Coupling life cycle assessment with energy system analysis

1 Background

One of the main drivers for switching the current energy system from a conventional fossil-base to one dominated by renewable technologies is climate change. However, energy system transformation aiming at reducing greenhouse gas (GHG) emissions may lead to increases in other types of environmental impacts. Incorporating environmental impacts beyond climate change into future energy systems is required, in order to develop energy policies that do not, or at least can reduce, conflict with other goals. With this as the background, the thesis couples life cycle assessment (LCA) with energy system analysis, to broaden the scope by including additional environmental impacts, and to switch from a direct emissions perspective to a life cycle perspective.

However, methodological challenges arise in the model coupling between LCA and ESM, mainly due to their different characteristics (e.g., different system boundaries, differences in databases, diverging assumptions, etc.). These methodological challenges could be summarized into two aspects: (1) how to identify elements in a systematic way in both models, which have to be harmonized, or at least matched, and (2) how to conduct a prospective LCA model which needs to consider technological progress in both market-proved technologies and emerging technologies. A methodological framework is thus required to guide the model coupling between ESM and LCA and to standardize the applications and overcome the challenges of model coupling as far as possible. This thesis fills in the gap by introducing the Environmental Assessment Framework for Energy System Analysis (EAFESA) as a guideline for studies to cope with the challenges in the model coupling between LCA and ESM.

The motivation of this thesis comes from the coexistence of both opportunities and challenges in the model coupling between ESM and LCA. Against this background, the overarching objectives are distinguished into two parts; from a methodological perspective and from a policymaking perspective. These are: (1) to develop a methodological framework to overcome the challenges in the model coupling between ESM and LCA models; and (2) to include the consideration of the life cycle non-climate environmental impacts besides GHG emissions in the energy system transformation, and to give possible solutions for policymakers for the trade-offs caused by mitigating climate change.

2 The development of the EAFESA framework

The core of the EAFESA is an intensive exchange of information to improve the findings, which makes use of the general setting of the LCA methodology, consisting of the following four steps: goal and scope definition, inventory analysis, impact assessment, and discussion and implications, as shown in Fig. 1. The challenges mentioned above are recognized and considered in the four steps of EAFESA. In the first step, goal and scope definition, it is crucial that a common goal is established, with background information exchange based on defined scenarios. Additionally, the research scope (e.g., system and geographical boundaries) should be clarified. In the second step, inventory analysis, LCA focuses on technological data collection through the whole lifespan, while ESM revolves around both economic and technological data collection through the energy sector. Meanwhile, this step offers an interface for technology mix definition, collected data exchange and harmonization. In the third step, impact assessment, the calculated results (e.g., environmental impacts and energy mix) are exchanged and discussed between LCA and ESM. The interrelation between LCA and ESM might lead to an iterative feedback loop. The energy mix derived by the ESM should be used as an input for the LCA. The resulting life cycle environmental impacts of each technology could affect the environmental performance of the identified transformation pathways, leading to a possible necessary adjustment of the pathways, if e.g., policy targets are violated. In the final step, discussion and implications, the implications for decision-making processes and policy impact assessment studies are discussed.

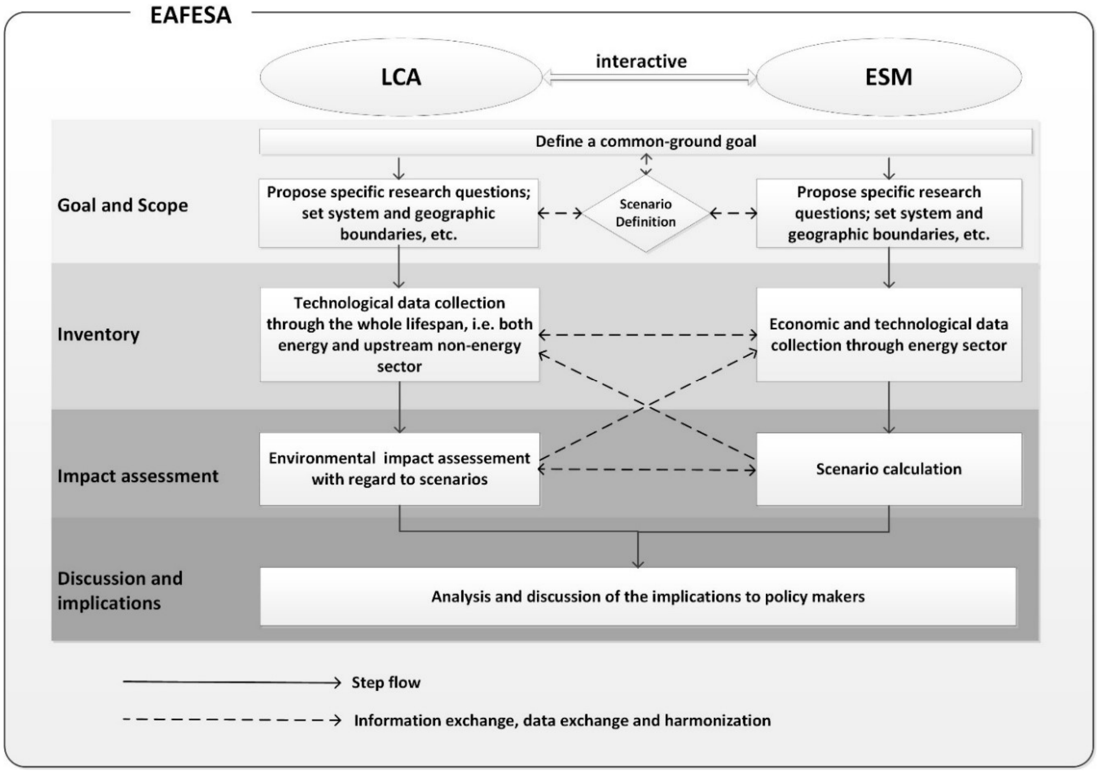

Fig. 1: Overview of Environmental Framework for Energy System Assessment (EAFESA)

3 The applications of the EAFESA framework

The applications of the EAFESA framework can be separated into two directions according to their different study aims: (1) to integrate the ESM output to LCA, and vice versa, i.e., (2) to integrate the LCA indicators to ESM. In the thesis, three case studies are conducted which each consider one of the two model coupling directions. Due to the page restrictions, in the following, Case study A demonstrates the applicability of the EAFESA framework, while Case study B and C only show the results.

3.1 Assessing the trade-offs in the low-carbon electricity system (Case study A)

Case study A analyzes and assesses possible future European electricity systems based on three different energy scenarios. The focus is on flexibility options with different levels of renewable penetration and carbon mitigation targets for EU27 + 3 (i.e., Switzerland, Norway and the United Kingdom[1]) countries as they performed in the Horizon 2020 project REFLEX (Herbst, Michaelis et al. 2016, Herbst, Michaelis et al. 2016, Poganietz, Kühn et al. 2017). The first scenario, termed Mod-RES, serves as a reference scenario assuming that current climate and energy policy targets and actions are realized with no new policy measures introduced. Both of the other two scenarios suppose additional policy actions which achieve a GHG reduction target of 80% of GHG emissions until 2050 compared to 1990, and a specific GHG reduction target for the electricity sector of over 80% for the same period (Zöphel, Schreiber et al. 2019). Although the climate target is becoming more stringent, as announced in the European Green Deal, to achieve carbon neutrality by 2050, the case study uses a looser target, as it was completed before the announcement of the new policy (Fetting 2020). The scenarios differ by assuming a more centralized setting (High-RES Central), comparable to the Mod-RES Scenario, and

[1] The Reflex project was completed prior to the UK exit from the EU, hence data refers to EU+28.

a more decentralized setting (High-RES Decentral) of the energy system (Herbst, Michaelis et al. 2016, Herbst, Michaelis et al. 2016, Poganietz, Kühn et al. 2017).

For this purpose, the framework of EAFESA is applied by coupling LCA and the ESM model ELTRAMOD. The coupling direction is to integrate the ELTRAMOD output to the LCA model. The challenges in the model coupling between LCA and ELTRAMOD are overcome during the four steps of the EAFESA framework and are reflected in the two aspects. Firstly, a prospective LCA considering both market-proved and emerging technologies is developed. The average technologies assumed in ELTRAMOD are disaggregated using LCA data. In this case, wind and solar energy are especially relevant. For example, four types of wind turbines are considered for the average wind technology used in the ELTRAMOD. Technological progress is implemented by varying resource inputs and key performance indicators (e.g., efficiency and lifetime). Additionally, material usage and substitution for future technologies is considered. For example, wind technologies are assumed to increase the tower height and use carbon fiber instead of glass fiber for the production of rotors. Secondly, the data harmonization is conducted, including energy conversion efficiencies, life time of technologies, installed capacities by technologies, emission factor by technologies, and electricity mix. According to the figures, about 33% of parameters of ELTRAMOD and electricity generations by technologies were required to be harmonized with the LCA modelling.

For the environmental assessment, five non-climate environmental impact categories are selected in addition to climate change. These are: particulate matter formation, ozone depletion, freshwater eutrophication, urban land occupation and metal depletion. Both life cycle and direct GHG emissions in 2050 in all scenarios show decreasing trends compared to 2014. However, a difference between the direct and life cycle emissions is also revealed. The share of the direct emissions at the life cycle emissions decreases from 61% (2014) to 25% (2050 High-RES Decentral). The results indicate the effectiveness of policy actions for carbon mitigation, yet reveal the increasing degree of importance of upstream and auxiliary emissions in an electricity system with a large share of RES.

The non-climate environmental impacts by technologies in the three scenarios for 2050 are compared to 2014. Generally, freshwater eutrophication shows a similar pattern to that for climate change, i.e., a noteworthy decline of the indicator value over all scenarios compared to 2014. In the case of Mod-RES, ozone depletion and particulate matter formation are at similar levels to 2014, while the more ambitious GHG reduction target, i.e., both High-RES scenarios, induces increases for both impact indicators. Regarding metal depletion and urban land occupation, any transformation of the European electricity sector leads to even higher impacts, indicating that attention should be paid to any conditions for these two impacts.

3.2 Considering the impact of metal depletion on the European electricity system (Case study B)

Case study B analyzes the impacts of different outlines of policy packages, which address both climate and resource policy targets, on the shape of the European electricity system in the year 2050. Apart from the focus on the interrelationship between climate policy and resource policy, the analysis in Case study B also includes system expenditure, as an additional factor addressed in political and societal discussions.

For the analysis, three different policy-ambitious levels are defined, each reflecting hypothetical decision-making preferences within the ranges between the utopia (0%) and nadir (100%) point, i.e., ambitious (25%), moderate (50%), relaxed (75%). Considering the main driver to transform the European energy system is to slow down climate change, in all scenarios the CO_2 price is set to 160 €/t CO2 in 2050 (International Energy Agency 2016). To reflect different decision-making preferences, the precise GHG emission targets vary between the scenarios, allowing for less ambitious climate policies. However, to emphasize the current societal environment, which strives to slow down climate change, the upper limit of climate change is limited to 50%. Policy packages allowing for a relaxed preference for slowing down climate change are not scrutinized in Case study B. As a result, six scenarios are defined: (1) CC ambitious and MD ambitious (CAMA), (2) CC ambitious and MD moderate (CAMM), (3) CC ambitious and MD relaxed (CAMR), (4) CC moderate and MD ambitious (CMMA), (5) CC moderate and MD moderate (CMMM), and (6) CC moderate and MD relaxed (CMMR). The results obtained from single objective optimizations are called selfish scenarios, i.e., EX selfish, CC selfish, and MD selfish.

Of the six identified policy package scenarios, the two most ambitious scenarios (CAMA and CAMM) result in no mathematically feasible solutions. The relationship between the system expenditure, GHG emissions, and metal depletion for the scenarios with mathematically feasible solutions are compared and analyzed. Comparing the scenario CC selfish with the scenario MD selfish confirms, from a different angle, the strong trade-off relation between climate policy and resource policy. The high costs of achieving the CC selfish scenario level emerge mainly when pursuing from the ambitious level (25%) to the utopia level (0%). Reducing the ambitious level of the climate policy will reduce the system expenditure notably, compared to the CC selfish scenario. A relaxed preference for slowing down climate change could achieve significant expenditure savings while still being ambitious from either a climate- or a resource-related perspective (see CAMR and CMMA). Taking into account the GHG emissions and the metal depletion of the scenario EX selfish as the bottom line, the CAMR scenario is the only one of all mathematically feasible policy package scenarios which sees improvements of both GHG emissions and metal depletion. The GHG emissions would drop by 13% and metal depletion by 8%; but CAMR is 2% more expensive. Other scenarios show a trade-off between GHG emissions and metal depletion, i.e., the reduction of metal depletion leads to an increase of GHG emissions.

The analysis shows that a reduction of the trade-off is possible, but the space for possible solutions is limited. Case study B thus also discusses the possible solutions for policymakers to overcome, or least to smooth the trade-offs between the policy targets. An obvious possible option is to replace primary resources with secondary ones through increased recycling of metals. Any substitution of primary resources by secondary resources would reduce the amount of metal depletion, potentially causing a diminishing effect on the trade-off between both policy targets; a sufficiently large substitution could even overcome the trade-off. More ambitious climate policy targets would demand a higher substitution rate.

3.3 Assessing the GHG emissions of electric vehicles considering different charging strategies (Case study C)

Case study C assesses systematically the GHG emissions of Electric vehicles (EV) in Europe in 2050 considering the different charging strategies. The investigated GHG emissions of EV are those associated with the generation of electricity mix during vehicle usage and EV battery production, including the use for V2G. Three scenarios with different charging strategies, i.e., UNCONTROLLED, ONEWAY, V2G, and a reference scenario WITHOUT_EV is calculated.

It should be noted that the EV battery lifetime is assumed with a fixed energy throughput (i.e., 30,000 kWh, which equals 150,000 km without V2G). The battery survives for the whole lifetime (i.e., 30,000 kWh) and dies at 30,001 kWh. Consequently, V2G leads to higher battery demand according to the assumptions.

The results show uncontrolled charging increases electricity production from natural gas slightly. The two controlled charging strategies, however, reduce dependence on gas-fired electricity production and increase the amount of electricity produced by renewable energy sources (mainly photovoltaics (PV)). Flexibilities from V2G exceed that of ONEWAY, as charging cannot only be postponed, but EV can be used as mobile storage in the electricity system. Due to the efficiency losses in EV charging and discharging, total electricity production in the V2G scenario is slightly higher than in the ONEWAY scenario.

The GHG emissions associated with the production of electricity in the UNCONTROLLED, ONEWAY, and V2G scenarios are compared to WITHOUT_EV in 2050. Emissions from UNCONTROLLED are higher than those of both controlled charging strategies. The emissions are lower in the ONEWAY scenario, and even further decreased by V2G, due to the increasing use of electricity from RES. It indicates that both controlled charging strategies have a positive impact on global climate change from an energy system perspective.

Using the WITHOUT_EV scenario as a reference, the life cycle GHG emissions of the UNCONTROLLED and ONEWAY scenarios are higher by 90 Mt CO_2-eq. and 57 Mt CO_2-eq., respectively, whereas emissions in the scenario V2G are 4 Mt CO_2-eq. lower. Considering the potential risk of accelerated battery degradation due to additional charging and discharging in V2G, V2G may cause more emissions only due to enhanced battery degradation. Nevertheless, in this scenario V2G still outperforms unidirectional charging in terms of GHG emissions. The reduced GHG emissions associated with electricity generation more than compensate for the increased emissions associated with the EV battery.

Case study C performs uncertainty analyses to examine the potential impacts of variations of some important inputs on the systematic performance. The first is related to further technical progress in EV batteries. The results confirm the effectiveness of technical progress in reducing life cycle GHG emissions. The second uncertainty is associated with EV availability in the V2G scenario. When the availability of EV increases from the initially assumed 50% to 100%, the total GHG emissions from EV increase, taking into account both electricity and battery production. One reason is the higher emissions due to the higher usage of the batteries. The other reason is due to the shift of electricity production from wind technologies towards PV technologies, as PV technologies produce more life cycle GHG emissions than wind technologies when generating the same amount of electricity. The results also show that a complete elimination of emission-intensive generation, such as electricity generation from gas, is not possible due to the days and longer periods without sufficient electricity generation from RES.

The discussion in the case study shows policymakers that the use of EV could reduce GHG emissions by 36% by simply replacing ICEV. Controlled unidirectional charging and V2G add another 4 or 11 percentage points on the European level. However, for these gains an efficient implementation of V2G is required.

4 Conclusions

Overall, the thesis shows the important role of coupling the LCA approach to energy system analysis in the transition to a decarbonized energy system. The developed EAFESA framework provides a guideline to overcome the challenges in model coupling between LCA and ESM. The case studies bring awareness of issues which often receive little attention in the political discussion, and provide possible solutions for policymakers:

- The effectiveness of renewable technologies on reducing GHG emissions has been verified, even from a life cycle perspective.
- The future decarbonized electricity systems are however accompanied by a series of environmental and resource-related trade-offs, especially increased metal depletion and urban land occupation.
- The trade-offs between climate change and metal depletion is possible to smooth with only slightly increased system expenditure. However, recovery of metals could to some extent potentially reduce and even diminish the trade-offs between climate change and metal depletion.
- The effectiveness of EV in reducing GHG emissions is verified. Controlled charging strategies (unidirectional and V2G) have an enhanced influence on the reduction of GHG emissions over simply replacing conventional cars. However, V2G needs to be implemented efficiently.

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1. Motivation

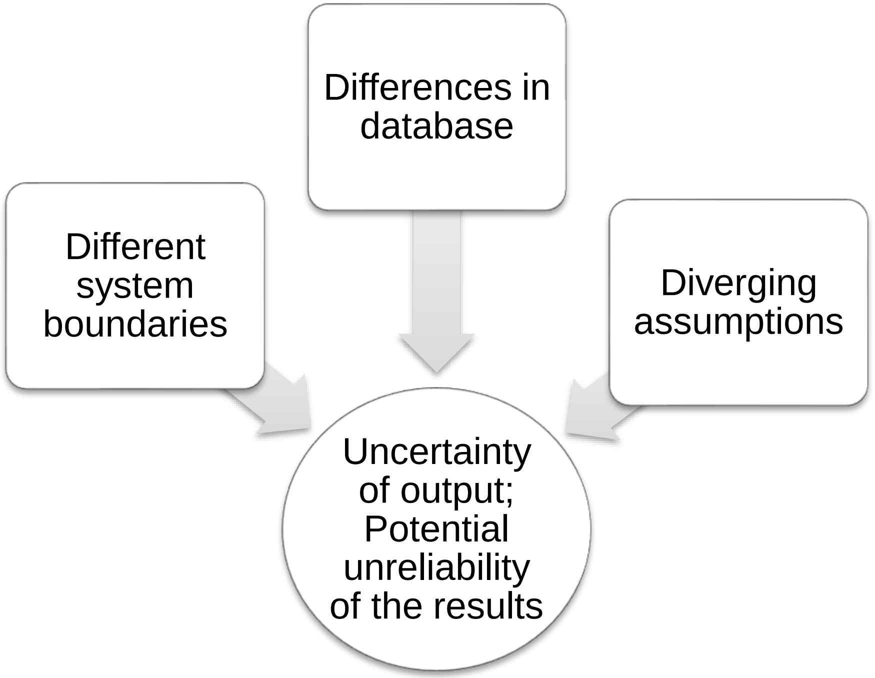
LCA and ESM : Coexistence of opportunities and challenges in the model coupling

Opportunities

A widen perspective

- For ESM: a life cycle persepctive, diversity of environmental impacts, study scope expansion
- For LCA: from a technology assessment to an energy system assessment, an energy system perspective
- For Policy: new insights gained from both life cycle and energy system perspectives

Challenges



Data harmonization and consistency

- To identify elements in a systematic way in both models

Assessment for future technologies or systems

- To conduct a prospective LCA model

2. Development of methodological framework

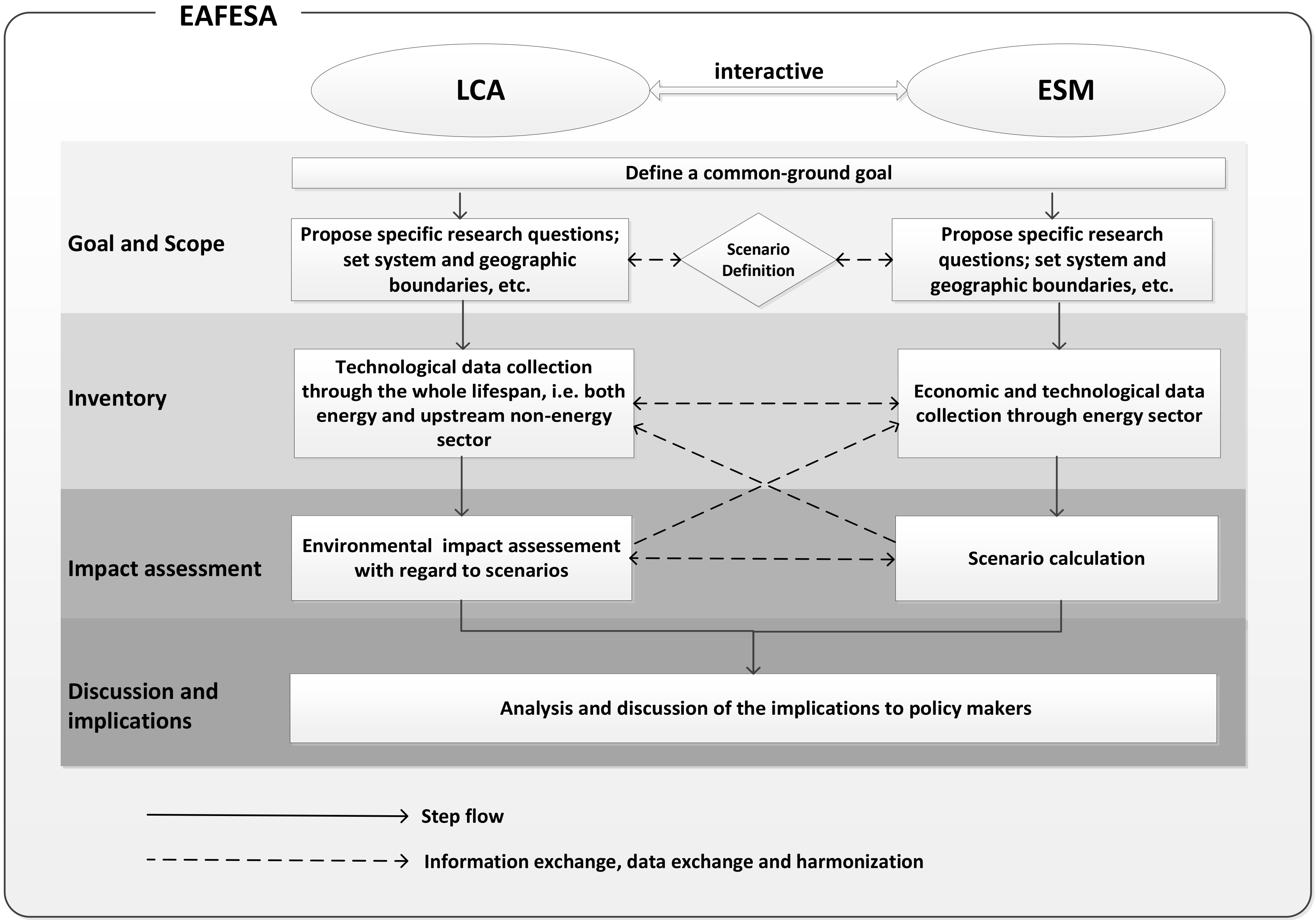


Fig. 1: Overview of Environmental Framework for Energy System Assessment (EAFESA)

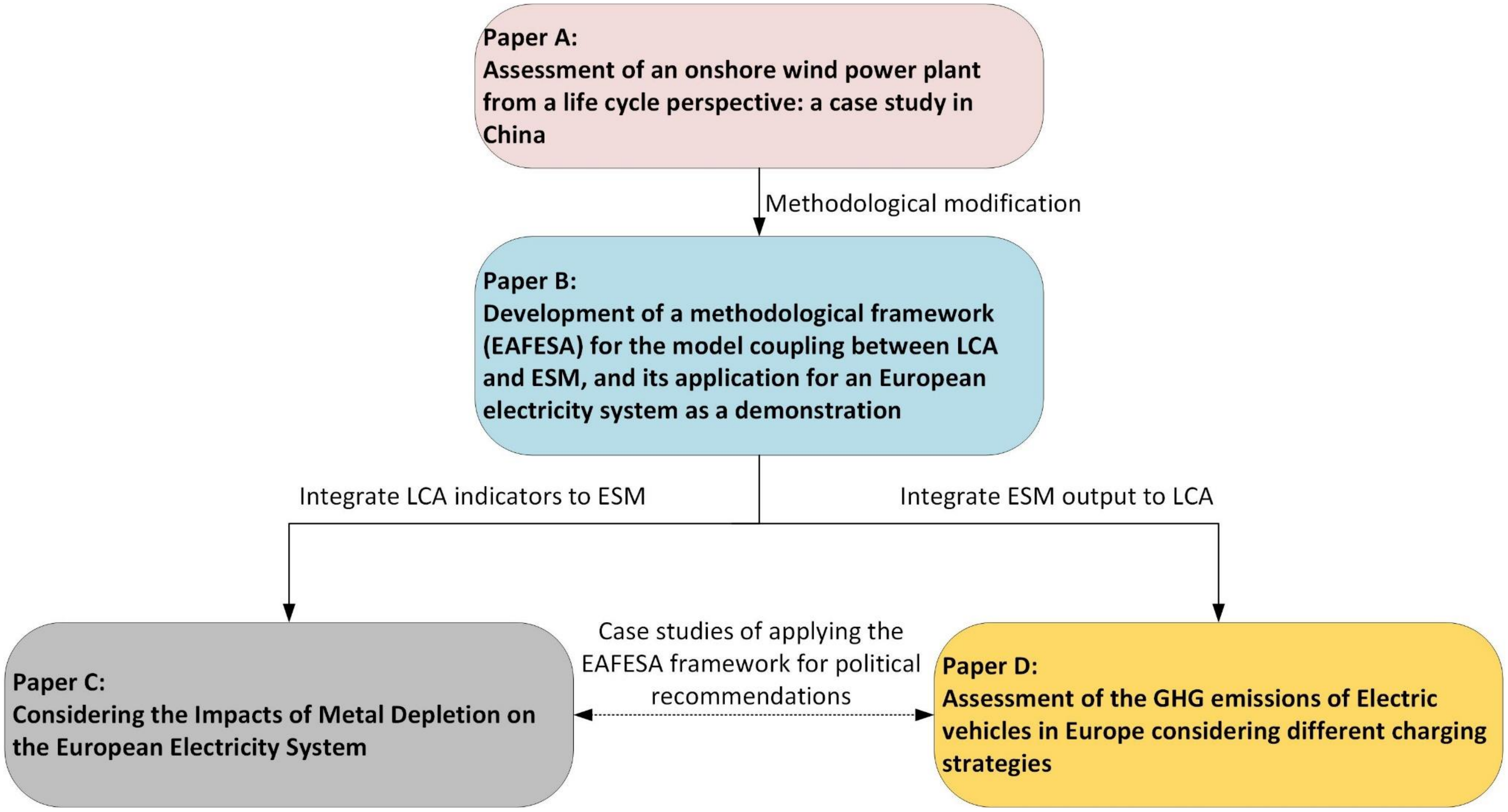
3. Case studies

- **Case study A**
  - Study aim: assess the environmental impacts of European electricity system with flexibility options in 2050
  - Implications:
    - Renewable technologies on reducing GHG emissions: effectiveness
    - Trade-offs: metal depletion, urban land occupation

- **Case study B**
  - Study aim: consider metal depletion in future decarbonized electricity system
  - Solutions to reduce the trade-offs between climate change and metal depletion
    - increase system expenditure slightly
    - recovery of the metals

- **Case study C**
  - Study aim: assess the greenhouse gas emissions of electric vehicles in the future
  - GHG emissions of electricity production: WITHOUT_EV > UNCONTROLLED (reduced by 36%) > ONEWAY (reduced by additional 4%) > V2G (reduced by additional 11%)
  - A higher EV availability shows higher GHG emissions from V2G due to a higher battery demand, implying an efficient implementation is requirement

4. Overview of the included papers



Paper A:
Xu, L., Pang, M., Zhang, L., Poganietz, W.-R., Marathe, S.D., 2018. Life cycle assessment of onshore wind power systems in China. *Resources, Conservation and Recycling* 132, 361-368.

Paper B:
Xu, L., Fuss, M., Poganietz, W.-R., Jochem, P., Schreiber, S., Zoephel, C., Brown, N., 2020. An Environmental Assessment Framework for Energy System Analysis (EAFESA): The method and its application to the European energy system transformation. *Journal of Cleaner Production* 243, 118614.

Paper C:
Xu, L., Wang, Z., Yilmaz, H.Ü., Poganietz, W.-R., Ren, H., Guo, Y., 2021. Considering the Impacts of Metal Depletion on the European Electricity System. *Energies* 14(6), 1560.

Paper D:
Xu, L., Yilmaz, H.Ü., Wang, Z., Poganietz, W.-R., Jochem, P., 2020. Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies. *Transportation Research Part D: Transport and Environment* 87, 102534.

Thank you for your attention !