Memo internationale standaarden

Geharmoniseerd overzicht van internationale standaarden voor energiemodellering

Februari 2026

Instrumentarium en Standaarden
voor Integrale Energiesysteem-analyse

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Memo in het kader van de ontwikkeling van een Instrumentarium en Standaarden voor Integrale Energiesysteem-analyse, opgesteld binnen het ISIE-consortium bestaande uit Common Futures, Zenmo, Technische Universiteit Eindhoven, CE Delft, Open Energy Transition en Resourcefully

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Aanbevelingen internationale standaarden voor energiemodellering

Binnen het ISIE-project (‘Instrumentarium en Standaarden voor Integrale Energiesysteemanalyse’) is onderzocht welke internationale standaarden beschikbaar zijn voor de verschillende fasen van een typisch energiesysteem-modelleerproject. Dit omvat de volledige keten van het verzamelen van ruwe data, de verwerking daarvan tot modelinput, de modellering zelf en de rapportage en archivering van resultaten. We hebben ons met name gericht op standaarden die relevant zijn voor modellen die in Nederland voor beleidsadvies worden gebruikt. Er bestaan veel meer standaarden in het energiedomein, bijvoorbeeld over de interactie tussen software hardware zoals laadpalen; deze vallen niet binnen de scope van de huidige studie.

Aanleiding voor dit onderzoek is de groeiende rol van energiesysteemmodellen in beleidsvorming en investeringsbeslissingen, gecombineerd met een toenemende diversiteit aan modellen, datasets en aannames. Dit maakt het vergelijken, evalueren en hergebruiken van modelstudies steeds lastiger. Standaarden kunnen hierbij een belangrijke rol spelen, mits zij doelmatig en consistent worden toegepast.

Appendix 1 bevat een overzicht van de internationale standaarden die in dit onderzoek zijn geïnventariseerd. Hiervoor is gebruikgemaakt van literatuuronderzoek en een aantal gesprekken met experts. Op basis hiervan zijn een aantal inhoudelijke conclusies en aanbevelingen geformuleerd, die in dit rapport worden toegelicht.

Relevante internationale datastandaarden worden nog beperkt en selectief toegepast

Voor verschillende typen inputdata voor energiesysteemmodellen bestaan internationaal goed ontwikkelde en breed toegepaste standaarden. Dit geldt in het bijzonder voor elektriciteitsnetwerkdata (bijvoorbeeld het Common Grid Model Exchange Standard, CGMES) en marktgerelateerde data (bijvoorbeeld CIM for Energy Markets), en ook voor generieke datatypes zoals tijdsperiodes en -intervallen. In Nederlandse energiesysteemmodellen worden deze standaarden echter nog niet consequent gebruikt, met name bij regionale en nationale systeemmodellering, en bij modellen die niet met of voor netbeheerders zijn ontwikkeld. Een belangrijke reden hiervoor is dat veel van deze standaarden primair zijn ontwikkeld binnen de context van netbeheerders en marktorganisaties, en daardoor minder bekend en bemind zijn bij andere modelleurs.

Voor modellen die expliciet gebruik maken van netwerk-representaties is CGMES (IEC 61970-600-1, IEC TS 61970-600-2:2021)[1] een bijzonder relevante standaard, mede vanwege de juridische status en het brede gebruik door Europese netbeheerders. Het gebruik van CGMES kan bijdragen aan betere aansluiting tussen netstudies en energiesysteem-modellen, al is de standaard minder geschikt voor lange-termijn scenario-analyses waarin

[1] https://www.entsoe.eu/data/cim/cim-for-grid-models-exchange/

netwerkdetails nog onzeker zijn. Daar bestaan wel andere methodes, zoals de Energy System Description Language (ESDL)[2] voor.

Voor andere categorieën inputdata, zoals vraag- en milieugegevens, bestaan nauwelijks formele standaarden. Wel zijn er internationaal veel gebruikte datasets, zoals Copernicus,[3] het Europese aardobservatieprogramma dat wereldwijd open satellietdata levert over klimaat, land, zee en atmosfeer, die in de praktijk een de-facto referentie vormen. Explicietere aansluiting bij deze datasets kan bijdragen aan meer consistentie tussen studies, ook zonder formele standaardisatie.

Metadata en dataverwerking vormen een belangrijk, maar onderbelicht aandachtspunt

Naast datastandaarden bestaan er internationaal volwassen standaarden voor metadata en data provenance: standaarden die gaan over hoe beschreven moet wordt wat data precies voorstelt, hoe de data tot stand is gekomen, welke aannames en bewerkingen zijn toegepast, en wie verantwoordelijk was is voor welke stap. Deze maken het mogelijk om systematisch vast te leggen waar data vandaan komt, welke aannames zijn gemaakt en welke bewerkingen zijn uitgevoerd. Zo biedt W3C PROV[4] bijvoorbeeld een framework om op een consistente manier vast te leggen waar data vandaan komt en welke conversiestappen door wie zijn toegepast. In de Nederlandse praktijk worden dergelijke standaarden tot nu toe echter nauwelijks toegepast in energiesysteemstudies.

Tegelijkertijd is het duidelijk dat dataverwerking een grote invloed heeft op modeluitkomsten. Keuzes rond aggregatie, disaggregatie, temporele resolutie en selectie van representatieve perioden verschillen sterk per studie en worden vaak alleen beperkt of impliciet gedocumenteerd. Er bestaan geen internationale standaarden die deze conversiestappen inhoudelijk voorschrijven.

Dit suggereert dat hier vooral ruimte ligt voor het ontwikkelen van best practices, bijvoorbeeld voor het expliciet beschrijven en documenteren van dataverwerkingsstappen en aannames. Aansluiting bij bestaande generieke standaarden voor metadata en provenance kan hierbij helpen, zonder dat energiespecifieke standaarden hoeven te worden ontwikkeld.

Beperkte standaardisatie van datakwaliteit en onzekerheid

De kwaliteit van inputdata en de wijze waarop onzekerheden worden behandeld, verschilt sterk tussen energiesysteemstudies. Hoewel er generieke internationale kaders bestaan om datakwaliteit te beschrijven, worden deze in de energiesysteem-modellering nauwelijks expliciet gebruikt.

Het ontbreken van gedeelde praktijken op dit vlak maakt het lastig om resultaten van verschillende studies goed te vergelijken of te interpreteren. Dit wijst op een mogelijke behoefte aan lichtgewicht best practices of richtlijnen voor het beschrijven van datakwaliteit en onzekerheden, zonder dat dit leidt tot zware of rigide standaardisatie.

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[2] https://www.esdl.nl/
[3] https://www.copernicus.eu/en
[4] https://www.w3.org/TR/prov-overview/

Rapportage en vergelijkbaarheid van modelresultaten zijn beperkt gestandaardiseerd

Voor de rapportage van modelresultaten bestaan nauwelijks formele internationale standaarden. Wel zijn er voorbeelden van best practices, zoals het gebruik van gestandaardiseerde KPI's in Europese vergelijkingsprojecten en richtlijnen voor modeldocumentatie en archivering in de Verenigde Staten.

Deze voorbeelden laten zien dat het mogelijk is om, zonder modelspecifieke details vast te leggen, toch meer structuur aan te brengen in de manier waarop resultaten worden gerapporteerd en gedocumenteerd. Met name het gebruik van gemeenschappelijke indicatoren en vaste rapportagestructuren kan bijdragen aan betere vergelijkbaarheid tussen studies. Een 'modelbijsluiter' die bij een studie wordt meegeleverd en duidelijk omschrijft welk model is gebruikt, waar dat model wel en niet voor geschikt is, welke belangrijke aannames zijn gemaakt (bijvoorbeeld: welk weerjaar is gebruikt), etc., zou zinvol kunnen zijn.

Dit lijkt een geschikt domein voor verdere ontwikkeling van best practices, eerder dan voor formele standaardisatie.

Beperkingen en aandachtspunten bij het gebruik van standaarden

De analyse laat ook zien dat standaarden niet zonder nadelen zijn. Sommige standaarden, zoals CGMES, zijn complex, moeilijk leesbaar voor mensen en leiden tot grote databestanden. Dit kan de toegankelijkheid van modellen en data verminderen, vooral buiten de directe kring van netbeheerders en specialisten.

Dit onderstreept het belang van een pragmatische benadering, waarin standaarden worden gebruikt waar zij duidelijke meerwaarde hebben, terwijl eenvoudiger en beter leesbare formats daarnaast kunnen blijven bestaan. Converters en vertaalstappen tussen verschillende formaten spelen hierbij een belangrijke rol. Het is geen enkel probleem voor de interoperabiliteit tussen energiesysteemmodellen als ze allemaal hun eigen dataformat gebruiken, mits het mogelijk is die data te converteren naar een door anderen te gebruiken format, en liefst één gebaseerd op internationale standaarden.

Overkoepelende observaties

Uit het overzicht blijkt dat er internationaal een aantal relevante standaarden en best practices beschikbaar zijn voor specifieke onderdelen van energiesysteemmodellering (bijvoorbeeld CGMES voor grid data, W3C-standaarden voor data provenance, ISO-standaarden voor generieke datatypes zoals tijdsperiodes), maar dat er geen end-to-end standaard bestaat die de volledige modelketen afdekt. De grootste lacunes liggen niet zozeer bij inputdata, maar bij dataverwerking, metadata, rapportage en vergelijkbaarheid van resultaten.

Dit suggereert dat verdere harmonisatie vooral gezocht moet worden in het beter benutten van bestaande internationale standaarden en in het ontwikkelen van gedeelde best practices op die onderdelen waar formele standaarden ontbreken. Binnen Nederland zijn er al wel pogingen gedaan voor meer standaardisatie, zoals de Handleiding Richtlijnen Uniformering Energiestudies, opgesteld door Quintel en DNV in 2023[5], maar deze zijn tot nu toe beperkt in

[5] https://topsectorenergie.nl/nl/kennisbank/handleiding-richtlijnen-uniformering-energiestudies/

scope, en met weinig referenties naar internationale standaarden. Binnen het ISIE-project zal daarom hier in het komende jaar een verdere slag mee worden gemaakt.

Ook voor opdrachtgevers, in het bijzonder publieke of semi-publieke opdrachtgevers zoals ministeries, gemeenten en netbeheerders, ligt hier een belangrijke rol. Zij kunnen aansluiting bij internationale standaarden en best practices afdwingen door deze expliciet op te nemen in modelleringsopdrachten, zodat de transparantie, vergelijkbaarheid en herbruikbaarheid van modelstudies toeneemt.

Appendix: International standards for energy modelling

1. Introduction

When considering best practices for energy modeling in the Netherlands, it is essential to look beyond national practice and take international standards and widely adopted best practices into account. Energy modeling is a mature field in many jurisdictions, and there is little value in reinventing approaches that have already been tested, refined, and operationalized elsewhere. Drawing on established international practice allows modelers to benefit from accumulated experience, reduce development effort, and improve the robustness and credibility of their work.

International alignment is particularly important because energy systems do not stop at national borders. The Dutch energy system is physically interconnected with those of neighboring countries, and data is routinely exchanged across borders for planning, operation, and market coordination. Aligning modeling practices and data representations with those used internationally therefore facilitates interoperability, improves consistency in cross-border analyses, and reduces friction when exchanging data or model results with external parties.

Some international standards are not merely best practice but have direct legal or regulatory implications. A prominent example is the Common Grid Model Exchange Standard (CGMES), which is mandated for the exchange of grid models between European transmission system operators. As the Dutch TSO, TenneT is therefore required to use CGMES for specific data exchanges; increasingly, Dutch DSOs are also adopting the same standard. Such standards strongly shape modeling workflows and tooling choices and must be taken into account when defining national best practices.

The landscape of standards and best practices in energy modeling is broad and heterogeneous. Rather than prescribing a single end-to-end approach, most standards apply to specific steps within a modeling workflow. In this report, we therefore structure the discussion along the main stages of that workflow. We consider standards and recognized best practices for:

- input data, including data formats, definitions, and quality requirements;
- standards and best practices for data conversion, covering the transformation of data between models, tools, and levels of aggregation;
- modeling conventions and methodological best practices that affect how models are constructed and used;
- standards and recognized best practices for reporting and communicating model outputs.

It is important to distinguish between academic research, consultancy practice, and grid operator environments in energy modeling, as their incentives, constraints, and levels of standardization differ significantly. Academic research is primarily driven by specific research questions. Modeling approaches are often tailored to individual projects. While researchers are typically aware of established best practices and may draw inspiration from them, the formal adoption of externally defined standards is relatively uncommon. Research groups usually develop their own conventions, documentation approaches, and workflows, which can vary considerably across institutions.

Consultancies and advisory firms operate in a commercial, client driven context. Their primary focus is on delivering applied results. Because revenue is tied to project delivery, allocating significant resources to improving or standardizing internal processes beyond what is required for the assignment can be difficult to justify. In addition, commercial considerations, intellectual property concerns, and competitive positioning can limit the extent to which models, data, and assumptions are disclosed. While many firms apply structured methodologies and internal quality assurance procedures, these are not necessarily aligned with publicly defined standards, and external visibility into modeling practices is often limited.

Finally, grid operators and utilities function in highly regulated, operationally critical environments. They tend to rely heavily on formal standards, validated tools, strict data governance, and clearly documented processes. Moreover, grid operators work in an international and interconnected context. For example, within frameworks such as ENTSO E, they are required to exchange data, coordinate scenarios, and ensure cross border consistency. This necessitates interoperability, harmonized data formats, and compliance with jointly agreed methodologies.

Given that the purpose of this document is to support practical implementation, the emphasis is placed on standards and best practices that are most relevant for applied, modeling environments, particularly those of grid operators, and consultants that perform assignments for governments or grid operators.

For many elements of energy system modeling, formal standards in the narrow sense of ISO, IEC, IEEE, or similar bodies simply do not exist. Large parts of the modeling workflow are instead governed by conventions, tool-specific practices, or methodological choices that have emerged organically over time. For this reason, this document also considers some de facto standards: approaches, data formats, and conventions that are widely used in practice and have effectively become standard through broad adoption. In addition, we include a number of best practices that are documented and promoted by leading organizations, even where these do not have the formal status of a standard.

As a consequence, this document should not be read as an exhaustive catalogue of all relevant standards, de facto standards, or best practices in energy system modeling. The field is large, evolving, and context dependent, and especially in the area of best practices there is no clear boundary between what should and should not be included. Instead, the aim is to provide a structured and pragmatic overview of the most relevant and influential practices for the Dutch context, with a focus on those that are most likely to inform and improve real-world modeling practice.

2. Input Data

The first step in energy system modeling is usually the collection of (raw) input data. Typical energy system modelling workflows use a wide range of input data. There is no single standard that describes the entirety of a model's inputs. We can categorise all the input data that are relevant to our models into the following categories:

- Grid data (network topologies, electrical parameters, etc.)
- Demand data (time series or individual values for electricity demand, demand for other carriers, etc., either forecast or historical)
- Flexibility (availability and parameters of flexible technologies, such as demand response)
- Technical parameters (capabilities and constraints of power plants, conversion technologies, etc.)
- Financial parameters (prices, costs, etc.)
- Environmental data (wind speeds, solar irradiation, etc.)

Each of the standards in this overview defines (part of) one, or several, of these categories.

2.1. Grid Data

There are several standards that describe how electricity grid data can be recorded and shared. Three standards are particularly relevant, although they have different scopes. The Common Grid Model Exchange Standard (CGMES) is widely used by grid operators across Europe. Based on the Common Information Model (CIM), which is itself a global standard describing power system assets, topology, measurements, and market data, it focuses on electricity, and on operational problems. Especially because of its legal status and governance structure, it is arguably the most important standard for operational grid modeling or near-term planning, when planners already know which equipment will be in place where. Although it can theoretically be generalized to other energy carriers, this has not been fully implemented.

The Energy System Description Language (ESDL) follows a similar Extensible Markup Language (XML) format as CGMES, but focuses on longer-term planning problems with multiple carriers. It is more useful for describing grid data further out into the future, when the exact equipment decisions have not yet been made. ESDL was developed in The Netherlands, and although it is used outside The Netherlands, its international adoption has been limited. ESDL is a multi-purpose language, which can be used to not just define grid data, but also energy demand, and other categories.

Finally, the Smart Grid Architecture Model (SGAM) is a reference architecture framework, developed by the EU, which structures smart grid systems. It is not a data standard as such, but instead an architecture framework to describe an energy system, with a particular focus on smart grids. It is particularly useful to define the components of a (smart) energy system, and how these relate to each other in a particular process, such as data exchange or system operation.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
CGMES	Input Data: Grid data	• Maintained by ENTSO-E as backbone of European exchange of grid data • Mandatory for: The ENTSO-E Common Grid Model, pan-European capacity calculations and operational planning • Implemented in most commercial software packages for powerflow modelling; less common for long term planning	• XML format • Separate profiles for EQ (Equipment), TP (Topology), SSH (Steady State Hypothesis), SV (State Variables) defines results, BD (Boundaries)	• Not easily readable for humans • Large file sizes • Different implementations between users • Limited support for flexibility sources • Based on IEC CIM, therefore easy to connect to EMS systems • Clear governance and proven implementability	Definition of AC-line segment: <cim:ACLineSegment rdf:ID="LINE_12"> <cim:IdentifiedObject.name>Line_1_2</cim:IdentifiedObject.name> <cim:ACLineSegment.r>0.01</cim:ACLineSegment.r> <cim:ACLineSegment.x>0.10</cim:ACLineSegment.x> <cim:ACLineSegment.bch>0.0005</cim:ACLineSegment.bch> </cim:ACLineSegment>
ESDL	Input Data: Grid data, Demand data, Technical parameters Environmental data	• Created and maintained by TNO • Not yet used by many external parties • No legal status	• XML format • Not a generic XML Schema, but an EMF (Eclipse Modelling Framework)	• Large files • Unclear how well maintained it is (last release was in May 2019, last commit was in July 2025) • Multiple software tools available with different purposes that utilize the format • Large scope	Definition a PV assets inside a house: <asset xsi:type="esdl:PVPanel" id="PV1" name="PV Panels on Roof" surfaceArea="16" power="3000.0"> <port xsi:type="esdl:OutPort" id="PVOP1" connectedTo="ENIP2"/> </asset>
SGAM	Architecture framework for smart grids	• Developed by the European Commission Smart Grid Task Force (Expert Group 1) • No formal legal mandate, but de facto reference model in European smart grid projects, standardisation, and regulatory studies • Used by TSOs, DSOs, vendors, regulators, consultants, and research projects	• Three-dimensional reference model with: • Domains: Generation, Transmission, Distribution, DER, Customer • Zones: Process, Field, Station, Operation, Enterprise, Market • Interoperability layers: Business, Function, Information, Communication, Component • Technology-agnostic	• Excellent for system thinking and architectural clarity • Helps identify interoperability gaps early • Neutral with respect to vendors and technologies • Very suitable for multi-stakeholder discussions • Scales well from pilots to national and regional systems • Not implementable on its own • Requires interpretation and discipline to apply consistently	Example mapping of TSO operational model exchange: Domain: Transmission Zone: Operation Layers: Business: Coordinated secure system operation. Function: Create and exchange grid models. Information: CIM profiles using CGMES. Communication: Secure file exchange. Component: TSO EMS and grid analysis tools.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
			• Supports mapping of standards such as CGMES, IEC 61850, IEC 60870-5-104, MQTT, CIM, market standards	• Different projects may map the same use case differently • Provides no guidance on data granularity or performance	
IRES	General: • Energy Statistics • Energy Balance Which contains: • Standard International Energy Product Classification • Measurement Units • Conversion Factors • Energy Flows • Statistical Unit • Data items • Data collection and compilation • Data quality assurance Dissemination	Created by United Nations Department of Economic and Social Affairs: Statistics Division Recommendation: Standards that countries are strongly urged to follow. There are no legal consequences, but data will be non-comparable with other countries. • Encouragement: Standards that countries can impose on themselves, mainly for national internal systems or having data quality higher than what is recommended.	• Table format	• Comprehensive, as described in the scope • High level globally accepted standard • Latest data in this format is 2023 • Data that follow this standards are often available only on an annual basis and with national scope (Low spatial and temporal resolution)	https://unstats.un.org/unsd/energystats/pubs/balance/2023/bmq.pdf Page 225 Netherlands

2.2. Demand Data

There are, to the best of our knowledge, no formal standards for demand data for energy models. The closest to an international standard is the International Recommendations for Energy Statistics (IRES), a UN-developed standard which is mostly used for energy data with a low temporal and spatial resolution.

In addition, there are large demand datasets that are publicly available, which are so often used that their formats have become de-facto standards that many modeling workflows can interact with. In particular:

- The European Commission publishes The JRC Integrated Database of the European Energy System (JRC-IDEES). This is a large database that has detailed information for each member state about both demand and supply of different energy carriers. It does not define any standards, but is an interesting source to harmonize model inputs. Alongside the energy demands it also specifies efficiencies and CO2 emissions. It includes data for the years 2000-2023.
- In the US, the Catalyst Cooperative maintains the Public Utilities Data Liberation Project, offering a similar database that collects and harmonizes data from individual

utilities. PUDL is widely used in the US, amongst others in popular ESMs such as PyPSA-USA, GenX and GridPath. Again, however, it is not a formal standard.

- The United Nation Energy Statistics publish high-level national energy balance and electricity profiles. The energy data aggregation is based on the International Recommendations for Energy Statistics (IRES). Compared to JRC-IDEES and PUDL, this database is more general in scope, but the data of all UN member states are available in this format.

Models often also need data about future demand. These projections are, by their nature, subjective. Although organizations like the IEA and ENTSO-e publish high-level demand projections (e.g., annual per country), detailed spatio-temporal datasets are rarely available. There are ongoing efforts to compile these datasets, such as the SECURES-Energy project, but these are still far from being even de-factor standards.

2.3. Flexibility

To model the impact of flexibility, both of production as well as the demand side, models typically require input data on the ‘amount’ of flexibility available. This is normally constrained by physical properties of the assets or the willingness/availability of the owner/manager. There are two standards for describing this amount of flexibility. Neither are developed specifically for energy system modeling, but rather for control applications. Nevertheless, they provide useful guidance for modelers and data providers, as they specify exactly which dimensions of flexibility need to be recorded.

The S2 standard defines different control paradigms for devices to utilize flexibility. Concretely, the standard defines a system architecture and 8 types of control paradigms for controlling energy flexibility. For example, the limit production pattern describes the category of devices that cannot control the amount of energy produced or consumed but can be limited. The different control paradigms are used by a component called the “customer energy manager” (CEM) which can control a group of flexible devices that adheres to the standard. Depending on the goal of the CEM it may use the flexibility in different ways.

The openADR standard defines an interface for real time communication between grid operators, balance responsible parties and the flexible assets connected to the grid. It is primarily used as a communication standard, but it does also define standards to quantify the flexible capacity of assets. To fully describe the flexibility of assets in an energy system it is most likely too limited, depending on model scope.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
OpenADR	Input Data: Flexibility This standard describes a format for signals from grid operators sent to asset owners/ managers.	• Developed and maintained by The OpenADR Alliance. • No legal status.	• Data model and Interface for demand response, pricing and distributed energy resource communication • 2.0a/b version: Python with XML formats • 3.0 version: Rust with JSON formats	• Adopted by the IEC as standard IEC 62746-10-1 • Used by Dutch DSOs with parties such as CPO ELaadNL • There are also open source implementations, for example from Electric Power Research Institute, (EPRI) and OpenLEADR • More focussed on the real time applications instead of modelling	{ "event": { "id": "550e8400-e29b-41d4-a716-446655440000", "modification_number": 0, "status": "active", "priority": 1, "market_context": "http://MarketContext01", "created_date_time": "2023-10-27T10:00:00Z", "event_signals": [{ "intervals": [{ "duration": 3600, // Duration in seconds (1 hour) "uid": 0, "signal_payload": 10.5 // Target: reduce load by 10.5 kW }], "signal_type": "level", "signal_name": "SIMPLE", "signal_id": 0 }], "targets": [{ "resource_id": "CustomerSite_123" }], "active_period": { "start": "2023-10-27T14:00:00Z" } } }

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example

S2	Operational paradigms for flexibility	• Developed and maintained by the S2 Consortium	• Architectural and operational communication standard for utilizing flexibility. Defines control paradigms for different types of flexibility	Pros:
				Quite unique in what it specifies
				Has extensive examples available and implementations available in order to get started with it
				Cons:
				• Not yet broadly implemented by industry
					Example message from a PV installation to an energy manager, specifying its properties
					{
					"message_type": "ResourceManagerDetails",
					"message_id": "xxx",
					"resource_id": "acme_pv_installation",
					"name": "Solar panels on roof",
					"roles": [
					{
					"role": "ENERGY_PRODUCER",
					"commodity": "ELECTRICITY"
					}
					],
					"manufacturer": "ACME",
					"model": "InverterType2024",
					"serial_number": "123",
					"firmware_version": "v1.0",
					"instruction_processing_delay": 5000,
					"available_control_types": [
					"POWER_ENVELOPE_BASED_CONTROL"
					],
					"provides_forecast": true,
					"provides_power_measurement_types": [
					"ELECTRIC.POWER.L1"
					]
					}

2.4. Technical parameters

The technical parameters an energy system model requires depend heavily on the model's purpose and scope. Take heat pumps as an example. A long term model focussed on costs might model their heat pumps with a seasonal coefficient of performance (SCOP), another model will use a (data-fitted) formula to determine the COP at each timestep based on temperatures, yet another model might simulate the individual components of the heat pump to determine the efficiencies and will need 'deep' physical parameters, such as properties of the refrigerant or sizes and materials of compartments. Thus there will be no single way to describe assets that suffices for all different models. ESDL (see above) might give enough details about the assets for the models that are of interest for long-term modeling. And commonly used open-source databases, such as technology-data, the Danish Energy Agency technology catalogues, or the NRL data catalogue, may provide formats that are accepted by a wider range of models.

2.5. Financial parameters

In this category, the most relevant standard 'CIM for Energy Markets', sometimes informally called the Market Information Model (MIM) which defines a standard for data related to the electricity market. It can be viewed as the market counterpart to CGMES, providing a standardized way to describe market information such as bids, offers, and prices. It is based on IEC 62325-301 and 62325-450.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
CIM for Energy Markets	Input and output data for electricity market processes. Covers bids, offers, prices, schedules, allocations, and settlement data Applies primarily to wholesale electricity markets	• Standardised by IEC TC57 under IEC 62325 • Implementation rules and profiles defined by ENTSO-E and NEMOs • Mandatory or de facto mandatory for many European market processes, including day-ahead and intraday market coupling, cross-border capacity allocation, and balancing platforms • Widely implemented in market operator and TSO systems • Not open governance in the software sense, but stable and institutionally backed	• Based on CIM, specifically IEC 62325 • XML-based message exchange • Strong temporal structuring (time series, periods, intervals) • Optimised for inter-organisational data exchange rather than internal optimisation models	• Strong alignment with European market design • Consistent modelling of time series and market products • Naturally integrates with CGMES through shared CIM concepts • Complex and verbose XML messages • Hard to read and debug manually • Limited flexibility for novel or local market designs • Not as well defined as CGMES; little to no tooling available	Simplified toy example of a bid time series structure: <Bid_MarketDocument> <mRID>bid-123</mRID> <BidTimeSeries> <Period> <timeInterval> <start>2026-03-17T00:00Z</start> <end>2026-03-17T02:00Z</end> </timeInterval> <Point> <position>1</position> <quantity>100</quantity> </Point> <Point> <position>2</position> <quantity>120</quantity> </Point> </Period> </BidTimeSeries> </Bid_MarketDocument>

For many energy system models there are also inputs related to the costs of assets, e.g., capital (CAPEX) and operational (OPEX) costs. These can have large influences on model results. There appears to be little standardization in this space, which can lead to unintended mismatches between models. For example, when describing the costs of a solar panel or battery, does CAPEX include installation costs, or the cost for an inverter? Widely used datasets use different conventions here.

2.6. Environmental data

Environmental data includes information about Solar irradiance, wind speeds and directions, temperatures, and expected climate change. Most sources for this data will make assumptions to compute data for a particular point in time and a particular place, as measured data is not universally available. The next chapter on data conversion will elaborate on this in more detail. Moreover, the exact data specifications matter. For example, a key difference between datasets could be the height above the ground at which the temperature and wind speed are measured. For different applications, modelers may need a wind speed at different heights.

The most prominent standard for environmental data is GRIB (General Regularly-distributed Information in Binary form). This is not a format that is easy to work with, but is very detailed and efficient in terms of file sizes. It is designed for large datasets of meteorological institutions and researchers, not energy system models. This means that datasets are often available in this format, but they might not specify all relevant parameters and often specify many parameters that are irrelevant to energy system models. Other, de-facto standards are formed by two widely used datasets: the Copernicus Climate Data Store, which contains a large number of climate-related datasets, and the SECURES-Met dataset.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
GRIB	File format for: Atmospheric data, including wind data, Land/Soil data, Oceanographic data,	• Maintained by the WMO • Used by many major weather and climate centers, such as KNMI and Copernicus	• In binary form, so software/libraries such as: ecCodes, wgrib2 and xarray are required to read the data	• Efficient file size • Contains metadata describing details • Not designed for energy system modeling • Relies on external tables for IDs which are version dependent • Complex to parse • Compression can lose data precision	(Human-readable representation of binary:) Discipline: Meteorological Parameter: Wind speed Level: 100 m above ground Forecast time: 24 hours Grid: Lat: 50.0 to 58.0 Lon: -4.0 to 9.0 Resolution: 0.1 x 0.1 Data: (50.0, -4.0) → 9.2 (50.0, -3.9) → 9.5 (50.0, -3.8) → 9.7
Climate Data Store	Input Data: Environmental	• Published by Copernicus • Updated monthly	• Format: NetCDF, GRIB	• Contains both historical data and projections • Global coverage • Contains data not related to modelling energy systems	See website
SECURES-Met	Input Data: Environmental	Published by Zenodo • Not regularly updated	A large dataset that could be used as a standard Contains data about: Temperature, Radiation, Wind & Hydro Time resolution is hourly • Format: csv	• Contains both historical data and projections • Has data for at least the entire EU • Was created specifically for modelling energy systems • Only has NUTS-3 level data for Austria, the rest is NUTS-0 (states) and NUTS-2 (provinces) • Data is already processed, e.g. aggregated to the levels mentioned above or converted from raw measurements to energy specific parameters	See website

3. Data Conversion

A review of modelling practice and official modelling guidance shows that, despite the central role of data conversion in energy system modelling, there are no domain-specific, widely adopted standards that prescribe how spatial or temporal aggregation and disaggregation should be performed prior to model execution. Conversion steps such as the selection of representative periods, the aggregation of spatial units, or the downscaling of annual data to sub-annual resolution are typically treated as implementation choices within individual models or modelling frameworks rather than as standardised procedures. Even in large government and intergovernmental modelling efforts, data conversion methods are generally documented as part of model-specific workflows, not as transferable standards intended to ensure consistency or comparability across models. As a result, conversion practices vary substantially between studies, and often between different applications of the same model, while remaining only partially visible in published results. For example, for temporal aggregation of demand (e.g., quarterly to hourly), some models use a simple average, which reduces peak demand but preserves the total; some use peaks, which increases the total demand, some use representative periods, and some cluster to synthetic periods based on one of a number of clustering algorithms. However, there are a number of metadata-related standards that are relevant.

3.1. Data provenance standards

One area where formal standards do exist and are applicable to energy modelling data conversion is data provenance and transformation lineage. The W3C PROV family of standards provides a structured way to describe relationships between original datasets, transformation activities, and resulting derived data products. When applied to energy system modelling, such provenance descriptions can capture aggregation, disaggregation, resampling, or calibration steps as explicit transformation activities linked to their inputs and responsible agents. Although not specific to energy modelling, PROV offers a general mechanism for making data conversion processes explicit and traceable.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
W3C PROV	Representation of data provenance and transformation lineage. Used to describe how datasets are generated, transformed, and derived from other datasets, including processes, agents, and inputs.	• Developed and maintained by the World Wide Web Consortium (W3C). • Published as W3C Recommendations. • Open standard, royalty-free. • Adopted across multiple domains (science, data engineering, digital humanities), but limited explicit uptake in energy system modelling practice.	• Graph-based model defining Entities (data), Activities (transformations), and Agents (people/software • Supports causal relationships such as "wasDerivedFrom" or "wasGeneratedBy". • Multiple serialisations (RDF, XML, JSON-LD).	• Explicit, formal representation of transformation steps • Technology-agnostic • supports machine-readable lineage across complex pipelines. • Does not prescribe what transformations should be done • Adds documentation and modelling overhead • Not tailored to energy-specific concepts.	Hourly demand time series explicitly recorded as being generated by a temporal disaggregation step applied to annual demand data, using a specific script: entity(annual_demand, [prov:type='dataset', prov:label='National annual electricity demand']) entity(hourly_demand, [prov:type='dataset', prov:label='Hourly electricity demand time series']) activity(temporal_disaggregation, [prov:type='processing,

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
					prov:label='Temporal disaggregation from annual to hourly']) agent(load_profile_script, [prov:type='software', prov:label='Load profile disaggregation script']) used(temporal_disaggregation, annual_demand) wasGeneratedBy(hourly_demand, temporal_disaggregation) wasAssociatedWith(temporal_disaggregation, load_profile_script)

3.2. Temporal representation standards

Although not strictly speaking a standard for data conversion, ISO 8601 is an example of a well-established standard for the representation of dates, times, durations, and intervals. While ISO 8601 does not address modelling logic or conversion methods, it illustrates how a narrowly scoped standard can remove ambiguity in data processing by enforcing consistent temporal representations. In the context of energy system modelling, consistent use of ISO 8601 conventions clarifies whether data represent instants or intervals, how durations are defined, and how timestamps are interpreted across datasets and conversion steps. Consistent use of this standard makes temporal aggregation/disaggregation among multiple models possible, as opposed to current widely spread practice where only data is only coded with simple timestamps, without information about whether it represents an instantaneous value at that timestamp, an average between that timestamp and the next, a point in the middle between that timestamp and the next, etc.

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
ISO 8601	Standardised representation of dates, times, durations, and intervals to avoid ambiguity in temporal data.	• Maintained by the International Organization for Standardization (ISO). • Formal international standard. • Very high adoption across software systems and data exchange formats.	• Defines formats for dates, times, time zones, durations, and intervals. • Explicit distinction between instants and intervals.	• Removes ambiguity in time encoding • Simple and widely supported • Independent of modelling choices. • Does not encode semantics such as power vs energy • Does not define aggregation or sampling rules.	An interval of one hour on a specific date: 2024-01-01T00:00PT1H

In summary, energy system modelling currently relies on extensive data conversion, yet conversion methods themselves are largely governed by model-specific practice rather than formal standards. Existing standards relevant to this domain focus primarily on representation and traceability, such as provenance and temporal encoding, rather than on the substantive methods used to aggregate or disaggregate data.

3.3. Data quality standards

Standard	Scope	Status and governance structure	Properties	Key pros and cons	Example
DQV	Describing, assessing, and communicating data quality characteristics. Not energy specific	• Standardised and maintained by the W3C • Final W3C Recommendation • Used in data portals, semantic web applications, open data platforms, and research projects • No legal mandate • Increasingly referenced in data governance and FAIR data contexts	• RDF/OWL vocabulary • Designed to be used with linked data standards • Defines concepts such as: Quality dimensions, Quality metrics, Quality measurements. Quality annotations • Technology-agnostic with respect to storage and exchange • Can be layered on top of existing data models such as CGMES, ESDL, CSV, JSON, or databases	• Standardised and domain-neutral • Lightweight and extensible • Explicit separation between data and data quality metadata • Well suited for automated quality assessment and reporting • Compatible with FAIR and open data principles • Abstract and non-prescriptive • Requires additional tooling and discipline to use effectively • No predefined energy-specific quality metrics • RDF-based approach can be a barrier for non-semantic tooling • Rarely used out-of-the-box in energy systems	Expressing that completeness is a quality metric for a dataset @prefix dqv: <http://www.w3.org/ns/dqv#> . @prefix dcat: <http://www.w3.org/ns/dcat#> . :dataset1 a dcat:Dataset ; dqv:hasQualityMeasurement :qm1 . :qm1 a dqv:QualityMeasurement ; dqv:isMeasurementOf :Completeness ; dqv:value "0.95" ; dqv:computedOn "2026-01-01" .

4. Modelling Conventions

Unlike for input data, we have not found any specific standards for the modelling process itself, particularly when it comes to energy system modeling rather than, for example, the modeling of individual building energy systems. In this section, we instead describe the general categories of energy system models that are used internationally, their main modeling philosophies, and typical users. This is relevant for the Dutch ecosystem, as interoperable ESM modeling systems will likely have to interact with these models.

4.1 General Categories of ESM

We can categorize modelling frameworks based on their underlying principles to clarify their fundamental differences and define the expected scope of their outputs. Hooman Farzaneh (2019) and Van Beek (1999) have made such categories.

Generally, ESM serves three purposes: forecasting the future, exploring potential scenarios, and identifying the pathways necessary to reach that future. While a single model may encompass several of these general objectives, its specific purpose is singular, defined by which segment of the energy balance it aims to address:

- Demand-Side models focus on determining the final energy consumption
- Supply-Side models focus on determining how the energy can be supplied
- Integrated models balance both supply and demand

The modelling paradigm is fundamentally divided into top-down and bottom-up approaches. The top-down approach aims to represent an entire economy via a relatively small number of aggregate variables and equations. It has implicit representation of technology, generalized using the production frontier. On the other hand the bottom-up approach aims to find what is technically possible by arranging technologies and linking them by their inputs and outputs. It requires detailed description of technologies and highly disaggregated data. Ultimately, the choice between these paradigms is dictated by the availability and quality of the required data.

These are commonly used methodological approaches in ESM:

- Simulation models: Descriptive frameworks designed to illustrate potential behaviors and pathways within an energy system.
- Optimization models: Normative frameworks to identify the most optimal solution within defined sets of constraints.
- Macroeconomic models: High-level frameworks that evaluate the entire economy to achieve macroeconomic objectives.
- Econometric models: Statistical frameworks to extrapolate past market behaviour into the future.

Between these categories, optimization models are most widely used.

The "engines" behind those methodological approaches can be one of the following:

- Analytical Programming: Using mathematical functions to directly transform inputs into outputs through explicit formulas.
- Mathematical Programming: Using defined objective functions and constraints to solve for an optimal system configuration.
- Dynamic Programming: Using the results of previously solved sub-problems to construct complex solutions dynamically over time.
- Genetic Algorithms: Using a process where the solutions closest to the objective are iteratively reproduced and refined, mimicking natural evolution.
- Artificial Neural Networks: Using layered architectures to identify and replicate complex patterns found in historical data.

Out of these, mathematical programming engines are the most widely used. The table below are some examples of modelling frameworks and its categories. Note that this is not an extensive list, and that it focuses on internationally widely used packages.

Modelling Framework	Developer	Specific Purpose	Modelling Paradigm	Methodological Approach	Mathematical Approach
PRIMES	National Technical University of Athens, NTUA	Integrated	Hybrid	Simulation	Dynamic programming
LEAP	Stockholm Environmental Institute	Integrated	Hybrid	Simulation	Analytical programming
WEPS	International Energy Agency	Demand- Side	Top-Down	Optimization/ Simulation	Mathematical programming

Modelling Framework	Developer	Specific Purpose	Modelling Paradigm	Methodological Approach	Mathematical Approach
OSeMOSYS	Open-Source community, UCL	Demand- Side	Bottom-Up	Optimization	Mathematical programming
TIMES	International Energy Agency	Supply-Side	Bottom-Up	Optimization	Mathematical programming
PLEXOS	Energy Exemplar	Supply-Side	Bottom-Up	Optimization	Mathematical programming
PyPSA	Technical University of Berlin	Supply-Side	Bottom-Up	Optimization	Mathematical programming
pandapower	University of Kassel and Fraunhofer Institute	Supply-Side	Bottom-Up	Optimization	Mathematical programming
PowerFactory	DIgSILENT GmbH	Supply-Side	Bottom-Up	Optimization/ Simulation	Mathematical / Dynamic prog.
PSS/E	Siemens	Supply-Side	Bottom-Up	Optimization/ Simulation	Mathematical/ Dynamic prog.
Sienna	National Renewable Energy Laboratory	Supply-Side	Bottom-Up	Optimization/ Simulation	Mathematical/ Dynamic prog.
Power Grid Model	Alliander	Integrated	Bottom-Up	Simulation	Mathematical programming

4.2 Users of ESM

While supply-side, bottom-up optimization represents the most common framework in ESM, all frameworks are frequently adapted to reflect the diverse priorities and technical requirements of different stakeholders. The specific application of a model is often dictated by the user's jurisdiction and the data available for their decision-making.

For governments and energy ministries, the focus is primarily on high-level energy planning and its impact on the economy. These users typically collect broad energy parameters to inform energy policy decisions, where a general supply-demand equilibrium is more than sufficient. Because the goal is often to understand the total energy balance rather than day-to-day operations, modelling frameworks such as PRIMES, LEAP, or WEPS are frequently selected to model medium to long-term scenarios.

Energy ministries and Transmission System Operators (TSOs) require a more technical perspective, shifting the focus toward the infrastructure of the energy system. At this level, the scheduling of power plants and renewable supply becomes critical. Supplying energy to consumers on an hourly basis is the main task for these users. Modelling frameworks such as TIMES, PLEXOS, or PyPSA are used to optimize system cost with constraints. PLEXOS, in particular, is the international market leader within this segment.

Within TSOs and Distribution System Operators (DSOs), the priority shifts from planning to the physical reality of the grid. These users are tasked with the practicalities of installing transmission lines and transformers while ensuring grid stability. In this context, the physical characteristics of electricity such as frequency and voltage must be modeled at a resolution of seconds or milliseconds. These require frameworks such as PowerFactory, PSS/E, or Sienna to model system dynamics.

Local decision makers, such as energy communities or local asset managers, also use energy system models. Simulation models, for example, allows battery asset managers to optimize charge and discharge schedules, integrating short-term price forecasts with battery health metrics to ensure operational efficiency. There is no standard model at this level; a wide range of international and national vendors offer modeling solutions. Models typically focus on user-friendly interfaces, and have little technical detail on the wider energy system (e.g., simply using exogenous assumptions about energy prices).

4.3 Modelling Data Formats

There is no standardized format and data access protocol for information related to energy and environmental systems. We have huge models with very sophisticated scientific methodologies but transferring data or results automatically from one model to another is nearly impossible even if the contents of their datasets overlap substantially (Voß, 1994).

However, model input data is typically organized according to one of two broad structural conventions: hierarchical, object-based structures and tabular, record-based structures. While these conventions are rarely formalized as standards in themselves, they strongly influence how models are built, maintained, exchanged, and interpreted in practice.

Hierarchical data structures represent the modeled system as a collection of objects with explicit relationships, often arranged in tree-like or graph-based hierarchies. These structures are commonly implemented using XML or closely related formats. Well-known examples include PLEXOS input data and standards based on the Common Information Model, such as CGMES. This approach is well suited to representing complex systems with many interdependent components, as relationships between elements are explicitly encoded. Hierarchical structures are also relatively easy to extend with new object types or attributes, which makes them attractive in environments where models evolve over time. However, they tend to be verbose and can be cumbersome to inspect, edit, or version-control manually, particularly for large systems.

Tabular data structures, by contrast, organize model inputs as flat or relational tables, where each row represents an entity and each column an attribute. This convention underlies a wide range of widely used formats, including PSS/E RAW and DYR files, as well as the CSV-based inputs used by many planning, market, and capacity expansion models. Tabular representations are generally easier to understand at a glance, lend themselves well to bulk editing and automated processing, and integrate naturally with databases, spreadsheets, and data analysis tools. Their main limitation is that complex relationships between entities are not expressed directly, but must be implied through identifiers, naming conventions, or additional linking tables.

In practice, the distinction between hierarchical and tabular input data is not absolute. Many modeling tools and workflows combine both conventions, using tabular data for assets, parameters, and time series, and hierarchical structures for configuration, scenarios, or metadata. The choice of convention is therefore less about the information content and more about trade-offs between expressiveness, usability, and interoperability. Understanding these conventions, and the implications they have for data management and exchange, is an important part of assessing best practices for model input data.

When it comes to data formats, a wide range of formats are used by these software packages, depending on their type and provenance. Grid models are often serialized in RDF (CGMES) or one of a number of object/JSON serialization. Grid measurements originate as IEC61850 or 104, are then distributed via message ques (Kafka/avro, MQTT/JSON, etc.), usually ending up in a time series database. GIS data is usually encoded as GML/WKT/ or ESRI formats. Metadata (provenance, data quality, cataloging information etc) is often RDF or tabular/CSV.

There are ongoing efforts to increase interoperability of model input datasets, with more and more tools being able to parse and export file formats from competing frameworks. For example, Sienna can parse PSS/E .raw files directly. Another common workaround is to export results into "lowest common denominator" formats, such as .csv, and use an intermediary script or process to recontextualize the data for the target model. Using the second method however, requires taking into consideration different component definitions and unit conversion factors.

In most modeling data conversions, the underlying mathematical approach, for example specific variables and constraints defined within an optimization-based modelling framework, is lost in the process. This means that Voß's statement in this aspect remains to be true.

5. Best practices for reporting model outputs

The final step in the model workflow is the reporting of model outputs. Apart from the data standards mentioned above, there are, to the best of our knowledge, no formal standards for reporting model outputs. There are a number of 'best practices', defined by different institutions:

- For comparing different flexibility market models the EU OSMOSE project has defined different numerical key performance indicators (KPIs) that can be measured in an energy system to evaluate their performance. These are economic indicators, market performance indicators, technical indicators and other indicators. Some of the latter categories of KPIs are less clearly defined and focus on implementability, environment impact and efficiency of market models.
- A US standard defining energy model documentation and archiving practices has been developed by the EIA. The standard defines documentation best practices, documentation templates and procedures to ensure model outputs are reproducible and interpretable. The standard goes as far as formulating guidelines on how to report mathematical equations unambiguously. Furthermore, the standard also defines a checklist in order to properly archive models for reuse and reproducibility in the future.
- CGMES's StateVariables definition, in the power flow modeling domain, provide guidelines for reporting outputs of power flow models.
- The US Department of Energy has recently developed a set of best practices for Integrated Resource Planning (IRP) processes. These are, at the moment, mere guidelines, with individual state-level regulators deciding which practices their utilities have to follow. Although some recommendations are specific to to the US context, many apply internationally, including the use of appropriate metrics that match the time horizon of the study, clear reporting of results including standard summaries, and the inclusion of benchmarks against other studies.