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The water use of heating pathways to 2050: analysis of national and urban energy scenarios

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Abstract

Sustainable energy systems can only be achieved when reducing both carbon emissions and water use for energy generation. Although the water use for electricity generation has been well studied, integrated assessments of the water use by low-carbon heat systems are lacking. In this paper we present an analysis of the water use of scenarios for heat and electricity production for the year 2050 for the Netherlands and its capital, Amsterdam. The analysis shows that (i) the water withdrawal for heating can increase up to the same order of magnitude as the current water withdrawal of thermoelectric plants due to the use of aquifer thermal energy storage, (ii) the virtual water use for heating can become higher than the operational water consumption for heating, and (iii) the water use for electricity production becomes a relevant indicator for the virtual water use for heat generation because of the increase of power-to-heat applications.

1. Introduction

Infrastructure for heat provision needs to change remarkably to lower carbon emissions in efforts to reduce the effects of global warming. Heating for industrial and domestic purposes accounts globally for 50% of the final energy consumption and 40% of carbon dioxide (CO_2) emissions [1]. However, transitioning towards low-carbon heating systems may significantly increase the water demand for energy generation. Water will for example be used for storing thermal energy, producing renewable energy carriers, and, indirectly, generating electricity for power-to-heat (P2H) applications. This paper proposes an integrated approach for assessing how future heating pathways can change the water use of future energy systems.

Such assessments are important to limit environmental degradation, reduce water shortages, and increase energy security. Currently hydropower dams and thermoelectric power plants are responsible for 98% of global electricity production [2]. However, these technologies can cause thermal pollution, harm aquatic ecosystems, change river flows, and affect livelihoods [3, 4]. It is estimated that these two technologies will have capacities limited due to reduced water availability and increased water temperatures in the future [2].

The current body of scientific literature on water use by the energy sector mostly covers the topics of water use for electricity generation and fuel production [5–7]. Studies have aimed to collect data on the water footprint (WF) of electricity production (e.g. [8–10]) or energy crop production (e.g. [11]). These data have been used to assess the current and future water use of electricity production [12, 13]. The consumptive water use of heat production has been assessed for the years 2000 and 2012 on a global scale, showing a growth in water use for heating mainly driven by increases in the use of firewood [14]. No study, to the authors' knowledge, has analysed how a mix of decarbonisation strategies would affect different types of water use for heating. Consequently, these studies offer a too narrow depiction of the water use for future heat generation. In this paper, we fill this knowledge gap by presenting an integrative assessment of the water use of future heating pathways, including the impact of electrification of heating.

To do so, a multi-scale energy and water use model was developed and used to comparatively assess the energy scenarios for the Netherlands and its capital, Amsterdam for the years 2015 and 2050. The energy transition in the Netherlands and Amsterdam is an interesting case study because of multiple reasons. First, future Dutch scenarios include a variety of low-carbon heating pathways that are also applicable across Europe, such as electrification of heating, the application of district heat networks supplied with the incineration of renewable energy carriers, and thermal energy storage [15–20]. By considering a diverse variety of heating technologies, our approach enables a quantitative analysis of the impact of different heating technologies on water use. Second, the future heating scenarios for the Netherlands are starkly different from the current energy mix. Currently, heating accounts for more than half of the national final energy demand [21], most of this heat (i.e. about 80%) is generated using natural gas [21]. The national plan to provide gas-free heating by 2050 [22] motivates an integrated analysis of transitional impacts of CO_2 mitigating infrastructure choices on water use. Additionally, the Dutch energy sector accounts for two-thirds of the national water withdrawal [23], which is mostly used to cool fossil-fuel based power plants. When we consider the national freshwater shortages caused by increasing droughts and desalinisation of coastal regions, it becomes clear that research on the water withdrawal by the energy sector is very relevant for the Netherlands and other nations that need to address the potential compounding impacts of new infrastructures on climate driven water scarcity [24].

2. Methods

2.1. Multi-scale energy and water use modelling framework

In order to model the water use of heating in an integrated way, we consider both the operational water use and the virtual water use embedded in energy carriers such as fuels and electricity (see figure 1). The operational water use is the water used at the location of energy generation whereas virtual water flows can come from elsewhere. We therefore developed a model which accounts for water uses at global, national and urban scale.

The operational water use includes both water withdrawal and water consumption. Water withdrawal refers to the abstraction of water from ground and surface water sources [25]. The amount of water which is not discharged back into a water body is called the water consumption. The water withdrawal and consumption rates for power plants were collected from literature (see supplementary material, tables A2 and A3 (available online at stacks.iop.org/ERL/16/055031/mmedia)). The water use values mentioned in literature for thermoelectric power plants can vary significantly, but a mean value is often given. Research shows that using the median values for modelling the water withdrawal and consumption for thermoelectric plants in European countries gives results that correspond reasonably well to water withdrawal and consumption reported in national statistics [26].

The water withdrawal rates for heat systems, excluding combined heat and power (CHP) plants, are based on our own calculations given in table A1 of the supplementary material. For these heat systems, heat is extracted from geothermal and hydrothermal energy sources, or underground thermal energy storage (UTES) systems. Geothermal energy refers to sources that tap into the Earth's sub-surface geothermal heat sources. Hydrothermal energy refers to thermal energy extracted from surface water. UTES systems can be open systems, called aquifer thermal energy storage (ATES), and closed systems, referred to as borehole thermal energy storage [27]. The water withdrawal needed to extract heat from these sources depends on the temperature difference between the water that is extracted and discharged back into the heat source. This withdrawal volume is expressed by the equation:

$$V = \frac{J_{\text{ext}}}{\Delta T \cdot C_{\text{water}}}, \qquad (1)$$

where V is the volume of water extracted, J_{ext} denotes the energy extracted from the volume of water, ΔT denotes the difference in temperature of the volume of water before and after heat extraction, and C_{water} is the volumetric heat capacity of the water [28]. The volumetric heat capacity in our model is set equal to the volumetric heat capacity of freshwater ($C_{\text{water}} = 4.182\ \text{MJ}\,\text{m}^{-3}\ \text{K}^{-1}$). In the case of hydrothermal energy, also brackish or salt water could be used. Salt water has a lower heat capacity, which would result in a higher volume of water withdrawal. For heat extraction from UTES systems and surface water, a ΔT of 4 degree Celsius (°C) was chosen, based on the average ΔT given by national statistics [28]. For geothermal energy, we used a ΔT equal to 40 °C [29]. The water consumption for these heat technologies is set equal to zero, since water is not consumed per se but is returned to the source at a different temperature.

The virtual water use of energy carriers in this work refers to the volume of water required to produce fuels and electricity [30]. The virtual water use of fuels (VW_{fuel}), i.e. combustibles and nuclear materials, was determined from WF data in literature. The WF of a product, such as an energy carrier, is the 'volume of freshwater used to produce the product', measured over its full supply chain [31] . The values we use for different carriers can be found in figure 2 and table A5 of the supplementary material. The WF

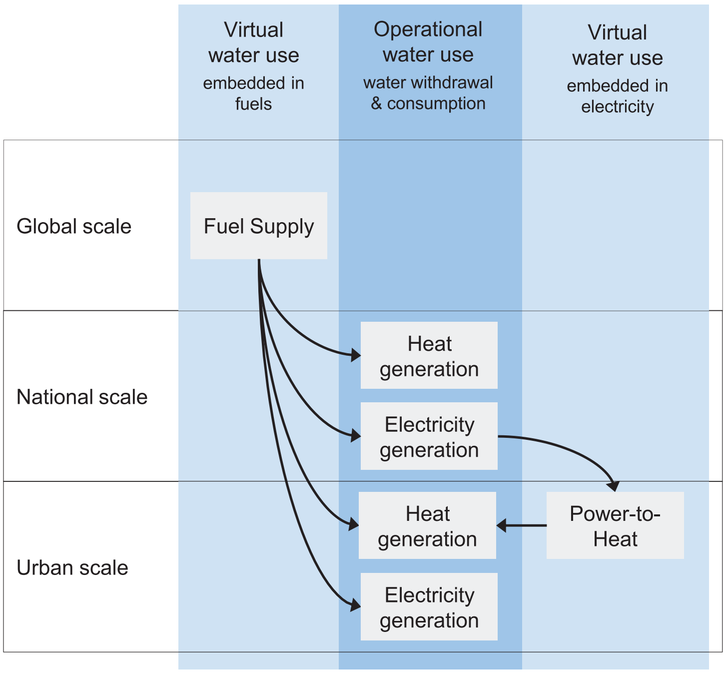


Figure 1. Conceptual visualisation of multi-scale water and energy use model that allows the delineation of localised operational water use and virtual water use through energy carriers. In our model we assume that the electricity needed for P2H applications on an urban scale is withdrawn from the national power grid.

values of fuels chosen in our main analysis and discussion are on the lower end of the WF values from literature. As such, we argue that they serve to analyse how the substitution of fossil fuels by renewable energy carriers may affect the water use of the energy sector, starting from the least impact. The VW_{fuel} per scenario was modelled by multiplying the amount of energy produced by the given technologies, the energy required for energy (ERE) values, and the WF per unit energy of the used energy carrier (see supplementary material, tables A4 and A5). The ERE value stands for the amount of energy from an energy carrier needed to produce one unit of energy [14]. It therefore corresponds to the heat value and heat rate of an energy carrier for heat and electricity production respectively. For the case of technologies that use 'gas', we assume that gas is supplied through the national gas grid. The grid is assumed to supply a mix of natural gas and biogas and the mix is different per scenario. The ratios between natural gas and biogas in the mix are given in table A6 of the supplementary material.

Only for the energy carrier electricity, the virtual water use was determined in a different manner. With electrification of heating, the water used for electricity production is concurrently used for heating purposes through P2H. We therefore argue that the virtual water use of electricity (VW_{P2H}) should not be overlooked in an integrated assessment of the water use for future heating pathways. The VW_{P2H} of heating appliances on an urban scale was determined by scaling down the water use for generating electricity on a national scale (see figure 1). This is because we assumed that electricity needed for heat generation on an urban scale is extracted from the national grid and therefore depends on the national electricity mix. The water use for electricity production on national scale is modelled in terms of water withdrawal, water consumption and VW_{fuel}. In this paper, the VW_{P2H} is therefore expressed in these three types of water use.

In order to calculate the electricity demand for P2H applications it was assumed that all heat pumps in the technology mixes would be electrified. We argue that this assumption is reasonable for the 2050 scenarios, where heat pumps are not expected to be fuelled by gas because of Dutch political ambitions to reduce the use of natural gas [22].

2.2. Future heating pathways for the Netherlands and the city of Amsterdam

In order to study the potential change in the water use of the national energy sector, four major energy scenarios for 2050 are compared with the technology mixes for heat and electricity production in 2015 (see figure 3). The year 2015 is chosen as reference year because, at the time of this study, this year was the most recent year for which national statistics existed on water withdrawal from the electricity sector and UTES systems. The year 2050 is chosen because the Netherlands has committed to phasing out fossil fuels and achieving a 95% emissions reduction by this year (compared to emission levels in 1990) [22].

The 2050 scenarios are based on the four major scenarios laid out by the main Dutch network operators in an integrated infrastructure exploration of possible low-carbon energy systems adhering to the

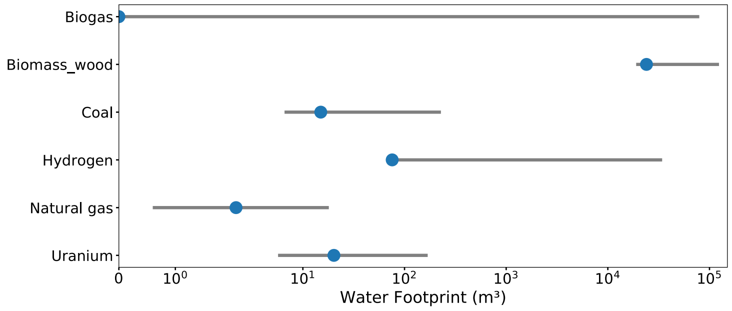


Figure 2. Range of values found in literature for the water footprint of fuels. The dot depicts the value chosen.

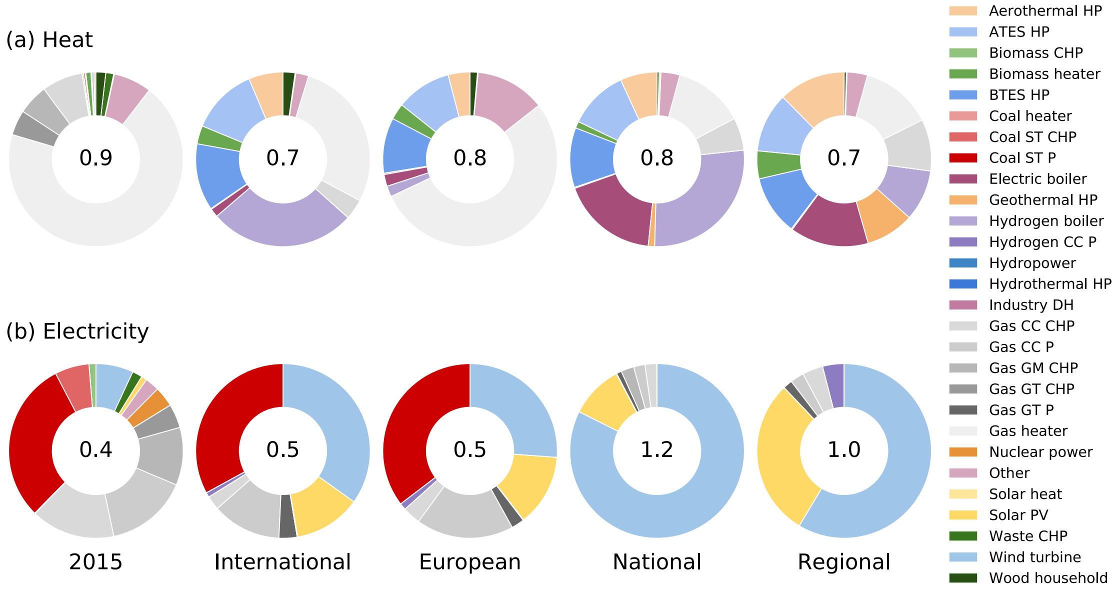


Figure 3. Technology mixes for (a) heat and (b) electricity generation in the Netherlands in 2015 and in four major scenarios for 2050. The amount of energy generated per scenario is presented in units of exajoules (EJ) in the middle of the doughnut diagrams. Abbreviations: ATES = aquifer thermal energy storage, BTES = borehole thermal energy storage, CC = combined cycle, CHP = combined heat and power, DH = district heating, GM = gas motor, GT = gas turbine, PV = photo-voltaic, ST = steam turbine.

Dutch Climate Agreement [32, 33]. The interpretation of these qualitative scenarios to specific technology mixes is inspired by the technology mixes given by the Energy Transition Model [34]. As the report states [32], the scenarios are not representative of the future energy system of the Netherlands, but rather typify extremities of different transition pathways and associated the possible technology mixes. The scenarios are therefore suitable for accessing the different potential impacts of a heat transition on the water use of the energy sector.

The labels of the scenarios refer to the conceptual 'governance structures', i.e. socio-economic drivers for shaping low carbon energy systems defined in the report on climate-neutral energy scenarios [32]. The 'International' scenario is mostly driven by an international energy market leading to more import of hydrogen compared to the other scenarios. The 'European' scenario is driven by European taxes on CO_2 emissions on all sectors, import duties at the European border and subsidies for relevant sectors. This scenario may be more effective than the current EU Emission Trading System because it covers all sectors [35]. The tax rates increase towards the year 2050 and will lead to more import of energy in the Netherlands. The strategies characterising this scenario is carbon capture and storage, and hybrid electrification. With hybrid electrification, conventional combustion technologies are partially replaced by electric solutions. The main driver in the 'National' and 'Regional' scenarios is self-sufficiency on the national and regional levels; the term Regional here refers to a scenario where the Dutch government gives control of the energy transition largely to sub-national regional government bodies. Given the climate and geography of the country, this leads to higher capacities in wind and solar energy combined with electrification of heating in the National scenario. Similarly, the Regional scenario is characterised by more electrification of heating, and use of geothermal

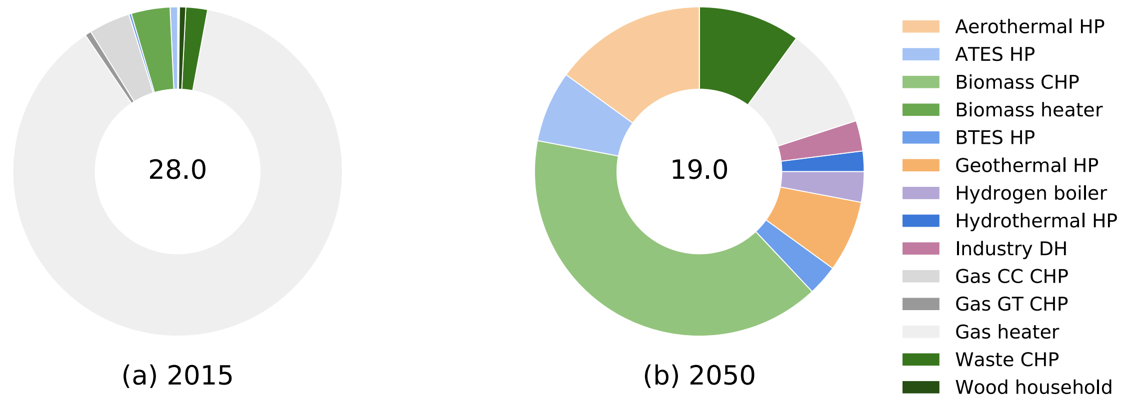


Figure 4. Heat technology mixes for 2015 and 2050 scenarios for the city of Amsterdam. The urban technologies mix for the year 2015 was derived from several sources [39–44]. The 2050 technology mix was based on the road map presented in the report 'New Amsterdam Climate' [38]. The amount of energy generated per scenario is presented in units of petajoules (PJ) in the middle of the doughnut diagrams. Abbreviations: ATES = aquifer thermal energy storage, BTES = borehole thermal energy storage, CC = combined cycle, CHP = combined heat and power, GT = gas turbine.

energy for heat networks. The report describes that citizens have a more active role in the Regional scenario leading to higher citizen awareness of low-carbon heating systems and an increased involvement in sustainable initiatives of citizens. This is an important driver given that social acceptability is expected to be a great challenge for decarbonising heating systems [36]. A more active role of citizens in decarbonising heating systems can increase literacy on low-carbon heating technologies and desirability of change, which is now often low across countries in Europe [36, 37]. Given the complexity of the mentioned socio-economic drivers in practice, we only estimate the water use of the given scenarios and do not elaborate further on the potential implications of socio-economic drivers on energy and water use.

In addition to the four national scenarios, we also considered urban heating scenarios for Amsterdam; see figure 4. This is done in order to show how the change in technology mix for electricity production on a national scale can affect VW_{P2H} on an urban scale. The 2050 scenario is based on the road map outlined in the report 'New Amsterdam Climate' [38]. This report sketches that 50%–60% of the heat demand in the built environment could be met with collective heat systems. Such systems can be fuelled with the heat from CHP plants or residual heat from industry. Another 35%–40% of the heat demand may be generated through all-electric heat systems. These systems can be connected to low-thermal heat sources, such as UTES and datacentres, in order to increase the efficiency. Around 15% of the heat demand could also be met with hybrid systems.

3. Results

The modelled water use of the national technology mixes are presented in figure 5. The figures in the middle column show the aggregated (1) water withdrawal, (2) consumption, and (3) VW_{fuel} of both electricity and heat production. Figure 5(1b) shows that, compared to the 2015 scenario, the calculated water withdrawal for heat production increases significantly in all four scenarios, for three scenarios even exceeding the water withdrawal for electricity production. Moreover, figures 5(2b) and (3b) suggest that the VW_{fuel} for heating is more than four orders of magnitude higher than the water consumption for heating in all four scenarios. This means that virtual water use becomes higher than local operational water consumption.

In the left and right columns, the water use per technology for electricity and heat production are depicted. Figure 5(1c) suggests that the water withdrawal for heat production increases primarily because of the use of ATES systems and secondarily due to geothermal systems. The water withdrawal for electricity production (see figures 5(1a) and (1b)) is highest in the scenarios where coal powered generation is employed, i.e. the International and European scenarios. The water consumption for heat production, mostly consisting of the water consumption by gas fired CHP plants, is significantly smaller than that for electricity production (see figures 5(2a–c)). The VW_{fuel} of both electricity and heat production depends on the employment of energy carriers such as biomass, coal gas, hydrogen, and wood (see figures 5(3a–c)). In some cases the relative contribution per technology might seem similar (e.g. the VW_{fuels} for the International and European scenarios in figure 5(3a)). This is because these columns prominently show only the relative water use contributions of the technologies that have higher water use indicators. Looking at the actual technology mixes in figure 3, the differences in the technology mixes of the International and European scenarios are significant in the technologies but for ones that use less water;

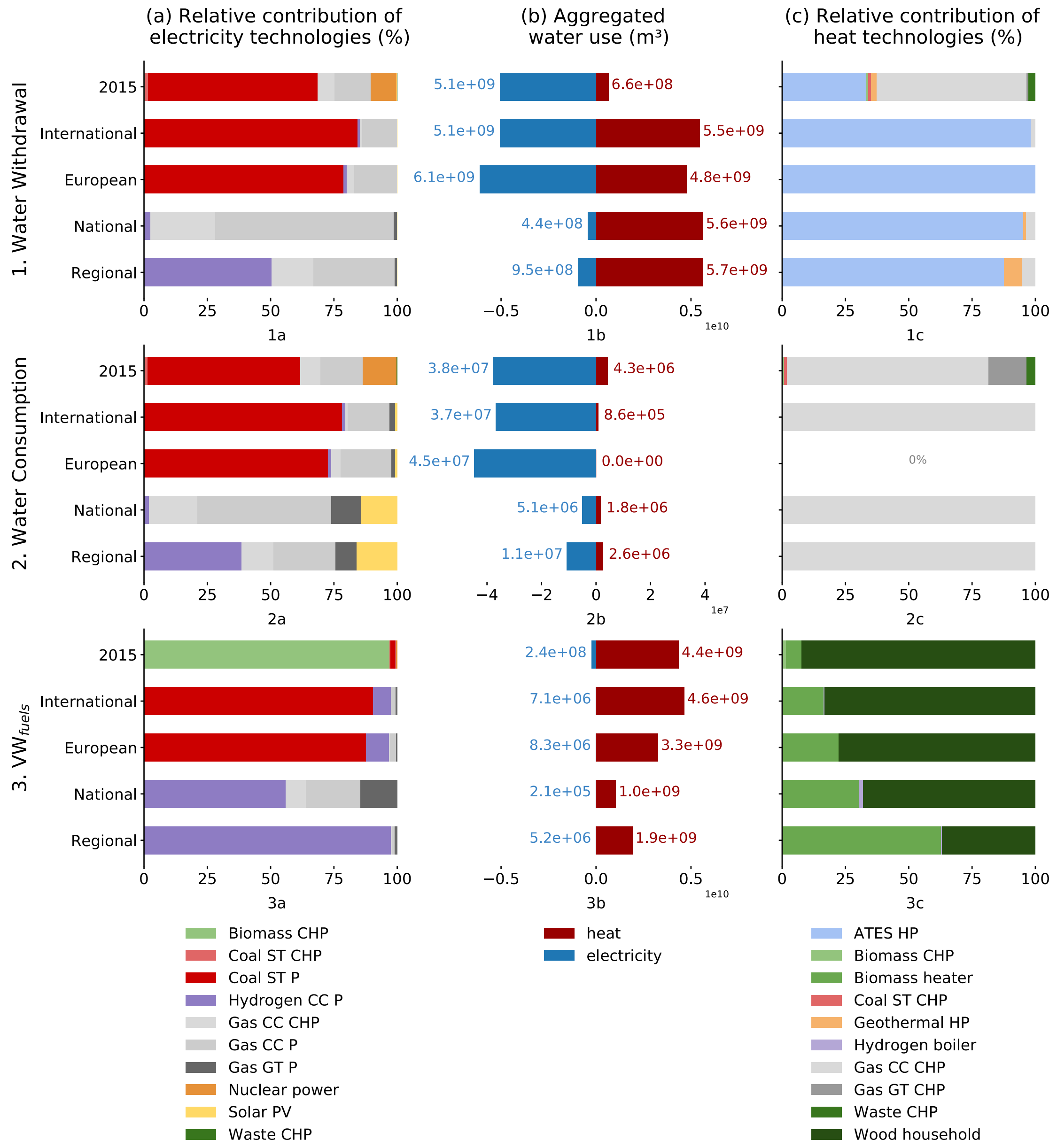
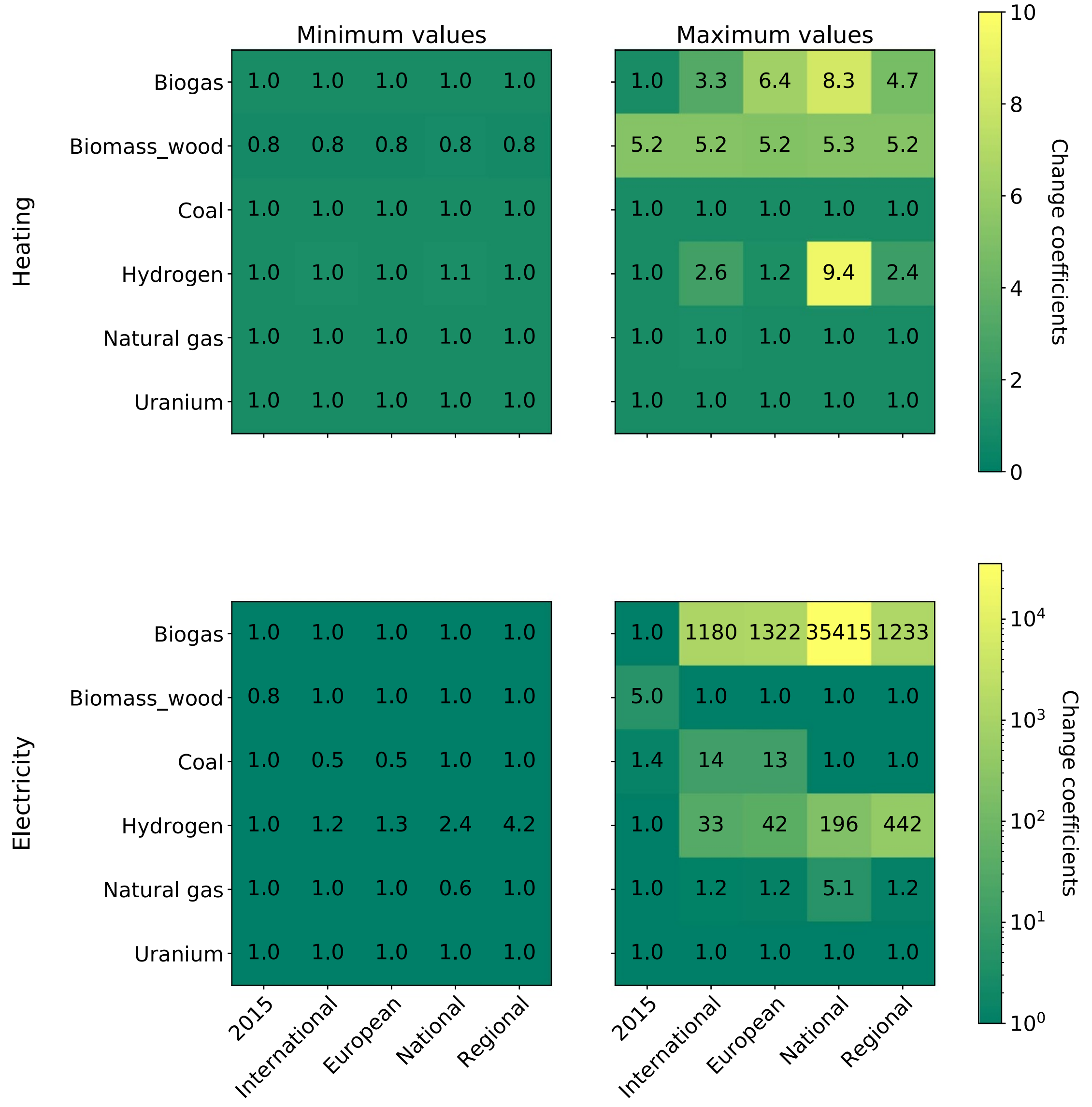


Figure 5. Water use for heat and electricity production in the Netherlands in 2015 and four 2050 scenarios called International , European, National and Regional. Water use is expressed using the indicators (1) water withdrawal, (2) water consumption, and (3) virtual water use for fuels. Column (b) depicts the water use for the production of electricity (in blue) and heat (in red). The left and right columns show the relative contribution of heat and electricity technologies, respectively, towards the corresponding aggregate water use indicators in column (b). Abbreviations: CC = combined cycle, CHP = combined heat and power, GT = gas turbine, ST = steam turbine.

for example, there is relatively more wind energy in the international scenario for electricity production, but still around the same ratio of coal and gas fired power plants as in the European scenario.

In order to assess how different WF values per fuel would affect the results, a first order sensitivity analysis was performed varying the WF value per fuel between the minimum and maximum values found in literature. The results of this analysis are shown in the heat maps in figure 6. The figure shows that the VW_{fuel} for heating scales almost linearly with the VW_{fuel} of biomass. The VW_{fuel} for electricity generation in the future scenarios does not increase when substituting higher values for biomass. Moreover, if the VW_{fuel} value for coal is changed, only the values for electricity generation in the International and European scenarios show a near linear change, both of which have a large mix of coal based power generation (see figure 3).

One strategy for decarbonising heating pathways is the electrification of heating, which we therefore investigate to assess how it would affect the (virtual) water use of heat production. The yearly national consumption of electricity for P2H applications was estimated to be 2.08 exajoules (EJ) in the 2015 scenario and projected to be between 65.0 and 450 EJ in the 2050 scenarios (the values per scenario are included in the supplementary material, table A7).



Heating — Minimum values

	2015	International	European	National	Regional
Biogas	1.0	1.0	1.0	1.0	1.0
Biomass_wood	0.8	0.8	0.8	0.8	0.8
Coal	1.0	1.0	1.0	1.0	1.0
Hydrogen	1.0	1.0	1.0	1.1	1.0
Natural gas	1.0	1.0	1.0	1.0	1.0
Uranium	1.0	1.0	1.0	1.0	1.0

Heating — Maximum values

	2015	International	European	National	Regional
Biogas	1.0	3.3	6.4	8.3	4.7
Biomass_wood	5.2	5.2	5.2	5.3	5.2
Coal	1.0	1.0	1.0	1.0	1.0
Hydrogen	1.0	2.6	1.2	9.4	2.4
Natural gas	1.0	1.0	1.0	1.0	1.0
Uranium	1.0	1.0	1.0	1.0	1.0

Electricity — Minimum values

	2015	International	European	National	Regional
Biogas	1.0	1.0	1.0	1.0	1.0
Biomass_wood	0.8	1.0	1.0	1.0	1.0
Coal	1.0	0.5	0.5	1.0	1.0
Hydrogen	1.0	1.2	1.3	2.4	4.2
Natural gas	1.0	1.0	1.0	0.6	1.0
Uranium	1.0	1.0	1.0	1.0	1.0

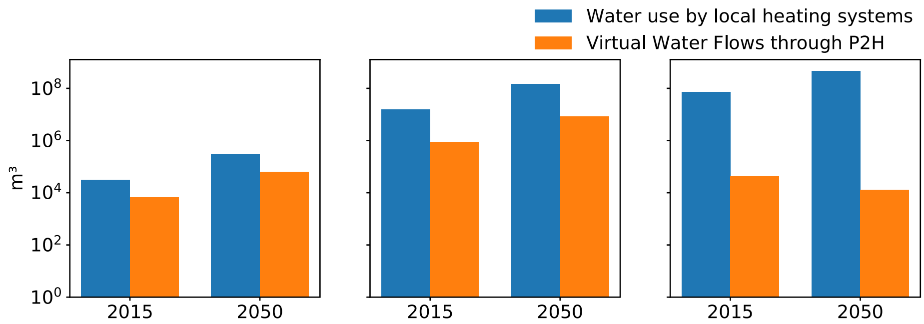
Electricity — Maximum values

	2015	International	European	National	Regional
Biogas	1.0	1180	1322	35415	1233
Biomass_wood	5.0	1.0	1.0	1.0	1.0
Coal	1.4	14	13	1.0	1.0
Hydrogen	1.0	33	42	196	442
Natural gas	1.0	1.2	1.2	5.1	1.2
Uranium	1.0	1.0	1.0	1.0	1.0

Figure 6. Sensitivity analysis: minimum (left column) and maximum (right column) values given for VW_{fuel} when changing the water footprint of fuels according to the range of values found in literature. The change coefficient shows the relative change of the VW_{fuel} with respect to analysis for the VW_{fuel} of heating (upper row) and electricity (bottom row) generation.

In other words, the calculated fraction of electricity needed for heating compared to the total electricity production, given in figure 3, is 0.5% for the 2015 technology mix and between 14% and 37% for the four 2050 scenarios. For the case of Amsterdam, an increase in electricity demand for P2H applications from 68 TJ in the 2015 technology mix to 1309 TJ in the 2050 scenario was observed.

In figure 7 the operational water use and VW_{fuel} for urban heating systems are compared with the VW_{P2H} in the scenarios for 2015 and 2050. In the case for 2050, the average for the four national scenarios was taken (see supplementary material, table A8, for the results per scenario). The data in figure 7 suggest that the virtual water abstraction and water consumption for P2H applications is not negligible compared to the local water withdrawal and consumption of urban heating systems. The VW_{fuel} for P2H applications, on the other hand, is negligible compared to VW_{fuel} of the fuels used by local heating systems. In table 1 the ratio between VW_{P2H} and 'direct' water use of local heating technologies are given per scenario. The ratios between direct water use and VW_{P2H} for 2015 and the average of the 2050 scenarios remain similar for the operational water use and WF_{fuel} (i.e. 5.6% for water withdrawal, 21% for water consumption and around 0% for the VW_{fuel}). Nevertheless, the ratios for water withdrawal and consumption do differ among the four major 2050 scenarios between 0.3%–11% and 1.8%–41% respectively. This variation is to be explained with the significant variation in the water withdrawal and consumption for electricity generation per scenario as presented in figures 5(1b) and 5(2b).



(a) Water Consumption (b) Water Withdrawal (c) VF_{fuel}

Figure 7. Water use for local heat production for the city of Amsterdam and VW_{P2H}. Diagrams (a)–(c) depict the model output for water withdrawal, water consumption and the virtual water use for fuels respectively. The values are plotted on a logarithmic scale and are in units of cubic meters.

Table 1. Comparison of VW_{P2H} with other direct and virtual water use indicators of the urban heat mix for Amsterdam. The VW_{P2H} is divided into the water withdrawal, consumption and VW_{fuel} needed to generate the electricity needed for P2H applications.

Scenarios	$\frac{VW_{P2H,\ water\ withdrawal}}{water\ withdrawal}$ (%)	$\frac{VW_{P2H, water\ consumption}}{water\ consumption}$ (%)	$\frac{VW\ P2H, VW_{fuel}}{VW_{fuel}}$ (%)
2015	5.6	21	0.1
2050 average	5.6	21	0.0
International	10	35	0.0
European	11	41	0.0
National	0.3	1.8	0.0
Regional	0.8	4.7	0.0

4. Discussion

From the results we derive three main insights on how heat transitions can impact the water use of the energy sector. First, the national water withdrawal for heating for the 2050 scenarios is an order of magnitude higher that the water withdrawal in 2015. This means that the national water withdrawal for heating in the 2050 scenarios is of the same order of magnitude as that of the current water withdrawal for electricity generation. The increase in water withdrawal for heating between the 2015 and 2050 technology mixes is due to an increased use of ATES systems in the technology mix from 0% to 10%–12%. This means that the water withdrawal for heating can increase to the same order of magnitude as the water withdrawal of thermoelectric power plants in 2015 if only around a tenth of the heating is supplied through ATES. To validate the modelled water withdrawal for ATES systems, the output for the 2015 scenario was compared to national statistics. This value, 278 × 10^6 m^3, is based on energy sales data, data on energy storage and provincial data on groundwater flow, and include water withdrawal for both heating and cooling [45]. It is comparable with the modelled water withdrawal for ATES systems being 220 × 10^6 m^3 for the 2015 scenario (i.e. almost a third of the national water withdrawal for heating given in figure 5(1b)).

Second, the VW_{fuel} of heating remains higher than the water consumption for heating. To model the VW_{fuel} of gas, it is important to note that a mix of natural gas and biogas was used, varying in composition per scenario. The VW_{fuel} of biogas was set equal to zero because of two assumptions. The first assumption was that biogas would in future scenarios be produced through anaerobic digestion with mainly manure as mixing liquid instead of water. In comparison, the WF for the anaerobic digestion phase with water as mixing liquid is approximately 437, 450, 474 m^3 TJ^{-1} when digesting the energy crops Maize, Wheat and Sorghum respectively [46]. The second assumption is that the biogas made from residual materials, such as sewage sludge, has no virtual water use associated with it since the availability of these materials does not depend on the demand for biogas [45]. Resources for biogas can however be assigned a VW_{fuel}. The sum of the blue and green WF of biogas production from wheat, for example, is 79 340 m^3 TJ^{-1} [46]. Changing the VW_{fuel} of biogas to 79 340 m^3 TJ^{-1} in our model, increases the VW_{fuel} of heat generation by a factor of 3.3–8.3 depending on the considered scenario; for electricity generation the increase factors range from 1180 to 35 415 (see figure 6). The relatively high increase for VW_{fuel} for electricity production in the national scenario in comparison to the other scenarios is not to be explained by a higher share of gas fired power plants in the technology mix (see figure 3). Instead, this is due to the fact that the mix of gas in the national gas grid consists of relatively more biogas than natural gas in comparison to the other scenarios (see supplementary material figure A6). A higher value for biogas thus mostly affects the VW_{fuel} of electricity production. The replacement of natural gas with biogas in gas fired power plants can therefore significantly increase the VW_{fuel} of heat and electricity generation.

The sensitivity analysis also showed that the VW_{fuel} of electricity production would increase significantly when we substitute higher values for the WF of hydrogen (see figure 6). In our analysis, we used VW_{fuel} for hydrogen equal to 75.6 m^3 TJ^{-1}, which is the direct water use for producing hydrogen through proton exchange membrane electrolysis, assuming no water losses and not accounting for the WF of electricity [47]. Hydrogen can however be made in other ways. Research has shown that the water use for hydrogen production in nine potential production pathways can range between 326 and 34 216 m^3 TJ^{-1} [48].

Lastly, the third insight of this study is that the water withdrawal and consumption for electricity production for P2H applications is comparable to the local water withdrawal and consumption for heating in the case of Amsterdam. Assessments of water use for future urban heat generation should therefore include the virtual water flows embedded in electricity used for P2H applications.

The amount of electricity needed for heating is determined by the coefficient of performance (COP) of electric heating applications. In this research a COP of 1 for electric heaters, and 4 for heat pumps were used [28]. In practice the COP of heat pumps varies, depending on factors such as temperature differences between heat source and the space that is to be heated, and technology specifics. A range in COPs between 2.9 and 4.5 can be found in literature [49]. The amount of electricity needed for P2H applications—and therefore the VW_{P2H}—scales inversely proportionally with COP. The model output for VW_{P2H} will therefore be almost proportionally higher than the values presented in figure 5 if the COP value is set lower than 4.

The water use calculations for electricity generation depend on the parameters used for the different technologies in the mix. The modelled water withdrawal for electricity production was 5.1×10^9 m^3 for the technology mix in 2015. This number is less than half of the total water withdrawal for the cooling of power plants, which was reported to be about 11×10^9 m^3 in national statistics [23]. In a study using similar approaches an underestimation between 30% and 35% was shown [26]. We argue that our results are comparable, with the results from this study, given that we divided the water withdrawal of CHP plants to electricity and heat production instead of only to electricity production. A more accurate value for the water use for power generation could be obtained by using power plant specific water use data instead of water withdrawal rates from literature.

Since such specific data on power plants are often not openly available, an alternative method to model the water withdrawal and consumption of CHP plants could be developed. CHP plants produced 18% and 40% of the delivered heat and electricity respectively in the 2015 technology mixes for the Netherlands. The modelled water use of power plants was attributed to the water use of electricity or heat production proportionally to the total energy produced. In this work it was assumed that the water withdrawal and consumption rates of CHP plants were 10% of the water withdrawal and consumption for power plants which only produce electricity [14]. To the best of our knowledge, there is no other method given in literature to estimate the water withdrawal and consumption of CHP plants. In order to better estimate the water needed for heat networks, a method should account for the water use not only in the production of electricity, but also the production of heat. This approach addresses the water use attribution problem similarly faced by multipurpose hydropower reservoirs, where there are no agreed methods on how to attribute use and evaporation losses between different user sectors such as agriculture and hydropower [50].

Hydrogen fuelled combined cycle (CC) power plants are currently not applied at large scale and therefore knowledge on the water use is limited, and lacking in current literature. In this manuscript, the specifications, and therefore water use, of these plants were set equal to those of natural gas CC plants [34]. Although this technology accounts for only about 4% of the total electricity produced in the Regional scenario for 2050, it does have a significant share of the water withdrawal and consumption in this scenario.

5. Conclusion

From the results we draw three main insights: (i) the water withdrawal for heat production increases significantly in scenarios in which heat is stored with ATES systems, (ii) the future VW_{fuel} for heating is significantly higher than the operational water consumption for heating, and (iii) the virtual water consumption and withdrawal to generate electricity needed for P2H applications can be relevant for assessing the water use of heating. Based on these three insights, we argue that the water use of future heating systems needs to be assessed in an integrated manner to support sustainable policy. To create sustainable energy systems, water use should be added as an extra dimension in policy making besides reducing costs and CO_2 emissions. This means that water use for heating, including water use for storage and production of energy carriers need to be accounted for.

If not properly managed, the transition to low-carbon heating systems could exacerbate water stress or be limited by it. We therefore argue for an increased knowledge of water use for heating systems of the future, similarly to the well established knowledge base for electricity production. To make these data useful for preventing future water stress, environmental degradation, and reduced energy production capacity, projected water use for heating should be connected with spatially explicit models with time varying indicators such as water temperature, water availability and environmental water demand.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. Data will be available from 19 January.

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