LUT School of Energy Systems
Lappeenranta–Lahti University of Technology LUT

# FLEXIBILITY AGGREGATION OF LOCAL ENERGY SYSTEMS — INTERCONNECTING, FORECASTING, AND SCHEDULING

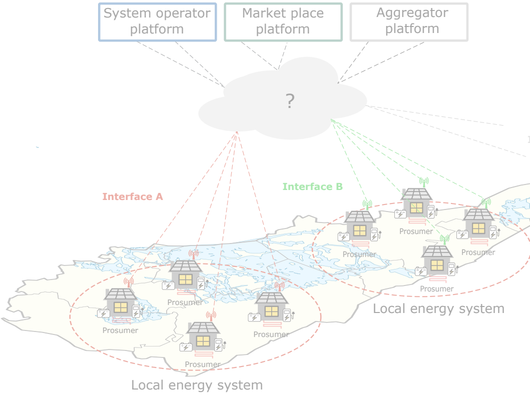
## LECTIO PRAECURSORIA

Presented by Aleksei Mashlakov

December 13, 2021

Supervisor: Prof. Samuli Honkapuro, LUT University

Opponent: Prof. Hannu Laaksonen, University of Vaasa



# OUTLINE

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# CONTEXT AND MOTIVATION

## Centralization of electric power system

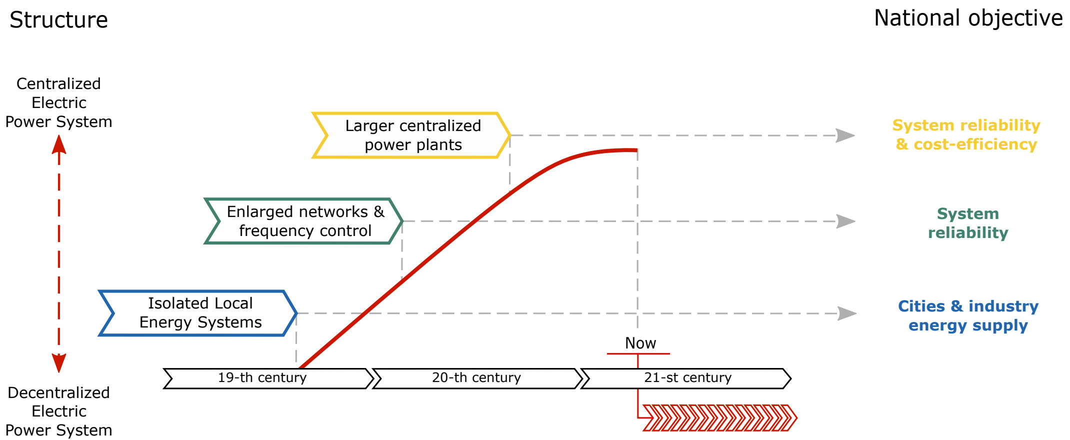
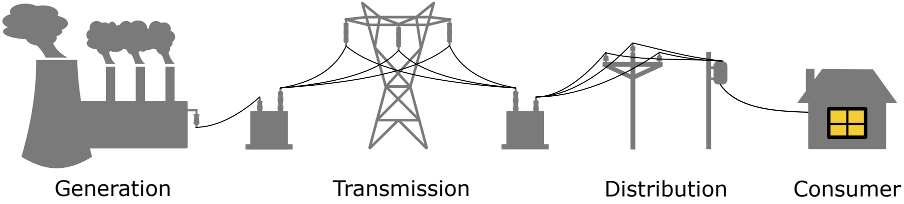



Figure: Evolution of an electric power system. Adapted from Siemens.

# CONTEXT AND MOTIVATION

## Centralized electric power system




- Unidirectional electricity supply to customers
- Supply is adjusted to follow demand
- System operators guarantee the security of supply
- Large-scale and supply-focused electricity markets
- Customer has no rule or influence over the system

# CONTEXT AND MOTIVATION

## Energy system transition

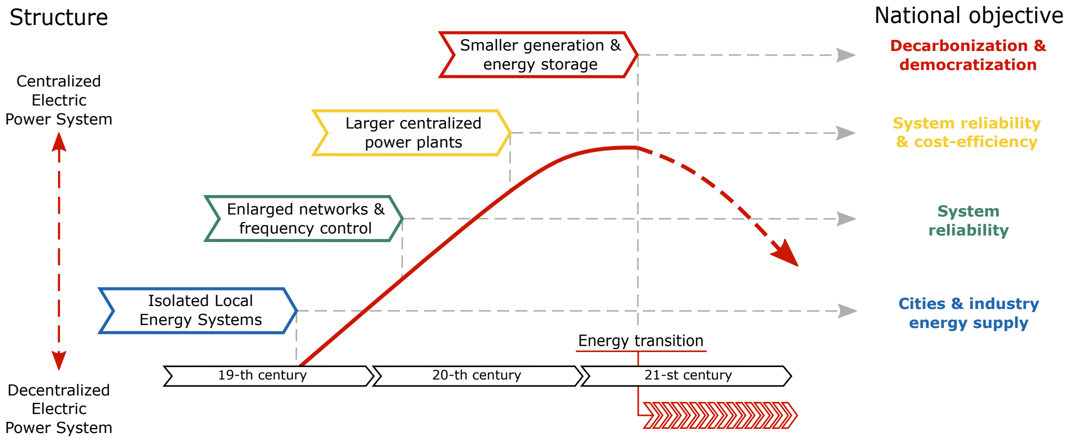
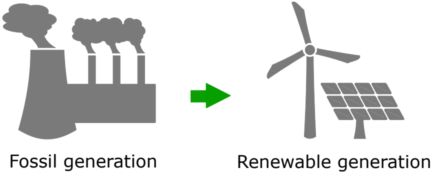



Figure: Evolution of an electric power system. Adapted from Siemens.

# CONTEXT AND MOTIVATION

## Supply decarbonization



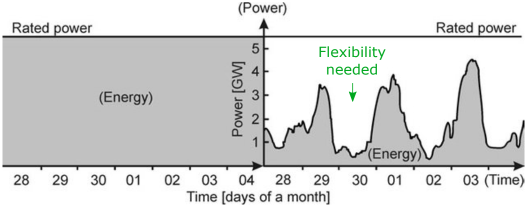
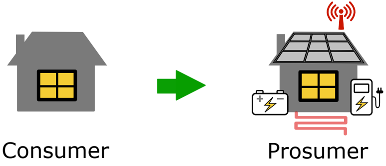




Figure: Dispatchable vs intermittent energy generation [3]

- More supply volatility
  - Less supply controllability
  - More forecast uncertainty
- *Risks of large redispatch costs for grid stabilisation*

# CONTEXT AND MOTIVATION

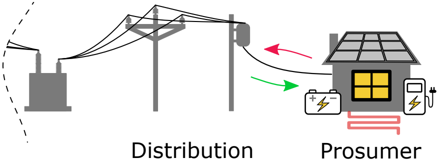
## Demand electrification




- Growing demand electrification
  - larger peak demand periods
  - bi-directional power-flows
- *Risk of worse power quality and reliability of supply in distribution grid*

# CONTEXT AND MOTIVATION

## Demand electrification

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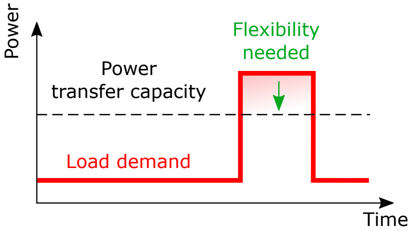
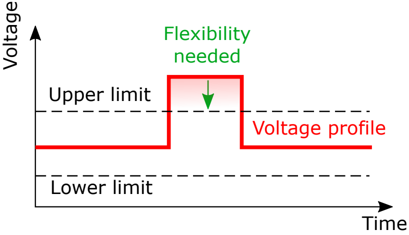
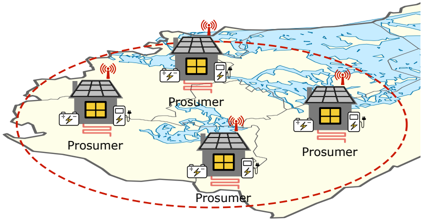


# CONTEXT AND MOTIVATION

## Demand democratization

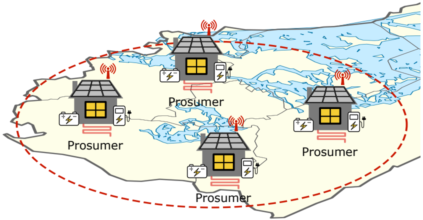



Local energy system

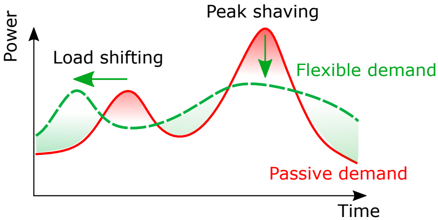
- Local energy systems
  - democratization of local energy governance
  - centralized supply as a back-up solution
- *Risk of system-wide efficiency loss*
- Joint management of demand flexibility
  - participation of prosumers in grid management
  - cost-efficient to capacity investments

# CONTEXT AND MOTIVATION

## Demand democratization




Local energy system




- Local energy systems
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- *Risk of system-wide efficiency loss*
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# OUTLINE

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# RESEARCH AIM

## Flexibility aggregation

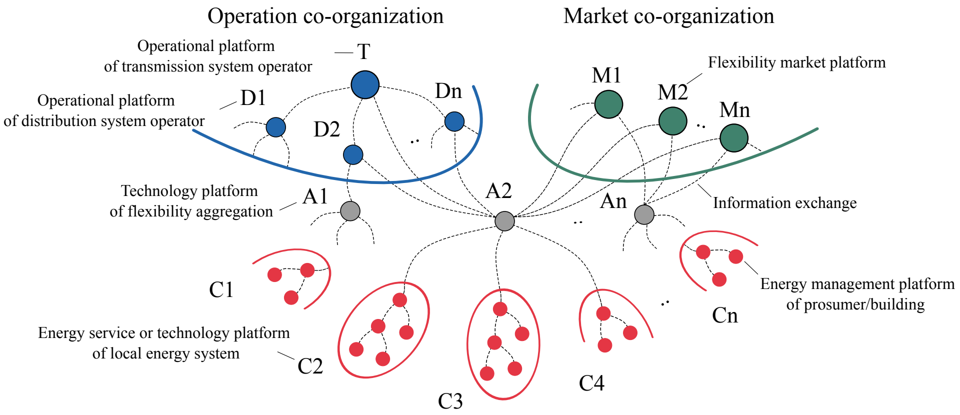


Figure: Conceptual representation of flexibility aggregation in decentralized power grid.

# METHODOLOGY

## Research areas and fields

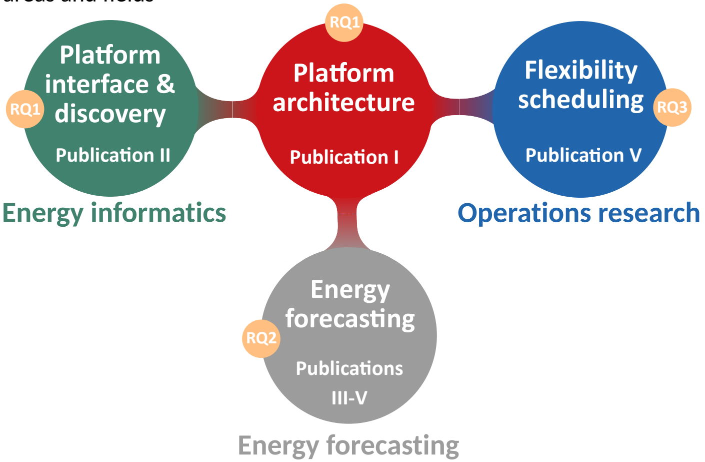


Figure: Overview of the research areas related to the contributions.

# RESEARCH QUESTION #1

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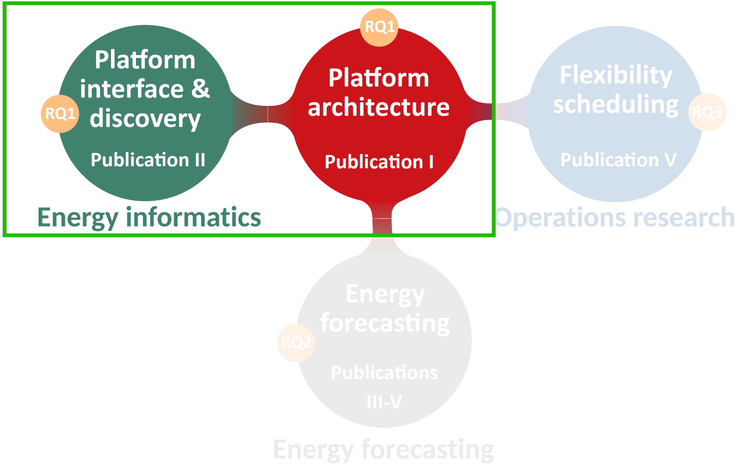
Can machines speak the same language?



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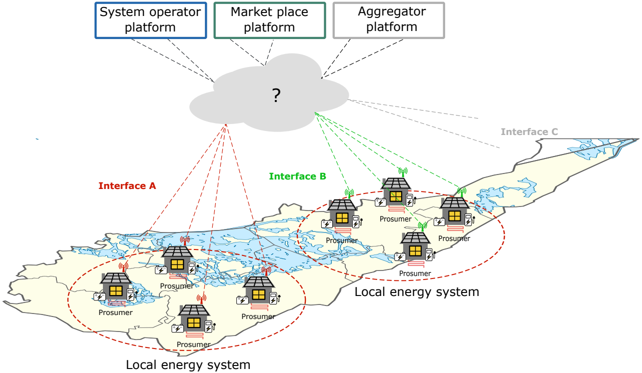


- Lack of interoperability
  - Automated flexibility procurement is out of system operator toolbox
- Heterogeneity of platforms
  - costly platform landscape
  - vendor lock-in

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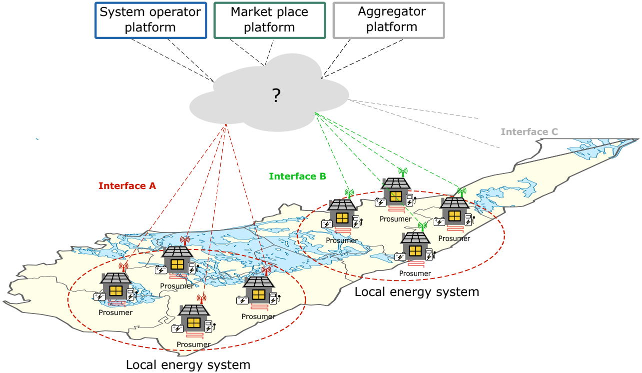


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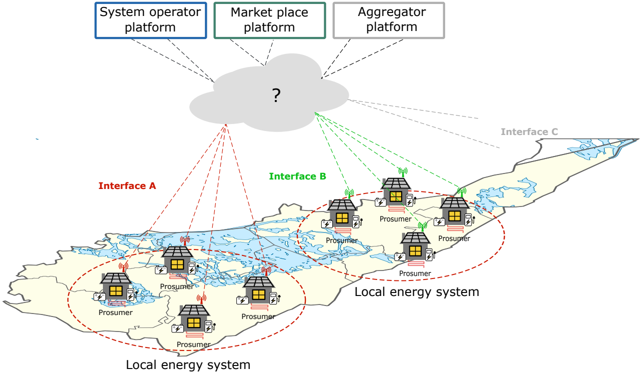



- Lack of interoperability
  - Automated flexibility procurement is out of system operator toolbox
- Heterogeneity of platforms
  - costly platform landscape
  - vendor lock-in

**RQ #1** *What are the requirements to enable interoperable technological integration of local energy management platforms into the provision of grid-flexibility services?*

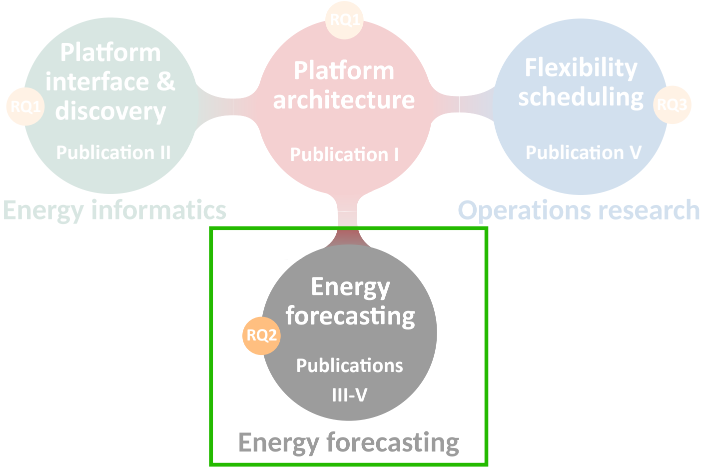
# CONTRIBUTIONS

## Research question #1

1. Design of a smart grid architecture enabling interoperable technological integration of local energy management platforms into the provision of grid-flexibility services (**Publication I**)
   - summaries functional, information, and communication requirements;
   - describes an interoperable information exchange solution.
2. Design and implementation of a high-performance architecture of a flexibility registry (**Publication II**)
   - stores and shares machine-readable information about local energy systems.

# RESEARCH QUESTION #2

- How uncertain are deep machine learning models?



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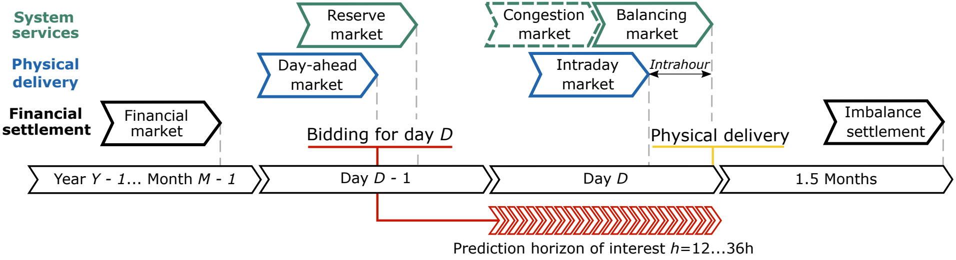

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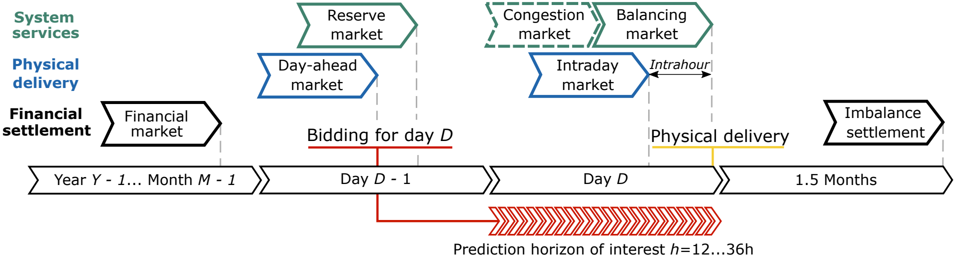
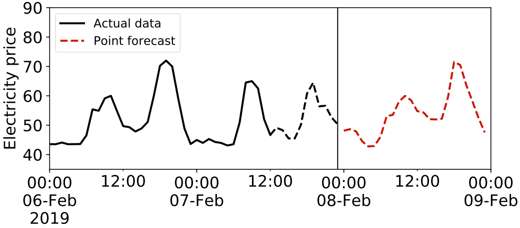


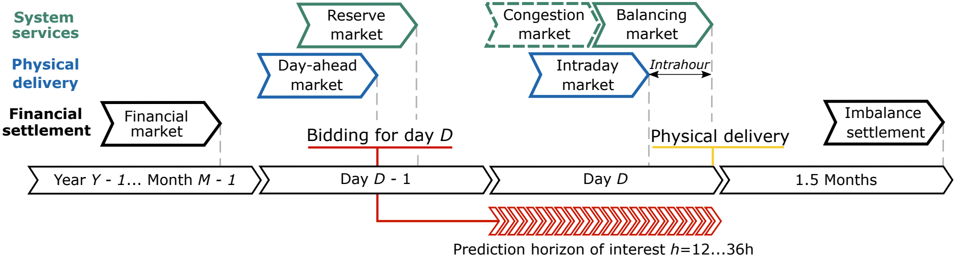



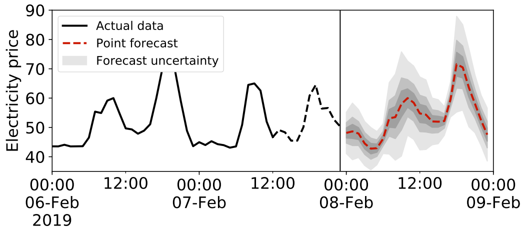

- Vulnerable to forecast errors
  - low risk-awareness

# RESEARCH QUESTION #2

LUT University

## How uncertain are deep machine learning models?

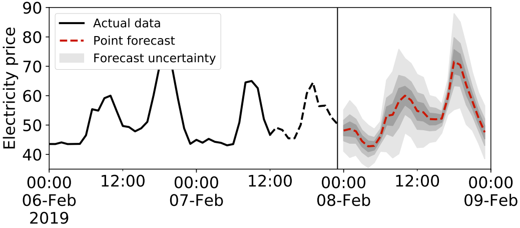



- Predictive region with degree of confidence
  - Enables risk-aware decision-making

# RESEARCH QUESTION #2

How uncertain are deep machine learning models?




**RQ #2** *What are the effective criteria in data-driven characterization of the energy forecasting uncertainties arising from the data generating processes associated with flexibility management?*

# CONTRIBUTIONS

## Research question #2

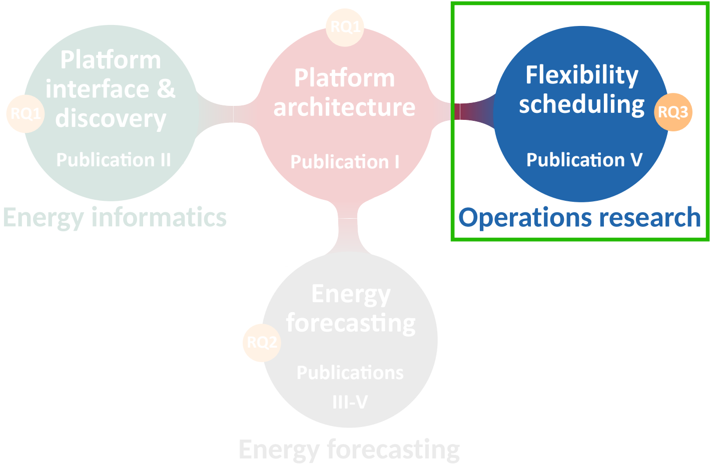
1. Empirical comparison of uncertainty-aware deep learning, machine learning, and statistical methods in a novel application domain (**Publication III**)
   - Battery storage energy activation under provision of a frequency control

2. Empirical evaluation of uncertainty-aware global deep learning models to multivariate energy forecasting problems (**Publication IV**)
   - individual electricity consumption as well as regional and national electricity consumption, market price, and renewable generation
   - model sensitivity to dataset transformation
   - model run-time efficiency

3. Empirical evaluation of diverse probability distributions on the predictive capability of global deep learning models
   - residential prosumer net load, national carbon intensity, and battery storage reserve activation parameters

# RESEARCH QUESTION #3

Are the prosumers willing to support the grid?



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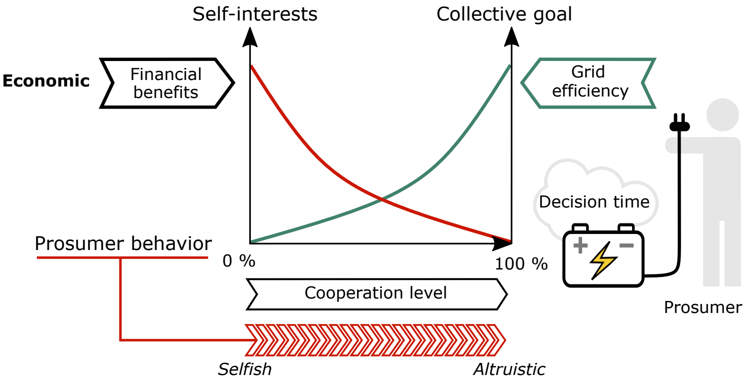


- Self-oriented decision-making
  - inefficient or harmful use of a shared grid
  - need of energy management coordination
- Heterogeneous prosumer motivations
  - need to fulfill the trade-off

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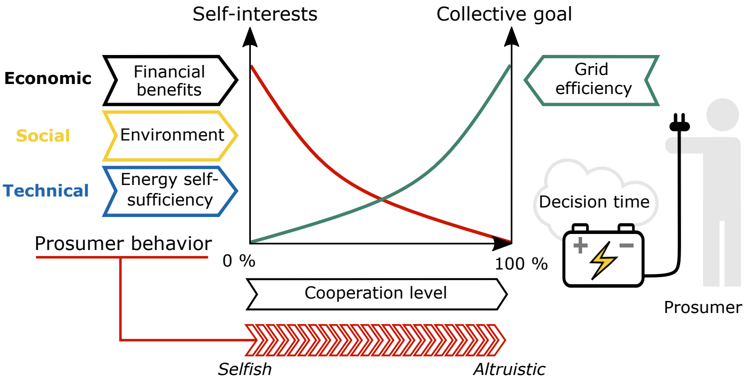


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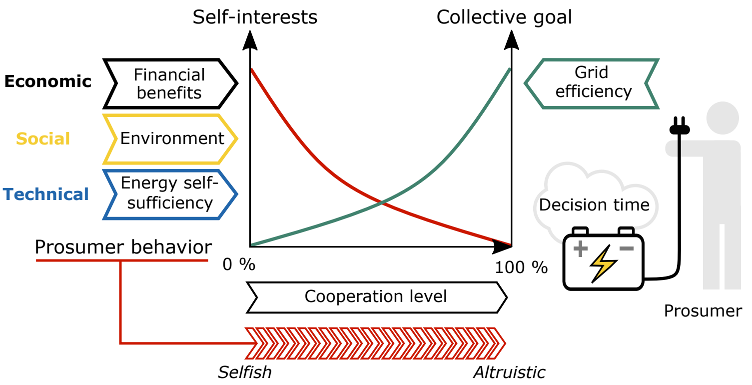


- Self-oriented decision-making
  - inefficient or harmful use of a shared grid
  - need of energy management coordination
- Heterogeneous prosumer motivations
  - need to fulfill the trade-off

**RQ #3** *What are the critical factors of the prosumer operational flexibility allocation fulfilling the system-wide multiobjective objective trade-offs for the preferred flexibility usage?*

# CONTRIBUTIONS

Research question #3 (**Publication V**)

1. A household-level flexibility scheduling framework for a local energy system that
    - captures the techno-socio-economic motivations of prosumers
    - performs cooperative and privacy-preserving coordination for grid efficiency
2. A socio-technical impact and optimality analysis of varying prosumer cooperation on
    - individual vs collective flexibility scheduling objectives
    - Pareto optimal cooperation level
3. Quantitative analysis of forecast uncertainty factors on
    - realization of a planned net load schedules
    - battery storage unavailability
4. Quantitative analysis of techno-economic efficiency of providing the frequency control service by a population of residential battery storages

# OUTLINE

1 CONTEXT AND MOTIVATION
- Supply decarbonization
- Demand electrification
- Demand democratization

2 RESEARCH AIM, SCOPE, AND QUESTIONS
- Research question #1
- Research question #2
- Research question #3

3 CONTRIBUTIONS
- Summary

# CONTRIBUTIONS

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## Summary

i. Lack of technological interoperability between the flexibility aggregation platforms:
   - Proposed a design of a decentralized smart grid architecture enabling interoperable integration of local energy management platforms into the provision of grid-flexibility services;

ii. Uncertainty quantification of energy forecast in the flexibility management:
   - Empirically evaluated novel deep learning models in probabilistic energy forecasting of data generating processes assisting in the decision-making of flexibility management;

iii. Flexibility allocation problem under heterogeneous prosumer interests in its usage:
   - Formulated and quantitative evaluated decentralized cooperative flexibility scheduling of a local energy system under individual techno-socio-economic trade-offs of prosumer flexibility allocation.

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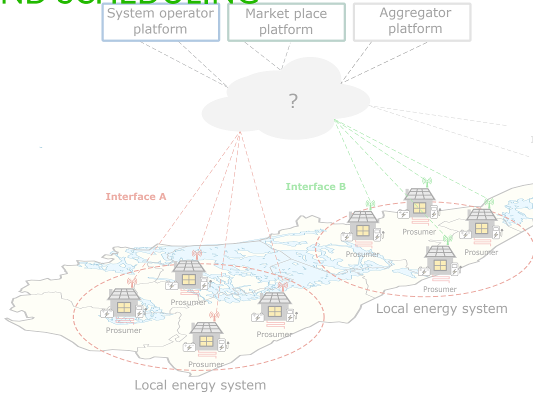


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# BACK-UP SLIDES

# PUBLICATIONS

**Publication I** Mashlakov, A., Tikka, V., Honkapuro, S., Partanen, J., Repo, S., Kulmala, A., Abdurafikov, R., Keski-Koukkari, A., Aro, M., and Järventausta, P. (2018). Use case description of real-time control of microgrid flexibility. In: *Proceedings of 15$^{th}$ International Conference on the European Energy Market (EEM)*, pp. 1–5, Lodz: IEEE.

**Publication II** Mashlakov, A., Keski-Koukkari, A., Tikka, V., Kulmala, A., Repo, S., Honkapuro, S., Aro, M., and Jafary, P. (2019). Uniform Web of Things based access to distributed energy resources via metadata registry. In: *25$^{th}$ International Conference on Electricity Distribution (CIRED)*, pp. 1–5, Madrid: AIM.

**Publication III** Mashlakov, A., Lensu, L., Kaarna, A., Tikka, V., and Honkapuro, S. (2020). Probabilistic forecasting of battery energy storage state-of-charge under primary frequency control. *IEEE Journal on Selected Areas in Communications*, 38(1), pp. 96–109.

**Publication IV** Mashlakov, A., Kuronen, T. , Lensu, L., Kaarna, A., and Honkapuro, S. (2021). Assessing the performance of deep learning models for multivariate probabilistic energy forecasting. *Applied Energy*, 285, pp. 116405.

**Publication V** Mashlakov, A., Pournaras, E., Nardelli, P.H.J., and Honkapuro, S. (2021). Decentralized cooperative scheduling of prosumer flexibility under forecast uncertainties. *Applied Energy*, 290, pp. 116706.

# METHODOLOGY

## Model-driven architecture development

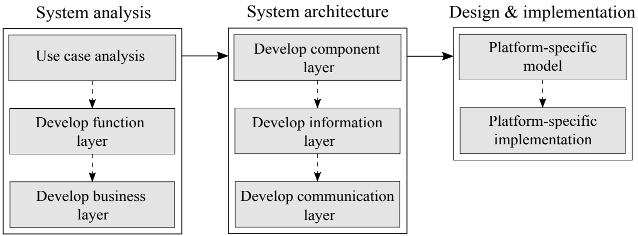



Figure: Model-driven architecture development. Adapted from [2].

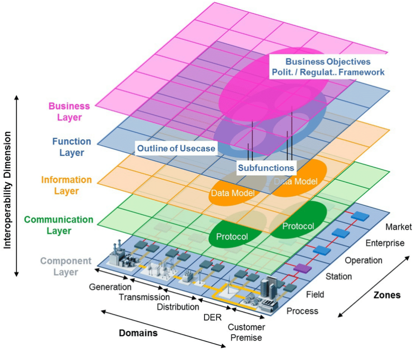
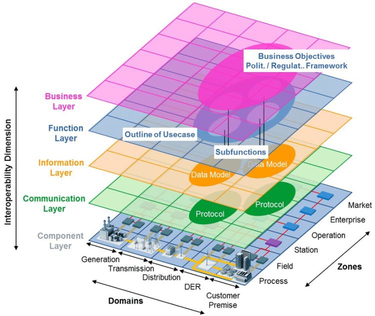
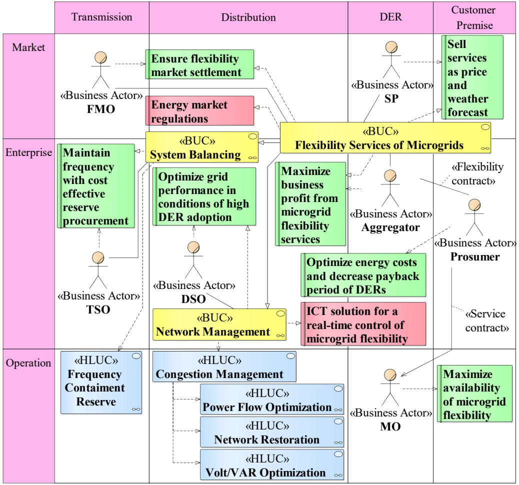



Figure: SGAM representation. Source: [1].

# FLEXIBILITY SERVICES OF MICROGRIDS

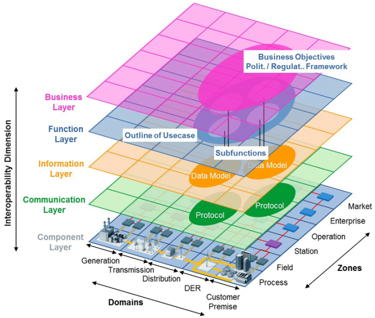
## Business use case

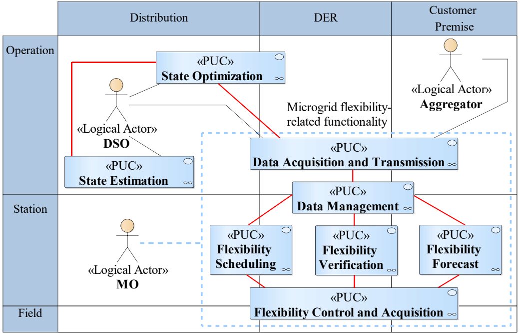


# FLEXIBILITY SERVICES OF MICROGRIDS

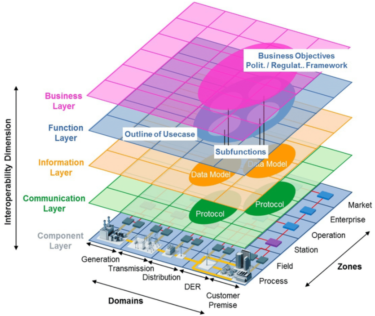
## Functional layer

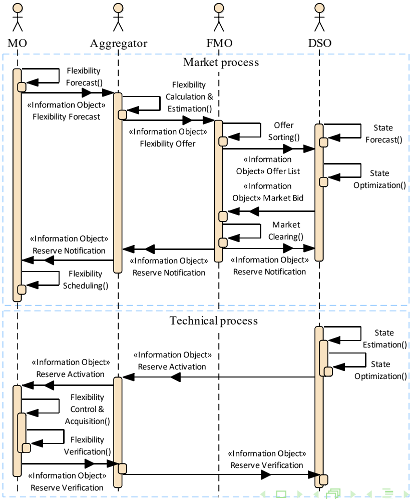


# FLEXIBILITY SERVICES OF MICROGRIDS

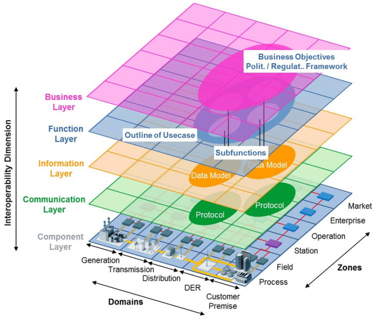
## Exchange messages

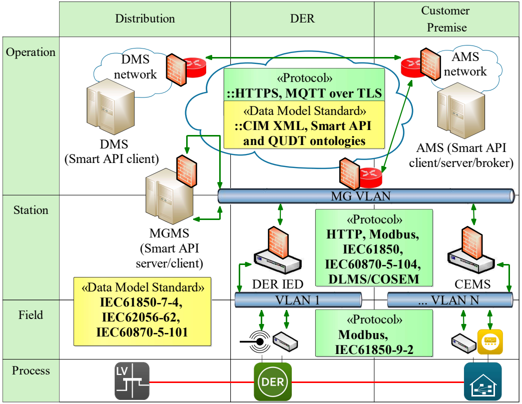


# FLEXIBILITY SERVICES OF MICROGRIDS

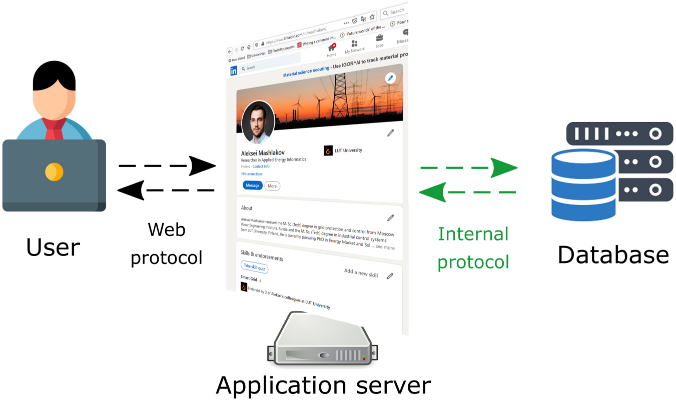
Information, communication, and component layers



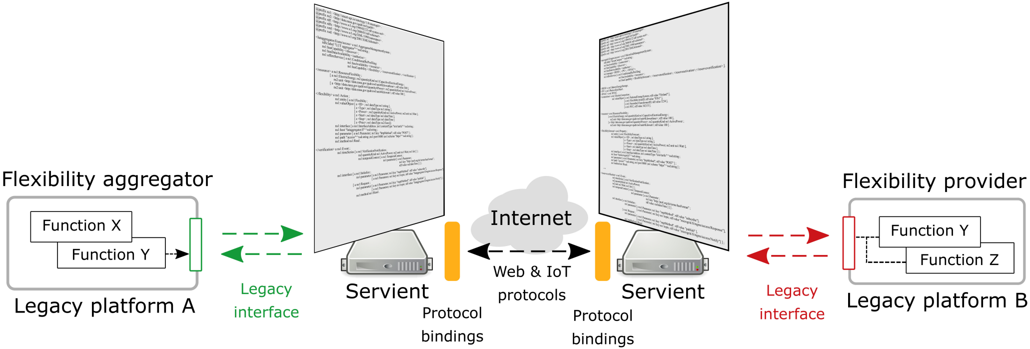
# FLEXIBILITY SERVICES OF MICROGRIDS

## Web-based information exchange



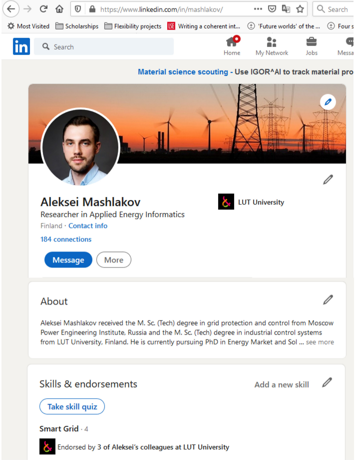
# FLEXIBILITY SERVICES OF MICROGRIDS

## Web-of-Things-based information exchange



# FROM WEB OF PAGES TO WEB OF THINGS

## Semantic metadata

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@prefix ns1: <http://smart-api.io/ontology/1.0/smartapi#> .
@prefix ns2: <http://data.nasa.gov/qudt/owl/qudt#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<microgrid.fi/mgms/access> a ns1:MicroGridManagementSystem ;
      rdfs:label "GreenCampus"^^xsd:string ;
      ns1:hasAvailability </connection> ;
      ns1:hasCapability </discover> ;
      ns1:hasDataAvailability </authorize> ;
      ns1:manages </BESS>, </PV>, </HVAC>;
      ns1:offersService [ a ns1:ConditionalReProfiling;
                              ns1:hasAvailability </resource> ;
                              ns1:hasCapability </flexibilityforecast>, </reservenotification>, </reserveactivation>,</reserveverification> ].

</BESS> a ns1:BatteryEnergyStorage .
</PV> a ns1:PhotovoltaicPanel .
</HVAC> a ns1:HVAC.
</connection> a ns1:ElectricConnection ;
                  ns1:valueObject [ a ns1:NationalEnergySystem; rdf:value "Finland" ],
                                  [ a ns1:FlexibilityAreaID; rdf:value "FIN1" ],
                                  [ a ns1:SecondaryTransformerID; rdf:value 3234 ],
                                  [ a ns1:PCC; rdf:value 342133 ].

</resource> a ns1:ResourceFlexibility ;
            [ a ns1:ElectricEnergy; ns2:quantityKind ns1:CapacitiveElectricalEnergy ;
              ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatthour>; rdf:value 100 ],
            [ a <http://data.nasa.gov/qudt/owl/quantity#Power>; ns2:quantityKind ns1:ActivePower ;
              ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatt>; rdf:value 100 ] .

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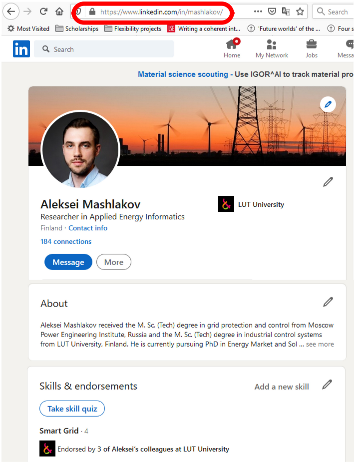
                 ns1:entity [ a ns1:FlexibilityForecast ;
                 ns1:valueObject [ a <ID> ; ns1:dataType ns1:string ],
                                 [ a <Type>; ns1:dataType ns1:string ],
                                 [ a <Power> ; ns2:quantityKind ns1:ActivePower; ns2:unit ns1:Watt ],
                                 [ a <Start>; ns1:dataType ns1:dateTime ],
                                 [ a <Stop> ; ns1:dataType ns1:dateTime ] ] ;
                 ns1:interface [ a ns1:InterfaceAddress ;ns1:contentType "text/turtle"^^xsd:string ;
                 ns1:host “lutmicrogrid.fi"^^xsd:string ;
                 ns1:parameter [ a ns1:Parameter; ns1:key "httpMethod"; rdf:value "POST" ] ;
                 ns1:path "/access"^^xsd:string ;ns1:port 8080 ;ns1:scheme "https"^^xsd:string ] ;
                 ns1:method ns1:Read .

    …

</reserveverification> a ns1:Event ;
                  ns1:timeSeries [ a ns1:VerificationNotification ;
                  ns2:quantityKind ns1:ActivePower;
                  ns2:unit ns1:Watt; ns1:list [ ] ;
                  ns1:temporalContext [ a ns1:TemporalContext ;
                                  ns1:parameter [ a ns1:Parameter ;
                                                  ns1:key "http://purl.org/dc/terms/hasFormat" ;
                                                  rdf:value xsd:dateTime ] ] ] .
                  ns1:interface [ a ns1:Initialize ;
                            ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "subscribe"],
                                          [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Response"],
                          [ a ns1:Request ;
                            ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "publish" ],
                                          [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Notify"] ] ;
                            ns1:method ns1:Read .
```

# FROM WEB OF PAGES TO WEB OF THINGS

## Semantic metadata




```
@prefix ns1: <http://smart-api.io/ontology/1.0/smartapi#> .
@prefix ns2: <http://data.nasa.gov/qudt/owl/qudt#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<microgrid.fi/mgms/access> a ns1:MicroGridManagementSystem ;
    rdfs:label "GreenCampus"^^xsd:string ;
    ns1:hasAvailability </connection> ;
    ns1:hasCapability </discover> ;
    ns1:hasDataAvailability </authorize> ;
    ns1:manages </BESS>, </PV>, </HVAC>;
    ns1:offersService [ a ns1:ConditionalReProfiling;
                        ns1:hasAvailability </resource> ;
                        ns1:hasCapability </flexibilityforecast>, </reservenotification>, </reserveactivation>,</reserveverification> ].

</BESS> a ns1:BatteryEnergyStorage .
</PV> a ns1:PhotovoltaicPanel .
</HVAC> a ns1:HVAC.
</connection> a ns1:ElectricConnection ;
            ns1:valueObject [ a ns1:NationalEnergySystem; rdf:value "Finland" ],
                            [ a ns1:FlexibilityAreaID; rdf:value "FIN1" ],
                            [ a ns1:SecondaryTransformerID; rdf:value 3234 ],
                            [ a ns1:PCC; rdf:value 342133 ].

</resource> a ns1:ResourceFlexibility ;
        [ a ns1:ElectricEnergy; ns2:quantityKind ns1:CapacitiveElectricalEnergy ;
          ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatthour>; rdf:value 100 ],
        [ a <http://data.nasa.gov/qudt/owl/quantity#Power>; ns2:quantityKind ns1:ActivePower ;
          ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatt>; rdf:value 100 ] .

</flexibilityforecast> a ns1:Property ;
            ns1:entity [ a ns1:FlexibilityForecast ;
            ns1:valueObject [ a <ID> ; ns1:dataType ns1:string ],
                            [ a <Type>; ns1:dataType ns1:string ],
                            [ a <Power> ; ns2:quantityKind ns1:ActivePower; ns2:unit ns1:Watt ],
                            [ a <Start>; ns1:dataType ns1:dateTime ],
                            [ a <Stop> ; ns1:dataType ns1:dateTime ] ] ;
            ns1:interface [ a ns1:InterfaceAddress ;ns1:contentType "text/turtle"^^xsd:string ;
            ns1:host “lutmicrogrid.fi"^^xsd:string ;
            ns1:parameter [ a ns1:Parameter; ns1:key "httpMethod"; rdf:value "POST" ] ;
            ns1:path "/access"^^xsd:string ;ns1:port 8080 ;ns1:scheme "https"^^xsd:string ] ;
            ns1:method ns1:Read .

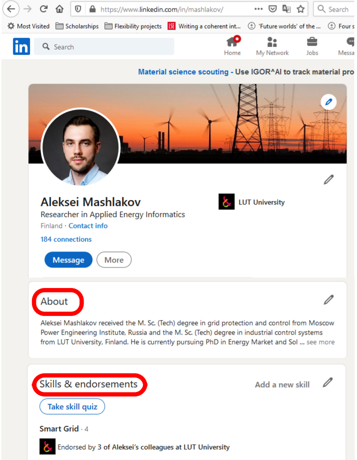
    …

</reserveverification> a ns1:Event ;
            ns1:timeSeries [ a ns1:VerificationNotification ;
            ns2:quantityKind ns1:ActivePower;
            ns2:unit ns1:Watt; ns1:list [ ] ;
            ns1:temporalContext [ a ns1:TemporalContext ;
                        ns1:parameter [ a ns1:Parameter ;
                                ns1:key "http://purl.org/dc/terms/hasFormat" ;
                                rdf:value xsd:dateTime ] ] ] .
            ns1:interface [ a ns1:Initialize ;
                    ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "subscribe"],
                                  [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Response"],
                  [ a ns1:Request ;
                    ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "publish" ],
                                  [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Notify"] ] ;
                    ns1:method ns1:Read .
```

Unique identification

# FROM WEB OF PAGES TO WEB OF THINGS

## Semantic metadata




Info & Properties

```
@prefix ns1: <http://smart-api.io/ontology/1.0/smartapi#> .
@prefix ns2: <http://data.nasa.gov/qudt/owl/qudt#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<microgrid.fi/mgms/access> a ns1:MicroGridManagementSystem ;
    rdfs:label "GreenCampus"^^xsd:string ;
    ns1:hasAvailability </connection> ;
    ns1:hasCapability </discover> ;
    ns1:hasDataAvailability </authorize> ;
    ns1:manages </BESS>, </PV>, </HVAC>;
    ns1:offersService [ a ns1:ConditionalReProfiling;
                        ns1:hasAvailability </resource> ;
                        ns1:hasCapability </flexibilityforecast>, </reservenotification>, </reserveactivation>,</reserveverification> ].

</BESS> a ns1:BatteryEnergyStorage .
</PV> a ns1:PhotovoltaicPanel .
</HVAC> a ns1:HVAC.
</connection> a ns1:ElectricConnection ;
                ns1:valueObject [ a ns1:NationalEnergySystem; rdf:value "Finland" ],
                                [ a ns1:FlexibilityAreaID; rdf:value "FIN1" ],
                                [ a ns1:SecondaryTransformerID; rdf:value 3234 ],
                                [ a ns1:PCC; rdf:value 342133 ].

</resource> a ns1:ResourceFlexibility ;
            [ a ns1:ElectricEnergy; ns2:quantityKind ns1:CapacitiveElectricalEnergy ;
              ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatthour>; rdf:value 100 ],
            [ a <http://data.nasa.gov/qudt/owl/quantity#Power>; ns2:quantityKind ns1:ActivePower ;
              ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatt>; rdf:value 100 ] .

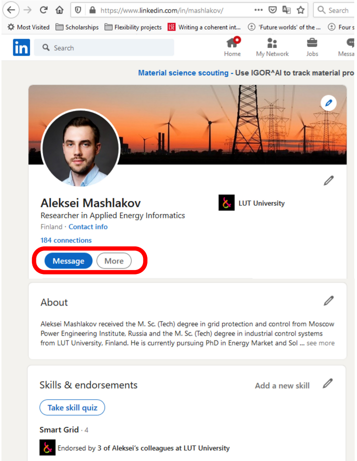
</flexibilityforecast> a ns1:Property ;
            ns1:entity [ a ns1:FlexibilityForecast ;
            ns1:valueObject [ a <ID> ; ns1:dataType ns1:string ],
                            [ a <Type>; ns1:dataType ns1:string ],
                            [ a <Power> ; ns2:quantityKind ns1:ActivePower; ns2:unit ns1:Watt ],
                            [ a <Start>; ns1:dataType ns1:dateTime ],
                            [ a <Stop> ; ns1:dataType ns1:dateTime ] ] ;
            ns1:interface [ a ns1:InterfaceAddress ;ns1:contentType "text/turtle"^^xsd:string ;
            ns1:host “lutmicrogrid.fi"^^xsd:string ;
            ns1:parameter [ a ns1:Parameter; ns1:key "httpMethod"; rdf:value "POST" ] ;
            ns1:path "/access"^^xsd:string ;ns1:port 8080 ;ns1:scheme "https"^^xsd:string ] ;
            ns1:method ns1:Read .

    ...

</reserveverification> a ns1:Event ;
            ns1:timeSeries [ a ns1:VerificationNotification ;
            ns2:quantityKind ns1:ActivePower;
            ns2:unit ns1:Watt; ns1:list [ ] ;
            ns1:temporalContext [ a ns1:TemporalContext ;
                                  ns1:parameter [ a ns1:Parameter ;
                                                  ns1:key "http://purl.org/dc/terms/hasFormat" ;
                                                  rdf:value xsd:dateTime ] ] ] .
            ns1:interface [ a ns1:Initialize ;
                            ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "subscribe"],
                                          [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Response"],
                          [ a ns1:Request ;
                            ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "publish" ],
                                          [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Notify"] ] ;
                            ns1:method ns1:Read .
```

# FROM WEB OF PAGES TO WEB OF THINGS

## Semantic metadata




```
@prefix ns1: <http://smart-api.io/ontology/1.0/smartapi#> .
@prefix ns2: <http://data.nasa.gov/qudt/owl/qudt#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<microgrid.fi/mgms/access> a ns1:MicroGridManagementSystem ;
    rdfs:label "GreenCampus"^^xsd:string ;
    ns1:hasAvailability </connection> ;
    ns1:hasCapability </discover> ;
    ns1:hasDataAvailability </authorize> ;
    ns1:manages </BESS>, </PV>, </HVAC>;
    ns1:offersService [ a ns1:ConditionalReProfiling;
                        ns1:hasAvailability </resource> ;
                        ns1:hasCapability </flexibilityforecast>, </reservenotification>, </reserveactivation>,</reserveverification> ].

</BESS> a ns1:BatteryEnergyStorage .
</PV> a ns1:PhotovoltaicPanel .
</HVAC> a ns1:HVAC.
</connection> a ns1:ElectricConnection ;
            ns1:valueObject [ a ns1:NationalEnergySystem; rdf:value "Finland" ],
                            [ a ns1:FlexibilityAreaID; rdf:value "FIN1" ],
                            [ a ns1:SecondaryTransformerID; rdf:value 3234 ],
                            [ a ns1:PCC; rdf:value 342133 ].

</resource> a ns1:ResourceFlexibility ;
        [ a ns1:ElectricEnergy; ns2:quantityKind ns1:CapacitiveElectricalEnergy ;
          ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatthour>; rdf:value 100 ],
        [ a <http://data.nasa.gov/qudt/owl/quantity#Power>; ns2:quantityKind ns1:ActivePower ;
          ns2:unit <http://data.nasa.gov/qudt/owl/unit#Kilowatt>; rdf:value 100 ] .

</flexibilityforecast> a ns1:Property ;
          ns1:entity [ a ns1:FlexibilityForecast ;
          ns1:valueObject [ a <ID> ; ns1:dataType ns1:string ],
                          [ a <Type>; ns1:dataType ns1:string ],
                          [ a <Power> ; ns2:quantityKind ns1:ActivePower; ns2:unit ns1:Watt ],
                          [ a <Start>; ns1:dataType ns1:dateTime ],
          ns1:interface [ a ns1:InterfaceAddress ;ns1:contentType "text/turtle"^^xsd:string ;
          ns1:host "lutmicrogrid.fi"^^xsd:string ;
          ns1:parameter [ a ns1:Parameter; ns1:key "httpMethod"; rdf:value "POST" ] ;
          ns1:path "/access"^^xsd:string ;ns1:port 8080 ;ns1:scheme "https"^^xsd:string ] ;

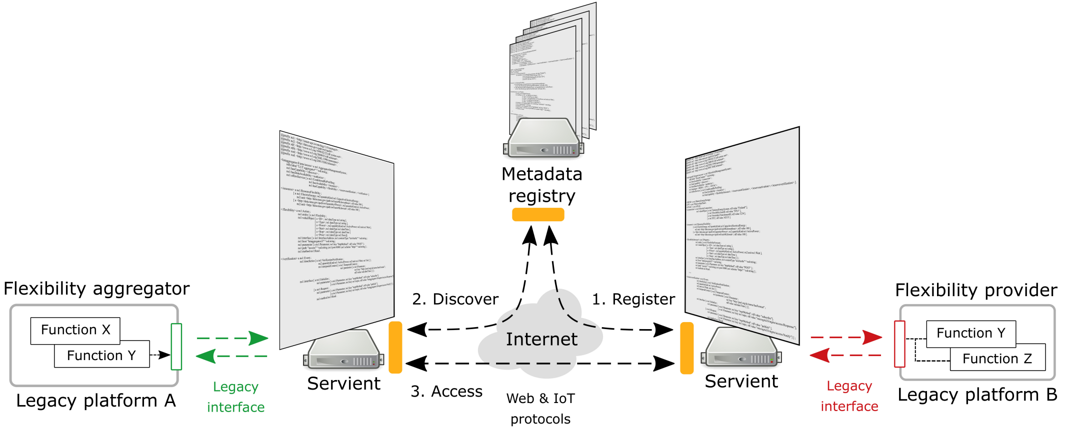
    ...

</reserveverification> a ns1:Event ;
            ns1:timeSeries [ a ns1:VerificationNotification ;
            ns2:quantityKind ns1:ActivePower;
            ns2:unit ns1:Watt; ns1:list [ ] ;
            ns1:temporalContext [ a ns1:TemporalContext ;
                                  ns1:parameter [ a ns1:Parameter ;
                                                  ns1:key "http://purl.org/dc/terms/hasFormat" ;
                                                  rdf:value xsd:dateTime ] ] ] .
            ns1:interface [ a ns1:Initialize ;
                    ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "subscribe"],
                                  [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Response"],
                  [ a ns1:Request ;
                    ns1:parameter [ a ns1:Parameter; ns1:key "mqttMethod"; rdf:value "publish" ],
                                  [ a ns1:Parameter; ns1:key ns1:topic; rdf:value "microgrid.fi/mgms/access/Notify"] ] ;
                    ns1:method ns1:Read .
```

Access interfaces

# FLEXIBILITY SERVICES OF MICROGRIDS

## Web-of-Things-based metadata registry



# FLEXIBILITY SERVICES OF MICROGRIDS

## Web-of-Things-based metadata registry

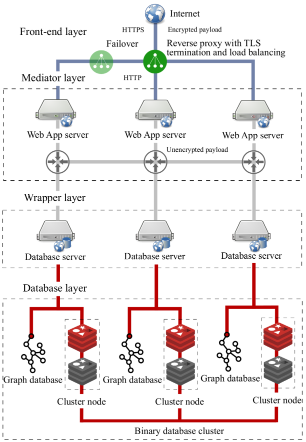



Figure: Flexibility registry architecture.

- Nonfunctional design principles:
  - multiple flexibility areas
  - system-wide and location-specific flexibility services
- Functional design principles:
  - security, scalability, and availability even at times of high loads

## Methodology

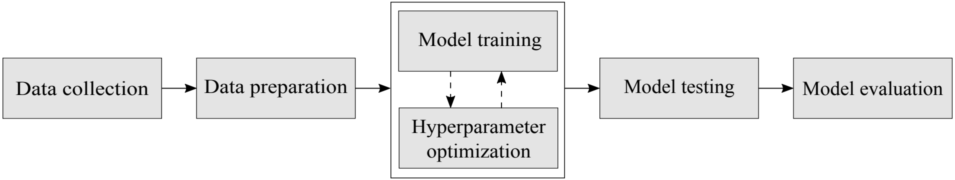



Figure: Research methodology for the performance estimation of probabilistic energy time series forecasting.

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Methodology

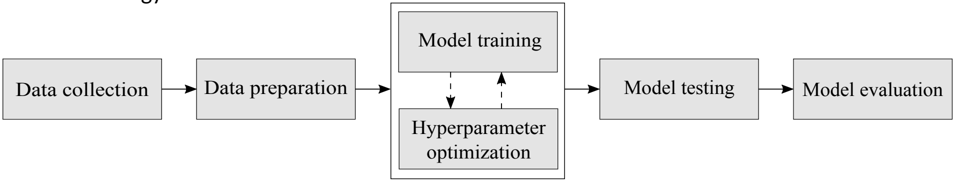



Figure: Research methodology for the performance estimation of probabilistic energy time series forecasting.

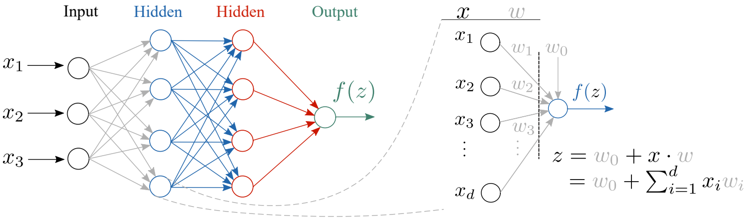



Figure: Deep learning model as a multi-layer artificial neural network.

# DEEP LEARNING

## Neural network training

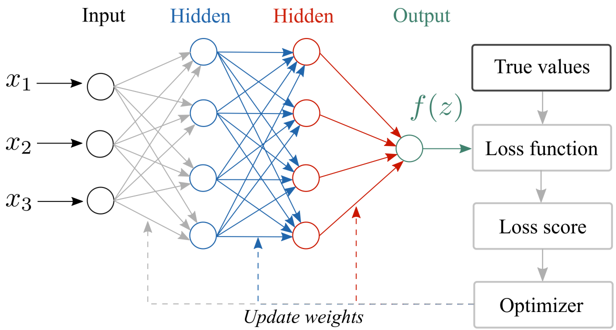



Figure: Neural network training for point forecasting.

# DEEP LEARNING

LUT University

## Neural network training

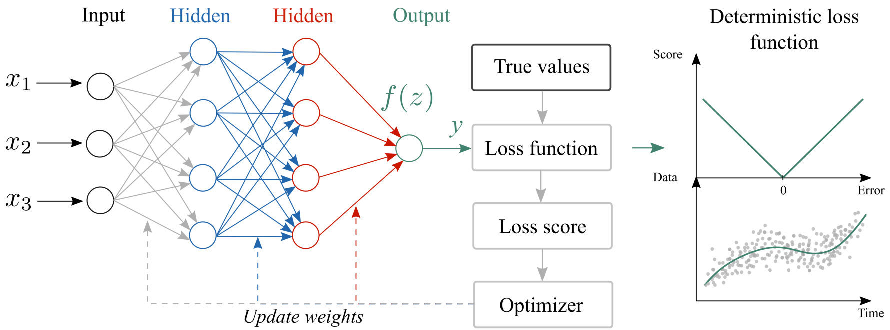



Figure: Neural network training for point forecasting.

## Predictive uncertainty methods – Quality-driven loss functions

1. Multi-quantile regression

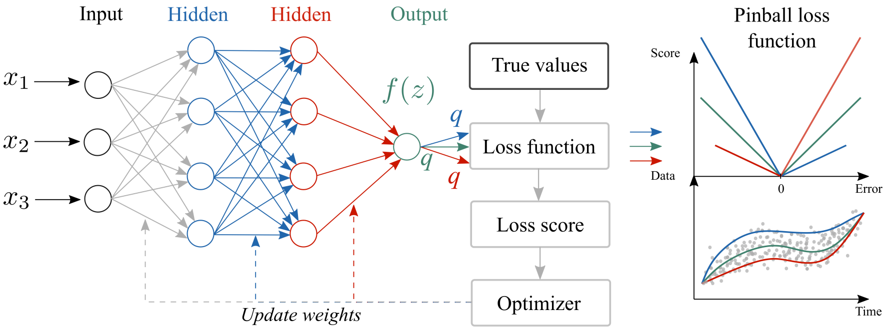



Figure: Neural network training with pinball loss function.

# DEEP LEARNING

## Predictive uncertainty methods – Quality-driven loss functions

2. Regularized maximum likelihood estimation

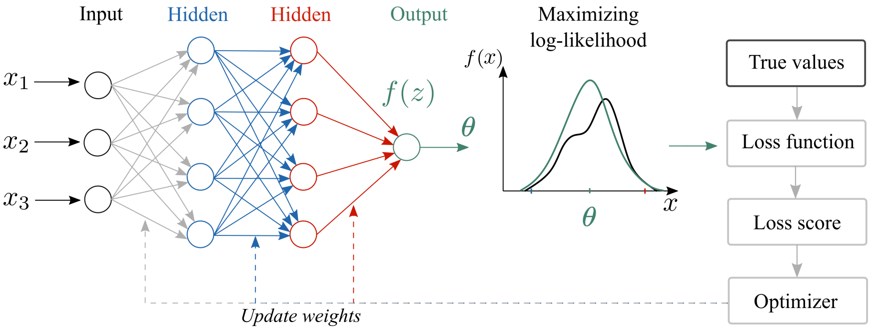



Figure: Neural network training with regularized maximum likelihood estimation.

# DEEP LEARNING

## Predictive uncertainty methods – Quality-driven loss functions

2. Regularized maximum likelihood estimation (cont'd)

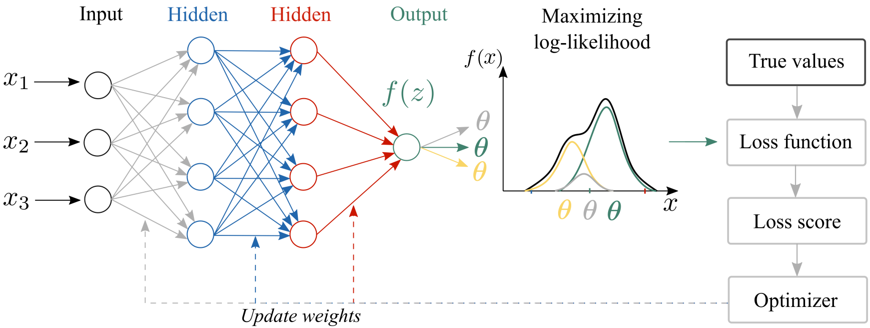



Figure: Neural network training with Mixture density networks.

## Predictive uncertainty methods – Bayesian approximation

3. Monte Carlo dropout

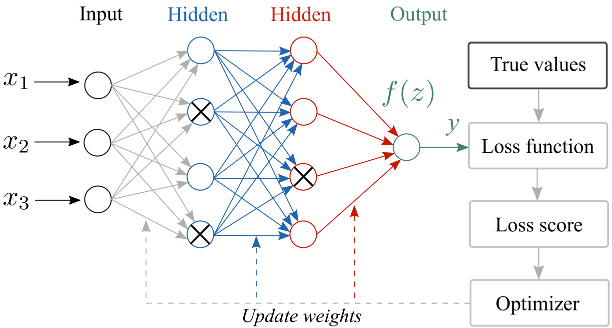



Figure: Neural network training with Monte Carlo dropout.

# DEEP LEARNING

## Predictive uncertainty methods – Bayesian approximation

3. Monte Carlo dropout

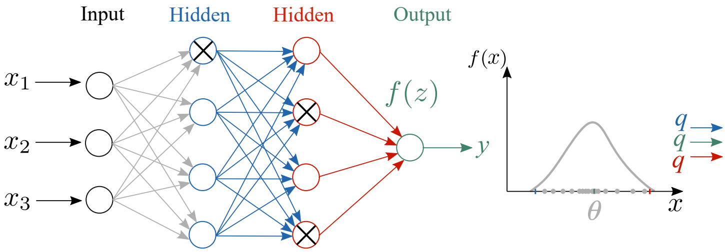
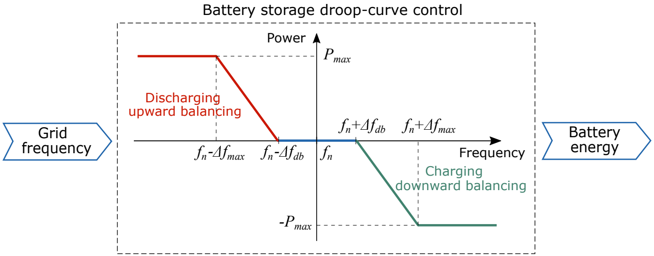



Figure: Random sampling of neural network predictions with Monte Carlo dropout.

## Case A – Univariate battery storage energy activation

### System balancing service




| Parameter | PFC | EFR-Wide | FCR-N |
|---|---|---|---|
| Full activation frequency deviation | ±200 mHz | ±500 mHz | ±100 mHz |
| Deadband | ±10 mHz | ±50 mHz | ±50 mHz |

### Synchronous areas

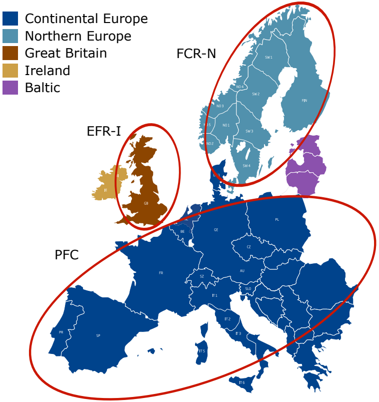



Figure: Characteristics of data generating process.

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case A – Univariate battery storage energy activation – Findings

*(a) EFR–I dataset*

| $\mathbb{E}$, | LQR | | | QRF | | | QGB | | | QRNN | | | Variational MARNN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.024 | 0.021 | 0.049 | -0.019 | 0.022 | 0.049 | -0.029 | 0.019 | 0.045 | -0.076 | 0.006 | 0.019 | 0.027 | 0.033 | 0.033 |
| 20 | -0.054 | 0.042 | 0.115 | -0.033 | 0.045 | 0.108 | -0.055 | 0.039 | 0.106 | -0.040 | 0.043 | 0.108 | 0.051 | 0.068 | 0.068 |
| 30 | -0.072 | 0.065 | 0.200 | -0.040 | 0.070 | 0.174 | -0.076 | 0.060 | 0.189 | -0.108 | 0.052 | 0.206 | 0.072 | 0.104 | 0.104 |
| 40 | -0.097 | 0.090 | 0.327 | -0.050 | 0.096 | 0.255 | -0.092 | 0.083 | 0.292 | -0.099 | 0.082 | 0.304 | 0.082 | 0.141 | 0.141 |
| 50 | -0.113 | 0.118 | 0.484 | -0.060 | 0.126 | 0.357 | -0.111 | 0.109 | 0.437 | -0.188 | 0.085 | 0.642 | 0.090 | 0.181 | 0.181 |
| 60 | -0.122 | 0.150 | 0.658 | -0.065 | 0.161 | 0.468 | -0.123 | 0.138 | 0.612 | -0.158 | 0.127 | 0.744 | 0.092 | 0.226 | 0.226 |
| 70 | -0.122 | 0.188 | 0.821 | -0.060 | 0.203 | 0.574 | -0.127 | 0.173 | 0.791 | -0.146 | 0.168 | 0.894 | 0.079 | 0.279 | 0.279 |
| 80 | -0.116 | 0.238 | 1.000 | -0.053 | 0.258 | 0.699 | -0.114 | 0.222 | 0.916 | -0.170 | 0.198 | 1.284 | 0.062 | 0.344 | 0.344 |
| 90 | -0.088 | 0.320 | 1.084 | -0.043 | 0.345 | 0.878 | -0.091 | 0.296 | 1.033 | -0.090 | 0.298 | 1.033 | 0.034 | 0.442 | 0.442 |
| 95 | -0.062 | 0.397 | 1.137 | -0.033 | 0.423 | 1.012 | -0.065 | 0.365 | 1.068 | -0.075 | 0.356 | 1.109 | 0.016 | 0.527 | 0.527 |

*(b) PFC dataset*

| $\mathbb{E}$, | LQR | | | QRF | | | QGB | | | QRNN | | | Variational MARNN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.001 | 0.018 | 0.036 | 0.010 | 0.020 | 0.020 | 0.001 | 0.018 | 0.018 | -0.065 | 0.007 | 0.021 | 0.036 | 0.024 | 0.024 |
| 20 | 0.003 | 0.037 | 0.037 | 0.016 | 0.040 | 0.040 | -0.005 | 0.035 | 0.073 | -0.073 | 0.023 | 0.070 | 0.062 | 0.048 | 0.048 |
| 30 | 0.005 | 0.056 | 0.056 | 0.026 | 0.060 | 0.060 | -0.006 | 0.053 | 0.110 | 0.027 | 0.061 | 0.061 | 0.076 | 0.073 | 0.073 |
| 40 | 0.003 | 0.078 | 0.078 | 0.024 | 0.083 | 0.083 | -0.010 | 0.073 | 0.154 | -0.048 | 0.069 | 0.181 | 0.090 | 0.099 | 0.099 |
| 50 | 0.003 | 0.101 | 0.101 | 0.031 | 0.108 | 0.108 | -0.010 | 0.095 | 0.199 | -0.062 | 0.085 | 0.244 | 0.094 | 0.127 | 0.127 |
| 60 | 0.006 | 0.129 | 0.129 | 0.035 | 0.138 | 0.138 | -0.019 | 0.119 | 0.263 | 0.008 | 0.130 | 0.130 | 0.087 | 0.158 | 0.158 |
| 70 | 0.005 | 0.164 | 0.164 | 0.035 | 0.175 | 0.175 | -0.015 | 0.151 | 0.325 | 0.001 | 0.163 | 0.163 | 0.074 | 0.195 | 0.195 |
| 80 | 0.005 | 0.213 | 0.213 | 0.032 | 0.225 | 0.225 | -0.023 | 0.191 | 0.432 | 0.010 | 0.218 | 0.218 | 0.045 | 0.241 | 0.241 |
| 90 | 0.008 | 0.297 | 0.297 | 0.019 | 0.307 | 0.307 | -0.014 | 0.259 | 0.558 | 0.006 | 0.291 | 0.291 | 0.013 | 0.309 | 0.309 |
| 95 | 0.005 | 0.377 | 0.377 | 0.011 | 0.387 | 0.387 | -0.009 | 0.332 | 0.693 | 0.015 | 0.408 | 0.408 | -0.002 | 0.369 | 0.745 |

*(c) FCR–N dataset*

| $\mathbb{E}$, | LQR | | | QRF | | | QGB | | | QRNN | | | Variational MARNN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.006 | 0.011 | 0.022 | 0.009 | 0.011 | 0.011 | 0.006 | 0.010 | 0.010 | -0.041 | 0.006 | 0.015 | 0.012 | 0.017 | 0.017 |
| 20 | -0.011 | 0.022 | 0.047 | 0.020 | 0.024 | 0.024 | 0.008 | 0.021 | 0.021 | 0.032 | 0.025 | 0.025 | 0.017 | 0.034 | 0.034 |
| 30 | -0.015 | 0.037 | 0.079 | 0.034 | 0.039 | 0.039 | 0.012 | 0.034 | 0.034 | -0.094 | 0.022 | 0.079 | 0.021 | 0.052 | 0.052 |
| 40 | -0.015 | 0.054 | 0.118 | 0.039 | 0.056 | 0.056 | 0.007 | 0.049 | 0.049 | 0.053 | 0.059 | 0.059 | 0.010 | 0.071 | 0.071 |
| 50 | -0.019 | 0.075 | 0.167 | 0.035 | 0.077 | 0.077 | 0.005 | 0.068 | 0.068 | 0.016 | 0.073 | 0.073 | -0.007 | 0.091 | 0.188 |
| 60 | -0.014 | 0.102 | 0.219 | 0.040 | 0.103 | 0.103 | 0.004 | 0.091 | 0.091 | 0.051 | 0.108 | 0.108 | -0.025 | 0.113 | 0.259 |
| 70 | -0.010 | 0.136 | 0.286 | 0.032 | 0.136 | 0.136 | 0.002 | 0.121 | 0.121 | 0.015 | 0.129 | 0.129 | -0.046 | 0.139 | 0.359 |
| 80 | -0.011 | 0.183 | 0.386 | 0.027 | 0.181 | 0.181 | -0.001 | 0.163 | 0.328 | -0.025 | 0.157 | 0.358 | -0.077 | 0.172 | 0.544 |
| 90 | -0.001 | 0.262 | 0.527 | 0.012 | 0.252 | 0.252 | -0.004 | 0.231 | 0.472 | -0.011 | 0.227 | 0.480 | -0.087 | 0.221 | 0.750 |
| 95 | -0.000 | 0.340 | 0.340 | 0.003 | 0.321 | 0.321 | -0.004 | 0.296 | 0.604 | -0.020 | 0.279 | 0.619 | -0.087 | 0.263 | 0.893 |

Figure: Coverage metric of prediction interval forecasts.

- Prediction intervals with smaller coverage are easier to quantify
- Low systematic generalization of models to different regulatory environments of balancing services

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

LUT University

## Case A – Univariate battery storage energy activation – Findings

*(a) EFR–I dataset*

| $\mathbb{E}$, | LQR | | | QRF | | | QGB | | | QRNN | | | Variational MARNN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.024 | 0.021 | 0.049 | -0.019 | 0.022 | 0.049 | -0.029 | 0.019 | 0.045 | -0.076 | 0.006 | 0.019 | 0.027 | 0.033 | 0.033 |
| 20 | -0.054 | 0.042 | 0.115 | -0.033 | 0.045 | 0.108 | -0.055 | 0.039 | 0.106 | -0.040 | 0.043 | 0.108 | 0.051 | 0.068 | 0.068 |
| 30 | -0.072 | 0.065 | 0.200 | -0.040 | 0.070 | 0.174 | -0.076 | 0.060 | 0.189 | -0.108 | 0.052 | 0.206 | 0.072 | 0.104 | 0.104 |
| 40 | -0.097 | 0.090 | 0.327 | -0.050 | 0.096 | 0.255 | -0.092 | 0.083 | 0.292 | -0.099 | 0.082 | 0.304 | 0.082 | 0.141 | 0.141 |
| 50 | -0.113 | 0.118 | 0.484 | -0.060 | 0.126 | 0.357 | -0.111 | 0.109 | 0.437 | -0.188 | 0.085 | 0.642 | 0.090 | 0.181 | 0.181 |
| 60 | -0.122 | 0.150 | 0.658 | -0.065 | 0.161 | 0.468 | -0.123 | 0.138 | 0.612 | -0.158 | 0.127 | 0.744 | 0.092 | 0.226 | 0.226 |
| 70 | -0.122 | 0.188 | 0.821 | -0.060 | 0.203 | 0.574 | -0.127 | 0.173 | 0.791 | -0.146 | 0.168 | 0.894 | 0.079 | 0.279 | 0.279 |
| 80 | -0.116 | 0.238 | 1.000 | -0.053 | 0.258 | 0.699 | -0.114 | 0.222 | 0.916 | -0.170 | 0.198 | 1.284 | 0.062 | 0.344 | 0.344 |
| 90 | -0.088 | 0.320 | 1.084 | -0.043 | 0.345 | 0.878 | -0.091 | 0.296 | 1.033 | -0.090 | 0.298 | 1.033 | 0.034 | 0.442 | 0.442 |
| 95 | -0.062 | 0.397 | 1.137 | -0.033 | 0.423 | 1.012 | -0.065 | 0.365 | 1.068 | -0.075 | 0.356 | 1.109 | 0.016 | 0.527 | 0.527 |

*(b) PFC dataset*

| $\mathbb{E}$, | LQR | | | QRF | | | QGB | | | QRNN | | | Variational MARNN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.001 | 0.018 | 0.036 | 0.010 | 0.020 | 0.020 | 0.001 | 0.018 | 0.018 | -0.065 | 0.007 | 0.021 | 0.036 | 0.024 | 0.024 |
| 20 | 0.003 | 0.037 | 0.037 | 0.016 | 0.040 | 0.040 | -0.005 | 0.035 | 0.073 | -0.073 | 0.023 | 0.070 | 0.062 | 0.048 | 0.048 |
| 30 | 0.005 | 0.056 | 0.056 | 0.026 | 0.060 | 0.060 | -0.006 | 0.053 | 0.110 | 0.027 | 0.061 | 0.061 | 0.076 | 0.073 | 0.073 |
| 40 | 0.003 | 0.078 | 0.078 | 0.024 | 0.083 | 0.083 | -0.010 | 0.073 | 0.154 | -0.048 | 0.069 | 0.181 | 0.090 | 0.099 | 0.099 |
| 50 | 0.003 | 0.101 | 0.101 | 0.031 | 0.108 | 0.108 | -0.010 | 0.095 | 0.199 | -0.062 | 0.085 | 0.244 | 0.094 | 0.127 | 0.127 |
| 60 | 0.006 | 0.129 | 0.129 | 0.035 | 0.138 | 0.138 | -0.019 | 0.119 | 0.263 | 0.008 | 0.130 | 0.130 | 0.087 | 0.158 | 0.158 |
| 70 | 0.005 | 0.164 | 0.164 | 0.035 | 0.175 | 0.175 | -0.015 | 0.151 | 0.325 | 0.001 | 0.163 | 0.163 | 0.074 | 0.195 | 0.195 |
| 80 | 0.005 | 0.213 | 0.213 | 0.032 | 0.225 | 0.225 | -0.023 | 0.191 | 0.432 | 0.010 | 0.218 | 0.218 | 0.045 | 0.241 | 0.241 |
| 90 | 0.008 | 0.297 | 0.297 | 0.019 | 0.307 | 0.307 | -0.014 | 0.259 | 0.558 | 0.006 | 0.291 | 0.291 | 0.013 | 0.309 | 0.309 |
| 95 | 0.005 | 0.377 | 0.377 | 0.011 | 0.387 | 0.387 | -0.009 | 0.332 | 0.693 | 0.015 | 0.408 | 0.408 | -0.002 | 0.369 | 0.745 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.006 | 0.011 | 0.022 | 0.009 | 0.011 | 0.011 | 0.006 | 0.010 | 0.010 | -0.041 | 0.006 | 0.015 | 0.012 | 0.017 | 0.017 |
| 20 | -0.011 | 0.022 | 0.047 | 0.020 | 0.024 | 0.024 | 0.008 | 0.021 | 0.021 | 0.032 | 0.025 | 0.025 | 0.017 | 0.034 | 0.034 |
| 30 | -0.015 | 0.037 | 0.079 | 0.034 | 0.039 | 0.039 | 0.012 | 0.034 | 0.034 | -0.094 | 0.022 | 0.079 | 0.021 | 0.052 | 0.052 |
| 40 | -0.015 | 0.054 | 0.118 | 0.039 | 0.056 | 0.056 | 0.007 | 0.049 | 0.049 | 0.053 | 0.059 | 0.059 | 0.010 | 0.071 | 0.071 |
| 50 | -0.019 | 0.075 | 0.167 | 0.035 | 0.077 | 0.077 | 0.005 | 0.068 | 0.068 | 0.016 | 0.073 | 0.073 | -0.007 | 0.091 | 0.188 |
| 60 | -0.014 | 0.102 | 0.219 | 0.040 | 0.103 | 0.103 | 0.004 | 0.091 | 0.091 | 0.051 | 0.108 | 0.108 | -0.025 | 0.113 | 0.259 |
| 70 | -0.010 | 0.136 | 0.286 | 0.032 | 0.136 | 0.136 | 0.002 | 0.121 | 0.121 | 0.015 | 0.129 | 0.129 | -0.046 | 0.139 | 0.359 |
| 80 | -0.011 | 0.183 | 0.386 | 0.027 | 0.181 | 0.181 | -0.001 | 0.163 | 0.328 | -0.025 | 0.157 | 0.358 | -0.077 | 0.172 | 0.544 |
| 90 | -0.001 | 0.262 | 0.527 | 0.012 | 0.252 | 0.252 | -0.004 | 0.231 | 0.472 | -0.011 | 0.227 | 0.480 | -0.087 | 0.221 | 0.750 |
| 95 | -0.000 | 0.340 | 0.340 | 0.003 | 0.321 | 0.321 | -0.004 | 0.296 | 0.604 | -0.020 | 0.279 | 0.619 | -0.087 | 0.263 | 0.893 |

Figure: Coverage metric of prediction interval forecasts.

- Prediction intervals with smaller coverage are easier to quantify
- Low systematic generalization of models to different regulatory environments of balancing services

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

LUT University

## Case A – Univariate battery storage energy activation – Findings

*(a) EFR–I dataset*

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.024 | 0.021 | 0.049 | -0.019 | 0.022 | 0.049 | -0.029 | 0.019 | 0.045 | -0.076 | 0.006 | 0.019 | 0.027 | 0.033 | 0.033 |
| 20 | -0.054 | 0.042 | 0.115 | -0.033 | 0.045 | 0.108 | -0.055 | 0.039 | 0.106 | -0.040 | 0.043 | 0.103 | 0.051 | 0.068 | 0.068 |
| 30 | -0.072 | 0.065 | 0.200 | -0.040 | 0.070 | 0.174 | -0.076 | 0.060 | 0.189 | -0.108 | 0.052 | 0.206 | 0.072 | 0.104 | 0.104 |
| 40 | -0.097 | 0.090 | 0.327 | -0.050 | 0.096 | 0.255 | -0.092 | 0.083 | 0.292 | -0.099 | 0.082 | 0.304 | 0.082 | 0.141 | 0.141 |
| 50 | -0.113 | 0.118 | 0.484 | -0.060 | 0.126 | 0.357 | -0.111 | 0.109 | 0.437 | -0.188 | 0.085 | 0.642 | 0.090 | 0.181 | 0.181 |
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| 70 | -0.122 | 0.188 | 0.821 | -0.060 | 0.203 | 0.574 | -0.127 | 0.173 | 0.791 | -0.146 | 0.168 | 0.894 | 0.079 | 0.279 | 0.279 |
| 80 | -0.116 | 0.238 | 1.000 | -0.053 | 0.258 | 0.699 | -0.114 | 0.222 | 0.916 | -0.170 | 0.198 | 1.284 | 0.062 | 0.344 | 0.344 |
| 90 | -0.088 | 0.320 | 1.084 | -0.043 | 0.345 | 0.878 | -0.091 | 0.296 | 1.033 | -0.090 | 0.298 | 1.033 | 0.034 | 0.442 | 0.442 |
| 95 | -0.062 | 0.397 | 1.137 | -0.033 | 0.423 | 1.012 | -0.065 | 0.365 | 1.068 | -0.075 | 0.356 | 1.109 | 0.016 | 0.527 | 0.527 |

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| [%] | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC | ACE | PINAW | CWC |
| 10 | -0.001 | 0.018 | 0.036 | 0.010 | 0.020 | 0.020 | 0.001 | 0.018 | 0.018 | -0.065 | 0.007 | 0.021 | 0.036 | 0.024 | 0.024 |
| 20 | 0.003 | 0.037 | 0.037 | 0.016 | 0.040 | 0.040 | -0.005 | 0.035 | 0.073 | -0.073 | 0.023 | 0.070 | 0.062 | 0.048 | 0.048 |
| 30 | 0.005 | 0.056 | 0.056 | 0.026 | 0.060 | 0.060 | -0.006 | 0.053 | 0.110 | 0.027 | 0.061 | 0.061 | 0.076 | 0.073 | 0.073 |
| 40 | 0.003 | 0.078 | 0.078 | 0.024 | 0.083 | 0.083 | -0.010 | 0.073 | 0.154 | -0.048 | 0.069 | 0.181 | 0.090 | 0.099 | 0.099 |
| 50 | 0.003 | 0.101 | 0.101 | 0.031 | 0.108 | 0.108 | -0.010 | 0.095 | 0.199 | -0.062 | 0.085 | 0.244 | 0.094 | 0.127 | 0.127 |
| 60 | 0.006 | 0.129 | 0.129 | 0.035 | 0.138 | 0.138 | -0.019 | 0.119 | 0.263 | 0.008 | 0.130 | 0.130 | 0.087 | 0.158 | 0.158 |
| 70 | 0.005 | 0.164 | 0.164 | 0.035 | 0.175 | 0.175 | -0.015 | 0.151 | 0.325 | 0.001 | 0.163 | 0.163 | 0.074 | 0.195 | 0.195 |
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| 10 | -0.006 | 0.011 | 0.022 | 0.009 | 0.011 | 0.011 | 0.006 | 0.010 | 0.010 | -0.041 | 0.006 | 0.015 | 0.012 | 0.017 | 0.017 |
| 20 | -0.011 | 0.022 | 0.047 | 0.020 | 0.024 | 0.024 | 0.008 | 0.021 | 0.021 | 0.032 | 0.025 | 0.025 | 0.017 | 0.034 | 0.034 |
| 30 | -0.015 | 0.037 | 0.079 | 0.034 | 0.039 | 0.039 | 0.012 | 0.034 | 0.034 | -0.094 | 0.022 | 0.079 | 0.021 | 0.052 | 0.052 |
| 40 | -0.015 | 0.054 | 0.118 | 0.039 | 0.056 | 0.056 | 0.007 | 0.049 | 0.049 | 0.053 | 0.059 | 0.059 | 0.010 | 0.071 | 0.071 |
| 50 | -0.019 | 0.075 | 0.167 | 0.035 | 0.077 | 0.077 | 0.005 | 0.068 | 0.068 | 0.016 | 0.073 | 0.073 | -0.007 | 0.091 | 0.188 |
| 60 | -0.014 | 0.102 | 0.219 | 0.040 | 0.103 | 0.103 | 0.004 | 0.091 | 0.091 | 0.051 | 0.108 | 0.108 | -0.025 | 0.113 | 0.259 |
| 70 | -0.010 | 0.136 | 0.286 | 0.032 | 0.136 | 0.136 | 0.002 | 0.121 | 0.121 | 0.015 | 0.129 | 0.129 | -0.046 | 0.139 | 0.359 |
| 80 | -0.011 | 0.183 | 0.386 | 0.027 | 0.181 | 0.181 | -0.001 | 0.163 | 0.328 | -0.025 | 0.157 | 0.358 | -0.077 | 0.172 | 0.544 |
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Figure: Coverage metric of prediction interval forecasts.

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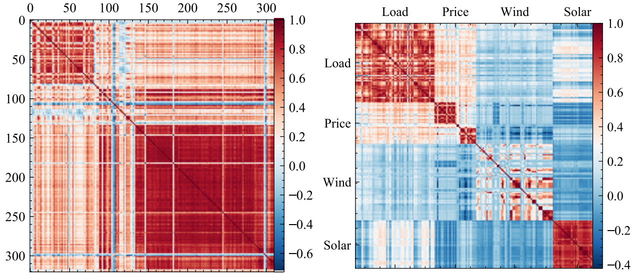
- Low systematic generalization of models to different regulatory environments of balancing services

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case B – Multivariate forecasts of high-dimensional datasets




(a) Customer electricity consumption

(b) Europe power system data

Figure: Correlation matrix of time series in the datasets.

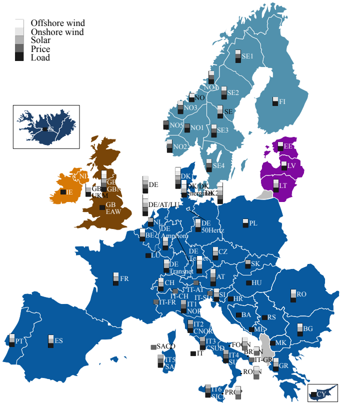
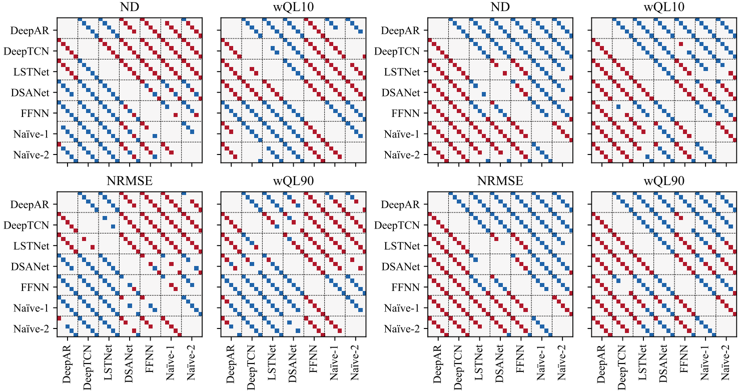



Figure: Geolocations of the variables in the power system dataset.

## Case B – Multivariate forecasts of high-dimensional datasets – Findings



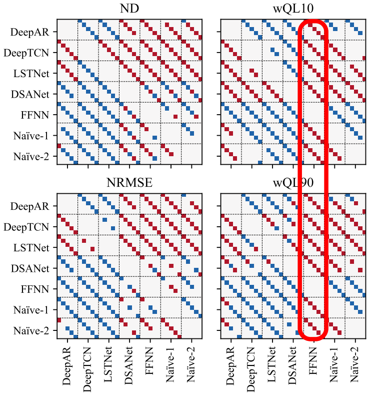

(a) Customer electricity consumption

(b) Europe power system data

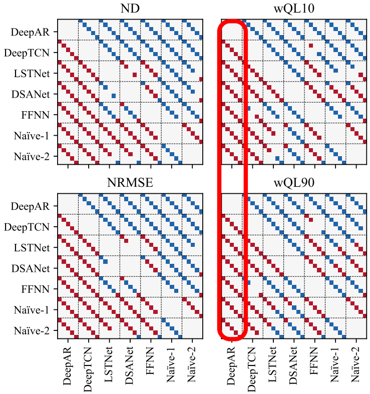
Figure: One-sided Diebold–Mariano tests at the 5% significance levels on the predictive accuracy (ND and NRMSE) and predictive uncertainty (wQL) of the 0.1 and 0.9 quantiles.

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case B – Multivariate forecasts of high-dimensional datasets – Findings




(a) Customer electricity consumption

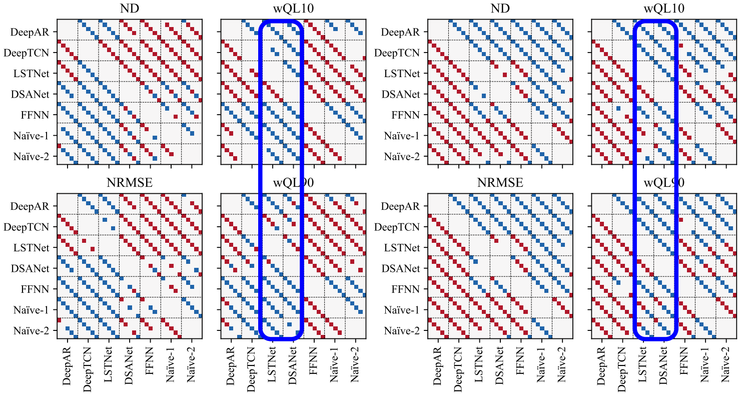



(b) Europe power system data

- Deep learning models trained with the cross-learning technique and regularized likelihood estimation show the best sharpness

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case B – Multivariate forecasts of high-dimensional datasets – Findings




(c) Customer electricity consumption (d) Europe power system data

- Deep learning models with Monte Carlo dropout poorly estimate the predictive uncertainty region

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case C – Multidistribution testing of half-hourly datasets

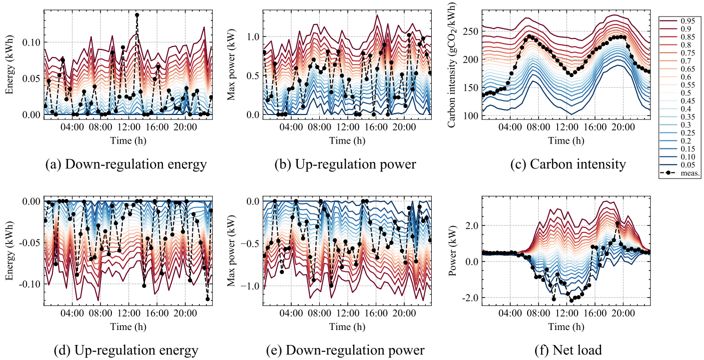



Figure: Example of the data generating processes.

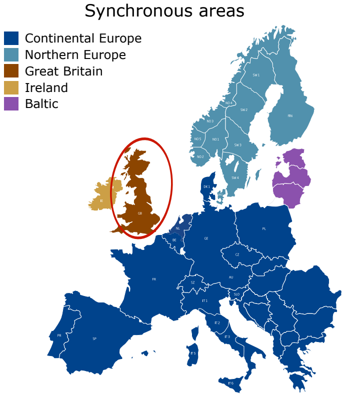



Figure: Geolocations of the data generating processes.

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case C – Multidistribution testing of half-hourly datasets – Findings

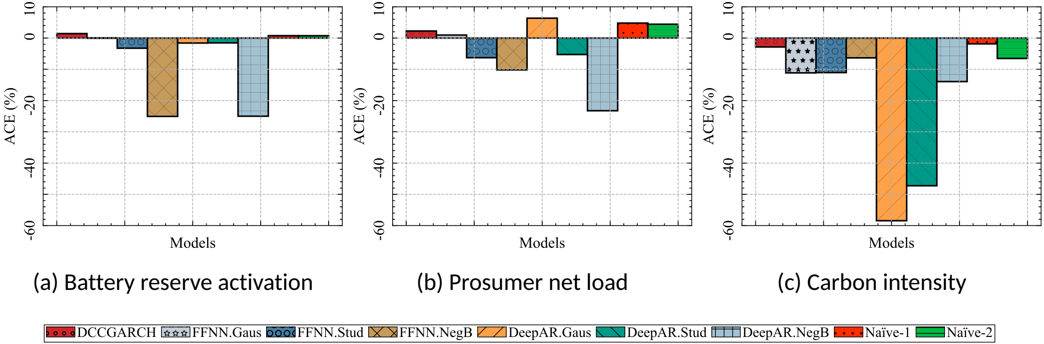



Figure: Average coverage error for 80% prediction interval of the 24 h ahead forecasts.

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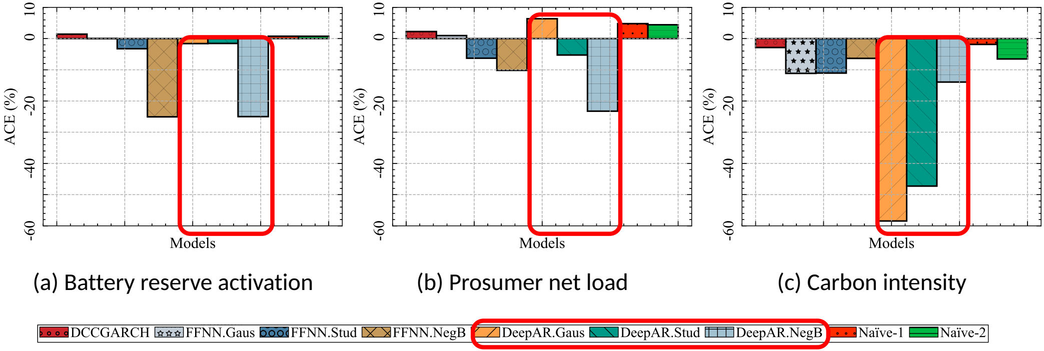
## Case C – Multidistribution testing of half-hourly datasets – Findings



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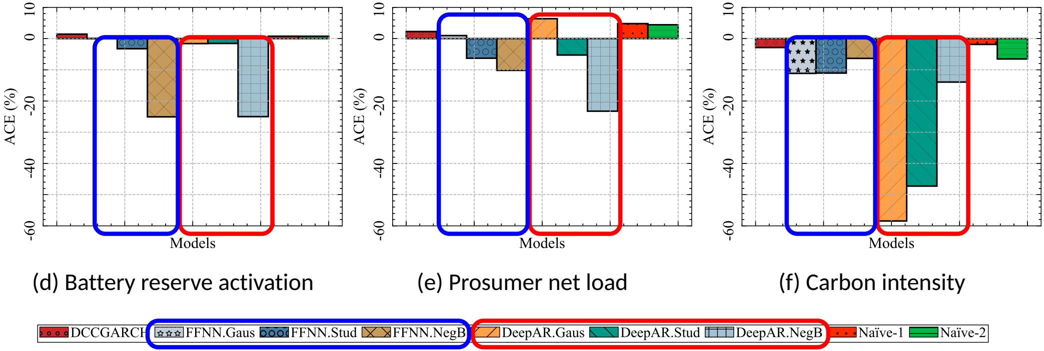
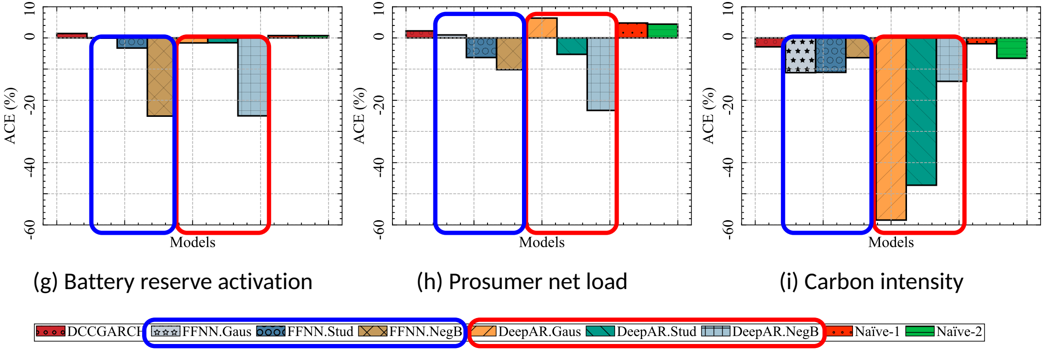



(d) Battery reserve activation (e) Prosumer net load (f) Carbon intensity

# UNCERTAINTY QUANTIFICATION IN ENERGY FORECASTING

## Case C – Multidistribution testing of half-hourly datasets – Findings




(g) Battery reserve activation (h) Prosumer net load (i) Carbon intensity

- Predictive uncertainty of deep learning models with maximum likelihood estimation highly depends on the appropriate distribution of a specific dataset

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Methodology

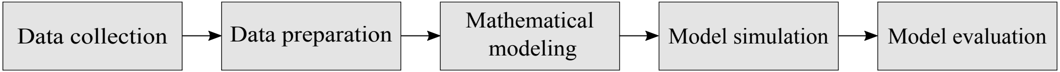



Figure: Research methodology for prosumer flexibility scheduling and coordination in a community microgrid.

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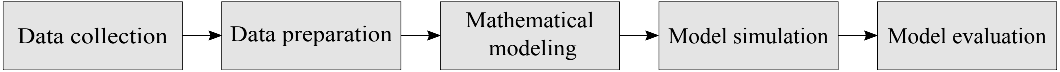


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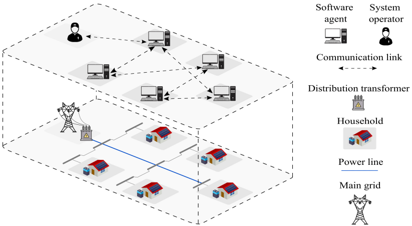



Figure: Community microgrid as a cyber-physical system.

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Methodology

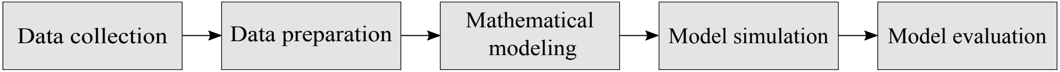



Figure: Research methodology for prosumer flexibility scheduling and coordination in a community microgrid.

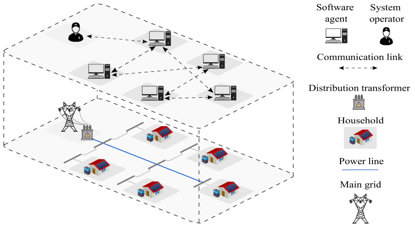



Figure: Community microgrid as a cyber-physical system.

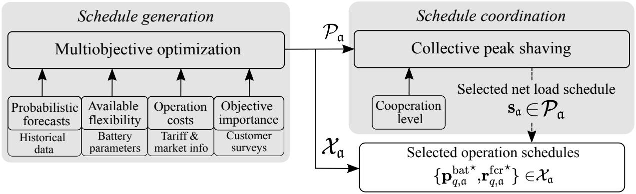
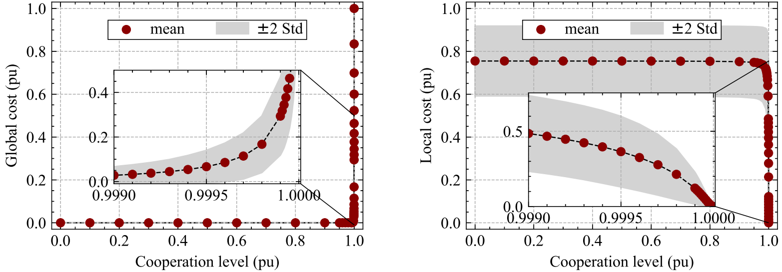



Figure: Prosumer decision-making framework.

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings

1. Socio-technical impact and optimality of varying prosumer cooperation




(a) Global cost

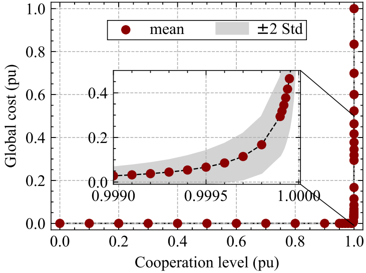
(b) Local cost

Figure: Impact of the agents' cooperation level $\lambda \in [0, 1]$.

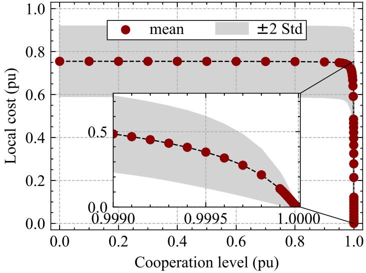
# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings

1. Socio-technical impact and optimality of varying prosumer cooperation




(a) Global cost



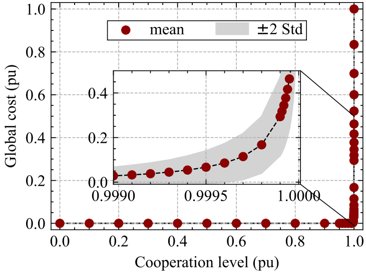

(b) Local cost

- *Noncooperative behavior* of individuals (high $\lambda$ values) *sacrifices the system-wide efficiency* of the shared power grid infrastructure

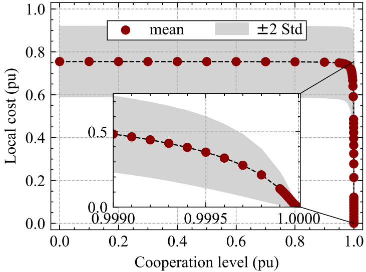
# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings

1. Socio-technical impact and optimality of varying prosumer cooperation




(a) Global cost



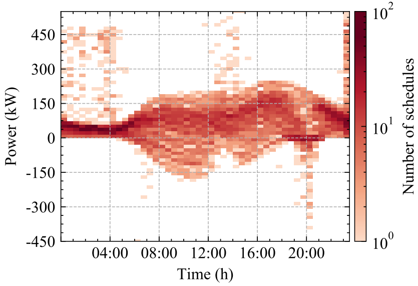

(b) Local cost

- With Pareto-optimal prosumer cooperation level:
  - peak shaving costs $\downarrow$ by 83%
  - prosumer dissatisfaction $\sim$ 28%

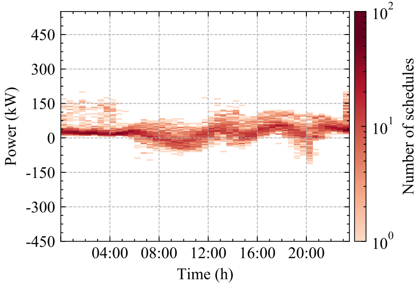
# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

1. Socio-technical impact and optimality of varying prosumer cooperation




(a) Uncoordinated scheduling



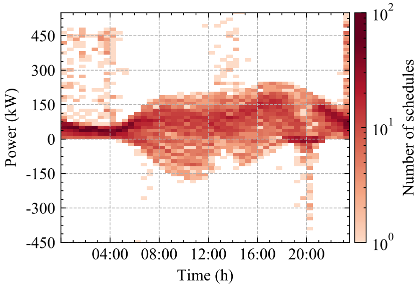

(b) Cooperative scheduling

Figure: Net load profile of the community microgrid.

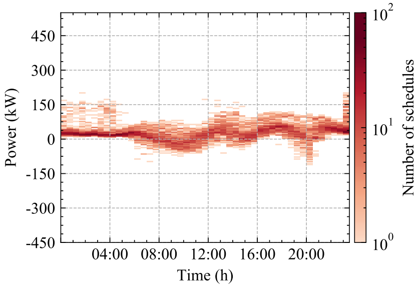
# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

1. Socio-technical impact and optimality of varying prosumer cooperation




(a) Uncoordinated scheduling



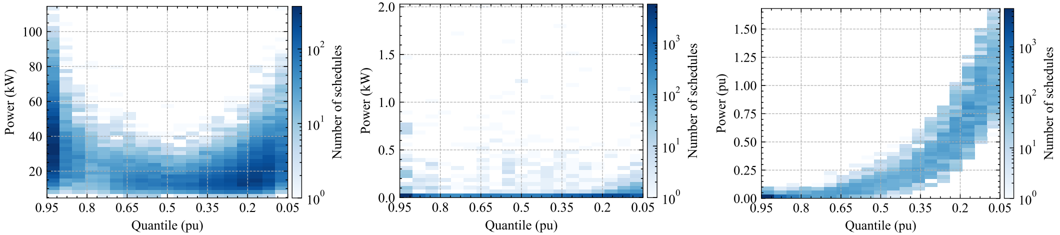

(b) Cooperative scheduling

**Finding #1** *Grid-oriented cooperative scheduling* improves the local energy system efficiency through reduced stress for the grid equipment

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

2. Effect of forecast uncertainty factors




(a) Net load imbalance

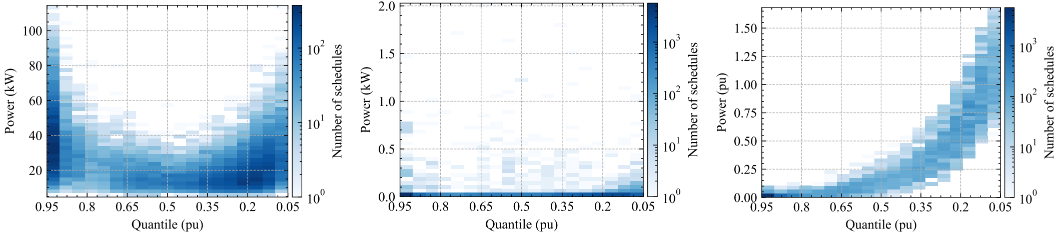
(b) Battery unavailability factor

(c) Forecast error

Figure: Effect of the forecast uncertainty (as a function of quantile levels).

## Findings (cont'd)

2. Effect of forecast uncertainty factors




(a) Net load imbalance (b) Battery unavailability factor (c) Forecast error

**Finding #2** The realization of the flexibility scheduling is heavily affected by the forecast uncertainty and requires *uncertainty-aware planning*

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

3. Techno-economic efficiency

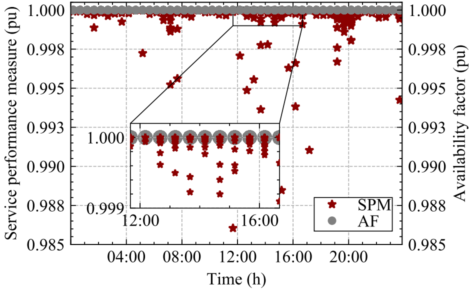
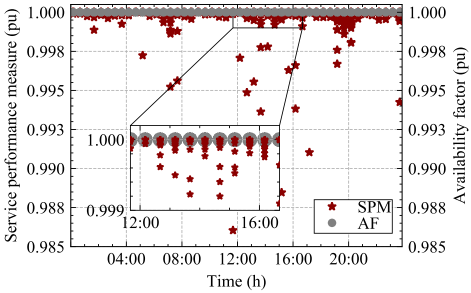



Figure: Technical (SPM) and economic (AF) indicators of the provided frequency control service.

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

3. Techno-economic efficiency

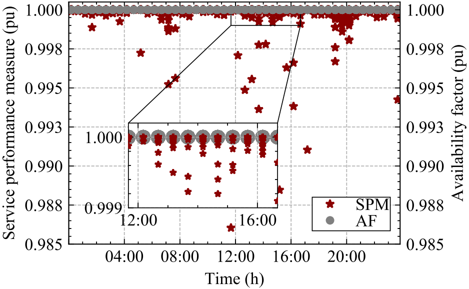



- Population of residential battery storages provide the highest quality level of the service performance above 98.5% and 100% availability

# PROSUMER FLEXIBILITY SCHEDULING AND COORDINATION

## Findings (cont'd)

3. Techno-economic efficiency




**Finding #3** The use of residential solar battery systems for the frequency control demonstrates low risks of resource unavailability

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[1] CEN-CENELEC-ETSI. *Smart Grid Reference Architecture*. Tech. rep. 2012.

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[3] Rafael Waters. "Energy from ocean waves: full scale experimental verification of a wave energy converter". PhD thesis. Uppsala University, 2008.