

INVESTMENT PLANNING IN MULTI-VECTOR ENERGY SYSTEMS: DEFINITION OF KEY PERFORMANCE INDICATORS

Martha Hoffmann^{1}, Sanket Puranik², Marc Juanpera³, José M Martín-Rapún⁴, Heidi Tuiskula², Philipp Blechinger¹*

¹ Reiner Lemoine Institut, Rudower Chaussee 12, Berlin, Germany

² Smart Innovation Norway, Håkon Melbergs vei 16, Halden, Norway

³ Universitat Politècnica de Catalunya Barcelona Tech, Barcelona, Spain

⁴ R&D Department at Inycom, Alaín 8, Zaragoza, Spain

*Martha.Hoffmann@rl-institut.de

Keywords: SECTOR COUPLING, SECTOR-COUPLED ENERGY SYSTEMS, ENERGY SYSTEM SIMULATION, KEY PERFORMANCE INDICATORS, LEVELIZED COST OF ENERGY

Abstract

With rising focus on integrating high shares of renewable energy into energy supply systems, the need to meet the viability of these renewable sources becomes pressing. Apart from storing electricity in electro-chemical storage units, the concept of sector coupling could promise to provide the needed flexibility and storage capacities. A strong metric is needed to determine the viability and economic feasibility of different sector-coupled energy systems. This conference paper presents an empirical method to develop a list of key performance indicators (KPI), as a direct adaption of the KPI of energy system with a single energy vector is not always possible. The list was developed based on a stakeholder workshop within the H2020 research project E-Land. We propose the introduction of three new indicators for the evaluation of sector-coupled energy systems, namely degree of autonomy, levelized cost of energy and degree of sector coupling. A sector-coupled case study is evaluated to validate the performance of such new indicators while proving their utility to better assist decision-making.

1. Introduction

H2020 project E-LAND develops multiple technical, social and business related tools for creating and managing multi-vector energy system (MES) [1]. These MES are defined as sector-coupled energy systems, in which multiple energy vectors, ie. electricity, heat and/or H₂, are interconnected and, intertwined. One of the tools developed within the E-Land toolbox outcome is an investment planning tool (Multi-Vector Simulator, MVS) to assist in decision making during the investment planning phase of a specific MES. To facilitate such decision making performance indicators are necessary as they allow investors to select between various design options available based upon their requirements. Previous studies have investigated in depth about optimal sizing and operation of hybrid energy systems [2-4]. Most of these studies consider single energy vector systems, while few studies exist for multi-vector systems [5-6]. Research on MES is limited and publications available mainly focus on operation strategies. [5] looks into an integrated energy system but is limited to a home system. While [7] provides a method for the optimal planning of an energy hub (another known term for MES), it only uses the net present value (NPV) both as objective function to be maximized and as a KPI. However, different stakeholders might prioritize

different KPI for their personal investment decision. From existing literature, it is not clear what traditional KPIs mean to investors/stakeholders when applied for assessing MES. This paper fills this gap by investigating and, if necessary, adapting traditional KPIs used for sizing individual technologies or single vector systems from the perspective of MES.

2. Methodology

An ad-hoc empirical methodology is applied to investigate KPIs for sector-coupled systems. First, a literature review was performed to identify the most common KPIs and the possibilities for defining new ones for sector-coupled system. Thus, eight commonly used KPIs for energy system analysis are selected based upon literature study and through feedback from the pilot site owners/operators. These KPIs belong to three categories, namely economic, technical and environmental. In consultation with three E-Land pilot site owners/operators, the list of KPI was reviewed and extended. In this paper, we focus on the eight most important KPIs for energy system analysis. To test the viability of the developed KPI to sector coupled systems, they are applied to a case study based on a specific E-Land pilot site. This pilot is then modelled and optimized using the MVS, a simulation tool developed specifically for this purpose within E-Land. The

selected KPIs are then calculated in a post processing step for further analysis. The result of this study will be presented to the pilot owner to validate the usability of the KPIs.

The dedicated simulation tool developed for MES optimization is described in section 2.1. The KPIs selected and investigated in this paper are presented in section 2.2. The Spanish pilot which forms the case study is described in section 3. The case study is optimized in the simulation tool based upon linear programming approach.

2.1. Simulation tool

Within the E-Land toolbox, the Multi-Vector Simulator (MVS) is developed, allowing the optimization, simulation and evaluation of local sector-coupled energy systems, i.e., MES. The MES can be composed of a multitude of components and include multiple energy carriers, i.e., electricity, heat and/or gas. It automatically sets up the energy system from a choice of components and then performs a capacity and/or dispatch optimization as well as cost and performance evaluation. Optimization objective is minimizing the annual costs to supply the system's energy demand. At the end of the research project, the tool will be provided as an open-source application [8]. The MVS is programmed with python utilizing the library Open Energy Modelling Framework (oemof) [9, 10]. An example of the optimization problem generated with oemof can be found in [11]. A graphical user interface will be provided with the Energy Planning Application (EPA).

2.2. Key performance indicators

To evaluate the MES systems into which system owners/operators can invest, a comprehensive list of KPI is needed. These include economical parameters, which follow from the optimized capacities and dispatch of the MVS simulations, and technical parameters that help to understand the MES systems operation better. We concentrate on the most important ones in this paper (for a full list of proposed KPI see

Table 2).

2.1.1 Net present cost (NPC): NPC is the present value of all the costs associated with installation, operation, maintenance and replacement of energy technologies comprising the sector-coupled system over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. The capital recovery factor (CRF) is used to calculate the present value of the cash flows.

$$NPC = \sum c_i + \sum \frac{CF_i(t)}{CRF(t)} \quad (1); \quad CRF(t) = \frac{d \cdot (1 + d)^t}{(1 - d)^t - 1} \quad (2)$$

with $i \in \text{onsite energy technologies}\{\text{PV, heat pump, ...}\}$,

$t = \text{time in years, and } d = \text{discount factor}$

2.1.2 Levelized cost of energy (LCOEnergy): As a sector-coupled system connects energy vectors, not only the costs associated to each individual energy carrier but the overall energy costs should be minimized. Therefore, we propose a new KPI- the levelized costs of energy (LCOEnergy) aggregates the costs for energy supply and distributes them over the total energy demand supplied, which is calculated by weighting the energy carriers by their energy content.

To determine the weighting factors of the different energy carriers, we reference the method of gasoline gallon equivalent (GGE) [12], which enables the comparison of alternative fuels. Instead of comparing the energy carriers of an MES to gasoline, we rebase the factors introduced in [12] onto the energy carrier electricity, thus proposing a unit *Electricity Equivalent* (ElEq). The necessary weights are summarized in Table 1. With this, we propose to calculate LCOEnergy based on the annual energy demand and the systems annuity, calculated with the CRF, as follows:

$$LCOEnergy = \frac{NPC \cdot CRF(T)}{\sum_i E_{demand}(i) \cdot w_i} \quad \text{with } i \in \{el, H2, \dots\} \quad (3)$$

2.1.3 Levelized cost of electricity (LCOElectricity): Specific electricity supply costs, eg. levelized costs of electricity (LCOElectricity) are a common KPI that can be compared to local prices or generation costs. As in a sector-coupled system the investments cannot be clearly distinguished into sectors, we propose to calculate the levelized costs of energy carriers by distributing the costs relative to supplied demand. The LCOElectricity are then calculated with:

$$LCOElectricity = \frac{NPC \cdot CRF(T) \cdot \frac{E_{demand}(el) \cdot w_{el}}{\sum_i E_{demand}(i) \cdot w_i}}{E_{demand}(el)} \quad (4)$$

with $i \in \{el, H2, \dots\}$

2.1.4 Levelized cost of hydrogen (LCOH): LCOH is calculated analogously to LCOElectricity.

2.1.5 Renewable energy fraction (REF): Describes the share of the MES demand that is supplied from renewable sources.

$$REF = \frac{\sum_i E_{RES.generation}(i) \cdot w_i}{\sum_j E_{generation}(j) \cdot w_j + \sum_k E_{grid}(k) \cdot w_k} \quad (5)$$

with $i \in \text{Renewables}\{\text{PV, Geothermal, ...}\}$,

$j \in \text{all Generations}\{\text{generation assets } 1, 2, \dots\}$,

and $k \in \{\text{grid } 1, 2 \dots\}$

2.1.6 CO₂ emissions: The total CO₂ emissions of the MES in question can be calculated with all aggregated energy flows from the generation assets and their subsequent emission factor:

$$CO_2 \text{ Emissions} = \sum_i E_{generation}(i) \cdot CO_{2eq}(i) + \sum_k E_{grid}(k) \cdot CO_{2eq}(k) \quad (6)$$

with $i \in \{\text{generation asset } 1, 2, \dots\}$ and $k \in \{\text{grid } 1, 2, \dots\}$

2.1.7 Degree of autonomy (DA): The DA represents the level of autonomy that the MES has from potential supply from a distribution system operators (DSO). A DA close to zero shows high dependence on the DSO, while a DA of 1 represents an autonomous or net-energy system and a DA higher 1 a plus-energy system. As above, we apply a weighting based on Electricity Equivalent.

$$DA = \frac{\sum_i E_{\text{generation}}(i) \cdot w_i}{\sum_i E_{\text{demand}}(i) \cdot w_i} \quad \text{with } i \in \{\text{el}, \text{H}_2, \dots\} \quad (7)$$

2.1.8 Degree of sector-coupling (DSC): While a MES includes multiple energy carriers, this fact does not define how strongly interconnected its sectors are. To measure this, we propose to compare the energy flows in between the sectors to the energy demand supplied:

$$DSC = \frac{\sum_{i,j} E_{\text{conversion}}(i,j) \cdot w_i}{\sum_i E_{\text{demand}}(i) \cdot w_i} \quad (8)$$

with $i, j \in \{\text{el}, \text{H}_2, \dots\}$ and $i \neq j$

Table 1: Conversion towards Electricity Equivalent

Energy carrier	Unit	Conversion factor (w)
Electricity	kWh	1 kWh _{elec} /kWh
H2	kg	32.87 kWh _{elec} /kg

Table 2 Complete list of identified KPI

Economic	Upfront investment cost Fixed operation and maintenance cost Net present cost Annuity Levelized costs of energy Levelized cost of energy carriers
Technical	Renewable factor Optimized capacity for each asset Peak power Daily maximum consumption Aggregated production per asset Storage mean level Degree of autonomy Degree of sector-coupling Reliability of supply
Environmental	CO2 emissions

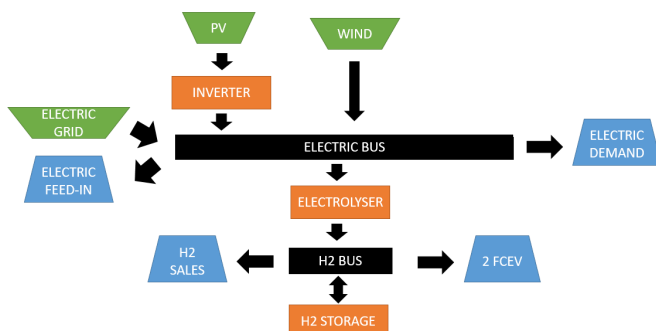


Figure 1: Visualization of the sector-coupled energy system

3. Case study and results

As an example, for a sector-coupled energy system, we look at one of E-Land's pilot sites, which has a weak connection to the national grid, but own renewable generation capacities and a test stand for H₂ generation. The park's energy demand is comprised of electricity and H₂ for FCEV. The operators have shown an interest in becoming more renewable and self-sufficient concerning its energy supply. We will take this energy system configuration to define a case study with changed system characteristics and input parameters.

3.1. System description

To illustrate the introduced KPIs we consider a simplification of above energy system, with a PV generation plant (10 kW_p), a wind plant (60 kW_p), an electricity profile of a single building, the demand of two FCEV, a connection to and from the national electricity grid, and a connection to the gas grid for feedin. As an optimisation goal, the needed electrolyser and H₂ tank are to be sized. Also, the optimal dispatch is obtained with the MVS. The described energy system is visualised in Figure 1.

The electricity price is 0.08 €/kWh and we assume a feed-in tariff for PV and of 0.06 €/kWh. H₂ feed-in into the H₂ grid produces a revenue of 1.6 € per kilogram of H₂.

3.2. Simulation results and discussion

As only the demand of a single building and two experimental FCEV has to be supplied while large renewable capacities are in place, the generation from wind and solar plants outweighs the MES consumption, resulting in high degree of autonomy of 1.16. This means that generation exceeds demand by about 16% annually. With such surplus generation, the feed-in revenues are substantial, effectively resulting in a very low NPC, and low levelized energy carrier costs. The LCOEnergy and LCOElectricity are equal, as the costs are normalized towards the electricity energy carrier. This can, however, be confusing and place electricity at the focus of all considerations. Therefore, using an alternative base for the weighting should be considered. Also, as it can be seen, both the LCOElectricity and the LCOH are lower than the corresponding feed-in tariffs, due to the fact that the investment costs of installed renewable capacities are considered as sunk costs and therefore not part of the NPC (because they are not relevant to the optimization), making electricity supply from existing renewables effectively cost-free. Finally, as only an unilateral flow from the electricity sector to the H₂ sector exists in the MES, the energy system is not strongly sector-coupled with a degree of sector coupling of about 18 %.

The case study shows that the proposed KPI are helpful to easily grasp the performance of the MES in question.

Table 3: KPI of the case study

Parameter	Unit	Value
NPC	€	28.4 k
Levelized costs of energy	€/ kWh _{elec}	0.024
Levelized costs of H ₂	€/kgH ₂	0.803
Levelized costs of electricity	€/kWh	0.024
CO ₂ emissions	kgCO ₂ eq	14.3 k
Renewable factor	%	69.9
Degree of Autonomy	factor	1.16
Degree of sector-coupling	%	17.9

4. Conclusion

To even the road for investments into sector-coupled systems in the future, comprehensive key performance indicators (KPI) are needed that both help system operators as well as system planners and researchers with the evaluation of these multi-vector energy systems (MES). This paper summarized a proposed list of KPI that should be output of the Multi-Vector Simulator, an open-source simulation tool for the optimization and evaluation of sector-coupled systems, which is currently being developed in context of the H2020 research project E-Land.

Special focus was given to those KPI that have to be re-defined in comparison to conventional single-sector energy systems. As such, we proposed to introduce the unit Electricity Equivalent (EIEq) which allows a weighting of different energy carriers according to their energy content. With this, the levelized costs of energy, electricity and H₂ can be defined. Weighing is also used to adapt the equations resulting in the MES's renewable share and degree of autonomy. Additionally, we propose to introduce an indicator which quantifies the degree of sector-coupling.

In following studies, we plan to investigate the practical relevance of the economical KPI when not considering the investments of existing capacities as sunk costs as well as an alternative base for the weighting of energy carriers. Applying the proposed indicators to a case study has proven that they can help to understand the more complex energy flows taking place in a multi-energy system. Further research, both based on simulations and stakeholder interviews, should follow to evaluate the KPI in extreme and commonplace case studies and ensure that the list of KPI is complete.

5. Acknowledgements

E-LAND project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824388. The information and views set out in this study are those of the author(s) and do

not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

6. References

- [1] Puranik, S., Tuiskula, H., Ilieva, I., et al.: 'Multi-vector energy optimization tools for energy islands'. Proc. IEEE PowerTech conference, Milan, Italy, 2019, pp. 1-6
- [2] Upadhyay, S., and Sharma M.P.: 'A review on configurations, control and sizing methodologies of hybrid energy systems' Renewable and Sustainable Energy Reviews, 2014, (38), 47-63
- [3] Al-Falahi, M. D., Jayasinghe, S. D. G., & Enshaei, H. J. E. C.: 'A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system'. Energy conversion and management, 2017, 143, 252-274
- [4] Okhuegbe, S. N., Mwaniki, C., & Akorede, M. F.: 'Optimal Sizing of Hybrid Energy Systems in a Microgrid: A Review'. Proc. of Sustainable Research and Innovation Conference, Nairobi, Kenya, 2019, pp. 88-100
- [5] Angenendt, G., Zurmühlen, S., Rücker, F., et al.: Optimization and operation of integrated homes with photovoltaic battery energy storage systems and power-to-heat coupling. Energy Conversion and Management: X, 2019, 1, 100005
- [6] Ceseña, E. M., & Mancarella, P.: 'Operational optimization and environmental assessment of integrated district energy systems'. Proc. IEEE Power Systems Computation Conference, Genoa, Italy, 2016, pp. 1-7
- [7] Salimi, M., Ghasemi, H., Adelpour, M., et al.: 'Optimal planning of energy hubs in interconnected energy systems: a case study for natural gas and electricity'. IET Generation, Transmission & Distribution, 2015, 9(8), 695-707
- [8] 'MVS - Multi-Vector Simulator of the E-Land toolbox'. https://github.com/rl-institut/mvs_eland, accessed 12.3.2020
- [9] Oemof Developer Group: 'Oemof—Open Energy Modelling Framework (V0.2.2)'. Zenodo. 2018
- [10] Hilpert, S., Kaldemeyer, C., Krien, U., et al.: 'The Open Energy Modelling Framework (oemof)—A new approach to facilitate open science in energy system modelling'. Energy Strategy Rev. 2018, 22, pp. 16-25
- [11] Hoffmann, MM., Pelz, S., Monés-Pederzini, Ò., et al.: 'Overcoming the Bottleneck of Unreliable Grids: Increasing Reliability of Household Supply with Decentralized Backup Systems', 2020, J Sustain Res, 2, (1)
- [12] US Department of Energy, Renewable Energy and Energy Efficiency: 'Fuel Conversion Factors to Gasoline Gallon Equivalents'. <https://epact.energy.gov/fuel-conversion-factors>, accessed 10.3.2020