An Ecosystem of Knowledge Graph-based Web Services for Greenhouse Gas Assessment

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Abstract. Technological and societal changes today are accompanied by a growing need to address the challenges posed by rising greenhouse gas (GHG) emissions. While national and international efforts are made to improve accountability for these emissions and to ensure accurate carbon footprint calculations, these efforts require substantial intervention of experts and the use of highly heterogeneous data sources and methodological standards. In this paper, we present the WISER ecosystem for the integration, exchange, computation, and elaboration of GHG assessments, based on ontologies and Knowledge Graphs to model not only GHG data sources but also the assessment standards that guide their use and application. Specifically, the WISER ecosystem has been applied to multiple real use-cases, of which we focus on: GHG assessments of industrial/production sites, GHG-informed procurement for ICT in cities, and decarbonization of data centers. These use cases have been developed and validated in collaboration with external industry partners as well as the ICT departments of Swiss municipalities.

Keywords: Knowledge Graph · Digital Ecosystem · GHG assessment.

1 Introduction

The evolution of human industrial activity, transportation, and energy use has significantly increased greenhouse gas (GHG) emissions, leading to the worrying effect of climate change [15, 13]. It is therefore helpful to develop GHG assessment methods and tools that support the reliable evaluation of these emissions and their linkages to human activities, so that we may identify pathways to slow the pace of climate change [16].

In essence, GHG assessments can be differentiated into three categories: those that account for atmospheric gas concentrations, those that account for annual

GHG emissions, and those that model GHG emissions across the full life cycles of human activities [5, 1]. The assessments can be based on direct or indirect measurements, observations, or modeled from scientific and environmental knowledge. To perform these assessments, it is important to follow standards that provide a well-defined framework for the accounting of GHG emissions from various anthropogenic sources [1]. Different perspectives exist in this regard. At the geopolitical level, guidelines exist to produce annual country-level inventories of GHG emissions, which may inform macroeconomic decisions and political actions. Other standards refer to organizational or product-level carbon footprints, linked to direct and indirect GHG emissions across their value chains.

Navigating these standards [8], as well as the different data sources and methods used for GHG assessments, is not straightforward (see Section 2) and currently requires substantial support from domain experts, limiting access to reliable GHG evaluations. This situation does not align with the current available resources of companies, public organizations, and SMEs, which need simpler tools and methods to facilitate this task while maintaining high levels of transparency, consistency, and comprehensiveness.

In this work, we present the WISER ecosystem of digital services, called WIDS (Web of Interoperable Digital Services). This ecosystem aims to provide decentralized web services and applications that facilitate the creation and realization of GHG assessments. Within its structure, the WIDS deliver various features such as the harmonization of GHG data source formats, verification of alignment between standards and studies, and the usage of different computational carbon footprint tools.

The main contributions of this work are: (i) the WISER ecosystem infrastructure, including its core API, which provides access to sustainability data and domain-expert knowledge on procedures and standards by connecting to ontologies and semantic models; (ii) the implementation of the WIDS, which includes methods for integrating heterogeneous knowledge and enabling the construction of advanced GHG assessment applications; and (iii) the implementation, deployment and validation of the WIDS for three main use cases, with direct involvement of public and private partners invested in GHG assessments of manufacturing sites, ICT use in cities, and electricity use in data centers.

2 Challenges in GHG assessments

Several challenges arise in assessing GHG emissions from human activities [1]. We focus on those related to the data needed for these assessments, as well as the variations in standards and methodologies.

2.1 Heterogeneity between and within GHG databases

Different types of data can be used to assess GHG emissions from products, services, or systems, depending on the selected assessment standard. For example, in the context of the well-known GHG protocol, Scopes 1 and 2 respectively account for direct emissions and indirect emissions from used and purchased energy [21]. These value chains typically require data from internal measurements or estimates for Scope 1, and energy mixes, as well as usage data for Scope 2. For Scope 3, which refers to indirect life-cycle GHG emissions across the value chain, the data may come from different sources with varying degrees of alignment with the rules of standards, as well as varying levels of availability. Among these data sources, Life Cycle Assessment (LCA) databases [10] are of primary importance, as they describe GHG emissions associated with the inputs and outputs of different products, services, and activities of a company or organization along value chains. These may include detailed emissions information for a reference product per functional unit of mass or volume, enabling the calculation of complex emission analytics. Certain LCA data sources capture data for an extensive range of services, activities, and industries in different geographic locations, such as ecoinvent[5] [2], or the GLAD repository [11], while others are specialized in specific sectors, as in the case of Plastics Europe [19] or worldsteel [22].

Given the degree of heterogeneity between LCA databases and their different models, their datasets cannot be seamlessly combined for a consistent assessment of different parts of value chains. The differences are not limited to the format or structure of the data, but also to various assumptions, modeling decisions, and uncertainty, which are the origin of inconsistencies among these data sources. Differences may lie, for example, in assumptions about the allocation rules for GHG emissions from multi-product systems, or in differences in granularity. In addition, different strategies for modeling future evolutionary scenarios may be important, as these models may evolve substantially over the life cycle. Thus, it is common for multiple versions of these datasets to be released over the years, and it is essential to maintain consistent choices for combining them reliably.

2.2 Diversity in GHG assessment standards

As mentioned earlier, different assessment standards are proposed to evaluate GHG emissions for a given system or value chain [1]. Such standards set out a series of rules and requirements for conducting GHG assessments, but may differ substantially depending on, among other factors, their goals and scope [8].

Standards defined by organizations, such as the GHG Protocol Consortium [21], offer rule sets complemented by recommendations, as well as specific vocabulary and reporting structures, to enable broader assessments, with the goal of generalizability and applicability across a wide range of companies across domains. Some sectors and consortia seek to address these differences by publishing more specific guidelines as supplements to their general assessment standards (e.g., the Agricultural Guidance [20] as a supplement to the Corporate Standard). However, the lack of clarity regarding mandatory and voluntary considerations in standards and on how to validate them leaves room for interpretation. This fact, combined with heterogeneity between and within LCA databases, may lead to inconsistencies and incoherent application of the standards. This suggests that

[5] https://ecoinvent.org/

there is a clear, common structure to all GHG assessment standards and that evaluations should typically proceed in a similar manner. With that said, the devil is in the details, and differences in standards prevent straightforward, consistent comparisons across assessments, making the exchange of GHG knowledge between organizations very challenging. Here are some examples of aspects that impede consistent comparison.

- Differences in system boundaries: If two organizations or value chains do not consider activities at the same level of comprehensiveness, there is a high probability that some GHG sources will be neglected in one of the assessments [17]. This means that comparisons between assessments will not be made on equal grounds. This can happen if the standards leave the decision to include or exclude certain parts of a value chain to the assessing party.
- Differences in how a system is modeled: The web of human activities worldwide is complex, and it can be modeled in many ways. For instance, one can assume that a company uses the electricity available in the region where it operates (location-based modeling), leading to a specific representation of its associated GHG emissions. On the other hand, it is also reasonable to link a company's electricity use to the energy sources they pay for, which may yield a completely different picture if substantial amounts of renewable energy are purchased with certificates (market-based modeling) [9].
- Differences in accepted background data sources: Database providers may use different sources of information to evaluate the scope 3 GHG emissions of various activities. These sources of information can vary in detail, use different modeling choices, and be updated at different times. Furthermore, database providers must use complex models that are rarely fully documented, which often prevents consistency checks across the entire background databases [18].
- Differences in the formats and vocabularies: The many organizations behind the various existing standards are connected to different regions of the world and sectors of the economy, which makes it easy to understand why they use different formats and naming conventions for their disclosure requirements, for instance. While easily understandable and very difficult to change, this nevertheless hinders a clear and efficient comparison between assessments.

In this landscape, the assessment work of companies is challenging since they need to comply with various standards, and need to find the proper guidance matching their system(s) and activities. This situation is even more complex to navigate for organizations operating internationally with diverse portfolios of products, services, and activities.

2.3 Procedures for GHG assessment

Regarding the actual implementation of the GHG assessment, which will use the standards and data described previously, the limitations become clearer, and their consequences are evident in current approaches. We analyze them through the different steps that constitute this process:

- Goal and scope definition. For this step, a comprehensive description of the system, including its activities, products, and services, is crucial to guarantee transparency and reproducibility. This includes, but is not limited to, specifying boundaries, scope, and modeling choices. However, these choices need to be consistent with those made by data creators who inform databases of GHG emission factors (e.g., LCA databases). Given the multiple, heterogeneous data sources and different assumptions and modeling approaches across standards, the involvement of LCA experts is required to ensure the development of consistent models for the assessed value chains.
- Information gathering and modeling. In this step, detailed information is gathered from the GHG data sources identified in step 1, namely internal measurements and their corresponding emissions, as well as external data from LCA databases and other sources providing GHG emission factors for energy use and complex value chains. At this point, it is necessary to integrate different data sources and verify that they comply with the chosen standard and its requirements, which requires extensive domain knowledge.
- Carbon footprint calculation. Using the previously gathered information, all necessary aggregations will be performed in accordance with the rules of the chosen standards, resulting in a calculated mass of GHG emissions, typically expressed as carbon dioxide equivalent (e.g., kg CO2-eq.). In many cases, these calculations are still performed in spreadsheets, but professional tools are available to aid in this task. These calculation tools are helpful only if experts have conducted consistency checks when creating models of value chains. In other words, they depend on the reliability of their inputs to offer standard-compliant results.
- Carbon footprint reporting. This stage will take the aforementioned steps to construct a data-informed narrative that presents the assessment findings, in accordance with the chosen standards' disclosure requirements. The produced reports will thus need to include the necessary information to provide transparency, comparability, and compliance with the regulations of the country, the sector or other regulatory bodies that the assessing party is obliged to. Current reporting strategy often lack the means to provide clear traceability that links the carbon footprint results with the data sources, including their different versions, assumptions, modeling decisions, etc.

3 The WISER ecosystem

To address the previous challenges in GHG assessments, this work presents the WISER initiative[6], which aims to streamline the processes and tasks undertaken by organizations to perform GHG assessments and carbon footprint calculations, while significantly reducing the required knowledge to carry them out.

More concretely, WISER proposes a digital ecosystem of Web services and applications that enable the integration of existing GHG assessment databases

[6] WISER initiative: https://wiser-climate.com/

and standards while guarding consistency and transparency. In particular, the WISER ecosystem provides the following features:

- Harmonization of different LCA data models and data sources through a common ontological model.
- Integration of heterogeneous LCA databases through a common interface—the WISER API—based on the ontology model.
- Modeling of GHG assessment standards within a Knowledge Graph, integrated into the WISER API.
- Consistency in the usage of different GHG assessment standards and the integrated data sources.
- Provision of API connections for decentralized computational tools.
- Access of third-party systems to the WISER services, to create user-facing dashboards and applications.

These components are schematically represented in Figure 1, where examples of LCA databases are shown in the upper-right corner and may include API-fronted data sources (e.g., ecoinvent[2]) accessible through various interfaces (e.g., REST). The WISER Knowledge Graph represents different smaller interconnected KGs, of which the most prominent are: knowledge pertaining to rules and guidelines within GHG standards (e.g., GHG Protocol, or ISO 14064-1), and also those fully embedding LCA information specific to a certain domain (e.g., the KBOB[7] data for the Swiss building sector). The WISER KG also incorporates other linked datasets, like Geonames [6], to provide geographical context for the assessments and databases, among others. The WISER ecosystem also interconnects computational tools that can provide additional calculations based on the activities/services LCA data. At the center of this ecosystem lies the WISER API, which, apart from providing the infrastructure to interconnect the aforementioned components, allows establishing authentication and authorization policies for these resources. The decentralized services that integrate the WIDS can operate autonomously while also interoperating with the rest of the WISER ecosystem through the API's semantic interfaces. Within this ecosystem, applications in specific domains can use parts or all of these features to develop their own user interfaces for very concrete tasks, such as GHG-aware procurement or GHG emission forecasting.

Overall, the WISER ecosystem targets the following aspects in GHG assessments, it (i) provides consistency of GHG assessments, by respecting rules of specific standards; (ii) enhances comprehensiveness of assessments by including relevant direct/indirect emissions linked to activities in different LCA data sources; (iii) allows transparency and recency of information, through versioning and provenance of all the information encoded in the KG and the original data sources; and (iv) allows extensibility by permitting other services and applications to be connected to the WISER ecosystem through its API.

To bootstrap the WISER initiative, a consortium has been formed comprising academic, industrial, and institutional partners. This initiative has been supported by Innosuisse Flagship's funding and includes the active participation of

[7] KBOB: https://www.kbob.admin.ch/de/oekobilanzdaten-im-baubereich

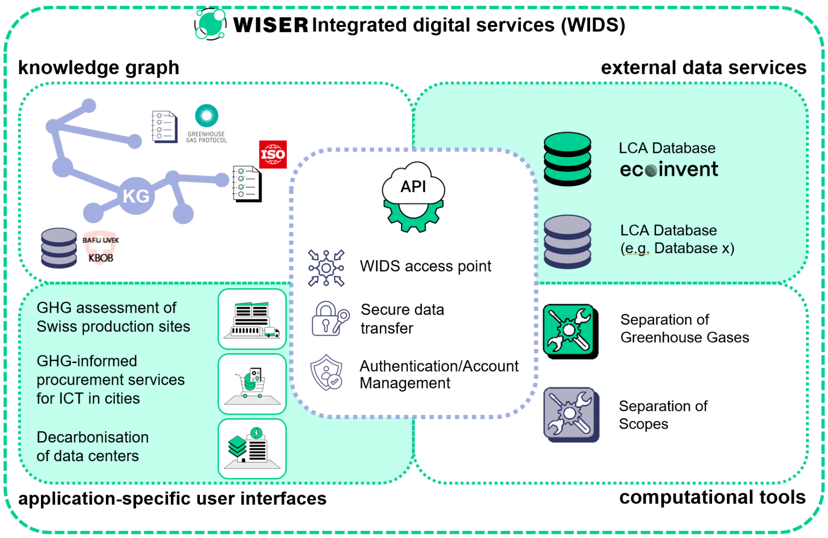

Fig. 1. The WISER ecosystem of integrated digital services: centered on the WISER API for interconnection and the WISER KG for data harmonization, the ecosystem includes access to heterogeneous data sources, GHG standards, and computational tools. Domain-specific applications connect to the WIDS for specialized tasks.

companies and the ICT department of a city in Switzerland[8]. These consortium members have actively participated in the construction and the validation of the different components of the WISER ecosystem.

4 WISER architecture and implementation

To design the WISER architecture and its components, we investigated the main pain points and concrete problems faced by professionals working on GHG assessment within the WISER consortium. We provide a summary of the main design principles as follows:

- Uniform GHG data accessibility: Different LCA databases (sources of GHG emission factors) can be accessed (e.g., ecoinvent, UVEK, etc.) through an API (e.g., ecoinvent API) or as data resources in different formats. The WISER API provides access to the information from these different databases in terms of the ontologies supported by WISER.
- Fine-grained access control: Access rights to databases conform to stakeholders' permissions (e.g., paid and/or restricted access according to a license). The WISER API ensures that the enforced restrictions on data access are respected.

[8] WISER industrial and academic members: https://wiser-climate.com/partners/

- Assessment standards representation: Metadata about the requirements of assessment standards are made available through the WISER API. This includes the main characteristics of these standards (e.g., the GHG Protocol) and their potential compatibility with existing databases and the selected activities for a potential assessment. This information is integrated within the WISER Knowledge Graph and is represented using explicit semantic relationships that allow reasoning and querying.
- Homogeneous activities/processes: Activities (or processes) of value chains are listed in the environmental data sources previously mentioned, and the WISER API is accessible through a unique model and format. Search and filtering are possible by category, location, and other activity characteristics. These relationships are accessible through specific APIs or embedded directly in the WISER Knowledge Graph.
- Unique identification: Entities in the WISER API have a unique identifier, i.e., URI that can help to name them across databases and versions, even though each database may have its own identifier (e.g., hashes, URNs).
- Access to GHG emission factors: The WISER API provides access to GHG emission factors of LCA databases. They may be linked to different impact methods and characterization factors. In WISER, the focus is on the climate change impact of all GHG represented in kg of CO2-eq.
- Filtering options for location/region are made available in the WISER API. Certain databases are specific to an area or country. Within a single database (e.g., ecoinvent), datasets for a process or activity may exist for different countries or regions.
- Computation capabilities: LCA calculations can be made available through the API, although actual implementation strategies may vary. For instance, computational results can be generated by invoking existing libraries such as Brightway2 [14] and then the outcomes can be stored and integrated within the WISER KG using the same semantic model.

4.1 WISER implementation

The WIDS proposed by the WISER initiative addresses the challenges of supporting integrated digital GHG assessment procedures that check for alignment between GHG data sources and assessment standards, proposing a digital ecosystem of open-source Web services. Concretely, the WIDS are implemented as independent Web Services that can be consumed and/or used by external applications in a configurable manner, as building blocks depending on specific needs. The architecture of how these services are structured and interconnected responds to the principles listed above. In the following, we first describe the WISER API implementation and then the different types of WIDS services currently integrated into the platform.

WISER API implementation. The current version of the WISER API has been implemented in Python, based on the Flask framework. The source code is available for project partners on Github. Although it is planned to be open-sourced,

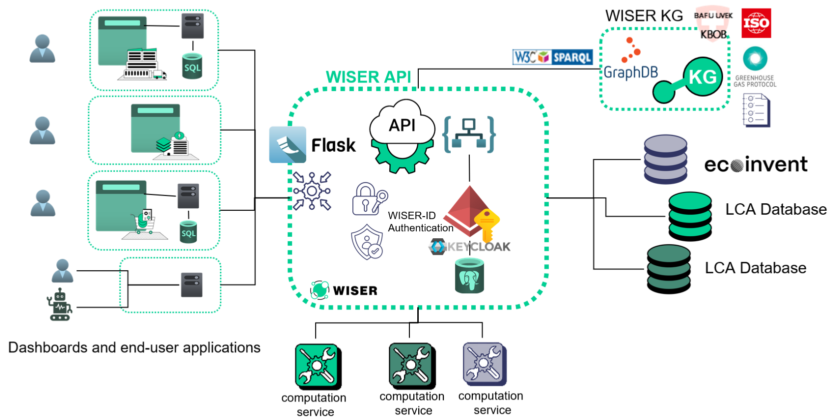

Fig. 2. Implemented and deployed architecture of the WIDS.

at this stage its usage requires an agreement with the WISER consortium, given the intellectual property restrictions of the participating industrial partners. The WISER API exposes data from the heterogeneous GHG data source using a unified semantic model, and provides access to the WISER KG (see Section 4.2). The API uses an authentication mechanism based on the OAuth 2.0 protocol, implemented with the Keycloak framework and a self-hosted service. The WISER API is currently deployed and accessible on a public address[9].

The rest of the WIDS can be classified in four main groups, those dedicated to: (i) the management of external and heterogeneous LCA data sources, (ii) the management of GHG assessment knowledge with a Knowledge Graph (KG), (iii) the provision of computation services, and (iv) the interaction with end-users through specialized dashboards and other front-ends for GHG assessment.

WIDS for heterogeneous data sources. Goal 1: Use and compare different data sources for various contexts. These WIDS can access data from various data managers/organizations. Data sources include primarily LCA databases like ecoinvent or UVEK, but it can potentially reach other relevant sources in the wider sustainability domain. These data sources conform to different schemas and data structures, therefore requiring a process of homogenization. For example, data sources like ecoinvent use de-facto standards like Ecospold [12]. This can be compatible to a certain degree with other standards like ILCD [4], but requires an explicit formalization and mappings between both models. We use ontologies to semantically represent all incoming data sources and map key concepts such as Activities, Classifications, Operational Boundaries, and GHG Emission Factors.

WIDS for GHG assessment knowledge Goal 2: Align value chain models and related data to different GHG assessment standards in a consistent way. GHG

[9] WISER API docs: https://docs.wiser.ehealth.hevs.ch/

assessment standards require verification of compatibility among different aspects, including LCA methods, datasets, regions, and other assessment details. The selection of these parameters is often part of the expertise offered by the LCA expert preparing a GHG assessment report. The WISER ecosystem integrates the information and logic needed to ensure consistency in how GHG assessment standards are used. This information is formalized in the WISER Knowledge Graph (KG), which is made accessible through the WIDS. The KG is currently deployed with GraphDB, and serves data following a unified ontology model inspired from Ecospold or ILCD. Sample queries are detailed in Section 4.2. Other services in the WISER ecosystem can access the Knowledge Graph using a dedicated API built specifically for that purpose.

WIDS for computational tools and APIs Goal 3: Connect various computational tools from different organizations with Application Programming Interfaces (APIs) to enable more useful and representative evaluations. Computations for GHG assessments can use specialized services and tools for this type of task, such as Brightway [14]. These tools may work in various ways, using different parameter sets and assumptions that might be difficult to master. For this reason, in WISER, the WIDS can invoke and perform these computations, integrating their outcomes into the WISER KG, so that other applications can reuse them according to their needs.

WIDS for expert users Apps and services Goal 4: Bring the GHG information from environmental experts to businesses with *easy-to-use* Web services. Although different client applications can access the WIDS, they are not intended for end users, e.g., LCIA experts or sustainability employees preparing assessment reports. For end-users, specialized applications can connect to the rest of the WIDS via the WISER API. These Apps typically implement domain-specific features, as shown in the use cases in Section 5.

4.2 Knowledge Graph Interfaces

One of the key components of the WISER ecosystem is its Knowledge Graph, which includes different–yet interconnected–subgraphs containing specific, well-defined subdomains. In particular, we have integrated the requirements of different assessment standards into the KG, as well as LCA databases. These resources are also linked to classification terminologies and geographic entities, which are essential for discerning which elements to filter or include in a GHG assessment. In the following, we present snippets of queries used to manage these resources, illustrating the use of the KG (prefixes and details omitted for brevity).

The snippet below shows a simple request for all operational boundaries linked to a given assessment standard available in the WISER KG. As we will see later, domain-specific applications (e.g., dashboards) can use this feature to allow selection of a specific standard (e.g. GHG Corporate Protocol [21], GRI Standard[7], ISO 14064-1, etc.) and operational boundary (e.g., Scope 1, Scope 3 upstream or downstream, etc.) for a GHG assessment. Regardless of their heterogeneous origin, all of the standards are typed as `wiser:Framework`, and similarly for operational boundaries. As stated above, we provide unique URIs to identify each framework (e.g., `wiser: GHG-CP-LOC` for the GHG Corporate Protocol-Location-based) and potentially connect them to other Web resources.

```
SELECT DISTINCT ?framework ?operationalBoundary ?operationalBoundaryLabel
WHERE {
    ?framework a wiser:Framework.
    ?framework rdfs:label ?frameworkLabel.
    ?operationalBoundary a wiser:OperationalBoundary.
    ?operationalBoundary wiser:hasFramework ?framework.
    ?operationalBoundary rdfs:label ?operationalBoundaryLabel.
}
```

Listing 1.1. Query snippet for GHG standards and operational boundaries.

Similarly, one can identify different categories linked to a framework and operational boundary. This can help maintain consistent use of categories relevant to a given standard and within a specific scope. Notice that categories may vary across assessment standards; therefore, the WISER KG provides the necessary mappings in this case. The query snippet below allows filtering these categories, given the assessment standard and assessment scope.

```
SELECT DISTINCT ?category ?categoryLabel  WHERE {
    ?framework a wiser:Framework.
    ?category a wiser:Category.
    ?category wiser:hasOperationalBoundary ?operationalBoundary.
    ?category wiser:hasFramework ?framework.
    ?category rdfs:label ?categoryLabel.
}
```

Listing 1.2. Query snippet linking GHG standards to categories.

Finally, the following snippet shows a query that searches for activities using different criteria, including country codes, classification, activity search terms, the LCA database to search, and its version (the WISER ecosystem may use multiple versions at the same time). This will allow finding different activities that match the search criteria, even if they are in very different (e.g., in terms of format and sectoral coverage) sources such as Plastics Europe or UVEK.

```
SELECT DISTINCT ?act ?uuid ?referenceProduct ?activity ?location ?dataset ?version WHERE {
    ?act a wiser:Activity; wiser:UUID ?uuid; wiser:Geography ?geo .
    ?geo wiser:geographyTerm ?location .
    FILTER(?location IN {?location_codes})
    ?act wiser:activityName ?activityName .
    ?activityName rdfs:label ?name .
    ?act wiser:classification ?class .
    ?class a ?classSubType .
    ?classSubType wiser:subClassificationOf ?classType .
    FILTER(?classType IN {?classifications}) .
    BIND(?name AS ?referenceProduct)
    BIND(?name AS ?activity)
    FILTER (CONTAINS(LCASE(?name), ?search_term))
    ?act wiser:wiserInfo ?wiserInfo .
    ?wiserInfo wiser:dataset ?dataset; wiser:version ?version .
    FILTER (?dataset = ?dataset)
    FILTER (?version = ?dataset_version)
}
```

Listing 1.3. Query snippet filtering activities in an LCA database.

5 Domain-specific Use-cases

The key services of the WISER ecosystem (WIDS) have been deployed and tested through *user-friendly* interfaces in collaboration with different companies and public institutions that are members of the WISER consortium, such as the ICT department of a Swiss city. In this paper, we present three examples of use cases. The three use cases touch different aspects in which GHG assessments can be of primordial importance in the scope of recent regulatory developments related to climate change. They target different users through dedicated dashboards and tools in the following domains:

– Dashboard for Manufacturing Sites: This dashboard offers a user-friendly interface, presenting and dealing with the GHG assessments of manufacturing sites that connect with global value chains.
– Dashboard for ICT Procurement and Planning: This dashboard aggregates and displays information about GHG emissions from ICT equipment in terms of procurement and usage.
– Dashboard for Electricity Uses in Data Centers: Addressing the environmental impact of data centers' electricity use on behalf of any time-flexible and energy-intensive operation, this dashboard focuses on detailed GHG assessments of energy use based on electricity mix data with a high temporal resolution, as well as forecasting electricity mixes in European countries (Switzerland and neighboring countries).

The front-end dashboards communicate with the WISER REST API, serving as a bridge between end users and the backend infrastructure. The API backend, in turn, interfaces with the Knowledge Graph, facilitating the verification of alignment between of rules and vocabularies of standards and GHG data. Simultaneously, the WISER API backend communicates with the external ecoinvent API and other data sources (in the Knowledge Graph), enriching the ecosystem with additional environmental data and formats.

The separation of front-end and backend components is a fundamental design principle. The dashboards serve as user interfaces that interact with the backend through the API. This separation ensures a streamlined user experience while maintaining the robustness and scalability of the backend infrastructure.

For all three dashboards, the GHG assessment procedure is split into three main support steps. These steps include: (i) assessment definition; (ii) user data input management, and (iii) reporting definition. This three-step process breaks down the complex path to analyzing GHG assessments into easily understandable chunks for the user, while maintaining strong alignment with the typical structure of GHG assessment procedures found in most assessment standards.

5.1 GHG assessments for manufacturing sites

This use case centers on GHG assessments in the manufacturing domain for companies with multiple production sites and complex global value chains. Within the WISER initiative, an industrial partner has actively participated in the co-development and evaluation of this prototype. The main goal of this prototype is to provide a Web service that streamlines GHG assessments of manufacturing sites in Switzerland with the following key features: (i) giving guidance on the choice of GHG emission factors that align with a selected assessment standard; (ii) semi-automated translation of the terminology and structure of the models when a different GHG assessment standard is selected for the same assessment; (iii) searching and filtering of activity datasets and their related GHG emission factors (see Figure 3) from different LCA databases based on their suitability and compliance with the selected assessment's context (e.g., standard, region, location); (iv) report creation with auto-generated elements based on disclosure requirements of the selected standard or from calculations made by the computational tools of the WIDS.

The three support steps of the dashboard help complete key aspects of any GHG assessment, including system definition, description of modeling choices, carbon footprint calculation, and creation of tables and figures for the report. After validating the dashboard with a leading Swiss industrial partner, we demonstrated how it helps reducing the effort of creating GHG assessments that meet the requirements of the selected assessment standard. Thanks to the WISER Knowledge Graph, the tool is able to guide and validate the creation of the assessment. It also provides a consistent structure that we considered reusable for other domains, and as such we used it as a basis for the other two use-cases. In the future, it could also be adapted with low effort to support the GHG assessment of other systems, products, or services if new GHG assessment standards are included in the Knowledge Graph.

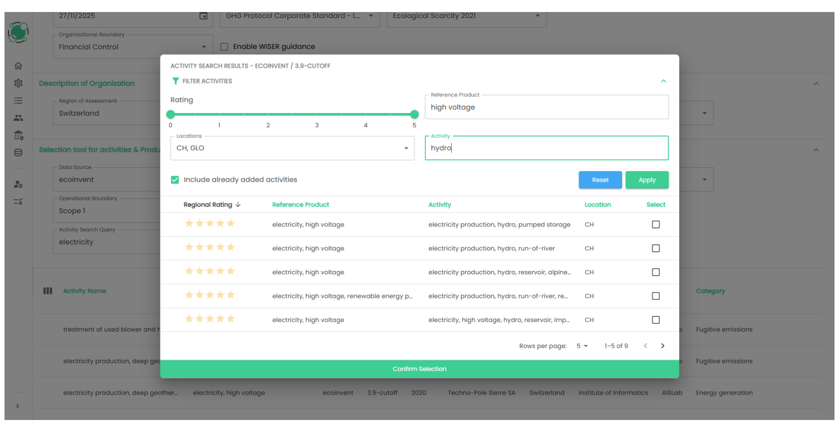

Fig. 3. Activity search for the manufacturing use case, connecting external databases (e.g. ecoinvent) for a specific GHG standard, enabled by the WISER KG and API.

5.2 GHG-informed procurement for ICT equipment used in cities

The main goal of this use-case is to provide a quick, easy-to-use tool that informs on carbon footprint values of ICT equipment for a more sustainable procurement procedure by city officials. The dashboard can also help to evaluate and communicate on the decarbonisation potential of different ICT development scenarios within a selected time horizon. Key features that support city officials with simpler GHG assessment of ICT equipment in this example are: (i) semi-automated connection between GHG datasets of a standard-compliant database, and their related GHG emission factors, with inventories of ICT equipment provided by the ICT department; (ii) restricted list of options for system definition based on a Swiss-compliant definition of the GHG assessment standard that are in the Knowledge Graph; (iii) possibility to define and calculate a timeline of GHG emissions from the buying and decommissioning of ICT equipment within a specified time horizon. This is done by separating information on the carbon footprint values of ICT equipment into GHG emissions from manufacturing and from waste management.

A validation phase was implemented in partnership with the ICT department of a major Swiss city, and therefore the dashboard was designed to tackle the key implementation concerns raised by the city officials. This sets a well-defined scope for the data that can be used in the assessment (i.e., Swiss context), aligning with the need for support from domain experts in defining the limits that the city should respect to provide reliable assessments that can be shown to the public. In Figure 4, the carbon footprint is shown for different types of ICT equipment, based on GHG Emission factor data from ecoinvent and user-controlled consumption data. Thanks to the semantic information integrated through the WISER API, different data sources can be consulted in order to perform the assessment and the calculations, providing actionable data for decision-making.

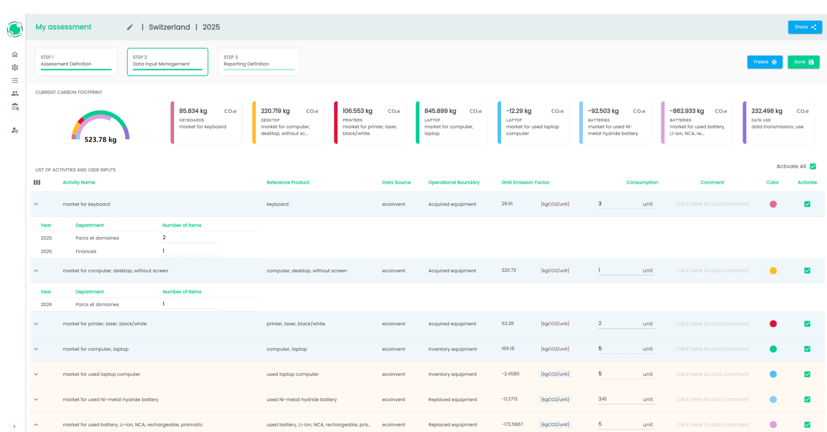

Fig. 4. Data input management and carbon footprint for a GHG assessment in the use case of ICT in Swiss cities.

5.3 GHG emissions from electricity use in data centers

The main goal of this application is to provide a web service that delivers detailed, temporally differentiated GHG emission values for electricity use in data centers. The key feature of this dashboard is related to the GHG evaluation for electricity use. More specifically, it enables the connection of standard-compliant GHG emission factors from different LCA databases with external information on electricity production from various European Countries to provide temporal profiles of variation in the past (historical), present (annual), and near future (forecasting). The main challenge in the development of this dashboard was the required effort to map the connections between LCA databases and external sources of information on electricity production (i.e., ENTSO-E [3]) since the data sources use different levels of aggregation in describing energy sources.

Thanks to the WISER ecosystem, data center managers have access to detailed temporal profiles of *GHG intensity* that can drive automated changes in electricity consumption (e.g., the computation period) to reduce the overall carbon footprint of data center activities. In the future, the Knowledge Graph could also support the provision of electricity GHG profiles, using diverse sources of GHG emission factors that better align with the requirements of assessment standards for specific European countries. This would simplify evaluation across different assessment contexts relevant to international organizations. This, however, will require further domain-expert work on the connection between the many available LCA databases and the ENTSO-E model of electricity production. In Figure 5, the carbon footprint profile of the Swiss electricity mix is shown for a selected period of time and with detailed information on the key sources of GHG emissions between different energy sources.

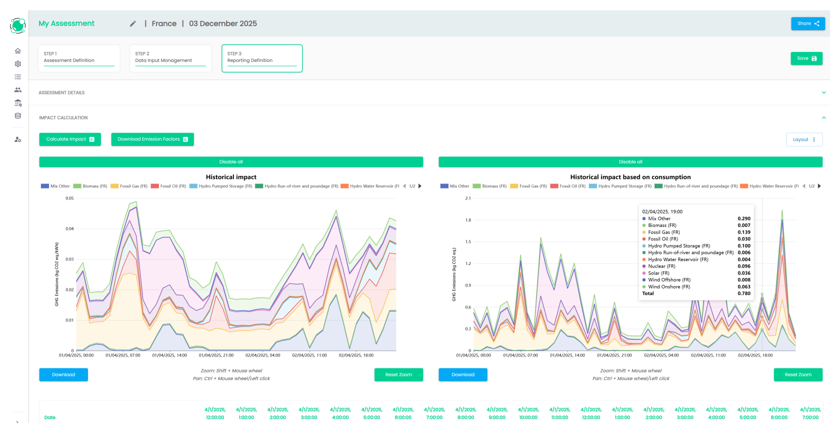

Fig. 5. Carbon footprint profile of the Swiss electricity mix with detailed GHG emissions data for different energy sources.

6 Conclusions

We have presented the WISER interoperable digital services, their underlying architecture and a concrete implementation of its core components. We have demonstrated how this digital ecosystem can connect different services and stakeholders of the GHG assessment procedure in an integrated manner to simplify the sharing of domain-expert knowledge, so that future GHG assessments can be aligned with different assessment standards. A fundamental aspect of the WISER ecosystem is its reliance on semantic models and ontologies that enable the integration of heterogeneous LCA data sources, while also encoding the dependencies, restrictions and relationships of GHG standards. We have also showcased the importance of the WISER Knowledge Graph, and the ability of the WISER API to integrate the multiple input sources used by GHG assessment professionals.

Moreover, we have shown initial adoption by domain practitioners in different sub-domains, with active participation of companies, an organization in the sector of data center management, and an ICT department in a Swiss city. The implementation of the WISER showcases the usage of semantic data, in this case especially through the WISER Knowledge Graph, for the integration of inherently diverse data sources. Specifically, we have co-constructed and validated the WISER platform in three use cases: one on GHG assessment in manufacturing sites, another on ICT procurement, and finally one on data center decarbonization with detailed information on the carbon footprint of electricity. All use cases have been conceived and evaluated in direct collaboration with these stakeholders, and will continue to be developed in the context of the WISER initiative and its extended membership.

One of the key lessons learned from this experience is the importance of including an interdisciplinary team including GHG and sustainability experts, ontology engineers, computer scientists, and end-users. The participation of the latter has been crucial for the validation of the ecosystem, as it forced the rest of the team to solve specific issues, relying on the available data and the WISER capabilities. Another important takeaway is the importance of extensibility, given the very wide range of potential users of this ecosystem. Being applicable to multiple domains, it has been crucial to focus on loosely coupled components working as an ecosystem, rather than providing a centralized framework.

The WISER ecosystem will continue to evolve through the collaboration of stakeholders from specific application domains, together with environmental, information and computer scientists. These synergies are expected to develop in the future, including the addition of other use cases (e.g., wind energy, hydropower, citizen-driven carbon footprint, product carbon footprint). We also anticipate the inclusion of AI-driven assistance, and the tighter integration of GHG assessment computational pipelines.

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