the software product.
	  o a development which is able to make a balance between rapid release and long term sustainability" [4]

Sustainable software	▪ "Software whose impact on the economy, society, humans and the environment resulting from the development, deployment and use of the software is minimal and / or ▪ has a positive effect on sustainable development" [4]
Green software	"Terms Green and Sustainable software have been used interchangeably" [4]
Green coding	▪ Energy-efficient software coding, optimizing to minimize energy consumption ▪ "green code, which addresses how to efficiently organize the software itself." [20]
Green IT	▪ "Concerns with the environmental footprint of the IT sector" [21] ▪ "such as lower energy consumption in data centers and for cloud services" [20]
Green ICT	▪ "Originally, green ICT was understood to be limited to the direct effects of ICT on the environment" ▪ "nowadays, it is often considered to include the use of ICT to improve the environmental efficiency of other industries and domains." [23]
Sustainable ICT	"Concept that encompasses environmental, economic and social sustainability" [1]
Energy efficiency	▪ Useful work done / Used energy [10] ▪ "The usage of less energy to achieve the same level of activity." [2]
Performance efficiency	"Performance with respect to the amount of resources used under stated conditions" [13]
Direct emissions	"Emissions from sources that are owned or controlled by the reporting company" [11]
Indirect emissions	"Emissions that are a consequence of the activities of the reporting company, but occur at sources owned or controlled by another company" [11]
Downstream emissions	"Indirect GHG emissions from sold goods and services" [11]

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[1] https://www.aka.fi/en/research-funding/apply-for-funding/calls-for-applications/apply-now2/research-development-and-innovation-programme-ict-2023-sustainable-and-energy-efficient-ict-solutions-for-the-future/

[2] https://www.niis.org/s/NIIS_XRoadFootprint_Final.pdf (26.5.2021)

Upstream emissions	"Indirect GHG emissions from purchased or acquired goods and services" [11]
Carbon handprint (of a product)	▪ "A carbon handprint is the reduction of the carbon footprint of others." [17] ▪ "An indicator of the climate change mitigation potential. Describes the GHG emission reduction in a user's activities that occurs when the user replaces a baseline solution with the offered solution." [17] ▪ "Is achieved by comparing the carbon footprint of the baseline solution with that of the carbon handprint solution when used by a customer." [3]
Environmental handprint	▪ "An umbrella concept incorporating various positive environmental impacts" [17]
Life cycle assessment (LCA)	"A methodology to quantify and assess the inputs, outputs, LCA and potential environmental impacts of a product system throughout its life cycle" [17]
Immediate effects	"Direct effects of the production, use, and disposal of software systems o Includes the immediate benefit of system features and the full life-cycle impacts" [5]
Enabling effects	"Arise from a system's application over time. o changes induced by system use" [5]

Structural effects	"persistent changes observable at the macro level.
	   o shifts in capital accumulation;
	   o changes in social norms, policies, and laws;" [5]

Proxy data	"Data from a similar process or activity that is used as a stand-in for the given process or activity without being customized to be more representative of the given process or activity" [11]

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[3] https://www.handprint.fi/

Executive Summary

Sustainability is one of the NIIS core values, and NIIS has set an ambitious goal to make X-Road the most sustainable data exchange solution of its kind. Hence, sustainability is one of the strategic focus areas in the X-Road software development.

NIIS has previously (2021–2022) addressed X-Road sustainability by conducting a study of the environmental impact of X-Road and the possibilities of reducing it (including the *Emissions Calculator*). In addition, there have been internal investigations for evaluating the sustainability of the X-Road development process and integrating green software development principles into X-Road's current development process (2023). Furthermore, a public X-Road Academy course Sustainability in Software Development has been created.

Grounding on the abovementioned prior works, the planned aims (in 2022) of the present study were to investigate the following themes—focusing on the environmental sustainability:

- X-Road software development process environmental impacts evaluation and improvement opportunities discovery (WP1)

- X-Road environmental handprint evaluation (WP2)

- X-Road carbon footprint measurement in actual operative environments comparing to the X-Road Emissions Calculator estimations (WP3)

In addition, to begin with, the NIIS and X-Road sustainability strategy was discerned in general in order to justify and position this investigation reasonably in the overall context.

The key findings and conclusions of the study are as follows:

- Sustainability strategy: There should be a shared understanding of what sustainability means for NIIS, and especially what (environmentally) sustainable X-Road software is. The strategic sustainability goals should be communicated to all X-Road stakeholders (software developers, X-Road operators, and member organizations). The X-Road product roadmap and features/enhancements (backlogs) should then be managed to satisfy them.

- X-Road sustainable software development (WP1): Sustainability should be treated in similar ways as security throughout the software development life-cycle. Sustainability requirements should be defined and managed. Technical sustainability may be as important as environmental sustainability.

- X-Road handprints (WP2): Considering X-Road as a part of solutions may open new business opportunities (product strategy). In addition to environmental positive effects, there may be economic and social benefits.

- X-Road carbon footprints (WP3): The focus should be on energy consumption (and consequent carbon emissions) of most significant, meaningful workloads representing actual X-Road usage in typical instances and execution patterns over time. The actually induced carbon emissions in

different X-Road instances should be determined taken into account possible time dynamics of current electricity production systems.

To finish, the study suggests future work items (research questions) for each theme, including the following:

- Communicating NIIS and X-Road sustainability

- **Energy management support within the X-Road infrastructures**

- X-Road handprints: What could be economic, social benefits—in addition to environmental ones?

- Relationships between X-Road software energy consumption and the carbon emissions in actual X-Road instances

Finally, supplementing this report document, the study produced also additional artifacts (e.g., enhancements for the X-Road development process description). They are available separately.

1. Introduction

Sustainability is one of the NIIS core values.[4] NIIS considers ethical, social, environmental, cultural, and economic dimensions in its products, services and processes. Aligned with the values, NIIS has set an ambitious goal to make X-Road the most sustainable data exchange solution of its kind, in terms of the full ESG (Environmental, Social, and Governance) scope. The NIIS aim is not to do "greenwashing" but to take concrete steps towards the ambitious goal considering the full scope. Hence, sustainability is one of the focus areas in X-Road development. Also, NIIS favors the attainment of the UN SDGs and adheres to the ESG principles.

ESG represents a framework for evaluating an organization's or product's environmental and social impact. When referring to ESG in the context of a product, it generally means assessing and considering the environmental, social, and governance aspects associated with that particular product throughout its life cycle. ESG scores are frequently used proxies for evaluating sustainability in organizations [21]. They are not designed to measure sustainability concepts, but with ESG different stakeholders can evaluate how organizations manage sustainability related risks and opportunities [24].

1.1 Background

Previously (2021–2022) NIIS has addressed X-Road sustainability as follows:

- *Towards a sustainable digital future with X-Road[6]*
- https://x-road.global/sustainability

In doing so, the following documents and artefacts have been produced:

- *Report: study of the environmental impact of X-Road and the possibilities of reducing it[6]*
- *Evaluating the Sustainability of the X-Road® Development Process*
- *Sustainability in Software Development - X-Road Academy*
- *Integrating Green Software Development Principles into X-Road's Current Development Process (Draft)*
- *ESG in the X-Road development*

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[4] https://www.niis.org/strategy
[5] https://www.niis.org/blog/2022/1/14/towards-a-sustainable-digital-futurenbspwith-x-road (14 January 2022)
[6] https://www.niis.org/s/NIIS_XRoadFootprint_Final.pdf (26.5.2021)

1.2   This Study

With those headings and prior results, the purpose of this research work was to investigate the following themes:

- X-Road software development process environmental impacts evaluation and improvement opportunities discovery (WP1)

- X-Road environmental handprint evaluation (WP2)

- X-Road carbon footprint measurement in actual operative environments comparing to the X-Road Emissions Calculator estimations (WP3)

1.3   Approach

The research approach leans partially on the GQM+Strategies methodology [1], [2]. The applied NIIS / X-Road Sustainability Framework grid (Appendix 1) was constructed according to the general structuring shown in Figure 1.

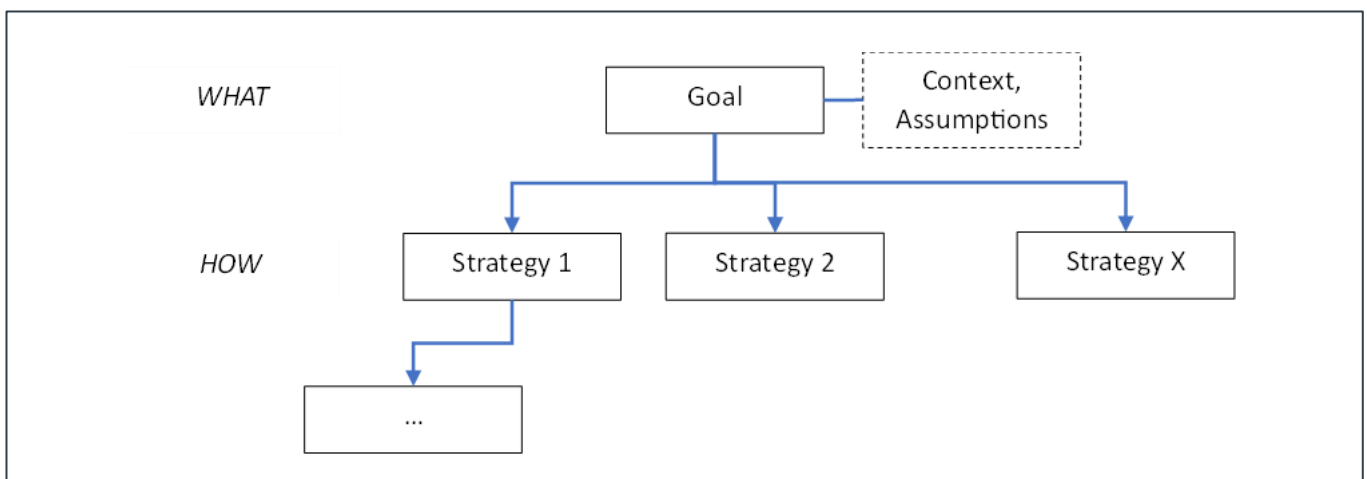

Figure 1. Research framework structure.

The highest-level goal in the grid was the overall NIIS sustainability, but this investigation focused subsequently on the X-Road sustainability parts of the grid. The elements and information in the gridwork are based on selected research literature, prior NIIS works (see 1.1), and continuous information-sharing discourses with NIIS representatives.

1.4 Structure and Organization

Ch. 2 reports the discoveries and inferences for the NIIS and X-Road sustainability strategy. The following main chapters (3, 4, 5) presents the key research activities and results of the study for each research theme (see 1.2). Finally, Ch. 6 summarizes the key conclusions and collects potential items for future studies.

Each main chapter (2–5) includes the following subsections:

Considerations and Recommendations

- Inferences, rationales, suggestions
- Question items for checkups, pondering and triggering further discussions and improvement actions (in structured tables)
- Recommendations

Supports

- Pointers to specific pages in Appendix 1
- Models, tools, and examples

The supporting material is included in partially separate documents.

2. Sustainability Strategy

To begin with, X-Road sustainability was considered holistically with respect to the overall NIIS sustainability strategy as shown in Figure 2 (page (1) in Appendix 1). It is important to understand the NIIS context and the aims, drivers, and constraints of X-Road sustainability improvements.
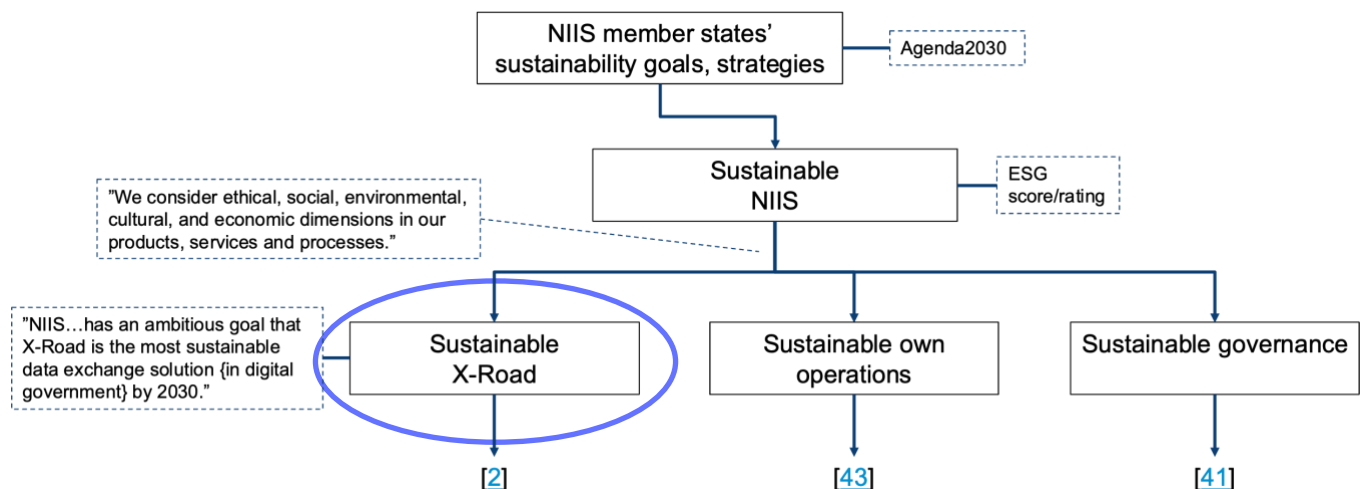

Figure 2. X-Road sustainability improvement context.

2.1 Considerations and Recommendations

In general, sustainability is systemic and multidimensional. Consequently, sustainable X-Road concerns many aspects ranging from the business and organizational strategies to software development technical matters. Table 1 explicates these different areas of interests, drivers, and constraints—primarily from the environmental sustainability point of view.

SUSTAINABILITY STRATEGY: In all, the strategic intent of NIIS to make X-Road the most sustainable data exchange solution in digital government by 2030 should be operationalized and actualized in practice. Overall, this means that the role of X-Road software in digital government services should be realized. The meaning and coverage of sustainability should then be explicated in the different contexts. The weighting of different sustainability dimensions is a strategic decision. In this study period, the environmental dimension was consciously emphasized.

STAKEHOLDER CONCERNS: There are many different stakeholders for X-Road—including the operators and member organizations in different ecosystems. Each one may have their own interests and goals for sustainability. It is important to recognize and understand their standpoints and reasonings, and then align X-Road product offerings accordingly to meet as many of the different sustainability goals

as deemed appropriate and feasible to achieve. Notably such factors may change over time, so the strategic planning should be continuous.

PRODUCT STRATEGY: Once the stakeholder needs and strategic choices are settled, the X-Road product strategy should be devised accordingly to align and satisfy them within the NIIS external and internal constraints and practical realities. There may be partial discrepancies—perhaps even conflict—requiring balancing and making informed tradeoff selections. Because sustainability is achieved over time, both short-term and long-term factors should be taken into account.

PRODUCT DEVELOPMENT MANAGEMENT: The product strategy and the resulting product roadmap direct the actual X-Road software product development for the product releases. The sustainability of the new features and enhancements should be addressed explicitly. That may require dedicated efforts and resources.

SOFTWARE DEVELOPER CONCERNS: Ultimately, the X-Road software developers implement the software releases realizing the defined sustainability goals satisfying the prioritized stakeholder needs and requirements. They have the competences and resources for achieving them in sustainable ways. Moreover, ideally, they have vested interests in doing so.

Table 1. Considerations for NIIS / X-Road sustainability strategy.

X-ROAD SUSTAINABILITY STRATEGY

• Are environmental impacts primary reasons for digitalization or developing new digital services with X-Road? [7]
• Have environmental impacts been typically evaluated? [7]
• Is X-Road as part of the problem and/or as part of the solution?
   o Does X-Road technology help organizations address environmental issues?
   o Is X-Road technology itself responsible for environmental degradation (e.g., by consuming energy)?
• What dimensions of sustainability (technical, environmental, economic, social, individual) of X-Road software development are considered?
• How is X-Road sustainability included in the NIIS corporate responsibility reporting?

X-ROAD STAKEHOLDER CONCERNS

• What are the interests of different actors and organisations in different X-Road ecosystems with respect to sustainability? [21]
   o Business, customers, shareholders, stakeholders
     o Do users (operators, member organizations) want to protect the environment by reducing carbon emissions and electricity use?
• What do the organizations want to achieve with respect to sustainability, and how? [21]
   o How does X-Road product support achieving these goals?

cont.

X-ROAD PRODUCT STRATEGY

- Is sustainability a product obligation, a requirement on the part of the users (operators, member organizations)? [4]
  - Does NIIS incorporate investments in business decisions to produce more sustainable software and implement sustainable Software Engineering practices?
- Do policies require or incentivize sustainability improvements in products and services? [21]
  - Do NIIS organizational policies support creating sustainable software products? [18]
- Do short-term priorities and/or KPIs conflict with sustainability goals? [21]
- Do technical and/or economic constraints or even attitudes of the customers/users (operators, member organizations) hinder the attainment of sustainability? [6]
- Are users (operators, member organizations) willing to invest in more sustainable products or services? [21]
- Does NIIS struggle to compete against less sustainable alternative suppliers? [21]
- Is there right talent who have knowledge of sustainability and can transfer that to software product opportunities? [21]
- How does the X-Road product strategy take into account the UN SDGs?
- How do new features (X-Road extensions) contribute to selected sustainable development goals/targets?
  - Is it country/ecosystem-specific (X-Road operators and members world-wide)?
- What impacts will global megatrends probably have on X-Road? [22]
  - "Competition for digital power gears up"

X-ROAD PRODUCT DEVELOPMENT MANAGEMENT

- Does the development of sustainable X-Road software require additional effort? [4]
  - Do the current projects foresee this type of cost to implement sustainable software?
- Has it been customary to rely on increasing hardware capacities rather than demanding software developers to optimize the software to be more resource-efficient and thereby more environmentally sustainable? [6]
- Is there appropriate awareness on whether the software product solutions are sustainable enough? [21]
- Are there sufficient technical skills to measure the impact of the software products on sustainability? [21]

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X-ROAD SOFTWARE DEVELOPER CONCERNS

- What are the X-Road software developers' personal interests with respect to sustainability? [21]
- Do they take on responsibility for the software and its sustainability impacts? [21]
- Do X-Road software developers consider sustainability as a part of their responsibilities?
- Is sustainability knowledge considered important for software developers? [21]
- Does NIIS join software developers with sustainability experts? [21]
- Are there enough talented programmers who can deliver energy-efficient code? [21]
- Do X-Road software developers have a deep enough understanding of how sustainability impacts the development processes and the resulting products? [21]
- What are the sustainability-related competencies and skills that the X-Road software developers need to achieve the established sustainability goals? [21]
  - sustainability-related skills and competencies, soft skills, and technical skills
  - software engineering for sustainability beyond the software systems themselves
- What are the NIIS and X-Road stakeholder needs for education and training from software engineers' perspective? [21]

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The following list recommends concrete tasks for the X-Road sustainability improvement actions for the NIIS / X-Road sustainability strategy. The question items in Table 1 can be used to assist them.

- Establish a common, shared understanding of what sustainable X-Road software is.
  - Document it openly (e.g., https://x-road.global/sustainability).

Sustainability conceptualization should be openly visible and transparent. Moreover, it should be concretely realizable in practical terms.

- Consider generic sustainability competences in NIIS:
  - Systems thinking
    - X-Road as a part of larger systems
  - Futures thinking
  - Strategic thinking and agency

Sustainability requires both generic and domain-specific competencies. Systems thinking is important for conceiving and understanding how X-Road is incorporated in larger systems. In there, sustainability effects may be direct or indirect caused for example the electricity production needed to run X-Road ICT systems but also for instance the other information systems utilizing it. Moreover, there may be indirect, systemic effects stemming from the end-user services which X-Road facilitates. Sustainability is also time-dependent requiring long-term future-oriented thinking for realizing different potential and desired futures and scenario paths. All that should be taken into account in strategy planning and management.

- Consider developing stakeholders about NIIS / X-Road sustainability (training and education). [13]

It is especially important to share a common understanding of what everything sustainability means for NIIS regarding X-Road and its software development. NIIS sustainability strategy should be realized.

➤ Organize a workshop on the potential impacts on and opportunities for X-Road caused and brought by megatrends [22]:
  o A fair digital world:
    o The data economy is growing.
    o Data collection is increasing.
    o The digitalizing world is increasingly vulnerable.
  o Restorative and regenerative economy:
    o Corporate responsibility is expanding.

Such joint workshops could support formulating and maintaining the NIIS / X-Road sustainability strategy. Furthermore, such co-developmental activities may bring new ideas for the X-Road product strategy and roadmap.

2.2 Supports

- Pages (1), (2), (41) in Appendix 1

- Figure 3 depicts an overall systems view of X-Road software sustainability with environmental sustainability—especially carbon emissions—as the focus area of this study. There are multiple actors and processes affecting the environmental impacts in different phases over time.
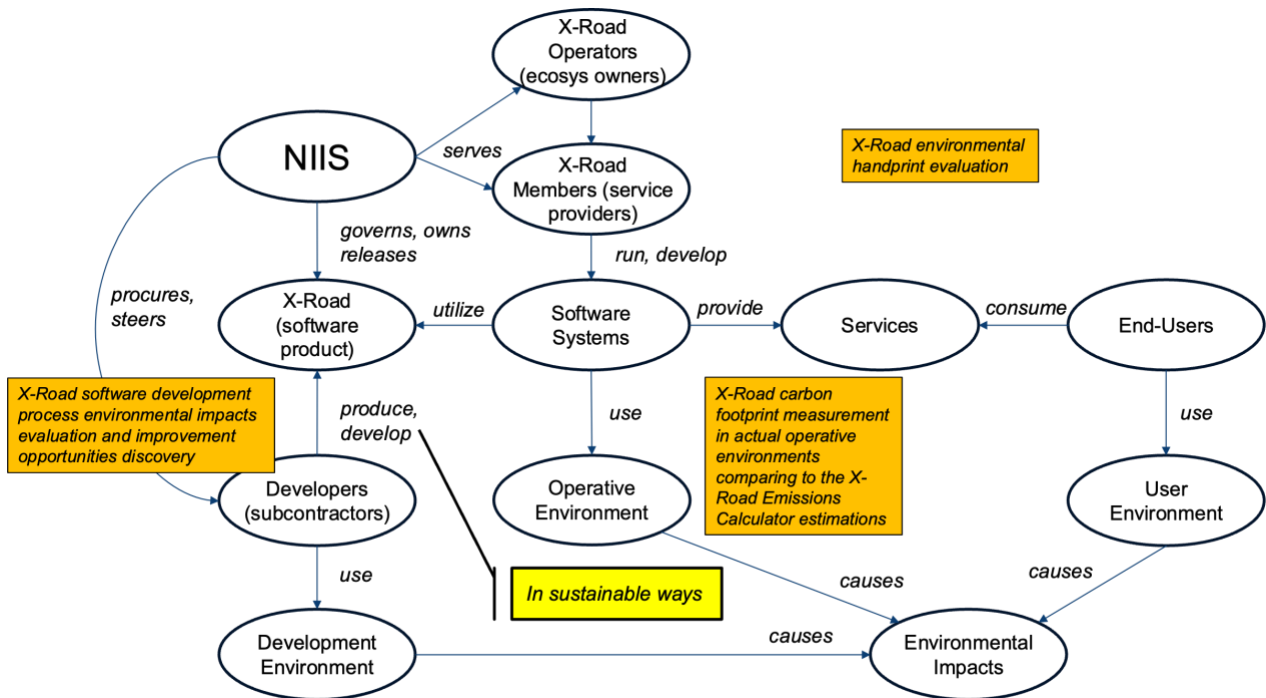
Figure 3. NIIS / X-Road sustainability development concept map.

- Figure 4 illustrates a focal company's direct and its linked indirect GHG emission sources across value chains [11].

  ➢ What are those items (e.g., "purchased goods and services") in case the "Reporting company" is
    a) NIIS (X-Road software as the product)?
    b) X-Road operator?
    c) X-Road member organization?
    d) X-Road service provider (outsourcing company)?

  ➢ "From an AWS customer perspective, emissions from your workloads running on AWS are accounted for as indirect emissions, and part of your Scope 3 emissions." [8]

Reporting company:
1) NIIS
2) X-Road Operator
3) X-Road Member

SOURCE: [11]

Figure 4. NIIS / X-Road related GHG emissions across value chains.

3. X-Road Software Development Process Environmental Impacts Evaluation (WP1)

The initial plan (2022) was to perform the following:
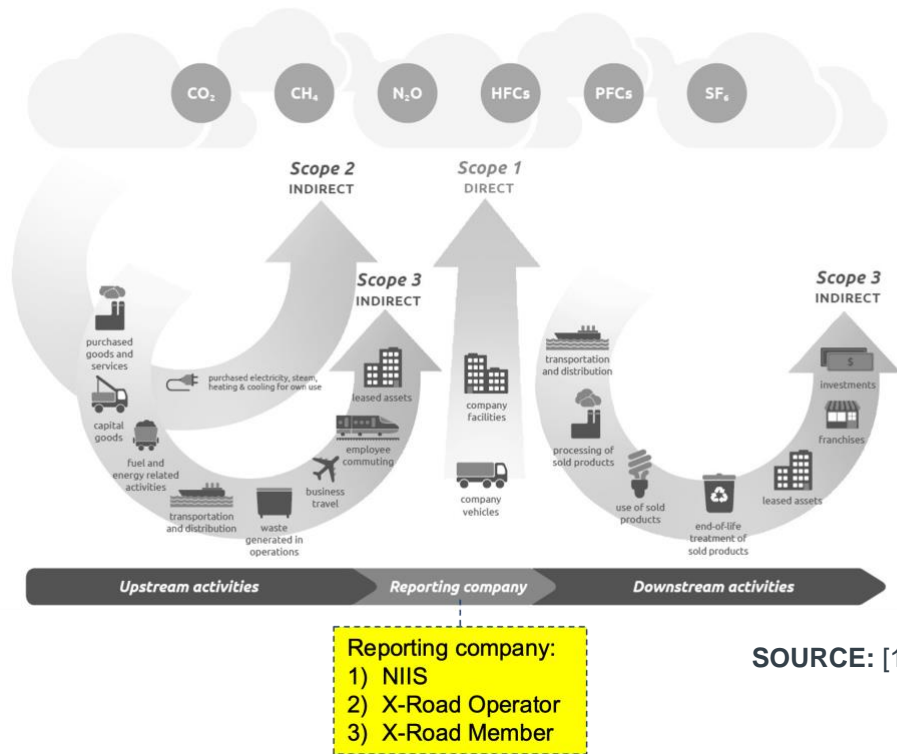
- Software Process Improvement (SPI) assessment in conjunction with WP2 (Ch. 4) and WP3 (Ch. 5)
- Selected improvement actions following the SPI assessment

The following contextual issues and subject points were recognized:

- NIIS does not do the actual software development, but it is outsourced to subcontractors.
- Do all the software development subcontractors adhere to the NIIS software development process definition?
- What sustainability requirements etc. does the software development process (defined and actual) take into account?
- How is the X-Road Academy *Sustainability in Software Development* course reflected in the software development process definition?

During the actual investigation, the research goals were emphasized as follows:

- Requirements engineering with respect to (environmental) sustainability
- Software architecture design and evaluation considering (technical) sustainability

Previously, NIIS has created an X-Road Academy online course for *Sustainability in Software Development* [7]. The purpose of this elementary course is to introduce sustainability to new software developers (onboarding). In the beginning of this investigation, the course material was reviewed and suggestions for improvements were provided. NIIS then revised the material accordingly.

Furthermore, the related NIIS works on the software development process sustainability (*Evaluating the Sustainability of the X-Road® Development Process*, *Integrating Green Software Development Principles into X-Road's Current Development Process*) were digested. Those inferences have been incorporated in this study (Appendix 1).

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[7] https://x-road.thinkific.com/courses/sustainability-in-software-development

3.1 Considerations and Recommendations

In principle, sustainability of X-Road software can be viewed from two main angles:

- Sustainability in X-Road software:
  - How can we make X-Road software more environmentally sustainable? [15]
  - How can we make the process of building X-Road software more environmentally sustainable? [15]
- Sustainability by X-Road software:
  - How can we achieve environmental sustainability goals through X-Road software? [15]

Sustainability in X-Road software and its development links to and is affected by many aspects ranging from the product roadmap and backlogs requirements engineering to software engineering technical matters. Table 2 explicates these different concerns and areas—focusing on the environmental sustainability.

SOFTWARE SUSTAINABILITY: Sustainability of the X-Road software spans the entire life cycle of the releases and concerns all the phases of the software development process from the product requirements to the testing and releasing. In all, sustainability should be treated explicitly throughout the development—as security. This includes keeping the intended sustainability impacts continuously visible.

SUSTAINABILITY IMPACTS ASSESSMENT: In general, each new backlog item have various impacts on different dimensions of X-Road software sustainability. It is crucial to recognize the key effects in terms of their magnitudes and directions (positive or negative impacts). For instance, if a new feature is used only occasionally in actual X-Road instances, its energy consumption may not be a key concern. Conversely, if new features require users (or software developers) to acquire new hardware, the negative environmental impacts caused by the manufacturing the equipment may be significant.

SUSTAINABILITY EVALUATION: Each new product feature and enhancement request should be evaluated with respect to their intended and expected sustainability impacts. The process should explicitly assign the evaluation responsibilities and define the phasing to perform them in the software development process.

SOFTWARE ENERGY-EFFICIENCY: Software energy consumption is one of the key factors of the environmental sustainability. Energy-efficient software does not use unnecessarily computing resources consuming energy—and thus causing negative environmental impacts due to the electricity production. Even more so, it does not waste energy. The software developers and other stakeholders should be aware of energy consumption concerns and issues. Making software energy-aware is a technical prime.

SOFTWARE DEVELOPMENT SUSTAINABILITY COMPETENCE AND CAPABILITIES: The responsible X-Road software developers should have the competences and resources for consciously specifying, designing, and implementing environmentally sustainable—especially energy-efficient—software. Moreover, ideally, they are interested in and capable of improving the software development process to address sustainability issues (e.g., "energy bugs").

Table 2. Considerations for X-Road software development process sustainability impacts evaluation.

X-ROAD SOFTWARE SUSTAINABILITY

- How is software sustainability currently addressed in the practice of X-Road software development projects? [4][15]
  - Is sustainability considered as a nonfunctional requirement (NFR)?
  - What phases of the X-Road software development life cycle do sustainable practices apply?
  - What tools have been used to support sustainability in the X-Road software development process?
  - How is the code documented regarding sustainability?
- Are the impacts of the product increment on the sustainability dimensions visible or known at all times? [16]

X-ROAD SUSTAINABILITY IMPACTS ASSESSMENT

- What sustainability effects (negative or positive) will the product backlog item have?
  - Is the feature executed more than 100,000 times in each month?
  - Is the feature executed less than 100 times in a month?
  - Does the feature require new hardware?
  - Will the feature decrease substantially the need for paper and mailing?
- How does the backlog item affect the sustainability of the digital services implemented by X-Road?
  - operators' and member organizations' hardware (e.g., servers)
  - operators' and member organizations' resource consumption (e.g., energy, storage)
  - Are there any indirect effects considering end-users (e.g., end-users' devices, end-users' resource consumption (e.g., network connections))—although end-users do connect directly to X-Road?
  - data transmission
- How does development of the backlog item affect the sustainability of X-Road?
  - developers' hardware (e.g., servers)
  - developers' resources (e.g., electricity, human resources)
  - maintenance (technical sustainability)

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<tr><td colspan="1" align="center">X-ROAD SUSTAINABILITY EVALUATION</td></tr>
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- Who should assess the impacts of product backlog items on different sustainability dimensions? [16]
  - Should sustainability assessment be a team effort (together with the operators/members)?
  - Should the product owner assess the impacts of the backlog items for all the sustainability dimensions except for the technical one?
  - Should the sustainability impacts on the technical dimension be primarily assessed by the software developers?
  - Should the clients assess the impacts on all the sustainability dimensions apart from the technical dimension?
- When should the sustainability impact assessment of backlog items be performed in the X-Road agile software development process? [16]
  - As early as possible?
  - During the product backlog refinement?
- How is the evaluation (estimation) accuracy continuously improved by comparing the estimated (prior to the implementation) and actual (measured) values?
  - Is such information recorded (including possible voids), especially including the assumptions and rationales of the estimates?
  - Why would such improvements be difficult to achieve in practice?

X-ROAD SOFTWARE ENERGY-EFFICIENCY

- How to create and maintain awareness of an energy consumption perspective among stakeholders involved in the development of the X-Road software product development? [4]
- Is the use of energy addressed during code reviews and/or other discussions? [15]
- Are problems with the use of energy more difficult to discover, diagnose and/or fix than other X-Road software/system performance problems? [15]

X-ROAD SOFTWARE DEVELOPMENT SUSTAINABILITY COMPETENCE AND CAPABILITIES

- Does the X-Road software development currently fully understand how to write, maintain, and evolve energy-efficient software applications? [4]
  - How does X-Road software development think about energy when writing requirements, design, construct, test and maintain the software?
- Do problems with the use of energy occur more frequently than other software performance problems? [15]

The following list recommends concrete tasks for the X-Road software development sustainability impacts evaluation and improvement actions. The question items in Table 2 can be used to assist them.

- ➤ Consider continuously *Evaluating the Sustainability of the X-Road Development Process*.
  - What methods, measures, and tools are applied to verify whether the software is considered as green or sustainable? [14]
  - Is there adoption of some sustainable design patterns in the software development process?
  - How do the software developers define sustainable software systems? [16]
    - Do they have a shared understanding of sustainable systems?

- o What, in their view, makes X-Road software sustainable (e.g., durability, usage of resources, maintainability, economic efficiency, extensibility)?
- o Does maintainability, extensibility/adaptability, scalability, privacy, security influence the sustainability of the X-Road software?
- o How important do they rate sustainability aspects in agile software development? [16]

Evaluating the sustainability of the software development process including the applied tools should be a continuous activity rather than an occasional snapshot event. Such continuous learning and process improvement is an inherent principle of agile software development. An underlying requisite is that the software developers really see and appreciate the value of sustainability in their daily work. They should share a common, explicit view of what everything sustainability means in the X-Road software and in its development—and how each developer contributes to it.

➢ Consider organizing joint trainings and/or workshops for key stakeholders (including software developers) of X-Road software systems energy use and energy-efficiency.

It is advantageous to establish a common, shared understanding of what factors affect the energy consumption of actual X-Road instances in different systems environments (e.g., utilized cloud services). Such system-level knowledge would inform X-Road software development energy-efficiency assessments and guide consequent improvements.

➢ Consider auditing the X-Road software development subcontractors regarding their actual software development process and practices with respect to energy-related matters.

Sustainable software development in general and energy-efficiency software development in particular requires many practices and competencies which may not have been explicitly addressed previously. Thus, the current ways of working should be discerned respectively.

➢ Consider appointing a dedicated sustainability expert. [16]

As sustainability requires multidisciplinary knowledge and cross-functional information, a dedicated sustainability expert (role) could be assigned. Such a person would support especially X-Road requirements engineering with respect to the software sustainability needs and goals.

➢ Consider that system visibility is a necessary precondition and enabler for sustainability design. [5]

Consciously sustainable software engineering requires comprehensive and continuous visibility to the system in its actual operative context—which may be dynamic. It is necessary to realize that for making informed design decisions and documenting the assumptions and rationales.

3.2 Supports

- Pages (7), (25) in Appendix 1

-

| X-Road Development Model |
| X-Road Non-Functional Requirements |

[8]

This an augmentation of the current NIIS development model (i.e., the change management process)[9]. It incorporates suggestions for additional activities during the evaluation and development of new feature and enhancement requests with respect to sustainability (environmental, technical). In addition, sustainability is advised to be treated as a non-functional requirement (NFR).

-

| X-Road Development Process |

[10]

This proposal extends the current X-Road software development process considering sustainability. The essence is to take sustainability into account throughout all stages and quality gates of the process—like security.

-

| X-Road Architecture |
| Technical Specification |

[11]

This augmentation suggests how sustainability (environmental, technical) is considered in the architectural design goals and design decisions of the X-Road system. In addition, the operational monitoring and environmental monitoring are linked to energy consumption measurement (see Ch. 5).

- Table 3 proposes a frame for sustainability evaluation of backlog items in the product backlog change management and software development:

  o What sustainability effects *will* the product backlog item have?

  o What sustainability effects *has* it had?

The idea is to begin with basic, coarse-grained evaluation (ordinal scale):

1) *Is the impact positive/neutral/negative?*

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[8] https://github.com/nordic-institute/X-Road-development/blob/master/DEVELOPMENT_MODEL.md

[9] https://github.com/nordic-institute/X-Road-development/blob/master/DEVELOPMENT_MODEL.md

[10] Available in a separate document.

[11] Available in a separate document.

When more information (and experience) is available, the magnitudes could also be assessed (interval scale):

2) *How much/significantly?*

For each sustainability dimension, it is important to first comprehend what they mean overall (c.f., Terms and Abbreviations). Only then it is possible to evaluate and reason rationally how the backlog item may affect the X-Road software sustainability in that dimension.

The table shows guiding questions for the evaluation process. They can be used as triggers but also as checklists—i.e., whether such concerns have been considered.

Notably, the result of the evaluation could also be 'Don't know' or 'N/A'. It is important to consider and document at least rudimentary evaluations even though the results may initially be very uncertain or unknown.

Table 3. Backlog item sustainability evaluation frame.

Sustainability DIMENSION	EFFECTS		
	Direct	Indirect	Systemic
Environmental (especially energy consumption)	• How significantly does the feature/enhancement change the energy consumption? • Does the feature/enhancement make X-Road software more energy-efficient?	• Will the feature/enhancement increase/decrease physical resource consumptions?	
Technical (especially maintainability)	• What is impact of the feature/enhancement on the software maintenance (e.g., changeability, testing efforts)? • Is the feature/enhancement amenable to X-Road software long-term evolution and adaptation to changes? • Is the feature/enhancement design/implementation reusable?	• What is the impact of the feature/enhancement on the maintenance of the existing X-Road instances (e.g., software update efforts, hardware upgrading needs)?	
Economic		• Will the feature/enhancement make the X-Road software more cost-efficient to host and run (e.g., hardware resource needs)?	
Social			• Could the feature/enhancement change end-user behaviors towards sustainability?
Individual	• How graceful is the feature/enhancement for the developers (e.g., motivating)?	• How valuable is the feature/enhancement for the X-Road operator and member organization workers?	

- Direct (immediate, first-order effects):
  - e.g., ICT energy consumption of the X-Road operators and the member organizations
- Indirect (enabling, second-order effects):
  - Triggered by the use of X-Road in its ecosystem contexts
  - e.g., manufacturing of the ICT hardware, the service development, third party network service components
- Systemic (structural, third-order effects):
  - Triggered by X-Road long-term and wide-spread use
  - e.g., substitution impacts (i.e., X-Road replacing something else that causes more negative impacts)

- Table 4 links main software product quality attributes to potential positive sustainability impacts potentially achieved by supporting and improving the software with respect to those attributes [13]. The impacts can be on three dimensions of software sustainability: environmental, economic, and social.

  This table can be used in conjunction to Table 3 to evaluate backlog items regarding their sustainability impacts. For instance, if an enhancement improves portability, there may be

consequent positive impacts on sustainability as suggested in the table.

Notably different quality attributes and their impacts on different sustainability dimensions may be interdependent in complex ways. There may even be trade-offs—e.g., between security and performance efficiency.

Table 4. Software product quality attributes and their sustainability impacts [13].

QUALITY ATTRIBUTES	Potential Positive Sustainability Impacts
Functional suitability	• Minimising maintenance and support costs • Minimising energy consumption • Minimizing environmental waste • Increasing user productivity
Performance efficiency	• Enhances software productivity. • Minimises expenditure on new hardware. • Minimises energy consumption through less software usage time. • Minimises social dependency on the newest technologies. • Enhances ecological footprint by extending the lifetime of hardware and minimising e-waste.

Compatibility	• Flexibility in exchanging information and sharing resources without harmful effects:
	   o Reduces investment and development costs.
	   o Reduces risks.
	   o Facilitates user communication.
	   o Increases satisfaction.

Usability	• Minimising support costs • Increasing customer satisfaction and the potential market • Eliminating learning barriers • Delivering technology to minorities and illiterate populations
Reliability	• Minimises risks of errors and failures. • Enhances software consistency and productivity. • Minimises support costs. • Minimises development costs. • Increases the longevity of software usage. • Increases user satisfaction and software reputation in markets.
Security	• Minimises risks. • Increases the trustfulness and customer base of software. • Reduces maintenance and support costs. • Increases user satisfaction and longevity of software usage. • Facilitates communication of users.

Maintainability	• Increasing the longevity of software usage • Minimising the costs of development, maintenance and support • Reducing the required time, risks, efforts, resources and waste for maintaining existing software • Accelerating time to market • Enabling software to meet societal demands continuously • Increasing customer base
Portability	• Increases the software's lifetime and its potential market. • Extends hardware lifetime and minimises waste. • Increases the flexibility of software usage. • Increases satisfaction and loyalty of customers.

• Table 5 Presents typical considerations with X-Road instances in cloud environments.[12] Such concerns affect both the software design and use phases (use cases).

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[12] https://www.niis.org/s/NIIS_XRoadFootprint_Final.pdf (26.5.2021)

Table 5. X-Road sustainability considerations in the cloud.

PRACTICES [8]	X-Road Software Development (NIIS)	X-Road Operators	X-Road Members
Choose Region based on both business requirements and sustainability goals	"When public cloud is seen as a feasible option, then also the skillset of the organization and experience with Docker or public cloud platforms must be considered."	Allow the member organizations in public cloud.	"shifting Security Servers to the public cloud can drastically drop the emissions…. Provide guidelines to X-Road members that explain, when and how could X-Road Security Server be used in a public cloud."
Scale workload infrastructure dynamically			Are the workloads scalable?
Optimize areas of code that consume the most time or resources	Where is most time, resources consumed? Can those parts be reasonably optimized?		
Optimize impact on devices and equipment	• Are environmental impacts of devices/equipment used by the operators and member organizations concerns? • Do new X-Road releases require replacing existing devices/equipment? • Is the software implementation optimized for certain types of device/equipment architectures?		
Use software patterns and architectures that best support data access and storage patterns	"When a Security Server is maintained in the public cloud, then it is more convenient to use it for storage as well."	Regulations for message logging; "Guide members, when and what should be logged in a message log of a Security Server"	"disabling the message logging or reducing the size of data that is logged (omitting payload in the logs)"
Use technologies that support data access and storage patterns	• Are the software and architecture patterns aligned to typical data characteristics and access patterns (e.g., dominant requests)? • Are the data and storage patterns assumed to be similar and remain consistently so?		
Use the minimum amount of hardware to meet your needs		Is it possible to anticipate the hardware needs and descale?	
Use managed device farms for testing	Is it necessary to test new X-Road software releases in different types (even older) of hardware environments?		

4. X-Road Environmental Handprint Evaluation (WP2)

The initial plan (2022) was to work out the following:

- Definition of the handprint
- Evaluating the handprint in selected cases according to the definition

The following basic difficulties were recognized:

- Are there in practice such alternative products which X-Road could outperform?
    - Which ones?
    - In what current existing service systems (data exchange ecosystems)?
- Are there such current or future services in which their carbon footprints are known and the carbon footprints of their alternative implementations using X-Road would be possible to evaluate?

During the actual investigation, the research goals were reconsidered as follows:

- SDG goals
    - How does X-Road contribute positively to the different SDG goals and targets?

In general, carbon handprints represent the positive impacts of organizations and their products on reducing the current GHG emissions of other organizations. That is, when the customer takes the product into use, its carbon footprint reduces[13]. There are estimations that ICT could reduce the carbon footprints in other sectors by as much as 15 % by 2030 [6].

In case of X-Road, this would mean assessing the carbon footprint of some existing service system currently implemented with some other technologies than X-Road. Even an existing manual process or service could be digitalized either entirely or partly utilizing X-Road. Then it would be possible to speculate, how the carbon footprint would change if the current implementation was replaced with a X-Road based solution. However, in practice such information is currently not readily available in existing X-Road instances (c.f., Ch. 5). In principle, as an overall reasonability boundary, the maximum comparison reference value could be a total point-to-point connection system without any message exchange layers.

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[13] https://www.vttresearch.com/en/news-and-ideas/carbon-handprint-new-environmental-indicator-evaluating-positive-climate-impacts (accessed Dec 6, 2023)

Notably while footprints can in general be measured in absolute terms, handprints are relative between the offered and baseline solutions [17]. Consequently, footprints can in principle be brought down to zero, but handprints could be increased indefinitely.

Markedly the carbon footprint/handprint is just one part of the environmental impacts. In this study, the environmental impacts of the X-Road software development process are examined more broadly Ch. 3 while the evaluation of the carbon footprint specifically in Ch. 5.

Potential positive impacts of X-Road can be evaluated and developed more broadly with respect to the different UN SDG goals. They bring a common shared frame of reference applicable and known world-wide in the X-Road ecosystems.

Considering especially environmental handprints, the following SDGs are relevant:

- 6: *Ensure availability and sustainable management of water and sanitation for all.*
- 7: *Ensure access to affordable, reliable, sustainable and modern energy for all.*
- 12: *Ensure sustainable consumption and production patterns.*
- 13: *Take urgent action to combat climate change and its impacts.*
- 14: *Conserve and sustainably use the oceans, seas and marine resources for* : *sustainable development.*
- 15: *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.*

4.1   Considerations and Recommendations

In principle, X-Road environmental handprints can be determined systematically and quantitatively. However, in practice there are potential issues and even obstacles to overcome. Table 6 explicates these different concerns and areas of the environmental handprints based on the stages and steps of the handprint approach suggested in the Carbon handprint guide [17].

HANDPRINT REQUIREMENTS AND OPPORTUNITIES: The positive environmental impacts of X-Road use phase may be various, not limited to reduced electricity production emissions. It is essential to identify potential or existing customers/users and discern, how the offered X-Road solutions may achieve different footprint reductions for their benefits. The potential indicators must then be defined accordingly in order to determine whether the projected benefits really happen.

HANDPRINT ANALYSIS REQUIREMENTS: Handprints are always relative to actual users and baseline solutions used over time. Consequent data needs and sources for the handprint calculations must be identified. Representative, comparable data for both the baseline solutions and the offered X-Road solution must then be defined accordingly. The data should be accessible.

HANDPRINT QUANTIFICATION: Handprint calculations are based on the footprints of the baseline solution and the offered X-Road solution. Consequently, it is possible to assess handprints quantitatively

only if the related footprints can be determined. Handprints are always quantified for a specific user and usage situation [17].

HANDPRINT COMMUNICATION: The prospected/achieved handprints can communicated to different audiences for different purposes—including marketing. In all, the handprint claims/achievements should be appropriate, credible, and transparent informed by relevant indicators.

Table 6. Considerations for X-Road environmental handprint evaluation.

X-ROAD ENVIRONMENTAL HANDPRINT REQUIREMENTS AND OPPORTUNITIES

• What new public digital services could be implemented by using X-Road?
  ○ What are their environmental impacts compared to the existing state of no such services?
• Where could X-Road replace currently used technologies in existing digital services?
  ○ What are the handprint effects?
  ○ Where/when would there be no handprint created with the current X-Road product characteristics compared to the other alternatives? [17]
• How could X-Road enable and support sustainable digital transformations?
• How could X-Road contribute to green/dual transitions?
  ○ How could X-Road sustainable digital technology enable a carbon-neutral EU by 2050? [14]
    - "Promoting robust cybersecurity and secure data sharing framework"
• How could X-Road serve UN to support acceleration of the environment related SDGs?
  ○ How could X-Road support collect and sharing SDG-related data (e.g., indicators)? [3]

X-ROAD HANDPRINT LIFE-CYCLE ANALYSIS REQUIREMENTS

• Can the user of the offered X-Road solution be specified? [17]
  ○ Is the offered X-Road product solution targeted to a specific and identified user or beneficiary?
• What is the relevant time frame in use?
• What are relevant and similar life cycle stages of the baseline solution and the offered X-Road solution?
• Is it country/ecosystem-specific (X-Road operators and members world-wide)?
• If the user can be specified, what primary data is available? [18]
  ○ If not, what statistical or average data is there?

cont.

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[14] https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/twin-green-digital-transition-how-sustainable-digital-technologies-could-enable-carbon-neutral-eu-2022-06-29_en (accessed Dec 13, 2023)

X-ROAD ENVIRONMENTAL HANDPRINT QUANTIFICATION
• $Handprint_{X\text{-}Road} = Footprint_{BaselineSolution} - Footprint_{X\text{-}RoadSolution}$ • How time and resource intensive is the process of quantifying the handprint? [17]
X-ROAD HANDPRINT COMMUNICATION
• How significant is the X-Road handprint within the NIIS offered solutions product portfolio? [17] • How are handprints used for X-Road marketing purposes? • What are the main audiences for the X-Road handprint achievements and opportunities? o Supporting decision-making of customers and other stakeholders, supporting political decision-making? [17] • How are the prospective/achieved handprint benefits informed accurately and justified? [18] o What are relevant indicators? o Are possibly negative changes also transparently communicated?

The following list recommends concrete tasks for the X-Road (environmental) handprints evaluation, development, and improvement actions. The question items in Table 6 can be used to assist them.

> ➢ Consider different business/industry sectors and application areas—such as in Figure 5.
> o Where could X-Road help users to reduce the footprint (negative environmental impacts) of their processes? [17]
>   o Where could X-Road technology with improved energy efficiency in the use stage have a significant resource handprint?
> o What offered X-Road product solution would generate environmental benefits? [18]
>   o What conditions will (most likely) occur in the absence of the offered X-Road solution?

In general, digitalization is currently affecting almost all industrial sectors and every public sector organization world-wide. Consequently, there are possibly more and more opportunities for X-Road to reduce environmental footprints. Such opportunity discovery and assessment could be done systematically sector by sector—for instance with foresight methods.

> ➢ Consider where X-Road could be an innovation (i.e., where no comparable solutions exist). [18]
> o Where are there corresponding references or alternative products on the market?
> o Could X-Road deliver functions not comparable to any currently available outcomes?
> o Could there be new ways of applying the X-Road product solution?

Sustainability is systemic. Thus, the basic role of X-Road as an enabler for different information systems to communicate with each other could be seen more broadly: what information systems and where (domains). Where are no information exchange systems currently not used—but could be? For instance, X-Road could possibly be utilized in many different sectors to immaterialize activities that otherwise would consume resources (e.g., ITS) or to extract data/information to optimize resource-intensive processes.

- ➢ Organize an expert panel consisting of industrial and sustainability experts together to discuss and evaluate possible footprint reduction pathways. [18]
  - o How could the offered X-Road solution achieve footprint reductions?

To be able to discover and evaluate potentially achievable handprint effects of X-Road, it is necessary to understand the current footprints and their contributing factors (e.g., energy consumption "hot spots"). With facilitated joint discussions and organized workshops, it could be possible to discern realizable ways of footprint reductions with X-Road in different domains and service systems.

- ➢ Consider marketing X-Road for environmental sustainability:
  - o How can X-Road be used for optimising societal activities in order to improve environmental sustainability? [23]
    - o Using X-Road to "raise people's awareness of the environmental impact of their actions and to channel their behaviour"
    - o "Reducing the use of diverse environmentally unsustainable re-sources" through X-Road-based solutions
    - o "Minimising the environmental load of diverse systems by optimising their operation" with X-Road

In general, environmental sustainability could be even a competitive advantage for X-Road. That argument could be used to promote X-Road for further distribution and also to strengthen the current X-Road instances uses. However, such marketing messaging should be based on transparent factual reasoning, ideally grounding on data.

- ➢ Consider SDG Data Hubs in different countries and X-Road ecosystems: "SDG Data Hubs for national governments to share data, monitor public investments, track SDGs and engage stakeholders."; "An SDG Data Hub is a platform to support reporting and monitoring progress towards achieving the SDG's." [15]

X-Road could possibly be used to support such data hubs—taking into account especially that there are already X-Road instances in place in many different countries and regions world-wide. Furthermore, because NIIS is a non-profit organization and X-Road is open source software, it would be by nature a feasible solution for UN related uses.

- ➢ Organize ideation workshops for discovering and identifying opportunities for X-Road to contribute to each SDG and their targets.
  - o e.g., Community events

The SDGs (17) and their targets (169) cover a very broad range of areas and issues of sustainable development (even planetary). Consequently, they may open up possibly plenty of different opportunities for X-Road to contribute (by 2030). Idea generation with the different X-Road operator and member organization participants (even globally) could produce a large set of

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[15] https://www.sdg.org/

potential items for further development. Such joint events should be organized regularly (at least annually)—possibly in conjunction to the X-Road community events.
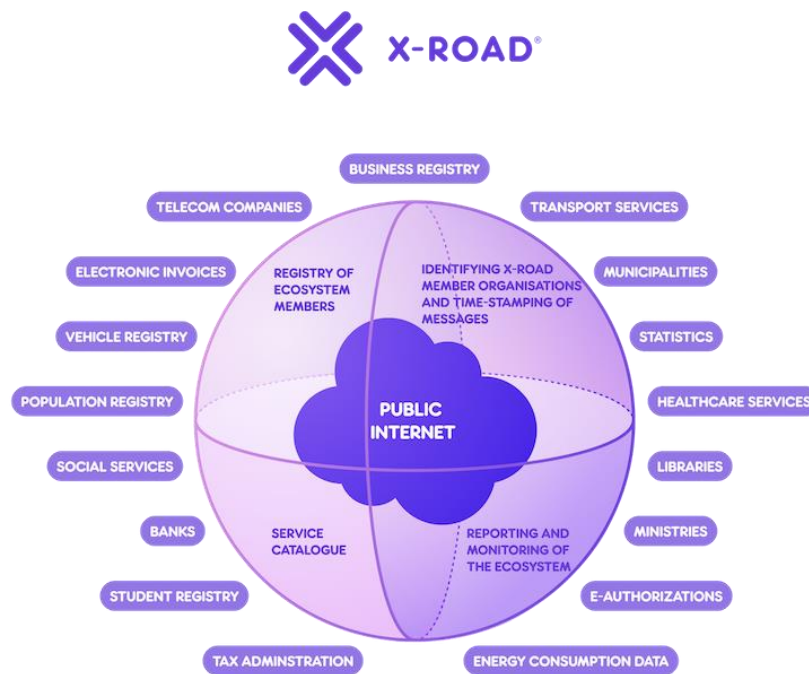

Figure 5. X-Road use domains (https://x-road.global/x-road-technology-overview).

4.2 Supports

- Pages (10), (3) in Appendix 1

- **X-Road & SDGs** [16]

This worksheet tabulates the UN SDGs (17) and their targets (169). In addition, it includes current X-Road cases[17] linked to different goals. Moreover, there are illustrative suggestions and potential ideas linked to the targets for considering how X-Road could possibly be used in further ways to advance the attainment of the different goals. The purpose of the worksheet is thus to facilitate ideation for instance in future X-Road product strategy and roadmapping workshops.

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[16] Available in a separate document.
[17] https://x-road.global/sustainability (accessed Nov 7, 2023)

- • Figure 6 illustrates a hypothetical yet plausible setup of a public sector digital healthcare service using X-Road. Clients use video applications to communicate remotely with healthcare organization professionals. X-Road software is at the core to provide secure, trusted information exchanges.
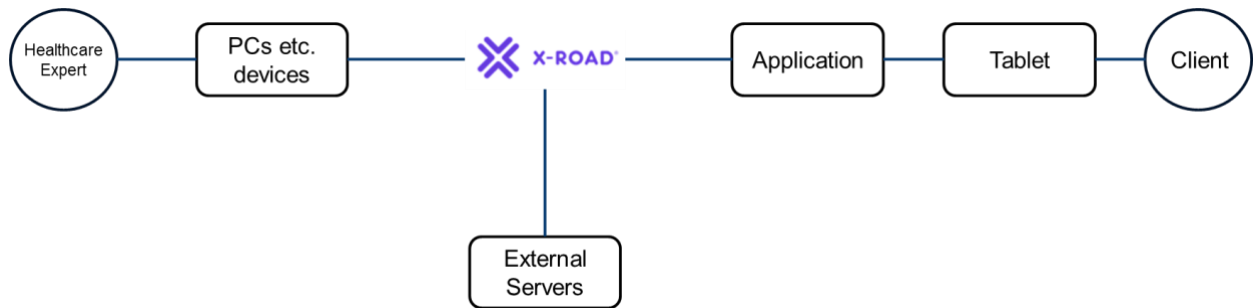
<div align="right">REF: [7]</div>

Figure 6. Illustrative example of a remote healthcare service with X-Road.

In such a use case, it is possible to analyze both the carbon footprint and the carbon handprint of X-Road. If the data exchange system component (in the middle in Figure 6) of the service is currently implemented with some other technology, it could possibly be replaced by X-Road. In that case the energy consumption and consequently the carbon footprint of the service use could be reduced—i.e., the X-Road carbon handprint could be positive. Furthermore, notably, it is possible to analyze also the carbon footprints caused by the manufacturing of the ICT devices required to provide the service.

5. X-Road Carbon Footprint Measurement (WP3)

The initial plan (2022) was to solve the following:

- Measurement Plan

- Conducting selected measurements according to the Measurement Plan

The following fundamental difficulties were recognized:

- X-Road is not an independent separate software but a part of some digital service etc. implementation in larger systems (c.f., middleware).

- What are meaningful workloads, representing real use cases (e.g., the Finnish Digital Agency in Finland)?

- How is energy consumption related to the CO_2 emissions of electricity production?

During the actual investigation—considering the above complications—the initial research goals were remodeled as follows:

- Research Goal ("<understand | characterise | compare | predict> the <consumption> of the <SWUT> run on <device(s)> in <context(s)>" [9]):

- "Characterise the energy consumption of the X-Road software when run on the NIIS load test environment in the context of AWS"

    o Measurement Method ("Instant power | Time | Model estimation"): Model estimation

- Analysis Method: What useful energy-efficiency information is available?

For addressing that, the following objectives were formulated:

- How applicable is the X-Road Emissions Calculator in the NIIS load test environment in the context of AWS?

- Proposals for augmenting X-Road development process load tests with resource (energy) consumption tests

- Suggestions for utilizing new X-Road metrics (energy consumption data, environmental monitoring data) for energy-efficiency measurements

To begin with, the *Emissions Calculator*[18] was scrutinized. Crucially, it treats the X-Road software as a "black box", i.e., it does not indicate where in the software functions etc. the load originates. The calculator input parameters[19]

- *Average CPU utilization (Average CPU utilization of the estimated Security Server in a week)*
- *Amount of data exchanged (Amount of data pushed over a Security Server in a year)*
- *Amount of data stored (Size of the archive files stored by a Security Server in a year)*

simply characterize some software workload consuming energy. The emissions are then calculated straightforwardly by multiplying the total energy consumption of those elements by a constant *Emission factor*.

An essential question is therefore to consider whether and how the calculator could possibly be utilized in the X-Road software development for reducing its energy consumption (and consequent emissions). By and large, the calculation model implies that this can be done by decreasing the CPU load, data transmissions or data storage. For that, the abovementioned input parameter data values should be collected in some execution environment.

The following main alternatives for the measurement environment were recognized:

A. NIIS load test environment (in the AWS cloud)

B. X-Road operators' existing Security Servers (e.g., the Estonian Information Systems Authority, the Finnish Digital Agency, the Digital Iceland)

C. Building a dedicated Security Server in some service provider on-premises data center

Of those, the first one (A) was considered the most viable possibility because the environment is readily available and in use with the X-Road software development. However, its AWS cloud infrastructure causes limitations for the available data—in particular, the energy consumption data. That is, the energy consumption would not be directly measurable. Another limitation realized was that the current load tests do not represent any real use case or production level weekly patterns as assumed by the *Emissions Calculator*. Currently the data collected is the message-passing response times.

Furthermore, we considered the NIIS long-term test environment (AWS cloud) in which the same workload is executed repeatedly. As with the NIIS load test environment, the workload does not represent any particular X-Road use cases. The measurement data collected includes message response times, CPU utilization, memory (RAM) and disk space usage, and network traffic volumes (AWS metrics *CPUUtilization, NetworkIn, NetworkOut, VolumeWriteBytes, VolumeReadBytes*). The energy consumption data is not reasonably available. Notably the measurements in the load test and long-term test environment differ since in the former the server instances are dynamically created and deleted while in the latter they remain the same.

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[18] https://www.niis.org/s/NIIS_XRoadFootprint_Final.pdf
[19] Appendix3_SimplifiedXRoadCarbonFootprintCalculator_locked_final

Thinking about the research problem further, it was realized that as the ultimate interest is the energy consumption, which is difficult to measure directly, it would be possible to measure it indirectly with proxy measurements. As described above, the *Emissions Calculator* assumes that the energy consumption of Security Servers results for the most parts from the resource usage of the CPU work, RAM and disk storage and network data transmissions. Similar data is available in the NIIS test environments. Consequently, it could be possible to calculate the energy consumption of the test environment runs based on those proxy values. The measurement period should be timestamped.

Following that line of reasoning, as the current primary interest is in the trends of the X-Road software releases energy consumption rather than its absolute values, the basic measurement approach could be as follows:

1) First, measure the baseline values of those proxy variables with the X-Road version '1'.

2) When the software implementation is then optimized (or expected otherwise to be more energy-efficient) in some way, repeat the same measurements with the optimized X-Road version '2'.

   ➢ The measured proxy values should be lower, i.e., indicating reduced energy consumption.

3) When some new software functionality is developed, the test workload should then be such that the modified parts of the software are executed in the X-Road version '2'.

   • The changes of the proxy values relative to the baseline (1) indicate the impacts of the new functionality on the energy consumption. The energy efficiency may or may not be higher. Consuming more energy may be acceptable if the new software version also does more useful work—consider the changes in the ratio.

In sum, assume—as in the *Emissions Calculator*—that the energy consumption (EC) results primary in the above way and can be reflected by the proxy variables:

$$EC \approx f(\text{CPUUtilization, NetworkIn, NetworkOut, VolumeWriteBytes, VolumeReadBytes})$$

Then, the minimum information would be whether the energy consumption has changed (increased, decreased or practically remained at the same level) between the releases (i.e., deltas). That kind of information could be gathered in the NIIS long-term test environment. However, the test workload should be such that the changes in the software implementations would be executed representatively. If the goal of the new X-Road software version is especially to incorporate optimizations for reducing energy consumption, that information is just what is interesting and beneficial to know.

In addition, it could in principle be possible to calculate absolute energy consumption values based on those measurement values in the similar way as is done in the *Emissions Calculator*, but in practice the EC trend is believed to be the most interesting and valuable information—i.e., how it changes between different X-Road versions.

The next step would be to assess how much the EC has changed. However, that is much more complicated to measure. Even more demanding would be to explain what elements inside the software (e.g., new features) contribute to the observed changes.

5.1 Considerations and Recommendations

Overall, the carbon footprint caused by the electricity consumption of the X-Road software can be affected (decrease or increase) both during the software development phase and the usage phase. Consequently, it is of interest to measure the energy consumption both in the software development process and during the run-time of the actual X-Road instances. It is crucial to be able relate the measurement results of developmental tests and actual service loads—in particular when the measurements are conducted in different computing environments.

Table 7 explicates these different concerns and areas.

X-ROAD DEVELOPMENT: In the X-Road software development, it is important to realize what key factors contribute most to the energy consumption—and consequent carbon footprints—in the actual usage. For that, typical use patterns and workloads in the X-Road instances should be known. The energy consumption data in such cases would then inform the development and corresponding test cases would then be devised accordingly. There should be established mappings between the developmental energy consumption/emissions measurements and actual energy consumption in X-Road instances.

X-ROAD USAGE: In the actual use of the X-Road instances, the carbon footprints can be analyzed and measured at different levels and in different scopes. The use of public/private cloud services, data centers and network infrastructures may have major impacts on the total energy consumption. Moreover, their carbon emissions may vary a lot depending on the electricity sourcing strategies of the data center operators.

Table 7. Considerations for X-Road carbon footprint measurement.

X-ROAD DEVELOPMENT

• What are typical X-Road instance use cases in different countries?
   o In Estonia, service request statistics could be used to pinpoint such typical and most frequently used services and their clients.[20]
   o For example, in Finland, it is believed to be fetching of individual citizen information from the national population information system.
• What are such typical weekly usage patterns which could yield most energy consumption reductions in different system types of X-Road instances?
   a. back-office systems
   b. end-user services systems
   c. batch processing systems
• How commonplace is background batch data transfer in different X-Road ecosystems?
   o How beneficial would reduced energy consumption actually be in such cases?
      o Such batch runs could be performed flexibly at such times when renewable energy is available.
• What level of granularity of software energy consumption data is necessary? [9]
   1) fine grained (individual lines of code or statements)
   2) midgrained (block of code or a method/procedure)
   3) coarse-grained (whole program execution over a period of time)

cont.

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[20] X-Road Metrics: X-Road Networking Visualization for instance EE (https://logs.x-tee.ee/visualizer/?profile=EE)

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X-ROAD USAGE

- What are relevant scopes of X-Road carbon footprint analysis? [7]
    1) Digitalized service
    2) X-Road software (ICT) part of the service
    3) Digitalization (footprint of the service change)
- Which one of the following is a more significant contributor of the carbon footprint of a particular digital service using X-Road? [7]
    a. Providing (data producer) the service to end-users
    b. End-users' (data consumer) access to the service
- Which one of the following forms the major share of the carbon footprint of a particular digital service using X-Road? [7]
    a. Direct (e.g., energy consumption)
    b. Indirect (e.g., manufacturing of the ICT equipment, third party service components)
- How much does the carbon footprint of a particular X-Road use case vary (even sporadically) depending on the dynamism of the network and the end-user access routings consuming energy differently at different times—i.e., possibly causing emissions in different geographical locations? [7]
- Is environmental sustainability taking into account when X-Road operators utilize public cloud services?
    o It may be difficult to estimate the total energy consumption of data centers. [6]
- Does the environmental impacts of the network infrastructure matter?
    o In general, fixed networks are more energy efficient than mobile networks. [6]

</div>

The following list recommends concrete tasks for the X-Road carbon footprint assessment and measurement activities. The question items in

Table 7 can be used to assist them.

➢ Collect an inventory of the current X-Road instances about their actual electricity sources (and their emission rates).
   o Take into account both private and public clouds.
   o Record also possible unavailability/uncertainty/volatility of such information.

For sensible energy-awareness and making informed decisions on improving the energy-efficiency of X-Road software, it is vital to understand the main causes and use cases (patterns, scenarios) of energy consumption and the consequent emissions in the actual X-Road instances. The actual carbon emissions may vary significantly depending on the electricity sourcing in different instances in different regions (including the data center distributions). It also astute to document explicitly, what is currently not known for example due to unavailability of information/data. Future data collection measures could then be developed accordingly.

➢ Consider where hardware-based approaches (physical power meters) to measure energy consumption of X-Road would be feasible to conduct—if at all in practice.
   o They may require significant investments (resources, specialized knowledge, access rights).

Direct hardware measurements have certain principal limitations especially in terms granularity. In the first place, the practically available measurement environments (e.g., data centers or lab servers) could be chartered. If they allowed conducting direct measurements, required equipment (hardware and software) could be acquired. Overall, it would be useful to make an inventory of the current X-Road instances and their measurement arrangements (e.g., already available measurement equipment and knowledge).

➢ Consider the possibilities to utilize the AWS Customer Carbon Footprint Tool.[21]
   o Note that the results may show zero in case of high (95+ %) renewable electricity production shares in certain regions or low usage magnitudes (causing less than 0.1 MTCO2e).

This depends on where and how AWS cloud services are used in different X-Road instances (and in the NIIS test environments). Overall, it would be useful to collect on inventory of such X-Road instances. It should also be noted that AWS tool may be under continuous development, so the possibilities to utilize it may change over time.

5.2 Supports

- Page (25) in Appendix 1

- Table 8 suggests an investigational procedure for conducting X-Road carbon footprint measurement in working environments and comparing to the calculated *Emissions Calculator*

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[21] https://sustainability.aboutamazon.com/products-services/the-cloud?energyType=true#carbon-footprint-tool

estimations. The basic idea is to collect performance data corresponding to the Emissions Calculator input parameters with general-purpose built-in monitoring tools (as in standard laptops). The power consumption measurements could in principle be done either by power metering devices or software tools—the latter supposed to be more workable in practice.

Table 8. Investigational procedure for X-Road carbon footprint measurement comparing to Emissions Calculator estimations.

Investigational measurement procedure

1. Assemble the HW environment according to the *Emissions Calculator* assumptions.
   - "Security Server contains a processor and RAM as the main energy consuming components".
   - "Infrastructure of a Security Server with processor with 4-8 cores is selected for calculations. For simplifications, the model Fujitsu, Server PRIMARY RX1330 M4 in which CPU model: Intel Xeon E-2288G is used as a reference".
   - "RAM of 4-16 GB is recommended for Security Server. Storage space RAM calculations are based on reference values: DDR3 RAM at 1333 MHz".
   - "An average value for electricity consumed for data transfer over a fixed line is used. For 2021, including the expected efficiency gains, this value is found to be 0.0075 kWh of electricity consumed for 1 GB of data transferred over the public internet".
   - "For calculation simplifications the reference model could be Seagate® BarraCuda® 3.5-inch HDD".

2. Execute such test workload which corresponds to the workload assumptions of the *Emissions Calculator*.
   - "Servers repeat a weekly pattern of data processing".
   - "The energy consumption for storing data for 30 days is included in Security Server calculations….data storage in HDDs"

3. Record, during the workload run(s)

   - Performance measurement data (Average CPU utilization, Amount of data exchanged, Amount of data stored)
   - Power consumption data
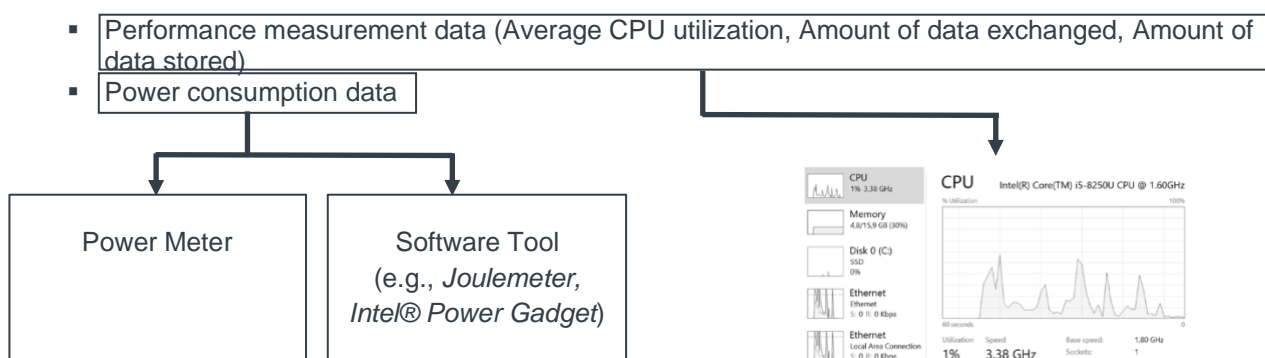
4. (Extract, purify and adjust the measurement data.)
5. Perform the Emissions Calculator calculations using the measured performance data values (Average CPU utilization, Amount of data exchanged, Amount of data stored).
6. Compare the calculated power consumption value to the measured power consumption.
   - Calculated: 'Total energy consumption by a Security Servers for one year' (=E38 [22]), 'Data transfer energy consumption' (=E50*E52), 'Total energy consumption by one HDD in one year' (=E71)

EMISSIONS:
ESTIMATED = f(EC_e (=E38), 'Emission factor' (=E29, E51, E70))
ACTUAL = f(EC_a, electricity system production properties)

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[22] Appendix3_SimplifiedXRoadCarbonFootprintCalculator_locked_final.xlsx

Notably the actual emissions caused by the electricity production may vary a lot depending on the electricity system properties. Especially, green energy transitions have changed such system properties significantly over the past few years in many countries. For instance, in Finland the electricity production is nowadays almost entirely emission-free (89 % in 2022). However, the emission rates may change even hourly depending on the available energy sources (especially wind power)[23].

In public cloud environments, the energy sourcing of the data centres may also vary considerable as the cloud service providers are responsible for their sustainability in different geographical locations. For example, AWS is responsible for sourcing renewable power (90 % in 2022 [24]) [8].

- Table 9 aggregates the EC measurement and emissions calculations as discerned and reasoned above. The basic idea is to measure the EC indirectly with proxy data values in the NIIS load test and/or long-term test environment. Direct EC measurements are not available in practice in the AWS cloud setups of those test environments.

Table 9. EC and emissions variables and calculations in the Emissions Calculator and NIIS Test Environments.

VARIABLES		NIIS *Emissions Calculator*	NIIS Load Test Environment	NIIS Long-Term Testing Environment
Security Server infrastructure	x_1 x_2 x_3 x_4	• *Public Cloud usage* • *Processor multiplier* • *Average CPU utilization* (Average CPU utilization of the estimated Security Server in a week) • *Emission factor*	• … • … • …	• … • … • …
Data exchange transactions supported by a Security Server	x_5 x_6	• *Amount of data exchanged* (Amount of data pushed over a Security Server in a year) • *Emission factor*	• …	• …
Data storage of a message log	x_7 x_8	• *Number of HDDs* • *Amount of data stored* (Size of the archive files stored by a Security Server in a year)	• … • …	• … • …
ENERGY CONSUMPTION (EC)		$= f(x_1, x_2, x_3, x_5, x_7, x_8)$	$EC_{measuredDirect}$ = N/A $EC_{measuredIndirect} = f(x_1, x_2, x_3, x_5, x_7, x_8)$ $EC_{actual} = EC_{measuredIndirect} \pm e$	
EMISSIONS		ESTIMATED = f(EC, x_4, x_6)	ACTUAL = f(EC_{actual}, electricity system properties)	

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[23] https://www.fingrid.fi/en/electricity-market/power-system/
[24] https://sustainability.aboutamazon.com/products-services/the-cloud?energyType=true (accessed Dec 10, 2023)

- Table 10 advices a generic template for planning and performing EC measurements in systematic ways. The first step is to define the measurement goal, which in the X-Road case would especially be to compare the energy consumption of (consecutive) software versions/releases. The NIIS load test environment could possibly be utilized as comprehended above.

Table 10. Generic EC measurement process and protocol template.

STEPS (Measurement Process [9])	HOW (Measurement Protocol [Err])	WHAT
Goal: Define research goal, context	-	*Compare two X-Road software versions/releases in the NIIS load test environment*
How: Define measurement method; Define analysis method	-	
Do: Prepare setup; Perform measurement	Restart environment;	
	Check time synchronization;	
	Close unnecessary applications;	
	Start performance measurements;	
	Remain idle for a sufficient amount of time;	
	Start EC measurements;	
	Run measurement and wait for run to finish;	
	Collect and check data;	
	Revert environment to initial state;	
Analyze		

In the analysis phase, when the objective is it assess EC reductions of X-Road software technical enhancement(s) and optimizations, it is important to confirm that the observed reductions are really caused by the implemented improvements—including taking into account other potentially simultaneous software loads (e.g., background OS processes) and SWUT idle time periods.

- More wide-ranging and complex analysis is to assess the impacts of X-Road on the total energy consumption and emissions in actual digital services and information systems of the X-Road operators and member organizations. Figure 6 illustrates one such hypothetical use case.

Typical X-Road use cases include fetching information of individual entities (citizens, companies, vehicles, etc.) from different registers (e.g., population registry, vehicle registry, etc.). Such operations may take place at different times of day in batches or in real time (e.g., healthcare services). Notably, as reasoned above, the actual emissions caused by electricity consumption may then vary a lot depending on the time and the current electricity production system properties.

Note in addition that carbon emissions are caused not just by the electricity production for the use phase but there may be even more emissions caused by the manufacturing of the ICT hardware

required to produce and use the digital services by software (c.f., Figure 4). However, if the ICT equipment is shared by multiple services and users, the total emissions are leveraged between them over the life cycles.

6. Summary

In this study, X-Road sustainability has been investigated from the following perspectives:

1) Software development process environmental impacts evaluation and improvement opportunities discovery (Ch. 3)

2) Environmental handprint evaluation (Ch. 4)

3) Carbon footprint measurement in actual operative environments comparing to the *Emissions Calculator* estimations (Ch. 5)

In addition, the overall NIIS / X-Road sustainability strategy has been addressed (Ch. 2).

In the following, the key discoveries and issues are summarized. In addition, suggested topics for further work are distilled.

6.1 Conclusions

Table 11 aggregates the key findings and investigational issues with derived recommendations. Overall, it should be noted the different themes are interrelated. For instance, the energy consumption measurements inform the software development which realizes the sustainability strategy of X-Road. The handprint calculations require the footprint information.

Table 11. Key findings and inferences.

THEMES	Key Points and Issues
Sustainability strategy (Ch. 2)	• There should be a shared understanding of what sustainability overall and in different dimensions means for NIIS, and what (environmentally) sustainable X-Road is. What is the criteria for "the most sustainable data exchange solution"? • The sustainability objectives should be explicated and communicated—also when there may be none relevant. • Sustainability competences are distinct. They should be developed systematically within NIIS, the software development partners, and X-Road users (operators/member organizations).

X-Road sustainable software development (Ch. 3)	• Sustainability should be treated in similar ways as security throughout the software development life-cycle. • Sustainability requirements (when applicable) should be defined and managed as other non-functional requirements. The software development process must then satisfy them (software quality attributes). • Technical sustainability may be as important as environmental sustainability.
X-Road handprints (Ch. 4)	• Considering X-Road for sustainability (X-Road as a part of solutions) may open new business opportunities (product strategy). • In addition to environmental positive effects, there may be economic and social benefits.
X-Road carbon footprints (Ch. 5)	• The focus should be on energy consumption (and consequent carbon emissions) of most significant, meaningful workloads representing actual X-Road usage in typical instances and execution patterns over time. • The relationship between X-Road software energy consumption and the actually induced carbon emissions in different X-Road instances (including third party services such as data centers) should be determined—taken into account possible time dynamics of current electricity production systems.

6.2 Future Work

SUSTAINABILITY STRATEGY

• Which one of the following traits is more important—currently and in the short-term/mid-term/long-term future?

    a. X-Road for environmental sustainability
    b. Environmentally sustainable X-Road

• What are drivers of X-Road for environmental sustainability?

    o e.g., environmental policies to develop and disseminate new environmentally friendly ICT? [23]

• How does X-Road innovation process and product design balances all the variables of sustainable development—environmental, economic, and social? [23]

- Do "greener" X-Road solutions need to outperform competing products in features other than environmental impacts (overall benefits)? [24]

- Which governments are key customers leading the way by taking into use environmentally sustainable X-Road solutions? [23]

    o Are X-Road sustainability decisions supported by governmental regulation or other incentives?

- Roadmap of X-Road for (environmental) sustainability

    o Expressing a vision, e.g. [23]:

        o X-Road contributes to decreasing resource consumption and resource-intensive lifestyles by providing consumers with accurate information about the ecological burden. X-Road offers achievable data for the people to decrease their ecological footprint. The emission information of products and services are monitored, collected, processed, and shared through international databases and marketplaces exchanging, processing and reporting environmental information between different operators, systems and even devices.
        o X-Road systems themselves are highly optimized.

    o Temporal: present (current releases) – short-term (1 year) – middle-term (3 years) – long-term

- Communicating NIIS and X-Road sustainability

    o e.g., https://www.niis.org/strategy

X-ROAD SOFTWARE DEVELOPMENT PROCESS ENVIRONMENTAL IMPACTS EVALUATION

- What could energy-awareness mean in the X-Road software?

- Means to design and optimize energy-efficient X-Road software architecture and algorithms—including taking into account different hardware environments of the X-Road instances

- Energy models of the X-Road software, algorithms

- Energy management support within the X-Road infrastructures

X-ROAD ENVIRONMENTAL HANDPRINT EVALUATION

- Could X-Road provide or facilitate the following positive environmental developments? [23]

    a. Solutions to measure and deliver environment-related information?
    b. Information and tools for citizens and consumers to assess their actions and decisions from the environmental point of view?
    c. Reducing the use of environmentally malign resources?
    d. Increasing the operational efficiency of products, systems, and services in order to reduce their environmental loads?

- "Environmental impacts related to X-Road, but not caused by X-Road" [25]

- X-Road handprints: What could be economic, social benefits—in addition to environmental ones?

X-ROAD CARBON FOOTPRINT MEASUREMENT

- What energy consumption and/or emissions data do the

   a. X-Road operators
   b. X-Road member organizations

   currently collect/measure?

- What are the relationships between X-Road software energy consumption and the carbon emissions in actual X-Road instances?

   o 'Emission factor' in the *Emissions Calculator*

- Energy models of the X-Road execution systems

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[25] https://www.niis.org/s/NIIS_XRoadFootprint_Final.pdf (26.5.2021)

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See Appendix 1 for further references.

Appendix 1.
NIIS / X-Road Sustainability Framework

As described in Ch. 1.3, a key developmental research artefact created during the investigation was the GQM+Strategies type gridwork. Altogether, it comprises more than 50 pages. Figure 7 depicts its overall structure. The full artefact is available in a separate document.
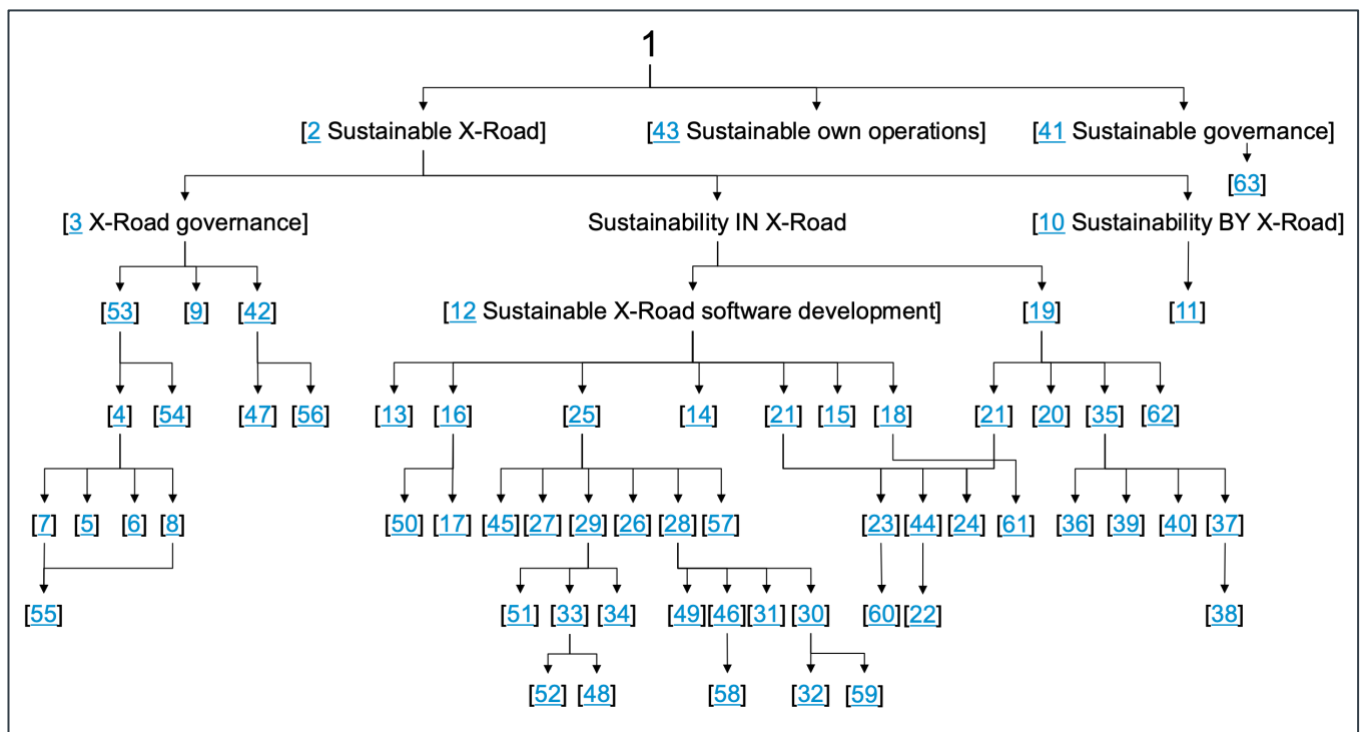

Figure 7. X-Road sustainability improvement framework overview.

In this study, selected areas in the framework were investigated in more depth whilst other areas very consciously chosen to be of less importance. This is also visible in the leveling in Figure 7.