**SUPPLEMENTARY MATERIALS**

Title: **A Supply Chain Knowledge and Information Integration Framework Toward Automated Assessment and Cross-Organizational Management of Integrated Energy Systems**

Number of Pages: 14

Number of Tables: 10

**Table S1**

Defined concepts in the ontology model along with their description

|  |  |  |
| --- | --- | --- |
| Concept (Associated Module) | Description | Upper Concept |
| Thing (Entity Module) | The base entity | - |
| AbstractThing (Entity Module) | The base abstract entity | Thing |
| ConcreteThing (Entity Module) | The base concrete entity | Thing |
| MathematicalEntity (Mathematical Module) | Basic mathematical concept | Thing |
| Parameter (Mathematical Module) | Concept used to represent elements of mathematic expression | MathematicalEntity |
| Variable (Mathematical Module) | Concept used to represent variable part of mathematic expression | Parameter |
| Constant (Mathematical Module) | Concept used to represent constant part of mathematic expression | Parameter |
| MathematicalExpression (Mathematical Module) | A combination of variables and constants | MathematicalEntity |
| Problem (Mathematical Module) | Concept employed to describe a supply chain problem | MathematicalExpression |
| Model (Mathematical Module) | Concept employed to reflect a supply chain entity model such as equipment operation model | MathematicalExpression |
| Metric (Mathematical Module) | A mathematical representation of different purposes assumed in a supply chain | MathematicalExpression |
| EconomicMetric (Mathematical Module) | Concept used to describe economic criteria mathematically | SustainabilityMetric |
| EnvironmentalMetric (Mathematical Module) | Concept used to mathematically represent environmental criteria | SustainabilityMetric |
| SocialMetric (Mathematical Module) | Concept used to describe social criteria mathematically | SustainabilityMetric |
| SustainabilityMetric (Mathematical Module) | Base Concept to realize economic, environmental and social metrics of a supply chain problem | Metric |
| ResponsivenessMetric (Mathematical Module) | A mathematical description of responsiveness in a supply chain | Metric |
| ReliabilityMetric (Mathematical Module) | A mathematical description of reliability in a supply chain | Metric |
| RiskMetric (Mathematical Module) | A mathematical description of risk in a supply chain | Metric |
| EnergyEfficiencyMetric (Mathematical Module) | Concept used to describe energy efficiency criteria mathematically | EfficiencyMetric |
| ManagementEfficiencyMetric (Mathematical Module) | Concept used to describe management efficiency criteria mathematically | EfficiencyMetric |
| EfficiencyMetric (Mathematical Module) | Base concept to represent efficiency metric of a supply chain problem | Metric |
| SCEntity (SC Module) | Elements that define actual supply chain | Thing |
| SCOperation (SC Module) | Management and operation of a supply chain in practice | Thing |
| Actor (SC Module) | Involved parties making decisions in a SC | SCEntity |
| Enterprise (SC Module) | A type of actor comprises different companies and processing units | Actor |
| FunctionalUnit (SC Module) | A type of actor to represent processing unit entailing different units | Actor |
| Activity (SC Module) | Tasks that each SC ‘Actor’ performs | SCEntity |
| Determining (SC Module) | The basic task representing different aspects of determination such as verification, selection, etc. | Activity |
| Balancing (SC Module) | Act of balancing between requirements and resources | Determining |
| Authorizing (SC Module) | Act of authorization resources such as payment | Determining |
| Verifying (SC Module) | Act of verification of resources such as invoice | Determining |
| Assessing (SC Module) | Act of assessment of entities such as inventory monitoring | Determining |
| Selecting (SC Module) | Act of selection of entities such as supplier selection | Determining |
| Assigning (SC Module) | Act of assignment of entities such as job assignment | Determining |
| Scheduling (SC Module) | Scheduling of entities such as production scheduling | Determining |
| Prioritizing (SC Module) | Act of prioritization of different tasks | Determining |
| Producing (SC Module) | Act of production | Activity |
| Procuring (SC Module) | Act of supplying | Activity |
| Transferring (SC Module) | Act of transfer of resources | Activity |
| Disposing (SC Module) | Act of disposition of entities | Releasing |
| Releasing (SC Module) | Act of release of entities | Exchanging |
| Receiving (SC Module) | Act of receiving of entities | Exchanging |
| Exchanging (SC Module) | Basic activity of receiving, releasing or disposing of resources or requirements | Activity |
| Entering (SC Module) | Act of installing or putting entities in a supply chain | Activity |
| Maintaining (SC Module) | Act of maintaining resources | Activity |
| Hoarding (SC Module) | Act of storing | Activity |
| Developing (SC Module) | Act of developing resources | Activity |
| Launching (SC Module) | Act of starting requirements or resources | Activity |
| Documenting (SC Module) | Documentation of resources or requirements | Activity |
| Utilizing (SC Module) | Use of resources or requirements | Activity |
| Identifying (SC Module) | Act of identification of entities | Finding |
| Finding (SC Module) | Basic activity representing finding or identifying resources | Activity |
| Packaging (SC Module) | Act of packaging certain resources | Aggregating |
| Consolidating (SC Module) | Act of integrating informational resources | Aggregating |
| Aggregating (SC Module) | Basic activity describing different aspects of aggregation such as packaging | Activity |
| Requesting (SC Module) | Act of requesting certain tasks in a supply chain | Activity |
| Negotiating (SC Module) | Concept representing act of negotiation | Activity |
| Resource (SC Module) | Various types of assets an actor uses to conduct an activity | SCEntity |
| MonetaryReosurce (SC Module) | Concept describes monetary resources in a supply chain | Resource |
| TransferResource (SC Module) | Basic entity that describes transfer resources such as materials in a supply chain | Resource |
| TransferObject (SC Module) | Basic concept represents informational resources | TransferResource |
| Inquiry (SC Module) | Informational resources that describe request content | TransferObject |
| Quote (SC Module) | Informational resources that describe reply content of a request | TransferObject |
| Order (SC Module) | Informational resources that describe order content | TransferObject |
| Invoice (SC Module) | Informational resources that describe reply content of an order | TransferObject |
| Payment (SC Module) | Informational resources that describe payment content of an order | TransferObject |
| Signal (SC Module) | Informational resources that represent all messages passed between actors in a supply chain | TransferObject |
| Material (SC Module) | Basic concept which represents material resources | TransferResource |
| RawMaterial (SC Module) | Concept representing raw material | Material |
| Intermediate (SC Module) | Concept that represents intermediate material | Material |
| Product (SC Module) | Basic concept which represents product | Material |
| FinishedProduct (SC Module) | Entity which represents final product | Product |
| DefectiveProduct (SC Module) | Entity that represents defective product | Product |
| ExcessProduct (SC Module) | Concept represents excess product that may be returned to supplier | Product |
| MROProduct (SC Module) | Concept which represents repaired product | Product |
| Waste (SC Module) | Entity which describes waste materials | Material |
| HumanResource (SC Module) | Entity that describes human resources | Resource |
| Record (SC Module) | Entity that describes records or documents in a supply chain | Resource |
| Publication (SC Module) | Entity which describes publications in a supply chain | Record |
| BusinessRuleRecord (SC Module) | Entity that contains business rules | Publication |
| RegulatoryPublication (SC Module) | Entity that contains regulatory publications | Publication |
| GenericDocument (SC Module) | Entity which represents generic documents | Record |
| Contract (SC Module) | Concept that describes contract | Record |
| Tool (SC Module) | Basic entity which represents equipment and infrastructure in a supply chain | Resource |
| Equipment (SC Module) | Basic concept which describes various equipment in a supply chain | Tool |
| Infrastructure (SC Module) | Basic concept which describes different infrastructure in a supply chain | Tool |
| OtherInfrastructure (SC Module) | Entity that describes infrastructure other than transfer infrastructure such as potential location to build a new production facility | Infrastructure |
| TransferInfrastructure (SC Module) | Basic concept that represents different types of transfer infrastructure such as material transportation networks | Infrastructure |
| TransportationLink (SC Module) | Concrete which transportation networks in a supply chain | TransferInfrastructure |
| InformationExchangeLink (SC Module) | Information exchange infrastructure | TransferInfrastructure |
| EnergeticResource (SC Module) | Entity which describes various energy resources in a supply chain | Resource |
| Requirement (SC Module) | Specification, constraints, etc. related to actors, activities and resources | SCEntity |
| ResourceRequirement (SC Module) | Requirements associated to resources | Requirement |
| ActivityRequirement (SC Module) | Basic requirements associated to activities | Requirement |
| ActivityPolicy (SC Module) | Requirements on how to perform an activity | ActivityRequirement |
| ActivitySpecification (SC Module) | Specification of an activity and execution order of various tasks | ActivityRequirement |
| ActorRequirement (SC Module) | Requirements associated to actors | Requirement |
| ExternalForce (SC Module) | Elements outside a supply chain that exert impacts on it | SCEntity |
| Regulation (SC Module) | Basic concept that describes external regulations imposed by different organizations | ExternalForce |
| LocalRegulation (SC Module) | External regulations imposed by local governments, agencies, etc. | Regulation |
| GovernmentRegulation (SC Module) | External regulations imposed by federal governments | Regulation |
| InternationalRegulation (SC Module) | External regulations introduced by international organizations | Regulation |
| Measure (SC Module) | Basic concept that represents legal means in regulations | ExternalForce |
| Permit (SC Module) | Concept which describes permits as a legal tool | Measure |
| Exemption (SC Module) | Entity which describes exemptions as a legal means | Measure |
| Incentive (SC Module) | Concept that represents incentives a as legal means | Measure |
| Restriction (SC Module) | Entity which describes restriction as a legal tool | Measure |
| Event (SC Module) | Basic concept which describes external such as natural disasters taking place in supply chains | ExternalForce |
| NaturalEvent (SC Module) | Concept that represents natural events | Event |
| ManMadeEvent (SC Module) | Concept which represents human-made events | Event |
| Outcome (SC Module) | Results of an activity, external forces, etc. | SCEntity |
| Impact (SC Module) | Consequences of an activity or external events | Outcome |
| Service (SC Module) | Results of an activity as a provided service | Outcome |
| Purpose (SC Module) | Basic concept which represents different intentions of actors or supply chain as a whole | SCEntity |
| Mission (SC Module) | Concept which describes mission of an actor | Purpose |
| Vision (SC Module) | Concept which describes vision of an actor | Purpose |
| Goal (SC Module) | Concept that describes midterm goal of an actor | Purpose |
| Objective (SC Module) | Concept which describes short-term objective of an actor | Purpose |

**Table S2**

Reflected association relation in the ontology along with corresponding domain, scope and multiplicity constraint

|  |  |  |  |
| --- | --- | --- | --- |
| Relation | Domain | Scope | Multiplicity |
| containsRegulation | RegulatoryPublication | Regulation | \* |
| containsRequirement | BusinessRuleRecord | Requirement | \* |
| executesActivity | Actor | Activity | \* |
| hasActorRequirement | Actor | ActorRequirement | \* |
| hasActivityRequirement | Activity | ActivityRequirement | \* |
| hasResourceRequirement | Resource | ResourceRequirement | \* |
| hasImpact | Event | Impact | \* |
| hasOutcome | Activity | Outcome | \* |
| holdsGoal | Enterprise | Goal | \* |
| holdsMission | Enterprise | Mission | \* |
| holdsObjective | FunctionalUnit | Objective | \* |
| holdsVision | Enterprise | Vision | \* |
| isAssociatedtoEnregeticResource | Assigning | EnergeticResource | 1..1 |
| Exchanging |
| Hoarding |
| Prioritizing |
| Procuring |
| Producing |
| Selecting |
| Transfering |
| isAssociatedtoHumanResource | Assigning | HumanResource | 1..1 |
| Prioritizing |
| Selecting |
| isAssociatedtoMaterial | Assigning | Material | 1..1 |
| Exchanging |
| Selecting |
| Transfering |
| Verifying |
| Maintaining | MROProduct |
| Entering | Product |
| Producing |
| Producing | Intermediate |
| Producing | Waste |
| Disposing |
| Procuring | RawMaterial |
| isAssociatedtoMonetaryResource | Assigning | MonetaryResource | 1..1 |
| Hoarding |
| Maintaining |
| Procuring |
| Receiving |
| Selecting |
| Transfering |
| isAssociatedtoPurpose | Assessing | Purpose | 1..1 |
| Assigning |
| Prioritizing |
| Selecting |
| isAssociatedtoRecord | Disposing | Record | 1..1 |
| Documenting |
| Hoarding |
| Verifying |
| Prioritizing | Publication |
| Assessing |
| isAssociatedtoRequirement | Assessing | Requirement | 1..1 |
| Balancing |
| Developing |
| Hoarding |
| Identifying |
| Launching |
| Prioritizing |
| isAssociatedtoResource | Finding | Resource | 1..1 |
| Utilizing |
| isAssociatedtoTool | Assigning | Equipment | 1..1 |
| Entering |
| Exchanging |
| Maintaining |
| Prioritizing |
| Scheduling |
| Transfering |
| Selecting | Tool |
| Developing |
| isAssociatedtoTransferObject | Requesting | Inquiry | 1..1 |
| Requesting | Invoice |
| Assigning | Order |
| Consolidating |
| Prioritizing |
| Requesting |
| Scheduling |
| Authorizing | Payment |
| Documenting | TransferObject |
| Entering |
| Receiving |
| Transfering |
| Verifying |
| isAssociatedtoTransferResource | Hoarding | TransferResource | 1..1 |
| isModeledBy | SCEntity | Model | \* |
| isPartOf | Metric | Purpose | \* |
| SCEntity | SCOperation |
| FunctionalUnit | FunctionalUnit |
| Enterprise | Enterprise |
| FunctionalUnit | Enterprise |
| Metric | Problem |
| Model | Problem |
| Metric | Impact |
| Measure | Regulation |
| Parameter | MathematicalExpression |
| Activity | ActivitySpecification |
| isRuledBySC | Problem | SCEntity | 1..1 |
| makesEntryForSC | Problem | SCOperation | \* |
| mayChangePurpose | ExternalForce | Purpose | \* |
| mayChangeRequirement | ExternalForce | Requirement | \* |
| mayDamageResource | Event | Resource | \* |
| mayHelpAchievePurpose | Outcome | Purpose | \* |
| mayHinderActivity | ExternalForce | Activity | \* |
| mayPromoteActivity | ExternalForce | Activity | \* |

**Table S3**

Incorporated properties in the ontology structure

|  |  |  |
| --- | --- | --- |
| Property | Domain | Scope (Data Type) |
| actorName | Actor | string |
| actorID | integer |
| actorLocation | string |
| segmentationVariable | string |
| refreshingPeriod | Activity | double |
| activityDuration | double |
| activityRate | Producing | double |
| Transfering |
| Hoarding |
| Developing |
| Documenting |
| Packaging |
| transferResourceID | TransferResource | integer |
| transferResourceOrigin | string |
| transferResourceDestination | string |
| isToxic | Material | boolean |
| isPerishable |
| materialPrice | currency |
| submittingDate | TransferObject | date |
| objectContent | string |
| dueDate | date |
| value | MonetaryResource | currency |
| consumableValue |
| retrunHorizon | date |
| salary | HumanResource | currency |
| recordContent | Record | string |
| recordVersion | string |
| equipmentCapacity | Equipment | double |
| surfaceInfrastructureArea | OtherInfrastructure | double |
| transferInfrastructureCapacity | TransferInfrastructure | double |
| volume | EnergeticReosurce | double |
| consumableVolume |
| achievingPeriod | Purpose | double |
| servicePrice | Service | currency |
| measureDuration | Measure | date |
| eventScale | Event | string |
| eventDuration | date |
| eventDamage | currency |
| requirementContent | Requirement | string |
| matrialDemand | ActorRequirement | double |

**Table S4**

‘Actor’ and ‘Service’ instances defined in the IES case study.

|  |  |  |  |
| --- | --- | --- | --- |
| Relation | Domain (Concept) | Scope (Instance) | Scope Description |
| instantiate | Enterprise | GasificationEnterprise | The company which manages gasification facility |
| CCGTEnterprise | The company that manages combined cycle gas turbine facility |
| CHPEnterprise | The company which manages combined heat and power facility |
| SMREnteprise | The company that manages steam methane reforming facility |
| EGEnterprise | The enterprise that manages external power grid |
| NGUGSEnteprise | The company that manages natural gas underground storage facility |
| SyngasPVEnterprise | The company that manages syngas pressurized vessels facility |
| HydrogenPVEnterprise | The company which manages hydrogen pressurized vessels facility |
| FuelingStationEnterprise | The company that manages fuel stations |
| DHNetworkEnterprise | The company which manages district heat network |
| UDPipelineEnterprise | The company which is responsible for underground hydrogen pipelines |
| SyngasTIEnterprise | The company that manages syngas transport infrastructure |
| NGTIEnterprise | Manager of natural gas transmission infrastructure |
| HydrogenTIEnterprise | Coordinator of hydrogen transport infrastructure |
| WindFarmEnterprise | The company which manages wind farm |
| FunctionalUnit | HEUnit | The unit which is responsible for hydrogen expansion system |
| HCUnit | The unit which is responsible for hydrogen compression system |
| NGEUnit | The unit which is responsible for natural gas expansion system |
| NGCUnit | The unit which is responsible for natural gas compression system |
| SGEUnit | The unit which is responsible for syngas expansion system |
| SGCUnit | The unit which is responsible for syngas compression system |
| FuelCellUnit | The unit which is responsible for fuel cell system |
| ElectrolyzerUnit | The unit which manages electrolyzer system |
| DomesticBoilerUnit | The unit which manages domestic boiler system |
| DomesticElectricHeaterUnit | The unit that manages domestic electric heater system |
| BoilerUnit | The unit that manages boiler system |
| Service | HeatEndConsumption | The service which demands heat |
| MobilityEndConsumption | The service which demands mobility fuel |
|  |  |  |  |

**Table S5**

‘Activity’ instances provided in the IES case study.

|  |  |  |  |
| --- | --- | --- | --- |
| Relation | Domain (Concept) | Scope (Intance) | Scope Description |
| instantiate | Producing | convertBiomass | Act of converting biomass |
| convertLPSyngas | Act of converting low pressure syngas |
| convertLPNG | Act of converting low pressure natural gas |
| convertLPHydrogen | Act of converting low pressure hydrogen |
| convertElectricity | Act of converting electricity |
| convertWindEnergy | Act of converting wind energy |
| converttoLPSyngas | Act of converting resources to low pressure syngas |
| converttoElectricity | Act of converting resources to electricity |
| converttoHeat | Act of converting resources to heat |
| converttoLPHydrogen | Act of converting resources to low pressure hydrogen |
| converttoHPHydrogen | Act of converting resources to high pressure hydrogen |
| Transferring | deliverHeat | Act of delivering heat |
| deliverLPHydrogen | Act of delivering low pressure hydrogen |
| deliverLPNG | Act of delivering low pressure natural gas |
| deliverLPSyngas | Act of delivering low pressure syngas |
| deliverHPHydrogen | Act of delivering high pressure hydrogen |
| deliverHPSyngas | Act of delivering high pressure syngas |
| deliverHPNG | Act of delivering high pressure natural gas |
| deliverElectricity | Act of delivering electricity |
| Exchanging | expandHPSyngas | Act of expanding high pressure syngas |
| expandHPNG | Act of expanding high pressure natural gas |
| expandHPHydrogen | Act of expanding high pressure hydrogen |
| compressLPSyngas | Act of compressing low pressure syngas |
| compressLPNG | Act of compressing low pressure natural has |
| compressLPHydrogen | Act of compressing low pressure hydrogen |
| Receiving | receiveElectricity | Act of receiving electricity |
| receiveHeat | Act of receiving heat |
| receiveLPHydrogen | Act of receiving low pressure hydrogen |
| Hoarding | storingHPSyngas | Act of storing high pressure syngas |
| storingHPNG | Act of storing high pressure natural gas |
| storingHPHydrogen | Act of storing high pressure hydrogen |
|  |  |  |  |

**Table S6**

Instances of ‘Resource’ reflected in the model.

|  |  |  |  |
| --- | --- | --- | --- |
| Relation | Domain (Concept) | Scope (Instance) | Scope Description |
| instantiate | RawMaterial | Biomass | Biomass resource |
| Intermediate | LPSyngas | Low pressure syngas |
| HPSyngas | High pressure syngas |
| LPNG | Low pressure natural gas |
| HPNG | High pressure natural gas |
| LPHydrogen | Low pressure hydrogen |
| HPHydrogen | High pressure hydrogen |
| EnergeticResource | DistrictHeat | District heat resource |
| Electricity | Power resource |
| WindEnergy | Wind energy resource |
| Equipment | GasificationSystem | Gasification equipment |
| CCGTSystem | Combined cycle gas turbine equipment |
| CHPSystem | Combined heat and power equipment |
| BiolerSystem | Boiler equipment |
| DomesticBoilerSystem | Domestic boiler equipment |
| DomesticElectricHeaterSystem | Domestic electric heater equipment |
| FuelCellSystem | Fuel cell equipment |
| ElectrolyzerSystem | Electrolyzer equipment |
| SMRSystem | Steam methane reforming equipment |
| FuelingStation | Fuel station |
| NGUGS | Natural gas underground storage |
| SyngasPV | Syngas pressurized vessel |
| HydrogenPV | Hydrogen pressurized vessel |
| HESystem | Hydrogen expansion equipment |
| HCSystem | Hydrogen compression equipment |
| NGESystem | Natural gas expansion equipment |
| NGCSystem | Natural gas compression equipment |
| SGESystem | Syngas expansion equipment |
| SGCsystem | Syngas compression equipment |
| WindTurbine | Wind turbine equipment |
| TransportationLink | DHNetwork | District heat transport infrastructure |
| UDPipeline | Underground pipeline infrastructure |
| SyngasTI | Syngas transport infrastructure |
| NGTI | Natural gas transmission infrastructure |
| HydrogenTI | Hydrogen transmission infrastructure |
|  |  |  |  |

**Table S7**

Instances of ‘Requirement’ defined in the ontology.

|  |  |  |  |
| --- | --- | --- | --- |
| Relation | Domain (Concept) | Scope (Instance) | Scope Description |
| instantiate | ActorRequirement | ElectricityDemand | Power demand |
| ActivitySpecification | HeatDemand | Heat demand |
| MobilityDemand | Mobility fuel demand |
| ResourceRequirement | GasificationOperation | The operation of gasification system that actually occurs in the energy system |
| CCGTOperation | Actual operation of combined cycle gas turbine |
| CHPOperation | Actual operation of combined heat and power system |
| BiolerOperation | Actual operation of boiler system |
| DomesticBoilerOperation | Actual operation of domestic boiler |
| DomesticElectricHeaterOperation | Actual operation of domestic electric heater |
| FuelCellOperation | Actual operation of fuel cell system |
| ElectrolyzerOperation | Actual operation of electrolyzer system |
| SMROperation | Actual operation of steam methane reformer |
| FuelingStation | Actual operation of fuel station |
| NGUGSOperation | Actual operation of natural gas underground storage |
| SyngasPVOperation | Actual operation of syngas pressurized vessel |
| HydrogenPVOperation | Actual operation of hydrogen pressurized vessel |
| HEOperation | Actual operation of hydrogen expansion system |
| HCOperation | Actual operation of hydrogen compression system |
| NGEOperation | Actual operation of natural gas expansion system |
| NGCOperation | Actual operation of natural gas compression system |
| SGEOperation | Actual operation of syngas expansion system |
| SGCOperation | Actual operation of syngas compression system |
| WindTurbineOperation | Actual operation of wind turbine system |
| DHNetworkOperation | Actual operation of district heat network |
| UDPipelineOperation | Actual operation of underground hydrogen pipelines |
| SyngasTIOperation | Actual operation of syngas transport network |
| NGTIOperation | Actual operation of natural gas transmission network |
| HydrogenTIOperation | Actual operation of hydrogen transport network |

**Table S8**

Association relations among instances of ‘Activity’, ‘Actor’, ‘Service’, and ‘Tool’/ ‘Requirement’.

|  |  |  |
| --- | --- | --- |
| Activity (Instance) | Performer (Instance) | Related Tool/Requirement (Instance) |
| convertBiomass, converttoLPSyngas, deliverLPSyngas | GasificationEnterprise | GasificationSystem |
| convertLPSyngas, convertLPNG, converttoElectricity, deliverElectricity | CCGTEnterprise | CCGTSystem |
| convertLPSyngas, convertLPNG, convertLPHydrogen, converttoElectricity, converttoHeat, deliverElectricity, deliverHeat | CHPEnterprise | CHPSystem |
| convertLPSyngas, convertLPNG, convertLPHydrogen, converttoHeat, deliverHeat | BoilerUnit | BiolerSystem |
| convertLPSyngas, convertLPNG, convertLPHydrogen, converttoHeat, deliverHeat | DomesticBoilerUnit | DomesticBoilerSystem |
| convertElectricity, converttoHeat, deliverHeat | DomesticElectricHeaterUnit | DomesticElectricHeaterSystem |
| convertLPHydrogen, converttoElectricity, deliverElectricity | FuelCellUnit | FuelCellSystem |
| convertElectricity, converttoHPHydrogen, deliverHPHydrogen | ElectrolyzerUnit | ElectrolyzerSystem |
| convertLPNG, converttoLPHydrogen, deliverLPHydrogen | SMREnteprise | SMRSystem |
| deliverLPHydrogen | FuelingStationEnterprise | FuelingStation |
| storingHPNG, deliverHPNG | NGUGSEnteprise | NGUGS |
| storingHPSyngas, deliverHPSyngas | SyngasPVEnterprise | SyngasPV |
| storingHPHydrogen, deliverHPHydrogen | HydrogenPVEnterprise | HydrogenPV |
| expandHPHydrogen, deliverLPHydrogen,  deliverElectricity | HEUnit | HESystem |
| compressLPHydrogen, deliverHPHydrogen,  receiveEletricity | HCUnit | HCSystem |
| expandHPNG, deliverLPNG, deliverElectricity | NGEUnit | NGESystem |
| compressLPNG, deliverHPNG,  receiveElectricity | NGCUnit | NGCSystem |
| expandHPSyngas, deliverLPSyngas  deliverElectricity | SGEUnit | SGESystem |
| compressLPSyngas, deliverHPSyngas  receiveElectricity | SGCUnit | SGCsystem |
| convertWindEnergy, converttoElectricity | WindFarmEnterprise | WindTurbine |
| deliverHeat | DHNetworkEnterprise | DHNetwork |
| deliverLPHydrogen | UDPipelineEnterprise | UDPipeline |
| deliverLPSyngas, deliverHPSyngas | SyngasTIEnterprise | SyngasTI |
| deliverLPNG, deliverHPNG | NGTIEnterprise | NGTI |
| deliverLPHydrogen, deliverHPHydrogen | HydrogenTIEnterprise | HydrogenTI |
| receiveHeat | HeatEndConsumption | HeatDemand |
| receiveEletricity, deliverElectricity | EGEnterprise | ElectricityDemand |
| receiveLPHydrogen | MobilityEndConsumption | MobilityDemand |

**Table S9**

Ad-hoc relations among instances of ‘Activity’, ‘Actor’, and ‘Material’/ ‘EnergeticResource’.

|  |  |  |
| --- | --- | --- |
| Activity (Instance) | Performer (Instance) | Related Material/EnergeticResource (Instance) |
| convertBiomass | GasificationEnterprise | Biomass |
| convertLPSyngas | CCGTEnterprise | LPSyngas |
| CHPEnterprise |
| BoilerUnit |
| DomesticBoilerUnit |
| convertLPNG | CCGTEnterprise | LPNG |
| CHPEnterprise |
| BoilerUnit |
| DomesticBoilerUnit |
| SMREnterprise |
| convertLPHydrogen | CHPEnterprise | LPHydrogen |
| BoilerUnit |
| DomesticBoilerUnit |
| FuelCellUnit |
| convertElectricity | ElectrolyzerUnit | Electricity |
| DomesticElectricHeaterUnit |
| convertWindEnergy | WindFarmEnterprise | WindEnergy |
| converttoLPSyngas | GasificationEnteprise | Biomass |
| converttoElectricity | CCGTEnterprise | LPSyngas, LPNG |
| CHPEnterprise | LPSyngas, LPNG, LPHydrogen |
| FuelCellUnit | LPHydrogen |
| WindFarmEnterprise | WindEnergy |
| converttoHeat | CHPEnterprise | LPSyngas, LPNG, LPHydrogen |
| BoilerUnit | LPSyngas, LPHydrogen |
| DomesticBoilerUnit | LPSyngas, LPNG, LPHydrogen |
| DomesticElectricHeaterUnit | Electricity |
| converttoLPHydrogen | SMREnterprise | LPNG |
| converttoHPHydrogen | ElectrolyzerUnit | Electricity |
| receiveElectricity | EGEnterprise | Electricity |
| HCUnit |
| NGCUnit |
| SGCUnit |
| HCUnit |
| receiveHeat | HeatEndConsumption | Heat |
| receiveLPHydrogen | MobilityEndConsumption | LPHydrogen |
| storingHPSyngas | SyngasPVEnterprise | HPSyngas |
| storingHPNG | NGUGSEnterprise | HPNG |
| storingHPHydrogen | HydrogenPVEnteprise | HPHydrogen |
| expandHPSyngas | SGEUnit | HPSyngas |
| compressLPSyngas | SGCUnit | LPSyngas |
| expandHPHydrogen | HEUnit | HPHydrogen |
| compressLPHydrogen | HCUnit | LPHydrogen |
| expandHPNG | NGEUnit | HPNG |
| compressLPNG | NGCUnit | LPNG |

**Table S10**

Implicit relationships between ‘Activity’ and ‘Actor’ instances.

|  |  |  |
| --- | --- | --- |
| Activity (Instance) | Performer (Instance) | Acted upon (Instance) |
| deliverHeat | CHPEnterprise | DHNetworkEnterprise |
| BoilerUnit |
| DomesticBoilerUnit | HeatEndConsumption |
| DomesticElectricHeaterUnit |
| DHNetworkEnterprise |
| deliverLPHydrogen | SMREnterprise | HydrogenTIEnterprise |
| FuelingStationEnterprise | MobilityEndConsumption |
| UDPipelineEnterprise | FuelingStationEnterprise |
| HydrogenTIEnterprise | HCUnit, UDPipelineEnterprise, CHPEnterprise, BoilerUnit,  DomesticBoilerUnit,  FuelCellUnit |
| HEUnit | HydrogenTIEnterprise |
| deliverHPHydrogen | ElectrolyzerUnit | HydrogenTIEnterprise |
| HydrogenPVEnterprise |
| HydrogenTIEnterprise | HydrogenPVEnterprise, HEUnit |
| HCUnit | HydrogenTIEnterprise |
| deliverLPNG | NGTIEnterprise | CCGTEnterprise,  CHPEnterprise,  BoilerUnit,  DomesticBoilerUnit,  SMREnterprise,  NGCUnit |
| NGEUnit | NGTIEnterprise |
| deliverHPNG | NGUGSEnterprise | NGTIEnterprise |
| NGTIEnterprise | NGEUnit |
| NGCUnit | NGTIEnterprise |
| deliverLPSyngas | GasificationEnterprise | SyngasTIEnterprise |
| SyngasTIEnterprise | CCGTEnterprise,  CHPEnterprise,  BoilerUnit,  DomesticBoilerUnit,  SGCUnit |
| SGEUnit | SyngasTIEnterprise |
| deliverHPSyngas | SyngasPVEnterprise | SyngasTIEnterprise |
| SyngasTIEnterprise | SGEUnit |
| SGCUnit | SyngasTIEnterprise |
| deliverElectricity | CCGTEnterprise | EGEnterprise |
| CHPEnterprise |
| FuelCellUnit |
| WindFarmEnterprise |
| EGEnterprise | ElectrolyzerUnit |