A battery electric vehicle charging infrastructure ontology for interdisciplinary research

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Abstract

Interdisciplinary analyses are prone to misunderstandings associated with rich discipline-specific semantics. The research of low-carbon energy systems is an example of such applications where concepts coming from multiple expert groups collide. One relevant case is the transport-energy nexus where 'sector coupling' analyses are performed. In this context battery electric vehicle charging infrastructure comprises a main point of interaction between both research disciplines. Ontologies like the Open Energy Ontology (OEO) were conceived to aid in the concretization of agreement in such interdisciplinary research. However since it is a tool whose focus is energy systems research, it falls short in concepts associated with transportation research. In this paper, we propose a FAIR Ontology, which should work as a first interoperability layer between ontologies and data models intending to represent concepts associated with battery electric vehicle charging infrastructure. We rely on the Basic Formal Ontology (BFO) as top-level ontology, to ensure compatibility with OEO. We develop this ontology using a methodology inspired by the OEO with a stricter requirements engineering approach. This methodology relies strongly on motivating scenarios and competency questions to keep the ontology slim. Current achievements are a documented development environment, the implementation of core terms like charging station, and the reutilization of existing ontology terms coming from ontologies like the OEO, the Common Core Ontologies, and the iCity Transport Planning Suite of Ontologies.

Keywords

Domain Ontology, Transportation, Interdisciplinary research, Energy systems modelling,

1. Introduction

Energy systems analysis is a discipline where specialized software tools are used to study the development of possible future energy systems. One modern example of such studies is [1] which uses a European instance of the energy systems optimization model PyPSA [2] to evaluate decarbonization pathways. In such publications the concept of 'sector coupling' is often used to state that the analysis comprises the evaluation of phenomena in multiple energy-consuming and producing sectors [3] The transport-energy nexus is

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often a subject of such sector-coupling discussions. For example, [4] reviews multiple studies where transport and power systems are co-analyzed. One of the first barriers to do such analyses lies in the terminology differences between the disciplines associated to the studied sectors. To address data interoperability challenges in the field of energy systems analysis the Open Energy Ontology (OEO) [5] was conceived. But once the analyses go too deeply into the field of transport research, e.g. the aforementioned sector coupling studies, its usability dwindles. There are many points of interaction between an energy system and a transport system. One of the most relevant is the battery electric vehicle charging infrastructure because it is directly associated with the process of electrification of the fulfilment of transport needs which accounted globally in 2018 for around 8 Gton of CO_2 emissions [6].

In this paper, we propose the theoretical basis and development plan of an ontology that should allow us to represent concepts associated with the process of charging an electric vehicle from the point of view of energy systems analysis and a transport research. The rest of this paper is divided into six sections. Section 2 consists of the justification, philosophy, and approach for the designing of an ontology that allows the description of concepts and phenomena associated with the charging of battery electric vehicles, we also use this section to introduce the Basic Formal Ontology (BFO) [7] as our top-level ontology. Section 3 is a summary of an extensive review of existing ontologies dealing with the topic. Section 4 describes the concrete needs, proposed methodology, and competency questions. Section 5 will be a description of current achievements and implementations. Section 6 points out the challenges and describes the future roadmap. We conclude our paper in section 7.

2. Background

The need for an ontology that represents entities and phenomena associated with charging infrastructure was identified first during the process of implementing the FAIR principles on the data published by the German Federal Network Agency [8]. There we noticed that the existing ontologies and vocabularies were insufficient to annotate concepts like charging plug type. After a short discussion in the OEO issue board[1] we concluded that things like ‘power plug’ and potential subclasses of the same are beyond the scope of the ontology. Along with concepts like ‘parking place’ or ‘mobility mode’, which are often used during transportation research analyses. It has been hard to argue to include them in the OEO, despite them being used during cross-domain analyses like the one done by [9]. This need is deeply explored by Mittermeier [10], but their approach used to address it relied mostly on including the terms in the OEO which we consider not viable in the long run. However, their research provides a solid theoretical basis for further developments in the field of knowledge representation of terminology in the discipline of transport research. From their work we take into account their implementation of electric vehicle charging station.

Katsumi and Fox [11] provide an extensive review of transport ontologies, taxonomies,

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[1] https://github.com/OpenEnergyPlatform/ontology/issues/1597

vocabularies, and other tools for data representing information on transport systems. They shed light on the large complexity of the data environments associated with this discipline. Their research concretized in the creation of the iCity Transportation Planning Suite of Ontologies (TPSO) [12]. They touch on the topic of charging infrastructure on a superficial level which is sufficient for transportation planning tasks. They leave the topic of adding more detail to BEV charging to future work. What we propose is an extension that not only deals with transportation planning but also promises interoperability with planning grid infrastructure and energy consumption estimations. The particular applications are explored in section 4 where we define scenarios that drive and bind the ontology development. It is important to point out that the actual implementations differ significantly from the TPSO because they define their own top-level ontology which is fundamentally different from BFO, the particularities of these differences are described in section 2.1.

There are some other vocabularies and models that deal with charging infrastructure, but most of them are constrained by their specific applications, as they prescribe what would be expected from the data models produced out of them. Relevant examples are the vocabularies provided by standards such as the Open Charge Point Protocol (OCPP) [2] and the ISO 15118, such standards despite their widespread use in the industry have strict copyright licences which can hinder the reusability of their contents. Another important mention is the work from [13] who proposed a power-systems ontology aimed at interoperability of the Internet of Things (IoT) domain. They provide a rich axiomatization of charging infrastructure specialized towards power systems' representation. Some elements of interest to us are present, but most relations are too specific to IoT, specifically Machine to Machine (M2M) communication.

2.1. The Basic Formal Ontology

Top-level ontologies or foundational ontologies intend to model domain-neutral categories and relations [7]. These are not a hard requirement to build an ontology but can make a difference regarding its interoperability. Choosing (or developing) a top-level ontology is not an easy task because a modeler needs to have a deep understanding not only of their domain and the possible applications but also any possible adjacent domains that may operate with the same data. In 2022 a special issue of applied ontology [14] allowed expert users and developers to exemplify the usage of multiple prominent top-level ontologies. In theory, we would select a top-level ontology using these examples as a way to implement the motivating scenarios defined in section 4. But since we intend to build on the efforts from the OEO we streamlined to using BFO. This decision is not without compromises.

BFO sacrifices expressivity for a simpler modeling intuition. It has weaknesses in the field of modal propositions which are prominent in both transportation research en energy systems analysis, particularly in the context of forecasts and simulation[3]. Unlike the TPSO foundational modules, BFO delegates its time indexing to the applications by

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[2] https://openchargealliance.org/protocols/open-charge-point-protocol/

[3] However this weakness is addressed by CCO with their ModalRelationOntology which we consider importing.

keeping it outside the OWL implementation. The perdurant component of entities is handled by pointing to their ‘history’, a practical and versatile construct. BFO has a rather simple initial learning curve that can be used to facilitate the inclusion of new developers. But still becomes steep when dealing with some of its more complex terms (i.e. ‘process profile’, ‘disposition’ vs ‘quality’), this can lead to frustrations and misuses.

There are some important features of BFO that we intend to take advantage of. The first is that it allows the existence of ‘sites’ in the same dimension as ‘material entities’. This is because charging events depend on the dynamics of vehicles being present and absent. We also need these entities to characterize the mereotopology of charging stations which usually consider parking spaces as their parts which in place can be part of parking lots along other parking spaces. To address this, we will rely on reinterpreting the axioms from the TPSO in the context of BFO, in a future stage we intend to explore the possibility of unintended models (i.e. a vehicle becoming infrastructure). A second important feature is the concept of ‘process profiles’ since we consider that the charging event can have multiple dimensions that can describe it that have to be associated with each other. Using those we can describe events by virtue of their occupancy, power rates, and energy transfers among other characteristics.

3. Existing ontology work

One of the key aspects of FAIR ontologies is that they are reusable and profit from the reusability of existing ontologies [15]. We did an extensive analysis of existing ontologies with infrastructure, charging stations, electric vehicles, and electricity grid in scope. In this section, we summarize the ontologies we considered for reutilization and justify the situations in which we decide not to reutilize existing concepts.

3.1. The Open Energy Ontology

The OEO has been in active development since 2021 with several releases since then. It exists to address a technical gap associated with knowledge management in the field of energy systems analysis. Said gap is the lack of common semantics to annotate and share datasets and tools associated with the mentioned discipline. One of the characteristics that make this and other FAIR ontologies transparent and accessible is the fact that it is being openly developed in a shared repository[4]. An important work on the inclusion of concepts coming from the transport sector was performed by Mittermeier [10], who did several implementations associated with the topic. However, since the size of the task is larger than what can be achieved during a master thesis, many implementations were left open in the form of GitHub issues. In some of these issues, it was made clear that the scope of the OEO is in some cases beyond what is often necessary to represent phenomena in the transport sector.

In our charging infrastructure ontology, we need a way of describing vehicles, particularly electric vehicles. The OEO has a rich taxonomy of vehicles. This taxonomy has two

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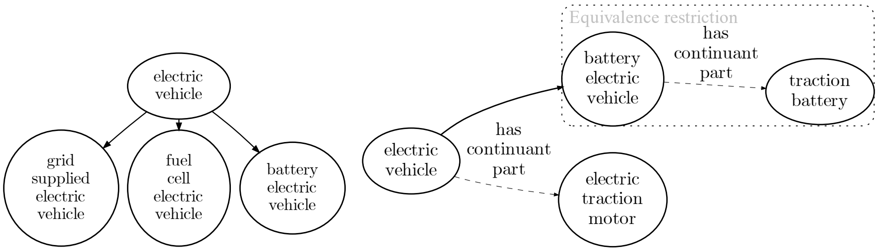
[4] https://github.com/OpenEnergyPlatform/ontology



(a) OEO electric vehicle taxonomy.

(b) OEO electric vehicle commitments

Figure 3.1.1: OEO ontological commitments relevant to the context of charging infrastructure. Note that we exclude grid related commitments, mostly because we have to properly outline a scenario to implement them. Solid arrows represent super-class relations.

parallel ramifications, one associated with its energy consumption mode like 'electric vehicle', 'internal combustion vehicle', and 'gas turbine vehicle' and another associated with its operational medium such as 'land vehicle', 'aircraft' or 'watercraft'. The former has axiomatization significant for electric grid and energy systems models which can be seen in figure 1(b) the latter has no own axioms and relies mainly on the former. For our application is only interesting to use the taxonomy of electric vehicles, which should include plug-in hybrid electric vehicles (Figure 1(a)). Its land vehicle taxonomy is rich (figure **??**) and contains elements that might produce conflicts with any future implementation in a transport ontology. Because of this, we rely on the Common Core Ontologies (CCO) for a lighter vehicle taxonomy.

3.2. The Common Core Ontologies

The CCO are twelve mid-level ontologies built as an extension of BFO and the Relations Ontology (RO) intended to be used as a basis to model domains of interest such as transportation infrastructure and spacecraft [16]. Like BFO, it is a realist ontology, which means that it intends to model the entities data represent. The ontology avoids being prescriptive and instead lets data modelers decide which asserted class axioms are relevant for their particular applications. It also comes with a guide that lets non-ontology experts understand how to implement terms which is helpful to involve domain experts of other fields in ontology development. We extract multiple terms, taxonomies and some axioms from these ontologies. These are explained in the rest of this section.

3.2.1. Vehicle taxonomy

From the 'Artifact Ontology' we extract terminology associated with vehicles. We consider that they offer a more manageable and expandable taxonomy of vehicles that can be utilized across different fields of application. The OEO classifies vehicles based on their energy consumption which is practical for their applications but, since we are not interested in non-electric vehicles, these become superfluous. Another reason to use the

'Artifact Ontology' axiomatization is to profit from the other declarations coming from the same suite of ontologies. The top upper levels of both taxonomies are slightly different besides both using BFO. The OEO classifies vehicles as 'artificial objects' whereas the CCO as 'material artifacts'. The lower levels, despite being developed independently, are so similar that they are practically already interoperable.

3.2.2. Infrastructure

The CCO offers a construct that aids in classifying 'material artifacts' as infrastructure. It uses what in BFO are called 'roles'. This allows arbitrary assignment of the class. This is practical to us because charging stations in reality are not always infrastructure, they are only in virtue of the agents who assign them this role. In this sense, a home wall box is not infrastructure for a government agency but a public column is. Infrastructure rarely comes as units but as complex aggregates of 'artifacts', this is the way we opt to import the concept of 'infrastructure system'. These axioms can be visualized in figure 3.2.2.

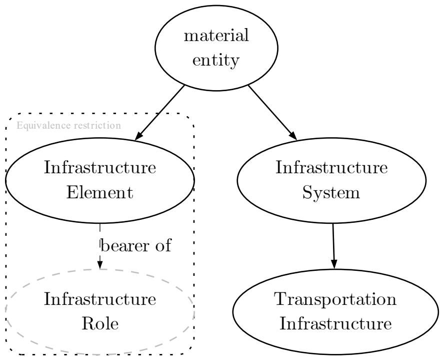


Figure 3.2.2: Common Core Ontologies infrastructure constraints. Solid arrows represent super-class relations

3.2.3. Other imports

We also import terms from the facility, information entity, and geospatial ontologies. We use the facility ontology to handle concepts like parking lots and dedicated charging stations. An alternative would be to stick to using material entities, but we consider this differentiation practical in the long run. The information entity ontology provides us with the 'designates' relation which the CCO recommends using to designate geospatial data to entities. The geospatial ontology provides terms like city and continent which we use to manage addresses.

3.3. iCity Parking ontology

The TPSO has a module for terminology associated with parking which provides concepts like parking spaces, areas, and fees. It also offers axioms for charging stations, but these are too shallow for our applications as they are at most features of parking spaces. The subclassification of charging stations are ‘standard’, ‘medium’, and ‘fast’ which are based on the definitions of some ‘Environmental Protection Department’ whose source was not explicitly pointed. Whether having such a classification is meaningful to our applications is yet to be defined. The TPSO has its own top-level ontology modules which supply axiom definitions for change, mereology, and time. These modules are incompatible with the BFO. The Change module of the ontology relies on the utilization of a four-dimensional approach to model time-changing concepts. This means that every object has a perdurant and its manifestations bear their changes. Since we are not intending to axiomatize time relations in OWL and instead delegate that to data modelers we opt not to share that approach. BFO handles descriptions of change differently, this will be addressed in its respective section. Some axioms that are interesting to us from the TPSO Parking ontology, excluding mereology of parking areas, can be visualized in figure 3.3.3. Our approach to reutilize them consists of doing an implementation using BFO and then adding mappings to this ontology.

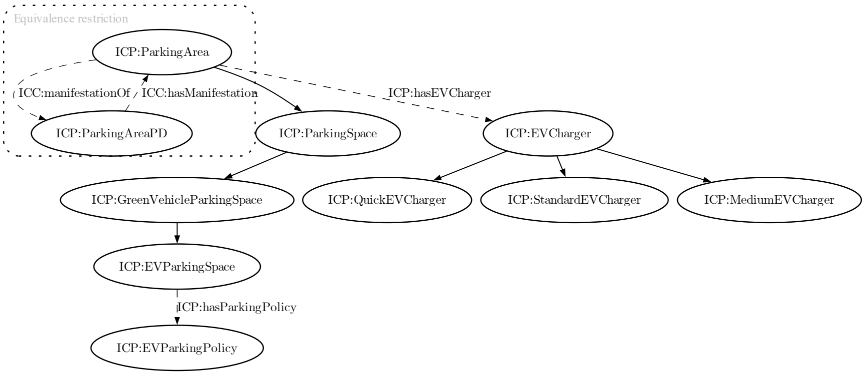


Figure 3.3.3: iCity parking ontology commitments associated with charging infrastructure. Solid arrows represent super-class relations.

4. Methodology

The ontology development loop is inspired by the open collaborative development of the OEO developing team. This consists of having user needs, stated in public issues, as the primary driving force of ontology development. This was not decided based on some detailed evaluation of ontology development methods but on the positive experience and satisfactory results that manifest in the OEO’s relatively consistent release cycle. The main difference consists of a stricter approach regarding new terminology coming into the ontology. Instead of implementing single terms per request, we will expect users and developers to either adjust their proposed terms to existing applications or propose a new complete motivating scenario. This is to overcome scoping issues that often arise during the development of OEO.

4.1. Motivating Scenarios

Motivating scenarios are descriptions of potential real or theoretical applications of the ontology which comprise the kind of questions that the ontology is intended to address. They were first proposed as a method used for the Toronto Virtual Enterprise (TOVE) ontology development [17]. We take inspiration from the original approach but adapt it to a modern context where we take advantage of ticket systems and public development based on version control. Competency questions are the smallest component of a scenario and in our development approach they are first-class citizens. The rest of this section will show the first motivating scenarios considered for this ontology along with some exemplary competency questions. Notice that some competency questions are written as statements that can be used as true/false queries in SPARQL or as an entailment test with a reasoner. The enumeration of the competency questions is not sequential, this is intended as they are excerpts of the full list of questions which can be found in the documentation of the ontology[5]

Scenario 1: The charging infrastructure register

This scenario is heavily inspired by the German charging infrastructure register [18], and it probably captures most of the requirements of this ontology. The scenario covers terminology and axioms necessary to perform descriptions concerning where infrastructure is found, which power they can deliver and what kind of connector they have.

Competency question 1.0
A public charging station is a kind of transportation infrastructure.

Competency question 1.5
A charging station has commissioning and decommissioning dates which delimit its lifetime.

Scenario 2: iCity Project Smart Parking Applications

This scenario is an extract of the iCity project by Katsumi and Fox. Particularly the section smart parking applications [19]. These are selected examples of the subset of questions relevant to us. They are interesting because charging infrastructure is intimately connected with parking infrastructure. These queries are mostly geographical and may overlap with scenario 1, but they have a perspective more in line with the daily operation of the stations. For more details on the ontology visit its repository[6].

Competency question 2.6
How many parking spots are designated for electric vehicles in a particular parking lot?

Competency question 2.7
What types of electric vehicle chargers are available in a particular parking lot?

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[5] https://github.com/dlr-ve-esy/charging-ontology
[6] https://github.com/EnterpriseIntegrationLab/icity

5. Development status

Being at an early development stage, the ontology is in the process of being implemented. At the time of this publication the ontology has an open git repository[7]. This repository has developer documentation where the motivating scenarios along with their competency questions are written. For the ontology documentation and the IRI resolution, we are still exploring solutions. We are tending towards Widoco[8].

We implemented a test suite that allows the incremental development of the ontology using competency questions. This suite classifies the queries into two types. Those who act on classes (TBox) like CQ 1.1 and those that act on individuals (ABox) like CQ 2.0. To handle the ABox queries we rewrite the natural language questions as ASK queries in SPARQL that returns either true or false values. We also declare a model in Turtle Syntax that instantiates the referred classes. For example CQ 2.0 is written as listing 5.1 and its corresponding model 5.2 populates the ABox. The TBox questions are evaluated by checking entailment using DL queries such as the one in listing 5.3 which corresponds to CQ 1.1.

```
ASK WHERE {
    SELECT (COUNT(?parkingSpaces) AS ?vehicleCapacity)
    WHERE  {  :SomeParkingArea obo:BFO_0000178 ?parkingSpaces .
              ?parkingSpaces rdf:type chio:CHIO_00000002 . }
    HAVING ( ?vehicleCapacity = 2 ) }
```

Listing 5.1: Example ABox query. (Given a parking area with two parking places) What is the (vehicle) capacity of parking lot P? (2). The namespaces are omitted.

```
:SomeParkingSpaceA a chio:CHIO_00000002 .
:SomeParkingSpaceB a chio:CHIO_00000002 .
:SomeParkingArea a chio:CHIO_00000001 ;
                 obo:BFO_0000178 :SomeParkingSpaceA,
                                 :SomeParkingSpaceB .
```

Listing 5.2: Example ABox instances. Two charging spaces (that can hold at most one car at a time) are part of some parking area. Namespace prefixes are omitted, the chio namespace refers to the charging ontology.

Since we aim for a high rate of reusability, most of the efforts have been aimed towards finding concepts from existing ontologies. We import the entire CCO version of the BFO which already includes basic RO axioms. We import the excerpts from OEO and CCO mentioned in section 4, we do this by providing scripts that ensure transparency and reproducibility. In some cases, we reimplemented terms and pointed out the ones from

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[7] https://github.com/dlr-ve-esy/charging-ontology

[8] https://github.com/dgarijo/Widoco

```
'charging station' SubClassOf 'parking facility'
    and 'has continuant part' some 'charging column'
```

Listing 5.3: Example DL Query used to evaluate TBox competency. A charging station is a kind of parking facility and has charging columns as parts.

other ontologies by using mappings. This was the case for the axioms from the TPSO Parking Ontology (figure 3.3.3). Our interpretation of parking areas and spaces is similar, but we rely on the mereology of BFO. Instead of assigning the charging stations to parking spaces directly we opt to use the facility axioms from CCO. These implementations can be visualized in figure 5.0.4.

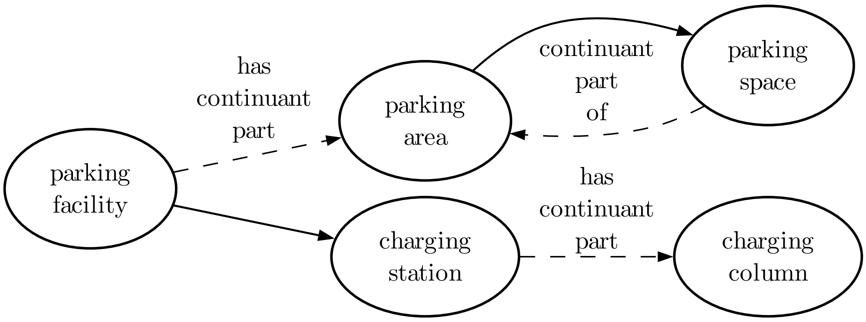

Figure 5.0.4: Parking area, place, and facility implementations in our ontology. This model builds on the taxonomy of the CCO Facility Ontology. Solid arrows represent super-class relations.

6. Discussion

One of the main disadvantages of writing competency questions as queries for most concepts is that implementations are slow. We consider that the benefits outweigh the drawbacks as the outputs are ensured to be concise without much further validation, as the validation occurs during the question definition (think Test Driven Development [20]). Sometimes is challenging to come up with competency questions when there are no implementations to refer to. The CCO provides clear documentation that we can turn to in such cases. Another problem is that the actual software implementation relies on calling java as a subprocess from Python. We are optimistic that thanks to new OWL-aware tools like horned-owl and its respective python embedding py-horned-owl[9] we will eventually be able to migrate to a pure python solution.

In its current state, the ontology is not yet ready to be considered FAIR. The first two principles are to a major degree currently beyond the design tasks. To be Findable it needs to be hosted in an indexed repository where it can be assigned a persistent identifier. To be accessible such repository should be callable by HTTPS or similar

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[9] https://github.com/phillord/horned-owl, https://github.com/jannahastings/py-horned-owl

protocols and have means of preservation of the ontology. Interoperability is achieved by using a widespread format (OWL) and the reutilization of existing ontologies. We enable Reusability by providing licences compatible with the imported ontologies.

7. Conclusion

Questions on electrification of the transport sector and other research trends have as the ultimate goal to put a stop to climate-change driving carbon emissions. These study fields deal with complex systems whose boundaries tend to differ based on the research questions themselves. These differences become troublesome when exchanging data because, in most cases, the person producing it is not always available to clarify misunderstandings. Metadata annotations improve this situation significantly, but their content is also subject to interpretation. Ontologies offer a way of explicitly declaring meta(data) semantics. With this ontology project, we intend to offer a reference point for communication not only between transport and energy researchers and computer agents developed by them. One of the most important lessons we learned during this work is that reutilization is the most valuable tool we have when developing FAIR ontologies. The ontology development is streamlined thanks to the effort that we invested in testing infrastructure. However, there are some open tasks to make the ontology FAIR and complete. Further activities consist of the completion and live hosting of the ontology. In the future we also expect to use our approach to create, map, and expand ontologies usable for transportation research and cover other niches that are out of the scope of infrastructure ontologies like the OEO, the CCO, and the TPSO.

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