Whole Energy System Modelling - Challenges and Considerations

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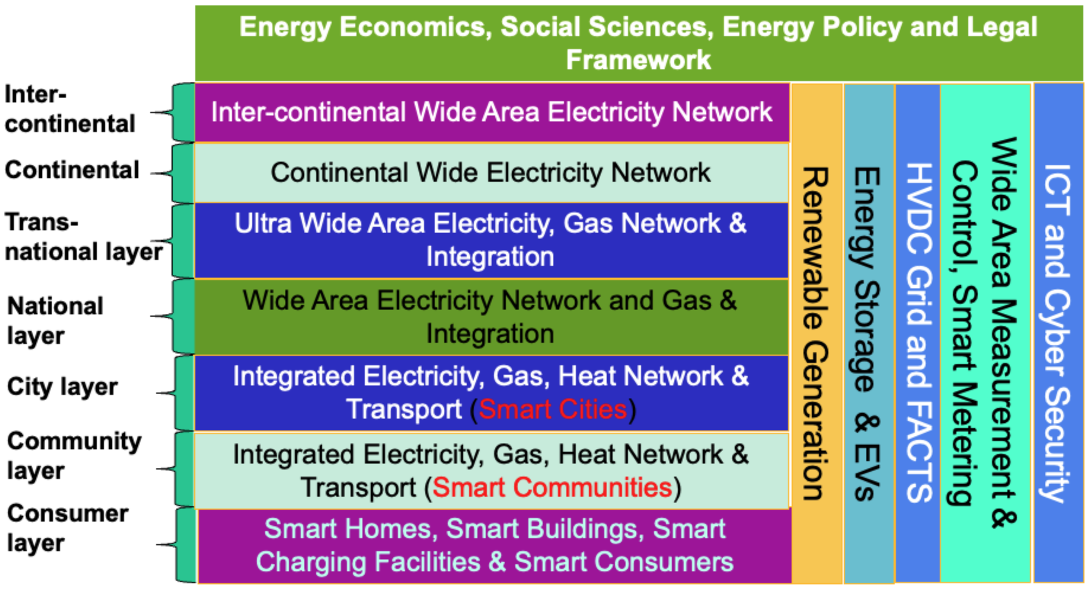
The Architecture of Whole Energy System



- **X-P Zhang, Development of European Energy Internet: The Role of Energy Union**, in "*The Energy Internet: An Open Energy Platform to Transform Legacy Power Systems into Open Innovation and Global Economic Engines*", edited by Wencong Su and Alex Q. Huang, pp. 347-367 (total 20 pages), Elsevier, 2019

- The concept of 'Energy Union' for the Global Grid governance was proposed at the workshop at the EU Sustainable Energy Week hosted in the European Parliament, Tuesday, 25 June 2013
- In 2015, European Commission subsequently established the 'Energy Union' to lead the energy transition in Europe

Challenges of Whole System Modelling

- Different scales of geographical coupling: Transnational, National, City, Community, Consumers (Homes/Buildings)
- Coupling between different types of energy systems: Electricity, Gas and Heat as well as Transport
- Different modelling methodologies and tools required for different types of energy systems
- Vast number of existing models and solutions!
- Availability of testing data sets
- There is a lack of reliable testing data sets

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Special Issues of Whole Energy System Modelling

- Heterogeneous transport properties of multi-energy flows lead to multi-timescale dynamics.
- Bidirectional energy flows result in mutual influences across various timescales, this would create exceptionally complex combined whole system model.
- From a mathematical standpoint, the whole system model is described by high-dimensional partial differential-algebraic equations (PDAEs).
- Balancing between modeling accuracy and solution efficiency while ensuring convergence and stability brings a formidable challenge
- Lack of standardized benchmarking datasets and simulation settings

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Selection of Appropriate Models for Different Energy Subsystems

- Timescales of gas and heating systems typically span from tens of minutes to hours. On the other hand, dynamic processes in the power system, such as electromagnetic and electromechanical transients, occur within microseconds to seconds
- The combined whole system model predominantly employs the static power flow model.
- In comparison, the GS and HS models are classified based on their respective timescales, two types of energy flow analysis in whole system modelling, i.e., either static analysis or dynamic analysis can be applied.

Static Energy Flow Models

- Static energy flow analysis focuses on determining the state distribution at a single time step by solving sets of algebraic equations (AEs).
- Static Energy Flow Models
  - Newton-Raphson (NR) method to calculate energy flows in integrated heat-electricity system. Both decoupling and united solutions were developed
  - NR method to incorporate integrated electricity-heat-gas system
  - Fixed-point iteration method
  - A distributed calculation framework, employing the NR method and holomorphic embedding methods for different subsystems
  - Topological and component decoupling methods, respectively, to accelerate the iterative processes between different subsystems

Dynamic Energy Flow Models

- Capturing the energy flow dynamics and their interdependencies across multiple time steps, by solving PDAEs
- Dynamic Energy Flow Models
  - Finite difference method (FDM) for energy flow optimization in discretising dynamic equations in GS and HS, respectively
  - The method of characteristics (MOC) for solving PDAEs. Transforming the original partial differential equations (PDEs) into ordinary differential equations (ODEs)
  - Representative function transformation methods for dynamic energy flow analysis: Fourier transformation; Laplace transformation; Differential transformation

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Models of Power Systems

- Static State Non-linear Power Flow Equations

$$P_{Gi} - P_{Li} = U_i \sum_j U_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij})$$

$$Q_{Gi} - Q_{Li} = U_i \sum_j U_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij})$$

$$P_{l,ij} = U_i U_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) - G_{ij} U_i^2$$

$$Q_{l,ij} = U_i U_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) + B_{ij} U_i^2$$

Models of Gas System: GS-Model1

- GS flow dynamics:

mass conservation = mass change + flux increment

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial x} = 0$$

momentum conservation=
Convection+ acceleration + surface stress + friction resistance

$$\frac{\partial (\rho v^2)}{\partial x} + \frac{\partial (\rho v)}{\partial t} + \frac{\partial p}{\partial x} + \frac{\lambda_g \rho v^2}{2D} = 0$$

$$p = \rho c^2$$

isothermal process

where p is the pressure, Pa; ρ is the density, kg/m^3; v is the flow velocity, m/s
D is the pipeline diameter, m; g is the gravity acceleration, m/s^2;
λ_g is the friction factor of gas pipeline.

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Models of Gas System: GS-Model1

- Density and flow velocity equation

$$q = Sv\rho$$

where S is the cross-section area of the pipeline, m^2;
q is the mass flow rate, kg/s.

Models of Gas System: GS-Model1

- Conservation law at the junctions :

$$p_b^{\mathrm{o}} - p_{nd,k} = 0,\ p_n^{\mathrm{i}} - K_{cp,k} p_{nd,k} = 0 \quad b \in \Phi^{\mathrm{o}}_{g,k}, n \in \Phi^{\mathrm{i}}_{g,k}$$

$$\sum_b q_b^{\mathrm{o}} - \sum_j q_j^{\mathrm{i}} - q_{nd,k} = 0 \quad k \in \Theta_g, b \in \Phi^{\mathrm{o}}_{g,k}, j \in \Phi^{\mathrm{i}}_{g,k}$$

where q_{nd} is the node mass flow rate, kg/s;

p_{nd} is the node pressure, Pa;

$K_{cp,k}$ is the compression ratio if node k is a compressor, else, $K_{cp,k}$=1;
superscripts ‘i' and ‘o’ are the symbols of inlet and outlet variables;

Φo g,k and Φi g,k are the sets of pipelines ending and starting at nod
k in the GS; Θ_g is the node set in the GS

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Models of Gas System: GS-Model2

- Neglecting the convection terms in GS-Model1

$$\frac{\partial p}{\partial t}+\frac{c^2}{S}\frac{\partial q}{\partial x}=0,\quad \frac{\partial p}{\partial x}+\frac{1}{S}\frac{\partial q}{\partial t}+\frac{\lambda_g c^2 q^2}{2DS^2 p}=0$$

where p is the pressure, Pa; ρ is the density, kg/m^3; v is the flow velocity, m/s
D is the pipeline diameter, m; g is the gravity acceleration, m/s^2;
λ_g is the friction factor of gas pipeline.

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Models of Gas System: GS-Model3

- Further neglecting the acceleration terms in GS-Model2

$$\frac{\partial p}{\partial t} + \frac{c^2}{S}\frac{\partial q}{\partial x} = 0, \quad \frac{\partial p}{\partial x} + \frac{\lambda_g c^2 q^2}{2DS^2 p} = 0$$

Models of Gas System: GS-Model4 & 5

- *GS-Model2 and GS-Model3* are linearized as follows

$$\frac{\partial p}{\partial t}+\frac{c^2}{S}\frac{\partial q}{\partial x}=0,\quad \frac{\partial p}{\partial x}+\frac{1}{S}\frac{\partial q}{\partial t}+\frac{\lambda_g wq}{2DS}=0$$

GS-Model4

$$\frac{\partial p}{\partial t}+\frac{c^2}{S}\frac{\partial q}{\partial x}=0,\quad \frac{\partial p}{\partial x}+\frac{\lambda_g wq}{2DS}=0$$

GS-Model5

Models of Gas System: GS-Model6

- At a larger timescale, the gas flow dynamics become static

$$\begin{cases} \dfrac{\mathrm{d}q}{\mathrm{d}x} = 0 \Rightarrow q = \text{constant} \\ \dfrac{\mathrm{d}p}{\mathrm{d}x} + \dfrac{\lambda_{\mathrm{g}} c^2 q^2}{2DS^2 p} = 0 \end{cases} \Rightarrow \begin{cases} \left(p^{\mathrm{o}}\right)^2 - \left(p^{\mathrm{i}}\right)^2 - K_g q^2 = 0 \\ K_g = \dfrac{\lambda_{\mathrm{g}} c^2 L}{DS^2} \end{cases}$$

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Models of Heating System: HS-Model1

- Hydraulic Model

$$\mathbf{A}\boldsymbol{m} = \boldsymbol{m}_{nd}$$

$$\mathbf{B}\Delta\boldsymbol{p} = \mathbf{0}$$

$$\Delta p_i = K_{f,i} m_i \left| m_i \right| \quad i \in \Phi_h$$

where **A** is the node-branch incidence matrix, a_{ij}=1/-1 if node *i* locates the inlet/outlet of pipeline *j*, else, a_{ij}=0; ***m*** is the vector of pipeline mass flow rate, kg/s; $\boldsymbol{m}_{nd}$ is the vector of node mass flow rate, kg/s; **B** is the loop-branch incidence matrix, b_{ij}=1/-1 if the loop *i* has the same/reverse direction as pipeline *j*, else, b_{ij}=0; K_f is the lumped pipeline resistance coefficient; Δp is the vector of pipeline pressure drop; Φh is the set of pipelines.

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Models of Heating System: HS-Model1

- Neglecting the fluid heat conduction, pipeline temperature equation:

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} + \frac{v}{C_w m \lambda_h} T = 0$$

where T is the pipe temperature that takes ambient temperature as the reference, ℃; C_w is the water specific heat capacity, J/(kg·℃); λ_h is the pipeline thermal resistance.

- Hot water flow mixing at the nodes

$$T_{nd,k}\sum_{b} m_b = \sum_{j} m_j T_j^{\mathrm{o}} \qquad k \in \Theta_h, b \in \Phi_{h,k}^{\mathrm{i}}, j \in \Phi_{h,k}^{\mathrm{o}}$$

where Θ_h is the set of nodes in the HS; Φo *h,k* and Φi *h,k* are the sets of pipelines ending and starting at node *k* in the HS; T_{nd} is the node temperature

Models of Heating System: HS-Model1

- Continuity equation: node and pipeline inlet temperatures

$$T_j^{\mathrm{i}} = T_{nd,k} \quad k \in \Theta_h, j \in \Phi_{h,k}^{\mathrm{i}}$$

- Supply and return temperatures at the nodes

$$\phi_i = C_w m_{nd,i} \left(T_{nd,i}^s - T_{nd,i}^r \right) \quad k \in \Theta_h$$

where T_{nd}^s and T_{nd}^r are the node supply and return temperatures,

ϕ is the thermal power

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Models of Heating System: HS-Model2

- Neglecting the temperature variation regarding *t* in HS-Model1

$$\frac{\mathrm{d}T}{\mathrm{d}x}+\frac{T}{C_w m\lambda_h}=0 \Rightarrow T^{\mathrm{o}}=T^{\mathrm{i}}e^{\frac{-L}{C_w m\lambda_h}}$$

where *L* is the pipeline length

Models of Heating System: HS-Model3

- Different from the above models deriving from the PDE, *HS-Model3* directly models the time delay and thermal loss in the HS and is called lumped model

$$T_t^{\mathrm{o}} = T_{t-\xi_{lp}}^{\mathrm{i}} e^{\frac{-L}{C_w m \lambda_h}} \quad \xi_{lp} = \left\lfloor \frac{L}{v\Delta t} \right\rfloor$$

where Δt is the time step size, ξ_{lp} is the pipeline time delay in *HS-Model3*.

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Models of Heating System: HS-Model4

- Another technique in modeling HS is called node method - *HS-Model4*.
- In *HS-Model4*, the mass flow along the pipeline is discretized into multiple blocks

$$T_t^{\mathrm{o}} = K_{NM} \sum_{k=t-\xi_{1t}}^{t-\xi_{2t}} T_{t-k}^{\mathrm{i}}$$

where

K_{NM} is the transfer coefficient;

ξ_{1t} and ξ_{2t} are the labels of time delay in *HS-Model4*

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Models of Coupling Units

- Combined heat and power (CHP) units

$$\phi_{bp} = \eta_{bp} P_{bp}$$

$$\eta_{ec} = \frac{\phi_{ec} - \phi_{ec,base}}{P_{ec,base} - P_{ec}}$$

- where subscripts ‘*bp*’ and ‘*ec*’ are the symbols of back pressure and extraction CHP units; η is the thermal-electric coefficient; ϕ_{base} and P_{base} are the rated thermal and electric power output of the extraction CHP units.

Models of Coupling Units

- Electric boilers (EB) and heat pumps (HP): The EB and HP consume the electric power to generate thermal power

$$\phi_{eb} = \eta_{eb} P_{eb}, \quad \phi_{hp} = \eta_{hp} P_{hp}$$

- where subscripts '*eb*' and '*hp*' are the symbols of EB and HP; η_{eb} and η_{hp} are the efficiencies of EB and HP.

Models of Coupling Units

- Gas turbines (GT), and power to gas (P2G) facilities: The GT consumes gas flow to generate electric power, while the P2G transforms the abundant electric power to generate gas flow

$$P_{gt} = \eta_{gt} q_{gt} h_g, \quad q_{pg} = \frac{\eta_{pg} P_{pg}}{h_g}$$

- where subscripts ‘*gt*’ and ‘*pg*’ are the symbols of GT and P2G, respectively; η_{gt} and η_{pg} are the efficiencies of GT and P2G; h_g is the calorific value of gas

Summary of Current Whole System Models

Model	Static/Dynamic	Nonlinear/Linear
PS-Model	Static	Nonlinear
GS-Model1	Dynamic	Nonlinear
GS-Model2	Dynamic	Nonlinear
GS-Model3	Dynamic	Nonlinear
GS-Model4	Dynamic	Linear
GS-Model5	Dynamic	Linear
GS-Model6	Static	Nonlinear
HS-Model1	Dynamic	Nonlinear
HS-Model2	Static	Linear in quality regulation; nonlinear in quantity regulation
HS-Model3	Dynamic	
HS-Model4	Dynamic	

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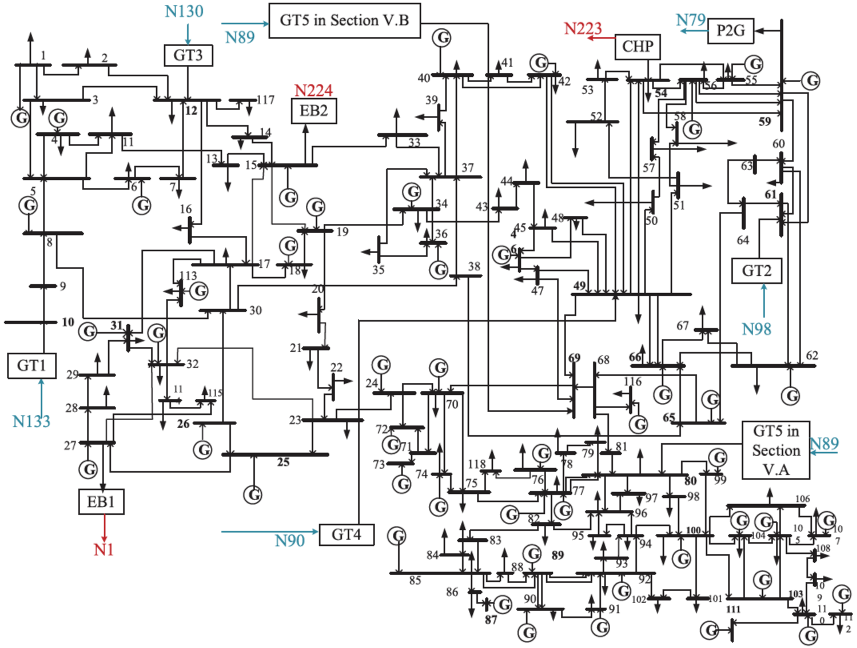
Case Study: Whole System Modelling with Gas and Electricity

- The analysis is performed in a large-scale whole energy system: 118-bus PS, 225-node HS, and 134-node GS.
- The 118-bus PS is modified from the IEEE 118-bus system
- Three systems are coupled with one back-pressure CHP unit, two EBs, five GTs, and one P2G
- The simulation period is 24h and Δt is 120s



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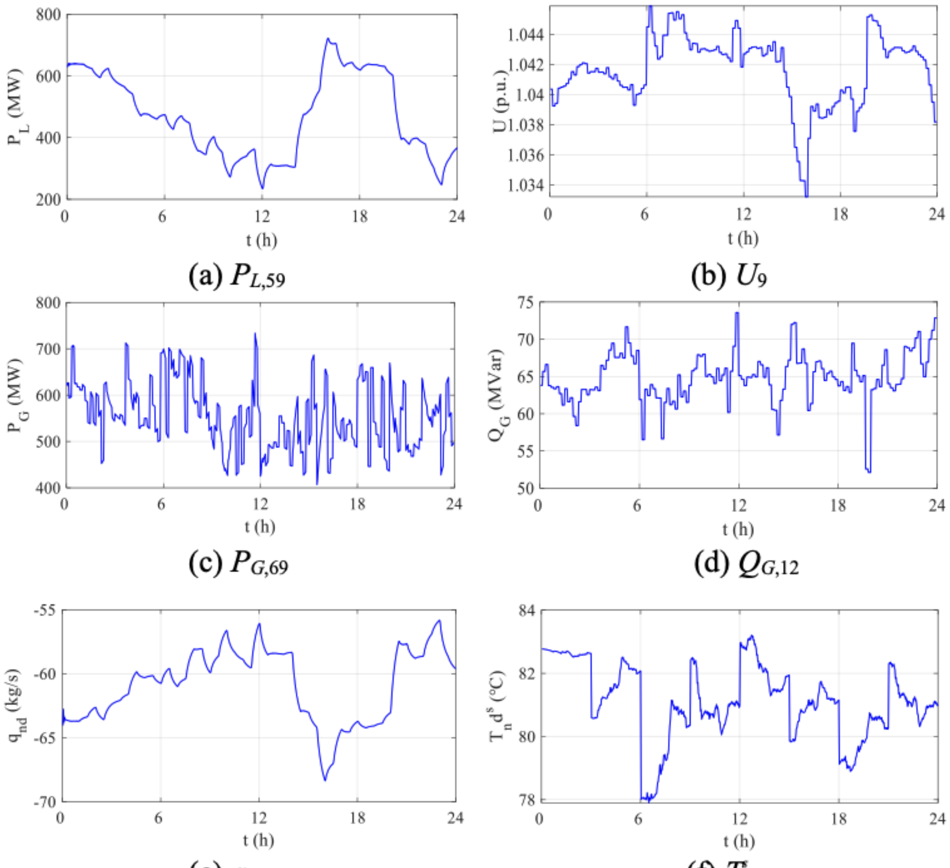
Case Study: Whole System Modelling

- Case 1: bidirectional weakly coupled between the subsystems
- no iterations or modifications exist between the subsystems.



(a) $P_{L,59}$ (b) U_9

(c) $P_{G,69}$ (d) $Q_{G,12}$

(e) $q_{nd,1}$ (f) $T^s_{nd,1}$

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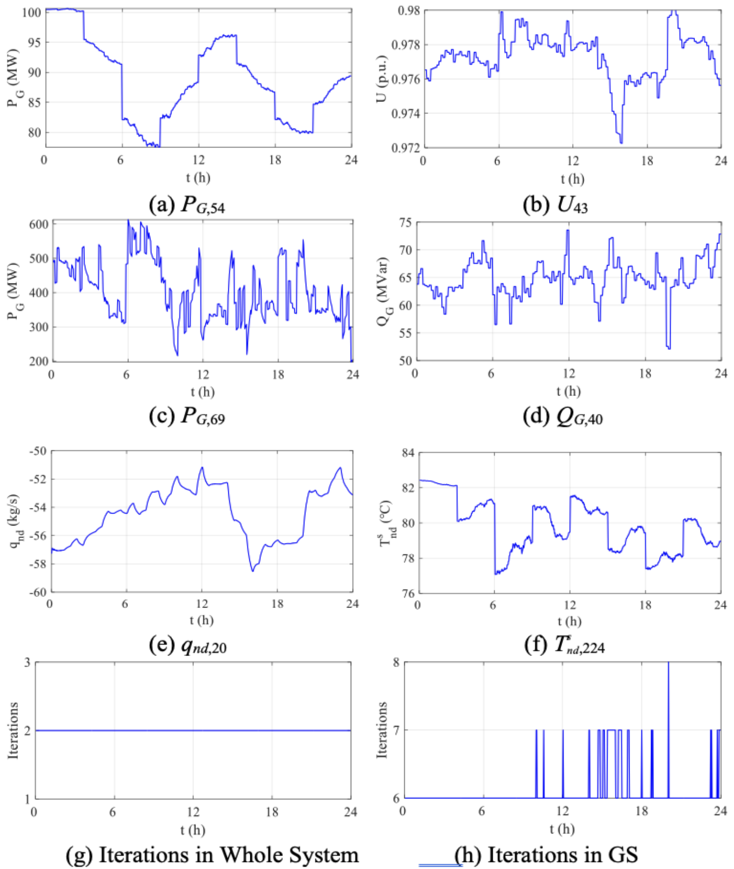
Case Study: Whole System Modelling

- Case 2: a bidirectional intensively coupled whole energy system
- GS and PS needs to iterate until converge



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Conclusions

- The challenges of whole energy system modelling has been highlighted.
- Models of power systems, gas systems and heat systems have been presented.
- This presentation has been focused on how to benchmark the system models and test systems for whole energy system modelling.
- Case study has been carried out to show the models.
- The data availability is still a big issue for real energy systems, in particular heat systems.

Further readings

- S. Zhang, W. Gu, X.-P. Zhang, C. Y. Chung, R. Yu, S. Lu, R. Palma-Behnke, “**Analysis for integrated energy system: Benchmarking methods and implementation**”, Energy Internet, 2024, vol.1, pp. 63–80.

  https://doi.org/10.1049/ein2.12002

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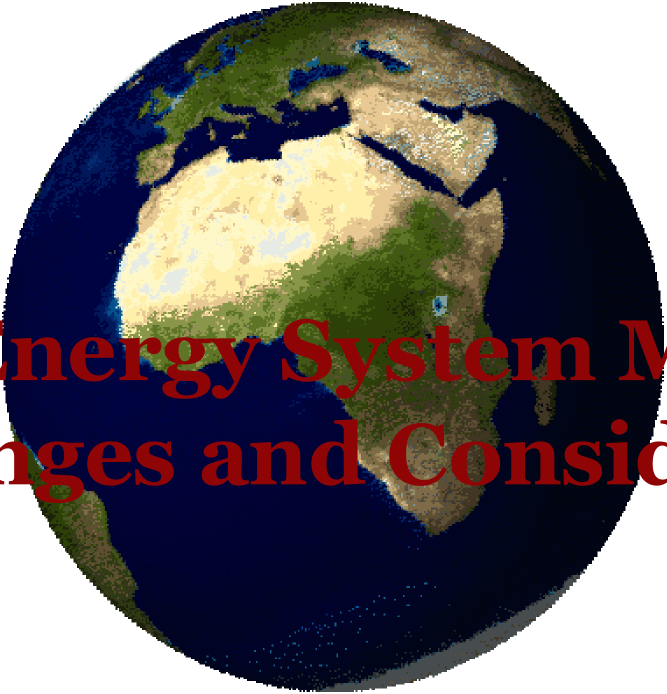

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