Hybrid Renewable Energy System Optimization is Lacking Consideration of System Resilience and Robustness: An Overview

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About the presenter

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Member of Power Systems Intelligence work group

- Researching decentralized, decarbonized, cyber-resilient energy supply solutions
- Focus on machine learning and artificial intelligence techniques
  - Price, load and flexibility prediction
  - Surrogate modeling for grid simulation
  - Learning of viable cyber-defence-strategies
  - Intelligent grid planning

Introduction

Shift to renewable energy sources requires redesign of grid

Progressive shift results in intermittent state

Mix of renewable sources, storage and fossil sources forms Hybrid Renewable Energy System (HRES) [1]

- can be connected to grid [2][3]
- or standalone systems [4][5]

HRES optimization is researched to design reliable and efficient systems [6]

- Economical and technical aspects are optimized most commonly
- Recently, environmental and socio-political goals are scrutinized

Introduction

Unpredictable events can disrupt system operation in unforseeable ways [7][8]

- Cyber attacks (e.g., Ukraine, 2015) [9]
- Overloading (e.g., Europe, 2021) [10]
- Natural disasters (e.g., Texas, 2021)

HRES must be resilient and robust to withstand those challenges

Are robustness and resilience considered in HRES optimization?

Agenda

1. **Resilience and robustness definitions**
2. **Optimization problems**
3. **Optimization methods**
4. **Simulation methods**
5. **Optimization goals**
6. **Research gap**
7. **Conclusion**

Resilience definitions

By Arghandeh et al. [11]:

The resilience of a system presented with an unexpected set of disturbances is the system's ability to reduce the magnitude and duration of the disruption. A resilient system downgrades its functionality and alters its structure in an agile way.

of the Presidential Policy Directive 21 of the United States of America [12]:

The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.

Resilience definitions - Summary

Handling of unexpected disturbances

Downgrading of functionality to avoid system collapse

Quick recovery and return to regular operation

Robustness definition

By Arghandeh et al. [11]:

Robustness is the ability of a system to cope with a given set of disturbances and maintain its functionality.

Given set of disturbances

Functionality is maintained

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Optimization problems

Formal description [13]:

$$Minimize/Maximize: \quad F(x) \tag{1}$$

$$subject\ to: \quad g_j(x) \leq 0;\ j = 1, 2, ..., m\ , \tag{2}$$

Multi-objective optimization [14]:

$$Minimize/Maximize: \quad F_{mo}(x) = [F_1(x), F_2(x), ..., F_k(x)] \tag{3}$$

$$subject\ to: \quad g_j(x) \leq 0;\ j = 1, 2, ..., m\ , \tag{4}$$

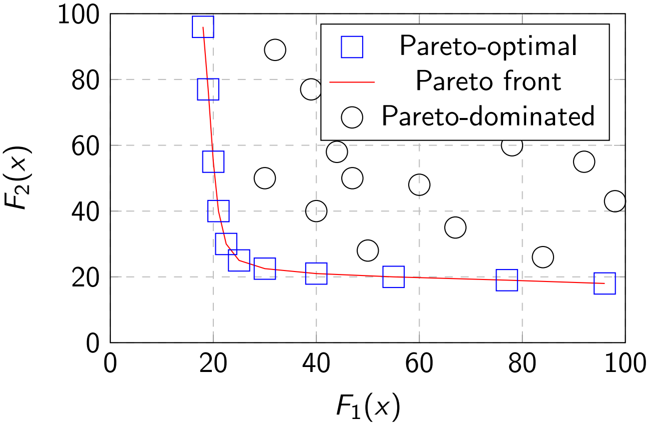
Two approaches to evaluate multi-objective function

Weighted sum [14]:

$$F_{mo} = \sum_{i=1}^{k} w_i \cdot F_i\ , \tag{5}$$

Multi-objective optimization

Pareto optimality [15]:



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Optimization methods

Practically, any optimization method can be used for HRES optimization

Common ones are:

- Evolutionary Algorithm (EA) [16][17][18][19]
- Particle Swarm Optimization (PSO) [20][4][21][22]
- Ready to use software solutions [23]
  - HOMER
  - iHOGA
  - DER-CAM
  - Calliope

Manually implemented optimization methods work with every optimization goal

Optimization methods

Existing software solutions are more limited [23]:

Optimization method	Possible goals
HOMER	NPC
Calliope	COE
DER-CAM	COE CO_2 emission
iHOGA	NPC CO_2 emission LLP

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Simulation methods

Simulation relies on load, wind speed and sun radiation profiles

Mathematical modeling of components is often used [20][16][4][17][21][18]

For every simulation step:

- Calculate output of renewable energy sources
- Compare generation to load
- Store surplus in storage device
- Use stored energy if demand can not be met
- If storage is empty: Use fossil fallback solutions and calculate fuel consumption

Review by Bhandari et al. provides a good overview [24]

Software solutions like HOMER include system simulation

Simulation methods

Component failure and other disturbances could be integrated into simulation

None of the reviewed publications incorporate such disturbances

Resilient behavior would require further simulation logic to allow for:

- Downgrading of system functionality
- Recovery of regular operation

Optimization goals

Target functions for optimizing HRES

- Economic optimization goals
- Technical optimization goals
- Environmental optimization goals
- Socio-Political optimization goals

Equations can be found in corresponding paper of this presentation

Economic optimization goals

Cost of Energy generation (COE) [3][16][4]

- Describes average annual energy creation expensiveness of system per unit of energy [USD/kWh]

Levelized Cost of Energy generation (LCOE) averages over entire project lifespan [20]

Net Present Value (NPV) measures difference between cash inflow and cash outflow of the system [25]

- Measurement for return of investment [USD]
- Called Net Present Cost (NPC) in HOMER [26]
- Used under that name in several publications [3][27]

Economic optimization goals

Annualized Cost of System (ACS) [17]

- Annualizes all cost of the entire system [USD]

Initial Capital Cost (ICC) [18]

- Measures the initial investment needed to build the system [USD]

None of the economic optimization goals measure robustness or resilience

Reducing cost is usually contradictory to robustness and resilience

Technical optimization goals

Loss of Power Supply Probability (LPSP) [20][4][17][22][28]

- Measures probability of system being unable to supply power to meet demand [%]
- Also known as Loss of Load Probability (LLP) [16][27]
- Often used as constraint
- Could measure system robustness and resilience **if** system is exposed to disturbances

Minimization of power losses [W h] [2]

- No impact on robustness and resilience

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Environmental optimization goals

Direct emission of CO_2 [kg] [27][17]

Carbon Footprint of Energy (CFOE) [20][29]

- Measures all emissions over the system's lifetime per unit of energy produced [kg$CO2_{eq}$/kWh]
- Includes emissions from material harvesting, manufacturing, transporting, installing, operating, maintaining and disposing

Renewable Energy Ratio (RER) [27] and Renewables Factor (RF) [20]

- Measure ratio of energy created by renewable and conventional sources [%]

No measure of robustness and resilience

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Socio-Political optimization goals

Socio [20]

- Quantifies socio-political impact of a HRES
- Incorporates qualitative and quantitative factors
  - Aesthetics
  - Employment
  - Perceived hazard
  - Land requirement and acquisition
  - Perceived local environmental impacts
  - Local ownership
  - Local skills availability
  - Local resource availability
  - Perceived service ability

Research gap

Curently, Robustness and resilience is not considered in HRES optimization

Some optimization goals (LPSP, Socio) have the potential to measure robustness and resilience

However:

- No disturbances are integrated into the simulation
- None of the systems had the ability to downgrade functionality
- No direct measure of robustness or resilience is included

Research gap exists in optimizing HRES with respect to robustness and resilience

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Conclusion

Overview of HRES optimization

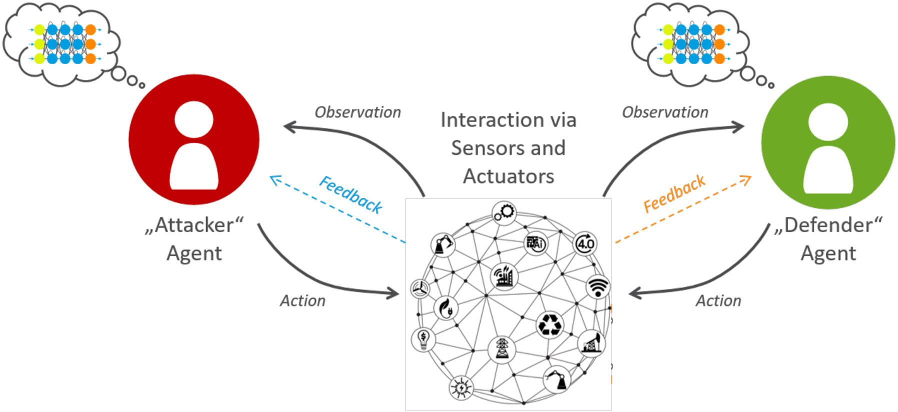
Identified a research gap in robustness and resilience consideration

Planned to address this research gap in the future

- Develop optimization goals that measure robustness and resilience
- Force disturbances upon systems in simulation
- Allow systems to downgrade functionality

Outlook

Main concept: Adversarial Resilience Learning (ARL) [30][31][8]



Shared Environment (digital twin of a HRES)

Outlook

Thank you for your attention!

If you have questions, please write an email to lasse.hammer@offis.de!

References I

[1] P. G. Arul, V. K. Ramachandaramurthy, and R. K. Rajkumar, "Control strategies for a hybrid renewable energy system: A review," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 597–608, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2014.10.062

[2] T. Niknam, S. I. Taheri, J. Aghaei, S. Tabatabaei, and M. Nayeripour, "A modified honey bee mating optimization algorithm for multiobjective placement of renewable energy resources," *Applied Energy*, vol. 88, no. 12, pp. 4817–4830, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2011.06.023

[3] R. Rajbongshi, D. Borgohain, and S. Mahapatra, "Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER," *Energy*, vol. 126, pp. 461–474, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2017.03.056

References II

[4] V. M. Sanchez, A. U. Chavez-Ramirez, S. M. Duron-Torres, J. Hernandez, L. G. Arriaga, and J. M. Ramirez, "Techno-economical optimization based on swarm intelligence algorithm for a stand-alone wind-photovoltaic-hydrogen power system at south-east region of Mexico," *International Journal of Hydrogen Energy*, vol. 39, no. 29, pp. 16 646–16 655, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.ijhydene.2014.06.034

[5] A. Helal, R. El-Mohr, and H. Eldosouki, "Optimal design of hybrid renewable energy system for electrification of a remote village in Egypt," *2nd International Conference on Communications Computing and Control Applications, CCCA 2012*, pp. 1–6, 2012.

References III

[6] E. L. Eriksson and E. M. A. Gray, “Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems – A critical review,” *Applied Energy*, vol. 202, pp. 348–364, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2017.03.132

[7] Y. Wang, C. Chen, J. Wang, and R. Baldick, “Research on Resilience of Power Systems under Natural Disasters - A Review,” *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1604–1613, 2016.

[8] E. Veith, L. Fischer, M. Tröschel, and A. Nieße, “Analyzing Cyber-Physical Systems from the Perspective of Artificial Intelligence,” in *Proceedings of the 2019 International Conference on Artificial Intelligence, Robotics and Control*. ACM, 2019, pp. 85–95.

References IV

[9] J. E. Sullivan and D. Kamensky, “How cyber-attacks in Ukraine show the vulnerability of the U.S. power grid,” *Electricity Journal*, vol. 30, no. 3, pp. 30–35, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.tej.2017.02.006

[10] ENTSO-E. (2021) System separation in the continental europe synchronous area on 8 january 2021 – 2nd update. [retrieved: Apr., 2021]. [Online]. Available: https://www.entsoe.eu/news/2021/01/26/system-separation-in-the-continental-europe-synchronous-area-on-8-january-2021-2nd-u

[11] R. Arghandeh, A. Von Meier, L. Mehrmanesh, and L. Mili, “On the definition of cyber-physical resilience in power systems,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1060–1069, 2016.

References V

[12] Critical infrastructure security and resilience. [retrieved: Apr., 2021]. [Online]. Available: https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

[13] O. Kramer, *A Brief Introduction to Continuous Evolutionary Optimization*, ser. SpringerBriefs in Applied Sciences and Technology. Springer International Publishing, 2013. [Online]. Available: https://books.google.de/books?id=22vABAAAQBAJ

[14] R. T. Marler and J. S. Arora, "The weighted sum method for multi-objective optimization: New insights," *Structural and Multidisciplinary Optimization*, vol. 41, no. 6, pp. 853–862, 2010.

References VI

[15] P. Ngatchou, A. Zarei, and M. A. El-Sharkawi, “Pareto multi objective optimization,” *Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems, ISAP’05*, vol. 2005, pp. 84–91, 2005.

[16] M. S. Ismail, M. Moghavvemi, and T. M. Mahlia, “Genetic algorithm based optimization on modeling and design of hybrid renewable energy systems,” *Energy Conversion and Management*, vol. 85, pp. 120–130, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.enconman.2014.05.064

[17] Z. Shi, R. Wang, and T. Zhang, “Multi-objective optimal design of hybrid renewable energy systems using preference-inspired coevolutionary approach,” *Solar Energy*, vol. 118, pp. 96–106, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.solener.2015.03.052

References VII

[18] K. D. Mercado, J. Jimémez, and C. G. Quintero M., “Hybrid Renewable Energy System based on Intelligent Optimization Techniques,” *International Conference on Renewable Energy Research and Applications*, vol. 5, pp. 661–666, 2016.

[19] M. Ming, R. Wang, Y. Zha, and T. Zhang, “Multi-objective optimization of hybrid renewable energy system using an enhanced multi-objective evolutionary algorithm,” *Energies*, vol. 10, no. 5, pp. 5–9, 2017.

[20] E. L. Eriksson and E. M. A. Gray, “Optimization of renewable hybrid energy systems – A multi-objective approach,” *Renewable Energy*, vol. 133, pp. 971–999, 2019. [Online]. Available: https://doi.org/10.1016/j.renene.2018.10.053

[21] M. Sharafi and T. Y. ELMekkawy, “Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach,” *Renewable Energy*, vol. 68, pp. 67–79, 2014.

References VIII

[22] A. Kashefi Kaviani, G. H. Riahy, and S. M. Kouhsari, “Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages,” *Renewable Energy*, vol. 34, no. 11, pp. 2380–2390, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.renene.2009.03.020

[23] M. A. Cuesta, T. Castillo-Calzadilla, and C. E. Borges, “A critical analysis on hybrid renewable energy modeling tools: An emerging opportunity to include social indicators to optimise systems in small communities,” *Renewable and Sustainable Energy Reviews*, vol. 122, no. June 2019, p. 109691, 2020. [Online]. Available: https://doi.org/10.1016/j.rser.2019.109691

References IX

[24] B. Bhandari, S. R. Poudel, K. T. Lee, and S. H. Ahn, "Mathematical modeling of hybrid renewable energy system: A review on small hydro-solar-wind power generation," *International Journal of Precision Engineering and Manufacturing - Green Technology*, vol. 1, no. 2, pp. 157–173, 2014.

[25] A. Pechmann, I. Schöler, and S. Ernst, "Possibilities for CO2-neutral manufacturing with attractive energy costs," *Journal of Cleaner Production*, vol. 138, pp. 287–297, 2016.

[26] HOMER Energy. (2020) Homer pro documentation - net present cost. [retrieved: Apr., 2021]. [Online]. Available: https://www.homerenergy.com/products/pro/docs/latest/net_present_cost.html

References X

[27] M. Sharafi and T. Y. ElMekkawy, “Stochastic optimization of hybrid renewable energy systems using sampling average method,” *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1668–1679, 2015.

[28] H. Yang, L. Lu, and W. Zhou, “A novel optimization sizing model for hybrid solar-wind power generation system,” *Solar Energy*, vol. 81, no. 1, pp. 76–84, 2007.

[29] R. García-Valverde, C. Miguel, R. Martínez-Béjar, and A. Urbina, “Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system,” *Solar Energy*, vol. 83, no. 9, pp. 1434–1445, 2009.

References XI

[30] L. Fischer, J. Memmen, E. M. S. P. Veith, and M. Tröschel, “Adversarial resilience learning - towards systemic vulnerability analysis for large and complex systems,” *CoRR*, vol. abs/1811.06447, pp. 24–32, 2018. [Online]. Available: http://arxiv.org/abs/1811.06447

[31] E. M. Veith, N. Wenninghoff, and E. Frost, “The Adversarial Resilience Learning Architecture for AI-based Modelling, Exploration, and Operation of Complex Cyber-Physical Systems,” 2020, [retrieved: Apr., 2021]. [Online]. Available: http://arxiv.org/abs/2005.13601