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ABSTRACT

The transition towards renewable energy will operate on different geographical scales. Many of the concrete steps will address the local level; however, these have to align with the broader energy perspective. It is therefore necessary to develop methods that enable cities to assess the compatibility of the local renewable energy strategy to the surrounding national and global energy systems. This paper presents a methodology to design Smart Energy Cities within the context of 100% renewable energy at a national level. Cities and municipalities should act locally with regard to local demands but acknowledge the national and global context when addressing resources, industry and transport. The method is applied to the case of transitioning the municipality of Aalborg to a 100% renewable smart energy system within the context of a Danish and European energy system. The case demonstrates how it is possible to transition to a Smart Energy City that fits within a 100% renewable energy context of Denmark and Europe. The suggested methodology is framed in a way that makes it applicable to other cases globally.

1. Introduction

Many cities, municipalities and local communities around the world have involved themselves in designing strategies for transforming the energy supply of their region into a future sustainable energy system. In Copenhagen they have an official plan that targets CO2 neutrality in 2025 [1], however here they do not leave room for the surrounding national and global energy system since they rely on export of electricity to offset emissions from transport [2]. In that context, an alternative plan exists that aims towards a 100% renewable Copenhagen in 2050. That report makes a qualitative assessment of how Copenhagen relates to the surrounding Danish and global energy system but does not systemise the inclusion of the surrounding energy system in a general way [3]. In Vejle, Denmark the goal is to become a resilient city, which includes that they want to be climate neutral before 2050. Here however, there is currently no mention about how Vejle will coordinate this with the surrounding national and global resources [4]. Frederikshavn, Denmark is also targeting 100% renewable energy in 2050. Here the focus is on the specific local steps towards 100% renewable energy, while how the local transition relates to the rest of Denmark is left out [5]. This shows that while Danish cities have clear ambitions towards a renewable transition, they do seldom consider the national and global transition, which their local actions might impact.

New York, USA [6] wants to reduce carbon emissions by 80% in 2050. While this ensures local actions and targets for the city of New York, it does not take into account the effect on the surrounding energy system in the state or the country. In the study of how Inland Norway can become 100% renewable [7], only the local resource potential in the two counties was used. The penetration of renewables in the city of Vaasa has been studied [8] in the context of the local region Ostrobothnia, but not in relation to overall development of renewables and energy systems in Finland or globally. The potential for hybrid renewable energy infrastructure is investigated for the city of Vancouver, Canada [9]. Here a framework for planning urban energy systems is provided, but this does not include taking into account the local energy systems effect on surrounding cities' and countries' opportunities to design renewable energy systems. The study only allocates local biomass resources in British Columbia to the city of Vancouver. These studies highlight that cities not only in Denmark, but globally are transitioning to 100% renewable energy, and there is a great interest in designing scenarios and plans that can fulfil local targets. In total, according to Sierra Club, over 150 cities have adopted clean energy targets in the US, including six cities that have already reached the target [10], Jacobson et al. has designed 100% renewable energy scenarios for 53 American

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cities which all utilise the wind, water, solar principle [11], and globally over 700 cities have committed to renewable energy in relation to the Paris Agreement [12]. All plans utilise different concepts and targets for the transition. Concepts such as decarbonized [13], net-zero energy [14], carbon neutral [15] and 100% renewable energy systems [16] are used and many different approaches and aims have been applied. These concepts and scenarios all set up principles and targets towards more renewable and sustainable futures for the individual city, but they do not mandate that the city or region to take into account how the renewable energy transition goes along with the rest of the country or world also transitioning to renewable energy and potentially using the same resources.

Overall, this shows an ambition towards a local transition to renewable energy and a more sustainable future, however these are very seldom put in relation to the surrounding global transition. It is therefore necessary that all these cities, and the cities not yet committed towards more renewable energy systems, all are able to fulfil a renewable energy transition. For this to happen, the cities need to leave room for each other and utilise the scarce national and global resources in a way that allows for, in the end, a global transition to 100% renewable energy. This does not mean that cities need to slow down their transition, but it requires cities to take into account the right knowledge when they are transitioning to 100% renewable energy.

Cities and local regions are important. Climate change mitigation cannot be addressed from global or national levels alone; local action and local strategies are essential for climate change mitigation shown by Thellufsen [17] and Calvillo et al. [18]. Cities and local regions can also drive concrete actions to promote a sustainable transition [19]. However, the local efforts need to be coordinated with global and national efforts in general, as well as the efforts of neighbouring cities and communities if the world should successfully meet the challenge of climate change mitigation in an affordable and possible way.

At the local level, such coordination raises questions like: How much biomass can be included in local strategies to still maintain a sustainable use of biomass at the global level [20]? How can transport needs be defined at the local level? Does it only involve transport within the region or should transit in and out of the region be included? Where and how to include international air transport and shipping? What about industry? Can a region with only limited industry disregard the embedded energy in its use of cement, steel and other products? Should a small-town region with a large steel plant account for all the resources needed for the local industry, even though it may export most of its products out of the region?

In literature, these challenges of defining needs and available resources have been met in many ways. This includes defining different concepts of future sustainable energy systems and solutions. For example, in the case of Gran Canaria, international transport is not included [21], and in the case of Inland Norway, the local biomass resources are used as the limit for the region [7,22]. The problem is, however, that such differentiated local solutions may result in conflicts of interest such as overexploiting the biomass resource and disregarding global issues that need to be considered locally. Thus, these strategies may not identify a proper affordable and coordinated solution at the global level.

It is necessary to propose a set of principles due to the large number of cities heading towards renewable energy, and a risk of a vast amount of local solutions that might fulfil local ambitions but will not allow the entire globe to transition to renewable energy. This paper seeks to develop a guiding principle and methodology applicable to cities and local communities when designing sustainable energy futures. The aim is for them to become coordinated elements of the national and global efforts. These principles and methodology are demonstrated on the case of designing a 100% renewable energy strategy for the municipality of Aalborg, Denmark.

2. Methodology and guiding principle

The overarching guiding principle is that local action should be balanced to match national or global action. Where Kant's Categorical Imperative dictates that actions should be able to form a generalised norm, the principle here is rather that local action should not necessarily mirror that of other local actions as local conditions may differ in terms of, e.g., resource availability. Instead, local action should be coordinated in such a way as not to hinder local action elsewhere, while working towards the same aim.

As a first step, within the guiding principle of the design of energy systems for sustainable futures for local communities, the systems should be designed to fulfil their role in meeting the national strategy. This should further be part of meeting overall international or even global strategies.

This requires that a region, city and municipality need to situate themselves within national and international contexts in order to make a coherent strategy to transition to for instance 100% renewable energy.

The second step of the guiding principle is to identify how to deal with issues that are not logically embedded in neither local nor global action. This study points specifically to five elements that need to be dealt with and highlights specific guidelines for including them in a local 100% renewable energy plan:

1) Identifying fuels for heavy transport, power plants and industry, and the availability of this fuel in a global perspective. In this study, biomass is used as a fuel for covering the last energy demands. When using biomass as a fuel, it is important to identify the amount of biomass that can be used due to both resource availability [20] and potential emission and health impacts. In terms of the sustainability of resource availability, only the residual biomass should be used to keep the environmental impacts low in terms of CO_2 emissions. This is shown both for biogas [23] and biomass [24]. Therefore, the principle used is that the local region should only use its share of national, European and global sustainably available biomass resources. This can be defined using the share of population.
2) The transport demand, including international aviation and shipping. The principle used is to cover the local transport demand but also a determined share of transnational transport, transit, international aviation and shipping. The local demand can be identified by using the distances driven by the city's population, but in this study the population share is used to define transport demands. Thus, this also includes demands for aviation and freight.
3) The industrial demand. Since energy demands for industry result in products available nationally and globally, the principle is that the local region should cover its share of the national, European and global industrial use of energy.
4) Access to national variable renewable energy sources. The principle is to identify the local renewable energy sources but also investigate the total national sources. Some regions will have more renewable energy available, while others will have less. The goal is for the intake of renewable energy to fit the local energy demands, including points 1–3 in the guidelines. In principle, some regions will be net exporters of renewable energy while others will be net importers. Thus, local typology can be taken into account [25]. For instance, good onshore wind resources might be utilised locally to leave offshore wind for the major cities.
5) Electricity import and export. The import and export of electricity should be balanced to take the city's share of national and international storage and flexible production technologies into account.

Heating and cooling demands are locally constrained to the city and municipality, thus the guiding principle here is to model the local demands but also to include local constrained resources, for instance industrial excess heat and geothermal resources. This can be done through mapping of resources [26].

One could raise and deal with more questions using the same guiding principle. The main point is that the strategy for a region is not designed for an isolated energy island but instead it forms an integral part of the national and global strategies.

To carry out such plans and to quantify the effects of the local energy system transition towards 100% renewable energy, the use of energy system analysis is required. The energy system analysis tool should be able to investigate the entire energy system in terms of electricity, heating, cooling, industry and transport demands. Furthermore, by conducting hourly analysis on the entire year it is possible to investigate potential system effects of system integration and the implementation of storages. The energy system analysis tool chosen by the planners and researchers should be able to carry out these aspects to ensure a renewable energy transition of the entire energy system. EnergyPLAN has been chosen for this study, which is further described in section 3.7.

3. Applying the general principle to the smart energy aalborg case

The study "Smart Energy Aalborg" is a vision of transforming the municipality of Aalborg into 100% renewable energy in 2050 [27]. The vision is made by researchers at Aalborg University at the request of the city council of Aalborg and in collaboration with local municipality-owned utilities and authorities. Moreover, the strategies have been discussed with local companies and industry to further a suitable implementation which could also facilitate job generation and economic development. The case of Aalborg is defined as the area within the administrative borders of Aalborg Municipality.

The following section uses the vision to demonstrate how to apply the guiding principle to a specific case with a focus on five essential aspects, namely.

- the definition of sustainable biomass,
- how to define and include transport needs
- how to define and include the industry
- the definition of available wind and solar resources taking into account national offshore potential
- the balancing of the electricity supply and demand.

The entire scenario is documented here [27], with some key numbers attached in Appendix A. The documentation covers the specific heat demands in Aalborg in 2050 and the implemented heat savings. It covers the design of the heating system in Aalborg, which is based on a concrete local analysis and thus requires local technologies. This paper focuses on the choices made regarding the demands and energy production units described in the guiding principle.

It is important to note that in accordance with the guiding principle, the Smart Energy Aalborg case is situated within the Smart Energy Vision for Denmark [28]. Thus, all principles are based on this national vision, while the national vision must be situated within the Smart Energy Europe context [29]. For the case of Smart Energy Aalborg, the primary energy system calculations were carried out in EnergyPLAN. This software is also described in this section.

3.1. Identifying the national and international context

In the case of the municipality of Aalborg, the goal is for Aalborg to transition to a 100% renewable energy supply in 2050 in such a way that Aalborg forms an integrated part of Denmark and meets the same national goal. This also means that Denmark should be coordinated with Europe and in the end with the global transition to 100% renewable energy. The following national strategy for Denmark and Europe is used:

- For Denmark, the national strategies of transforming the Danish energy system into a 100% renewable energy system by 2050 expressed in the *IDA Smart Energy Denmark* strategies created by the Danish Society of Engineers in 2006 [30], 2009 [31] and 2015 [28].
- For Europe, the study *Smart Energy Europe* [29] expressing a vision for the transformation of Europe into 100% renewable energy by 2050 using the same guiding principles as the Danish case.

These two strategies or visions for Denmark and Europe express solutions in which the use of biomass, the definition of transport needs and the balancing of variable renewable energy sources (VRES) are dealt with in such a way as not to compromise global efforts of meeting the same goals. Moreover, both strategies use a smart energy systems approach [32,33], i.e. they include the entire energy system and have an integrated focus to identify the most affordable solutions across traditionally separate energy sectors.

3.2. Sustainable biomass

It is important to determine the available biomass for Aalborg Municipality within the limits of sustainable use of biomass, preferably residual sources. In 2010, a specific assessment of the biomass resources in Aalborg Municipality was made [34]. The results are shown in Table 1. The table also shows Aalborg's share of Denmark's total biomass resources in 2050 based on the national IDA strategy [28].

As shown, the available biomass in 2010 in Aalborg was similar to the national available resources; however, the sources differ with more waste and less agriculture in Aalborg than in Denmark as a whole. This means that Aalborg produces for instance more waste than the average share of Denmark's overall waste production.

Going towards 2050, the guiding principle described in section 2 argues that it is necessary to consider the national share of biomass in 2050. For the Smart Energy Vision 2050, the Danish biomass potential is estimated at 150–250 PJ [28]. Aalborg's share (3.8%) of this potential is 5700–9500 TJ, based on Aalborg's share of Denmark's inhabitants.

Applying the guiding principle for available biomass in the case of Aalborg results in a very similar biomass availability when comparing the local production and the share of the national biomass resources. In other cases, this estimation could have allowed an import of biomass or required that a municipality use less biomass than available.

In the specific case of Aalborg, it has been chosen to utilise the local resources.

After examining 7 different studies, an average level of 27 GJ/person/year was identified in the study "Smart Energy Europe" [29]. The Aalborg numbers above (240,000 persons in 2050 according to Danish statistics) correspond to approximately 25 GJ/person/year and are therefore within the range of the sustainable use of biomass. However, the research in this field comes to a wide range of different results and is still ongoing [20], and potentially the biomass availability is lower than 25 GJ/person if only residual sources should be used. Regarding the health impacts of biomass, it is shown [35] that these can be limited by focusing the use of biomass in central plants. These can be located strategically and where proper filters can be installed. Therefore, the

Table 1
Biomass resources in Aalborg based on 2010 assessment.

[TJ/year]	Share of Denmark's expected biomass resources	Biomass resources in Aalborg Municipality
Straw	1800	980
Wood	1600	670
Biogas	1400	520
Fibre fraction	–	60
Energy crops	–	1360
- grass	–	200
Waste	1400	2300
TOTAL	6200	6090

Aalborg plan does not allow for biomass for heating in individual households nor for direct combustion in engines.

3.3. Transport needs

Transport in a municipality involves both local demands like local car trips and bus services as well as cross municipal transits. Furthermore, the inhabitants in the municipality also have a transport demand associated with domestic and international aviation and the international shipping of products.

Based on the guiding principle, Aalborg Municipality has to cover the transport demands associated with its population share of the total national transport demand. This national transport demand for Denmark has to be the Danish population share of the international transport demand. In the case of the Smart Energy Vision for Denmark, the European transport demand has been used as the international framework. These transport demands should consider the potential global demands in 2050. If all communities and countries apply the guiding principle, all transport demands will be accounted only once.

Aalborg Municipality's energy demand for transport in 2016 is determined based on the national transport demands [27]. Aalborg is responsible for 3.8% of the Danish transport demands. In 2016, the transport demand was almost entirely fuelled by oil. For the Smart Energy Aalborg case, the development in the transport demand follows the increase in population in Aalborg. However, based on the measures identified in the IDA Energy Vision, the entire transport demand shifts to a 100% renewable energy context. Heavy-duty transport and international shipping will be provided by electrofuels [36] to some extent, while private transport is comprised of smart charge electric vehicles [37]. Furthermore, rail transport will also be electrified.

In principle, by increasing the use of direct electric vehicles (cars, trucks, busses, trains, ships etc.), the efficiency of the overall system is also increased. However, not all transport needs can be supplied by direct use of electricity. Some transport needs still require gaseous and/or liquid fuels [38]. Due to the promising development in electrification [39], compared to the IDA Energy Vision, 20% more of the heavy-duty transport is assumed to be electrified. Table 2 shows the inputs of fuels to cover the transport demand in 2050. The increased efficiency in the transport sector predominantly aligns with increased electrification.

3.4. Industry

Currently, the local energy demand for industry is quite high in Aalborg Municipality compared to other parts of Denmark. In the 2016 energy balance, the fuel use in local industry (excluding wind and solar) to cover all current production and demand in the municipality is 3660 GWh out of a total 9431 GWh. The reason is that Aalborg Portland, a cement factory, is situated within the municipality. However, the energy demand for Aalborg Portland covers to a large extent the production of cement exported globally; thus, it is relevant to adjust the industrial demand for the Smart Energy Aalborg case.

The guiding principle defined in the methodology argues that Aalborg should be responsible for its population share of the primary energy demand for national industry in Denmark. This means that the energy supply that Aalborg needs to become renewable should only sufficiently cover approximately 3.8% of the Danish primary energy demand for industry.

Table 2
Energy demand for transport.

[TWh]	2016	2050
Diesel/DME	1.05	0.605
Petrol	0.6	0
Jet fuel	0.4	0.33
Biofuel	0.09	
Electricity	0.01	0.403

The application of the principle means that the fuel supply for industry to be covered by Aalborg was 990 GWh in 2016. This corresponds to almost a 75% less fuel needed for industry compared to the original fuel demand. The difference for the reference system is seen in Fig. 1. For the case of Aalborg, the guiding principle thus results in a lower amount of fossil fuels that need to be replaced.

By using a national average, the plan implements the technological developments of industry suggested in the Smart Energy Vision for Denmark. The Smart Energy Aalborg case therefore accounts for the following transition steps for the industrial sector:

- Conversion of fuel demand for industry to electricity demand
- Efficiency increases in the production facilities
- Heat demand savings and increased heat demand covered by district heating.

The fuel demand for industry in Smart Energy Aalborg 2050 is therefore 451 GWh. Based on the available biomass share, the fuel demand is supplied by 131 GWh of biomass and 322 GWh of gas produced by gasification and biogas. This is also shown in Fig. 1. The industry furthermore has an increased electricity demand from 381 GWh in 2016 to 781 GWh in 2050.

One of the important factors is that the guiding principle does not affect the actual heat delivered from industrial waste heat. The reason is that district heating systems are geographically limited, meaning that it is necessary to include the actual waste heat potential in order to model their operation precisely. The guiding principle for industry only accounts for the energy supply to industry. See Appendix 1 for more information regarding waste heat inputs from industry to the district heating system.

3.5. Share of national variable renewable energy sources

Aalborg Municipal cannot be seen as an island in terms of electricity production. On the other hand, it is also necessary to take into account the local resources and the extent to which local variable electricity production sources should cover the demand.

To discuss the balancing of electricity demand and supply, it is necessary to look at both the electricity demand and the electricity supply.

While an amount of the electricity demand is tied to the local household consumption in Aalborg, some of it is also specifically used for industry and commercial buildings that provide services to users and consumers outside Aalborg. In the energy balance for 2016, Aalborg locally uses 404 GWh for electric stoves and lighting, while electric engines in industries account for 934 GWh. On top is 15 GWh for electric heating. In total, the local electricity demand is 1353 GWh [27]. It is assumed that the electric stoves and lighting to a large extent can be attributed to the local electricity demand, while the electric engines are for industrial demands.

When applying the guiding principle, Aalborg should only be responsible for its population share of the national electricity demand. Based on the IDA Energy Vision, the electricity demand for Denmark was divided and households used 8800 GWh, while industry and services used 18,800 GWh. Aalborg's share of these two demands are 334 GWh for households and 714 GWh for industry and services. In total, this accounts for an electricity demand of approximately 1050 GWh. The system must furthermore account for grid losses. Thus, the total electricity demand for households and industries in Aalborg Municipality in 2016 is 1150 GWh excluding electricity demand for the heating and cooling of households.

Towards 2050, the IDA Energy Vision assumes a number of savings but also a number of services currently provided by fuels but later to be provided by electricity. This combination of savings and conversions results in an electricity demand of 1244 GWh in 2050 in Aalborg for

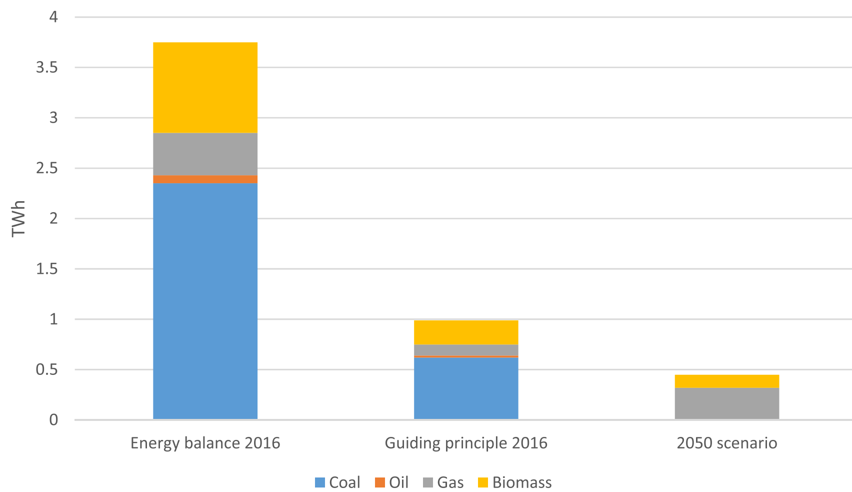

Fig. 1. Fuel demand for industry in Aalborg Municipality in 2016 based on actual industrial demand and allocated industrial demand. The fuel demands for industry in 2050 is also shown.

industry and households.

To cover the electricity demand, it is important to look at the available resources. For 2050, IDA Energy Vision 2050 assesses the national electricity production with the electric capacities highlighted in Table 3. Table 3 also shows 3.8% of the capacities, highlighting the available capacities for Aalborg.

The numbers in Table 3 give a total VRES production of 3230 GWh. However, the mix in renewable energy capacities has been chosen based on the availability of local resources in Aalborg. This reduces the need for offshore wind capacity, which can be used by the major urban areas in Denmark, for instance Copenhagen and the surrounding cities in the capital area. Based on [40], Aalborg is assessed to have sufficient roof tops to increase the solar power capacity and also sufficient land area for wind turbines [41].

Second, with only a few decentralised district heating areas, the decentralised CHP electric capacity is smaller than the Danish average. In addition, due to the large amount of surplus heat in the central district heating area, the need for central CHP and heat pumps for district heating is also lower. In total, this also lowers the electricity capacity on the central plants.

The local electricity capacities for Aalborg used in the model are also shown in Table 3. The VRES capacities have been determined based on discussions with the local municipalities and their potential projects for wind and solar, while the central power plant and combined heat and power plant capacities are based on the specific balance between import and export. The decentral CHP capacities are the same as today in Aalborg Municipality.

These capacities result in 2700 GWh of VRES production. Furthermore, this balances the grid in such a way that Aalborg has 40 GWh of electricity import but also 50 GWh of electricity export throughout the year.

This balancing of electricity between demand and supply is relevant to investigate further, since it relates to the surrounding energy system.

Table 3
Electric capacity in Denmark 2050, Aalborg's share of the Danish capacity and the implemented capacity in Aalborg based on local resources.

MW electric capacity	Denmark 2050	Aalborg's share	Aalborg 2050
Onshore wind	5000	190	285
Offshore wind	14000	532	277
Solar power	5000	190	458
Central PP/CHP	4500	171	110
Decentral CHP	1500	57	21.6
Electrolyser	9009	342	330

This next section therefore expands on how well the local electricity balance connects with the surrounding energy system.

Apart from the main scenario, which utilises electrolysers for the final balancing, three scenarios are posted. The first scenario involves an increased export of electricity (or turning off wind turbines); the second uses batteries for balancing, and the third involves steam storage.

3.6. *Balancing of electricity demand and supply*

An important issue to determine for a sustainable energy solution in a local community is to identify the extent to which the community can balance its electricity supply and demand on an hourly basis and the extent to which it should be allowed to rely on the assistance of neighbouring regions.

Applying the guiding principle to this question leads to the following result: On one hand, a local community should not be an isolated island, since all communities will have mutual collaboration benefits to some extent. On the other hand, all regions cannot rely completely on others to solve their problem.

Therefore, in principle, a local community should exchange with surrounding regions to such a level that the exchange is the best for the overall system and invest in flexibility to deal with the rest of the imbalances.

Studies have indicated that in a future 100% renewable European electricity supply based on wind and PV, up to 40% of the national imbalances can be dealt with by mutual exchange assuming no limits in the electricity transmission lines [42]. Moreover, large hydropower systems (especially in Norway) constitute a balancing capacity that could be used also by its neighbouring regions. One could argue that Aalborg could have a share of that if applying an optimal use to the overall system. Thus, for the case study of Aalborg it has been defined that approximately 50 GWh/year corresponding to 10–20% of the gross imbalances should be dealt with by import/export of electricity, while the rest should somehow be dealt with in the system. This corresponds to half of Aalborg's share of the national imbalances identified in the IDA Energy Vision. This number is used to analyse which kind of investments Aalborg needs to make to contribute to the overall system balancing. The specific number might be a little too high or too low. However, as shown later, the number is not decisive in the principle analysis comparing the feasibility of the different options. It should further be emphasised that the exchange will naturally differ from one year to another.

3.7. EnergyPLAN

To carry out the energy system analysis needed to assess a strategy for 100% renewable energy in Aalborg utilising the guiding principle described above, EnergyPLAN was used.

EnergyPLAN is an energy system analysis tool that simulates the entire energy system [17]. This includes the electricity, heating, cooling, transport and industry sectors. These sectors are all interconnected and simulated for every hour in a whole year. This includes technologies such as heat pumps, electric boilers, electrolysers, gasification plants and CO_2 capture units. To operate the model, the user needs to define inputs such as capacities, efficiencies, demands and costs based on which the model simulates the operation of the energy system. This generates outputs such as total annual costs, electricity balance, primary energy use and CO_2 emissions.

EnergyPLAN has the capability of operating in technical simulation or in economic simulation mode. This study uses the technical simulation strategy. Here EnergyPLAN prioritises units based on fuel efficiency, with maximum usage of local energy production. This means that electricity demands first are covered by variable renewable energy, then by power from combined heat and power plants, and finally by electricity imports and power plants. For district heating demands, first waste heat is used, then heat from heat pumps using electricity from variable renewable energy, then heat from combined heat and power plants and finally heat from boilers.

4. Results

Based on the general principle and methodology described above, it is possible to design a Smart Energy Aalborg vision for a sustainable future of Aalborg Municipality. This section presents the results of the application of the guiding principle to transition Aalborg Municipality to a 100% renewable smart energy system. The analyses have been carried out in EnergyPLAN [17], in which a reference model of Aalborg in 2018 has been made, based on current energy demands in Aalborg, combined with the guiding principle to determine industrial and transport demands. The 2018 reference scenario has been extrapolated to a 2050 reference scenario, the 2050 Business as Usual (BAU) scenario. From the 2050 reference scenario, a 2050 smart energy system has been designed, based on the principles of smart energy systems [33] and the guiding principle described in this paper. The process is fully documented here [27]. The starting point for the design of the vision is the existing energy supply (year 2018) illustrated in the Sankey diagram of Fig. 2. Fig. 2 is based on the inputs and outputs representing one year simulated in EnergyPLAN. As one can see, the current system is largely based on the burning of fossil fuels, even though wind, biomass and waste make a certain contribution.

The energy balance in the 100% renewable smart energy city of Aalborg can be seen in the Sankey diagram in Fig. 3, which shows the energy demands and the results from EnergyPLAN in terms of fulfilling these demands in 2050. In accordance with the guiding principle, the smart energy city is able to fulfil the local energy demands for heating while utilising local resources. However, the local resources are used in a way that allows other Danish cities, Denmark as a country and Europe to transition to 100% renewable smart energy systems. Due to the methodology suggested, the excess heat is accounted for as a local energy source, instead of being tied to the industry demand. This is because the industrial energy demand relates to Aalborg's share of the national industrial energy demand.

The Sankey diagram makes it possible to identify the usage of electricity from renewable energy in terms of wind, solar and biomass. The wind resources are predominantly used for covering the electricity demand, while biomass is gasified to a large extent and some of the waste resources are burned directly in an incinerator.

The biomass, combined with the electricity used in electrolysers, is used to produce gas for power stations and fuels for the transport and industrial demands which are determined based on the guiding principle. As mentioned, the biomass usage is equal to the local resources in Aalborg Municipality, which correspond to the nationally allocated biomass resource.

Electric heat pumps cover the heating demand for individual households. The individual heating demand is only 0.21 TWh out of a total demand of 1.86 TWh. For the district heating demand of 1.65 TWh, excess heat from the local industry provides 0.86 TWh of heat, which includes low-temperature waste heat sources that need boosting with a heat pump. Furthermore, heat pumps, geothermal sources and heat from

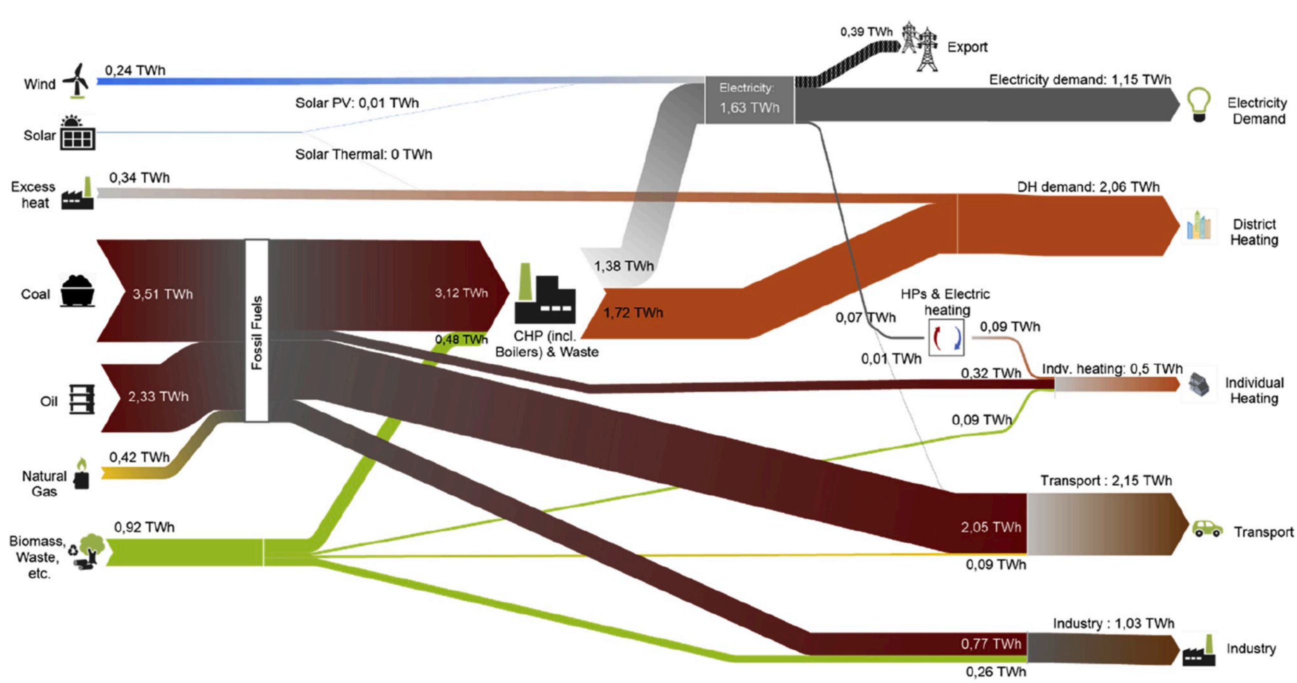

Fig. 2. Sankey diagram of Aalborg's energy system in 2018 based on the results of the EnergyPLAN simulation of the 2018 model. It shows the yearly input of primary energy and how it is utilised in various conversion technologies to supply the energy demands.

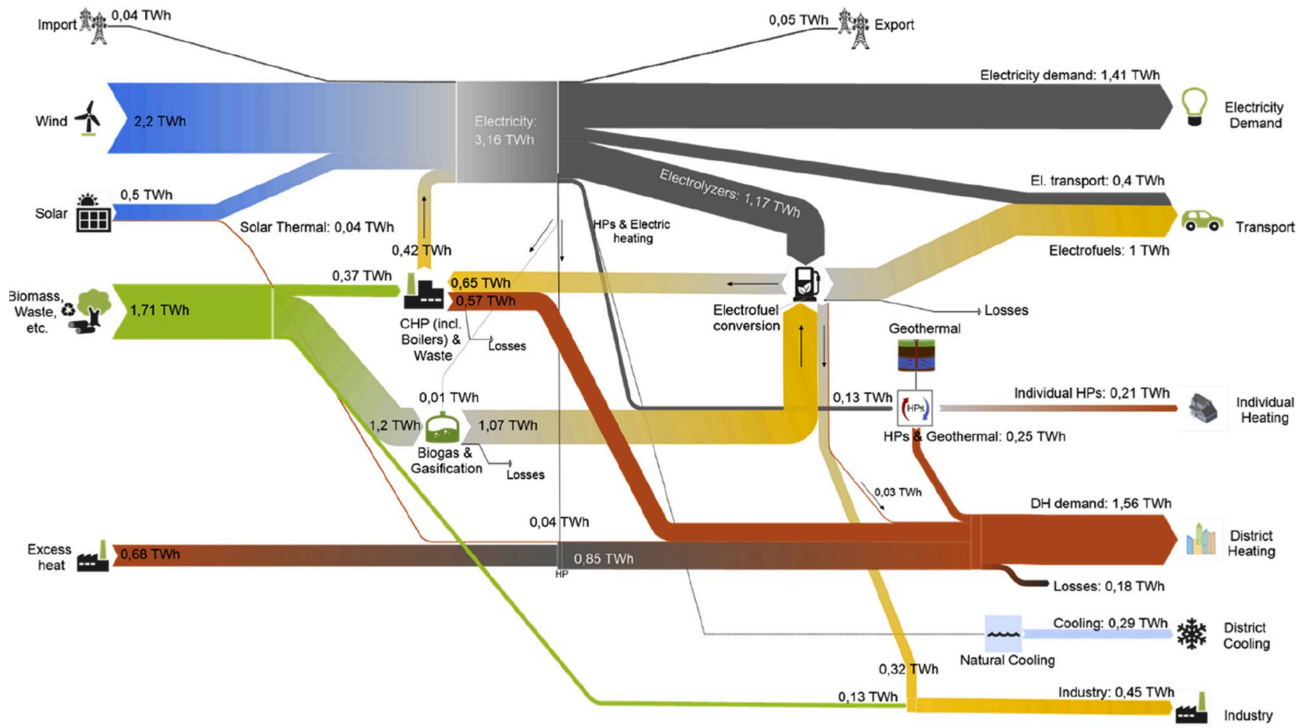

Fig. 3. Sankey diagram of Aalborg's energy system in 2050 based on the results of the EnergyPLAN simulation of the 2050 scenario. It shows the yearly input of primary energy and how it is utilised in various conversion technologies to supply the energy demands.

the combined heat and power plants (gas turbines and gas engines) supply the remaining district heating demands.

Fig. 4 shows the principle of how these different technologies work together in a system.

As already described above, the system fulfils the basic principles mentioned in the guiding principle. However, some remarks should be made regarding the analysis of the balancing of the electricity exchange. The Sankey diagram of the Smart Energy City of Aalborg shows a balanced system that uses electrolysers in combination with the gas demand to reduce the amount of excess electricity production from wind turbines and solar power. However, other options such as batteries and high-temperature steam storage are available. A comparison is made to show the differences between the different technologies and its results are presented in the following section. Additionally, it is important to mention that with the continuous decrease in prices of renewable energy technology [43], it might become economically viable to simply install more turbines and shut them off during hours of overproduction.

If no action was taken to deal with the potential excess production from renewables, the imbalances would be as high as an export of more than 500 GWh/year and an import of 300 GWh/year.

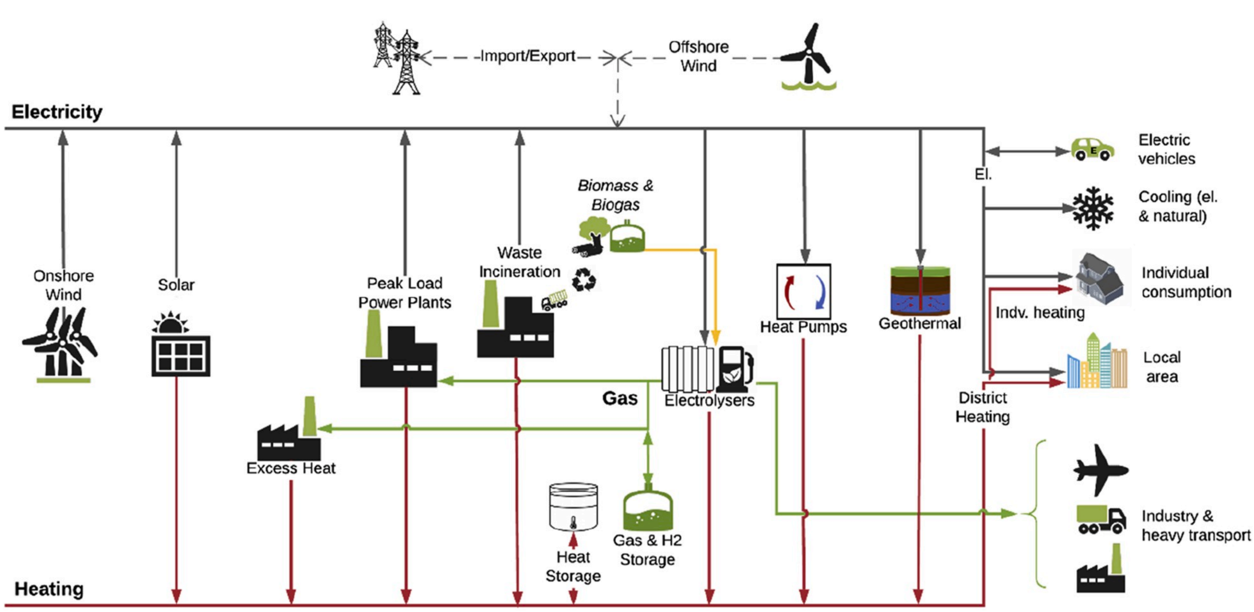

Fig. 4. Overview of system connection in the Smart Energy City Aalborg. The figure illustrates the system integration links utilised in the modelling approach to reach the final energy vision.

This situation has been used as a starting point for the analysis on how Aalborg could make its contribution in the most affordable way. As already mentioned above, the target has been set at a level at which Aalborg should be able to decrease the import and export to 40–50 GWh/year, thus exploiting mutual benefits of exchange and utilisation of common European hydropower options.

To deal with the import, an investment in a gas-fired power plant operated on green gas has been chosen. In principle, such a plant represents Aalborg's share of European needs for power capacities for the hours of insufficient wind power and PV production. In the Aalborg case, this corresponds to a power plant of 120 MW and green gas use of 450 GWh/year.

In order to evaluate the different options of reducing the excess export, a reference situation has been defined as a benchmark. The reference involves building slightly more wind power and PV and then waste the electricity by curtailment or similar. To calculate the cost and benefits, a simple calculation is made of the amount of saved wind power and PV and the corresponding reduction in investments compared to the investments in balancing technology. The feasibility is estimated based on this calculation.

To minimise the export (excess power production), the most obvious and affordable measures are 1) to operate heat pumps flexibly and make use of thermal storage capacities [44,45] and 2) to smart charge the electric vehicles instead of using dump charge [37]. These measures alone reduce the problem from an excess production of more than 500 GWh/year to approximately 250 GWh/year, as illustrated in Fig. 5. Furthermore, they reduce the necessary wind and PV from 1277 MW to 1099 MW. As illustrated in the figure, these efforts are clearly feasible.

The next step is to evaluate the mix of variable renewable energy production. The combination of wind and solar power can affect the utilisation rate of the variable renewable energy, since these sources are able to complement each other. The study therefore assesses different mixes of renewable energy. In the first mix, 10% of the VRES production comes from PV; in the second, 20% comes from PV, and in the third, 30% comes from PV. Fig. 6 illustrates the result of this analysis in the step 2 scenario. It shows that from both an economic perspective and in terms of imbalances, the mix between PV and wind power, where PV delivers 20% of the production, results in the best system.

The final step in bringing down excess electricity production is more difficult. The analysis evaluates three different alternatives as shown in Fig. 7.

The first is to invest in batteries. Since the cost of batteries is similar to the cost of many other electricity storage technologies, this option also represents pump hydro, compressed energy storage, fuel cell hydrogen systems and similar [46]. The additional benefit of these technologies is their ability to reduce the investments in wind and PV while avoiding investment in the power plant. However, as illustrated in the figure, the cost of the batteries is extremely high compared to the benefits and the expected investment costs. It would be much cheaper to curtail the excess production.

The next technology option is to invest in a high-temperature steam storage heating by excess electricity and utilise it for electricity production in the power plant. The advantage of this option is the much lower storage cost. However, investments will have to be made in a steam boiler and turbine power station raising the cost of the power plant. This option is more or less in balance, and given the uncertainties of expected investment costs, it cannot be ruled out but needs further investigation.

The third option is to invest in additional electrolyser capacity in the system. The electrolysers should not produce more hydrogen for electrofuels, but the additional capacities will make it possible to produce the same amount in a more flexible way. This is the option with the lowest costs. Thus, it has been used as part of the final energy system in the Aalborg vision. However, it should be emphasised that the feasibility compared to simply curtailing more wind is low and the sensitivity to additional needs for hydrogen storage capacity is high. Therefore, this option should also be subject to further investigation in the future.

In total, this energy transition results in significant fuel efficiency increases due to electrification and other efficiency measures such as energy savings and conversion to district heating. Furthermore, the vision results in lower total annual costs compared to the 2050 Business as Usual scenario (includes investment, fuel, CO_2, and operation and maintenance costs). These are illustrated in Fig. 8.

5. Conclusions

This paper has formulated a guiding principle and a methodology to be applied to cities and local communities in the design of sustainable energy futures in a way that makes such a transition compatible with a national and global transition to renewable energy. The argument is that in order to identify and implement the common best solutions to the green transition at the national and international levels, local action is needed. However, no isolated solutions should be defined at the local level. Instead, it is vital that the local communities aim at identifying their role to play in the best strategy for the overall system.

Such an aim poses several essential questions and challenges as well as practical issues to be dealt with in the design of strategies for implementing the green transition in future sustainable energy solutions.

For the case of Aalborg Municipality in Denmark, this paper has

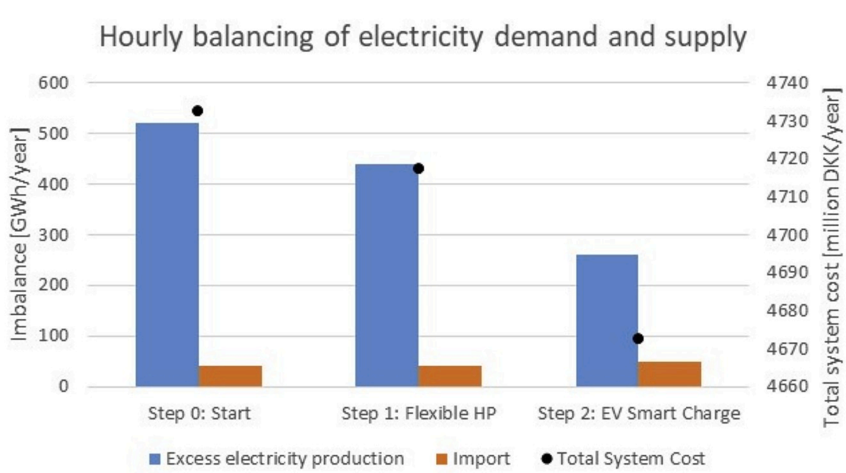

Fig. 5. The influence of flexible operation of heat pumps and smart charge of electric vehicles on reducing the excess electricity production of the Aalborg Smart Energy Vision.

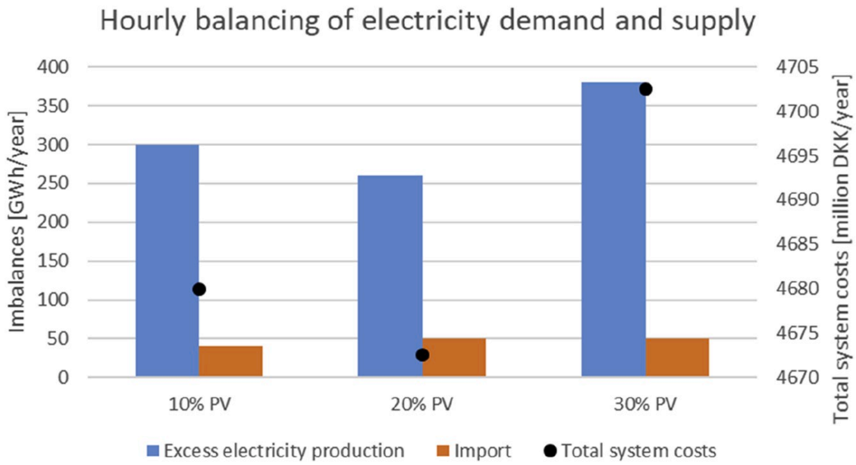

Fig. 6. Balancing capacities of different mixes of solar and wind power.

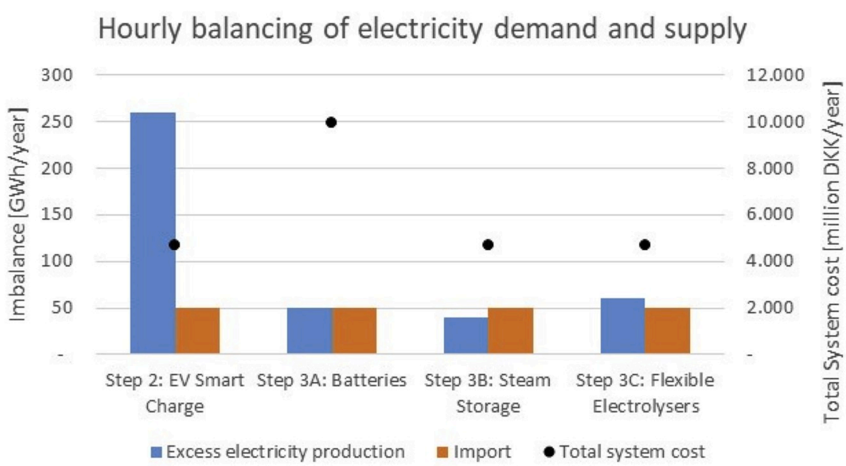

Fig. 7. Comparison of batteries, steam storage and flexible electrolysers to regulate excess electricity.

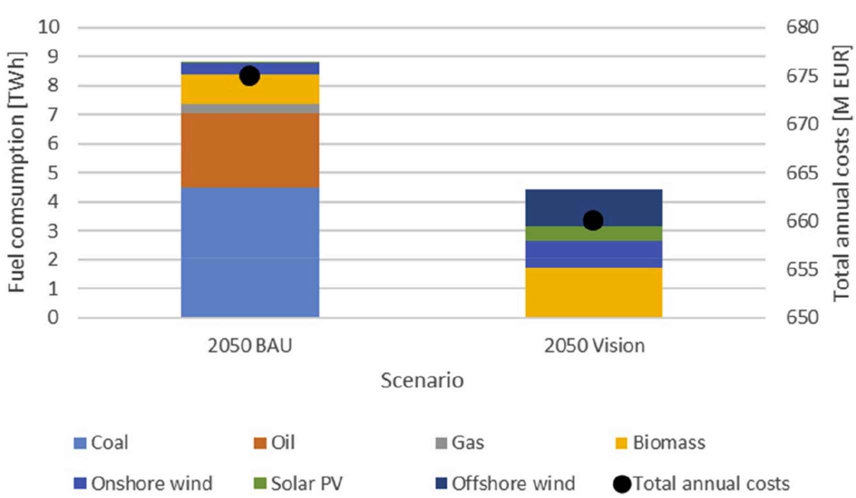

Fig. 8. Comparison of fuel consumption (stacked columns) and total annual costs (dots) of the Aalborg Energy Vision and the Business as Usual scenario.

shown a way to deal with these issues. A Smart Energy System vision for Aalborg to become 100% renewable in 2050 has been designed in such a way as to fit into a common best solution in Denmark as well as in Europe.

At the same time, this vision has been used to conduct detailed analyses of the options of balancing electricity supply and demand on an hourly basis with a focus on excess electricity production and how to deal with this. The result indicates that least cost options are 1) flexible operation of power to heat in terms of heat pumps in combination with thermal storage and district heating and 2) smart charging of electricity.

Batteries and similar electricity storage options (except for electric vehicles) are far from feasible compared to curtailment. Instead, steam storage and especially overcapacity in electrolysers are promising. These conclusions confirm, quantify and further similar conclusions presented in other scientific studies that were made on principal studies [33,46].

Finally, the analyses also confirm previous conclusions with respect to the best combination of PV and wind power (under Danish circumstances) [47]. This means that, on an annual basis, 20% of the electricity should come from PV and the rest from wind in order to minimise excess electricity problems. This study, however, takes these previous conclusions a step further by also introducing this combination as the economically least-cost solution.

Credit author statement

Thellufsen, J.Z.: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. Lund, H.: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. Sorknæs, P.: Conceptualization, Formal analysis, Writing - review & editing. Østergaard, P.A.: Conceptualization, Formal analysis, Writing - review & editing. Chang, M.: Formal analysis, Visualization, Writing - review & editing. Drysdale, D.: Investigation. Nielsen, S.: Investigation, Formal analysis. Djørup, S.D.: Writing - review & editing. Sperling, K.: Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.109922.

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