UK ENERGY SYSTEM MODELLING: NET ZERO 2050

Nuclear Deployment Scenarios to Support Assessment of Future Fuel Cycles

Executive summary

This report documents the results of full UK energy system modelling undertaken to support assessment of future advanced nuclear fuel cycles. The work has been performed as part of the Advanced Fuel Cycle Programme (AFCP) and will underpin future work in technology roadmapping and fuel cycle modelling.

NNL has worked with Energy Systems Catapult (ESC) and LucidCatalyst to produce four nuclear deployment scenarios in a 2050 Net Zero UK energy mix using the whole energy system model known as Energy System Modelling Environment (ESME). This extensive modelling represents crucial assessment of the potential role of nuclear in delivering Net Zero; the modelling fills a gap in publicly available data that is needed to understand the possible role and application of future advanced fuels and fuel cycles.

The energy system modelling reports are provided here in full with all assumptions and supporting data. The work considers the role of conventional large reactors, Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) working alongside other low carbon energy technologies; it considers the role of nuclear providing not only electricity but also heat and hydrogen, giving a range of nuclear deployment scenarios from 14 GWe to over 60 GWe in 2050. The range of nuclear technologies and scope of potential deployment requires assessment of a range of fuel and fuel cycle options.

Research, development and demonstration (RD&D) technology advanced fuel cycle roadmaps will be published separately taking its input from this energy system modelling and the associated nuclear deployment scenarios outlined. In addition, detailed fuel cycle modelling – using the data generated from the energy system modelling – is planned using the NNL developed ORION modelling capability to outline, for example, uranium ore requirements, spent fuel volumes and storage requirements, and fabrication requirements for the scenarios. It is hoped that this work will provide underpinning evidence for decision makers to inform future UK energy strategy and policy.

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1. Introduction

This report presents full UK energy system modelling work which outlines a range of scenarios to deliver Net Zero in 2050. The modelling was completed to underpin advanced fuels and fuel cycle technology roadmapping; this includes providing input data to enable future fuel cycle modelling to be performed using the NNL developed ORION modelling capability. Roadmapping and fuel cycle modelling will provide an evidence base to support decision makers when considering future UK energy strategy and policy.

Energy system modelling work has been undertaken by Energy Systems Catapult (ESC) and LucidCatalyst working with NNL. This report provides a brief overview of the modelling work and presents in full the detailed modelling work in Appendices. Nuclear deployment scenarios are presented. Technology roadmapping and fuel cycle modelling will be reported separately.

1.1. Overview of modelling work

As part of the current the Advanced Fuel Cycle Programme (AFCP), full UK energy system modelling work has been undertaken to inform four potential nuclear deployment scenarios in a 2050 Net Zero UK energy mix:

1. Constrained by policy to a capped level (14 GWe) of nuclear deployment

2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral

3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market

4. Greater nuclear ambition with new technologies for low-cost high-volume hydrogen and synthetic fuel production included.

This work was done by the Energy Systems Catapult (ESC) using the whole energy system model known as Energy System Modelling Environment[1] (ESME). ESME has been internationally peer reviewed and analysis using ESME has been considered by the Committee on Climate Change as part of its deliberations.

The AFCP modelling builds on ESC's Innovating to Net Zero analysis and report[2] plus ESC's Nuclear for Net Zero (NFNZ) project and associated report[3].

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1   Further information on ESME and the evidence base it incorporates can be found on the ESC website
    https://es.catapult.org.uk/brochures/esme-data-references-book/

2   Innovating to Net Zero. Energy Systems Catapult 10th March 2020.

3   Nuclear for Net Zero – A UK Whole Energy System Appraisal. Project Summary Report.
    June 2020 by Energy Systems Catapult. https://es.catapult.org.uk/reports/nuclear-for-net-zero/

Individual reports containing the detailed AFCP analysis are included in Appendices to this summary document.

Scenario	Policy Constrained	Base Case	Higher optimism	Greater Nuclear Ambition
Appendix 1	✔	✔		
Appendix 2			✔	
Appendix 3				✔

The following describes at a high level the additional/different analysis relative to the ESC NFNZ work completed:

Appendix 1 – Supplementary Report No.1: Additional Scenarios

- Advanced Modular Reactor (AMR) high temperature reactors configured to deliver a combination of flexible power generation and low temperature heat production for the energisation of city scale district heating systems

- A probabilistic run (sometimes referred to as a Monte Carlo run) with Light Water SMR (LWSMR) cogeneration switched off (i.e. no heat extraction for the energisation of city scale district heating systems)

Appendix 2 – Supplementary Report No.2: Revised Datasets Reflecting Higher Optimism

- Updated datasets from NFNZ to now comprise:

  — An increase in Nth of a kind (NOAK) construction duration for Gen III+ from 5 years to 5.5 years

  — A reduction in the NOAK cost for LWSMR with an increase in learner effect through to 2050

  — An advance of the first UK operations date of a commercial AMR from 2035 to 2030 with an increase in learner effect through to 2050.

Appendix 3 – Supplementary Report No.3: Additional Technologies – Greater Nuclear Ambition

- The additional nuclear technologies comprise:

  — The concept of a hydrogen gigafactory for dedicated production of high-volume low-cost hydrogen with a low carbon footprint

  — A technology to produce liquid synthetic hydrocarbon fuel, or Jet A, for "drop-in" application within the aviation sector as an alternative fuel with no net carbon emissions.

1.2. Nuclear deployment scenarios

The four nuclear deployment scenarios, plus a reference scenario of no nuclear, are shown in Table 1. Figure 1 to Figure 4 show further detail on the scenarios including deployment profiles between 2020 and 2050. These scenarios show that there is a potential role for nuclear in meeting UK Net Zero requirements, ranging from 14 GWe to over 60 GWe installed capacity with a range of applications and nuclear technologies. It is therefore essential to consider the fuel cycle implications associated with the deployment of Gen III+, LWSMR and Gen IV (AMR) reactor systems. In addition, the potential for over 60 GWe deployment necessitates the requirement to consider sustainable advanced fuel cycles ensuring best use of valuable material and considering impacts on repository designs.

In addition, based on the projected demand for low-cost hydrogen and clean synthetic fuels further ESME modelling was performed on a future hydrogen market and a cost sensitivity analysis performed. This included a 'gigafactory' concept to produce high-volume low-cost hydrogen, a scenario based on this low-cost hydrogen supply is called Greater Nuclear Ambition; again, if such a concept were to be deployed in the UK the associated fuel cycle would need to be carefully considered given the significant scale of deployment. Table 2 sets out some initial assumptions and open questions around the fuel types and fuel cycle for three scenarios.

Table 1 – 2050 nuclear deployment scenarios from full energy system modelling

Nuclear Deployment Scenario	Overall Grid Capacity GWe	Gen III+ Installed Capacity GWe	LWSMR Cogen Power and Heat GWe	Gen IV Cogen Power & H_2 GWe	Nuclear Electricity Generation TWh	Nuclear Heat to DH Network TWh	H_2 Supply from Gen IV TWh	Liquid Synthetic Fuel Jet A TWh	Total Nuclear Energy Supply TWh
No Nuclear	203	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0
Constrained	177	14	N/A	N/A	154	0	0	0	154
Base Case	144	4	19	22	298	167	33	0	498
Higher Optimism	148	4	13	49	399	131	87	0	617
Greater Nuclear Ambition	117	4	19	0	171	123	532	148	974

Table 2 – 2050 nuclear deployment scenarios and fuel cycle considerations

Nuclear Deployment Scenario (TECH100)	Gen III+ Installed Capacity GWe	Fuels	LWSMR Cogen Power and Heat GWe	Fuels	Gen IV Cogen Power & H$_2$ GWe	Fuels	Fuel Cycle Strategy?
No nuclear	0	n/a	0	n/a	0	n/a	Open cycle
Policy Constrained	14	UOX, MOX, ATF	0	n/a	0	n/a	Open cycle
Base Case	4	UOX, MOX, ATF	19	UOX, ATF	22	CPF, FR-MOX, MSR, others?	To be determined
Higher Optimism	4	UOX, MOX, ATF	13	UOX, ATF	49	CPF, FR-MOX, MSR, others?	To be determined

Uranium Oxide (UOx), Mixed Oxide (MOX), Advanced Technology Fuels (ATF), Coated Particle Fuel (CPF), Fast Reactor MOX (FR-MOX), Molten Salt Reactor Fuel (MSR)
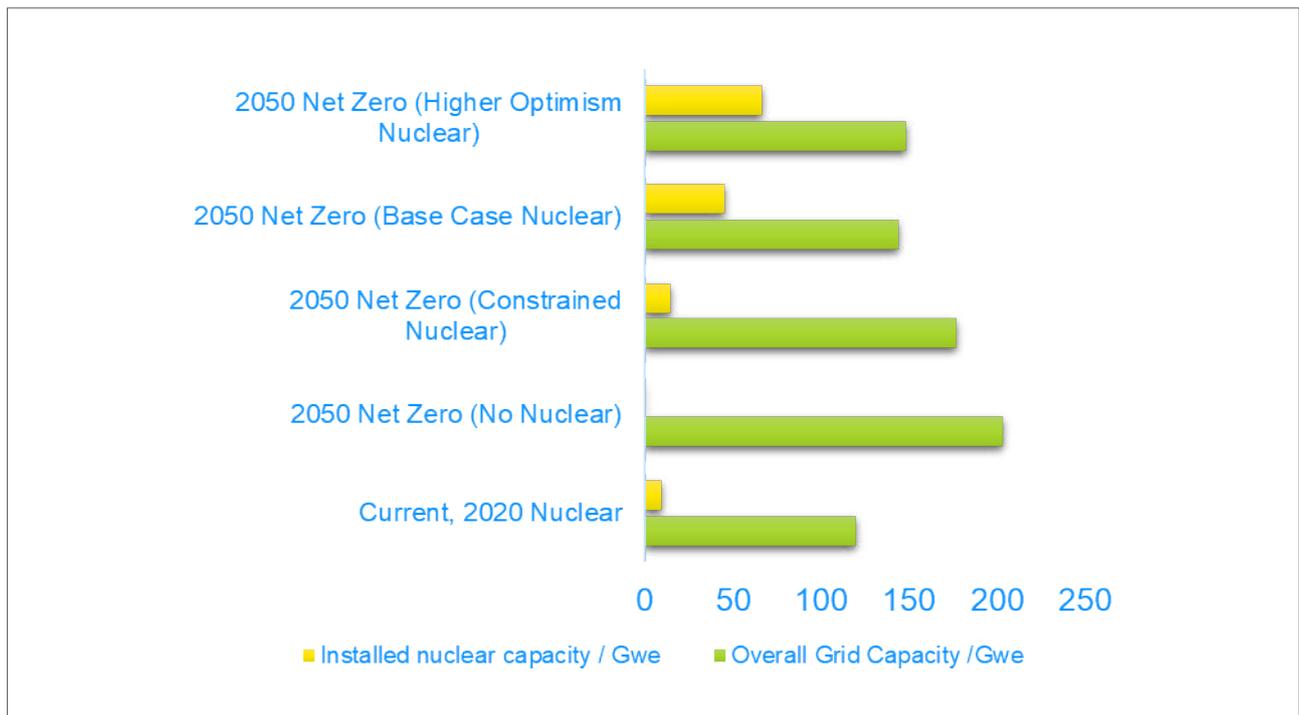
Figure 1 – Overall grid capacity and installed nuclear capacity for three deployment scenarios
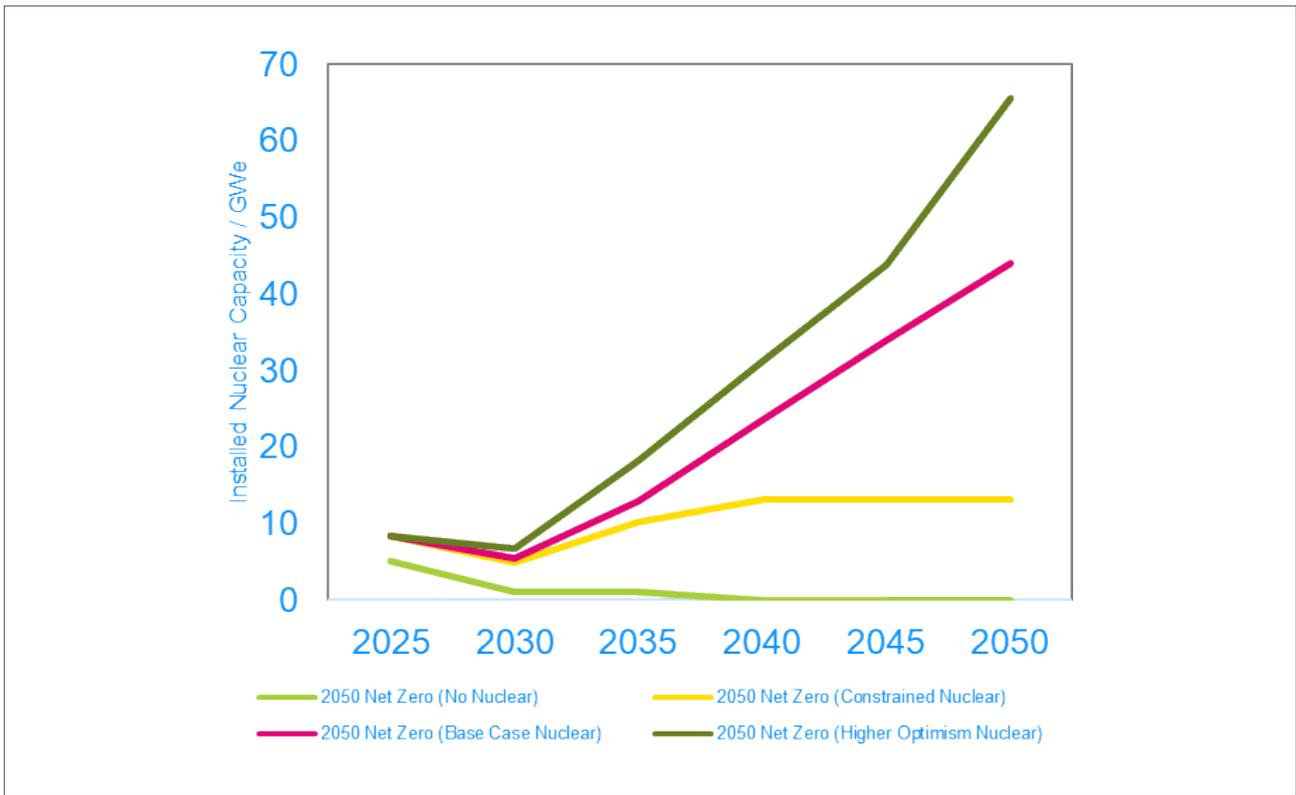
Figure 2 – Installed nuclear capacity for three deployment scenarios, 2020 to 2050
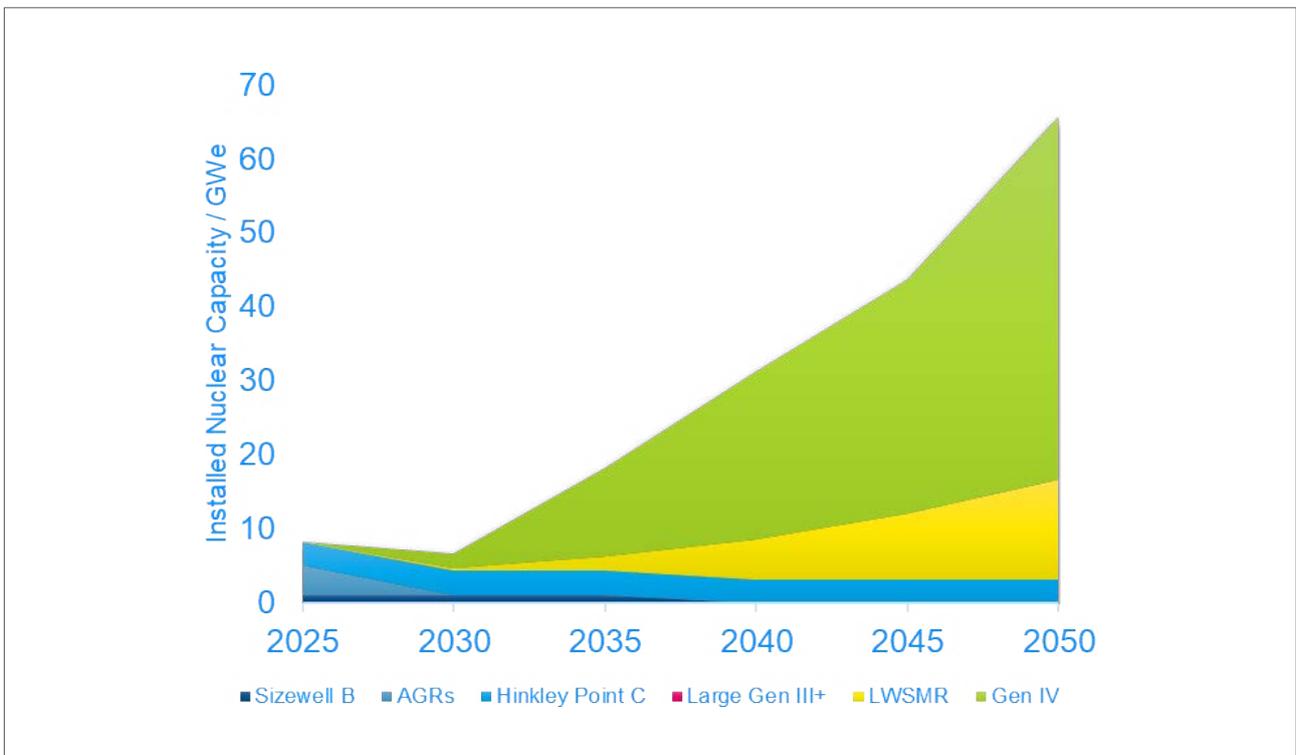
Figure 3 – Installed nuclear capacity for 'higher optimism' scenario, 2020 to 2050
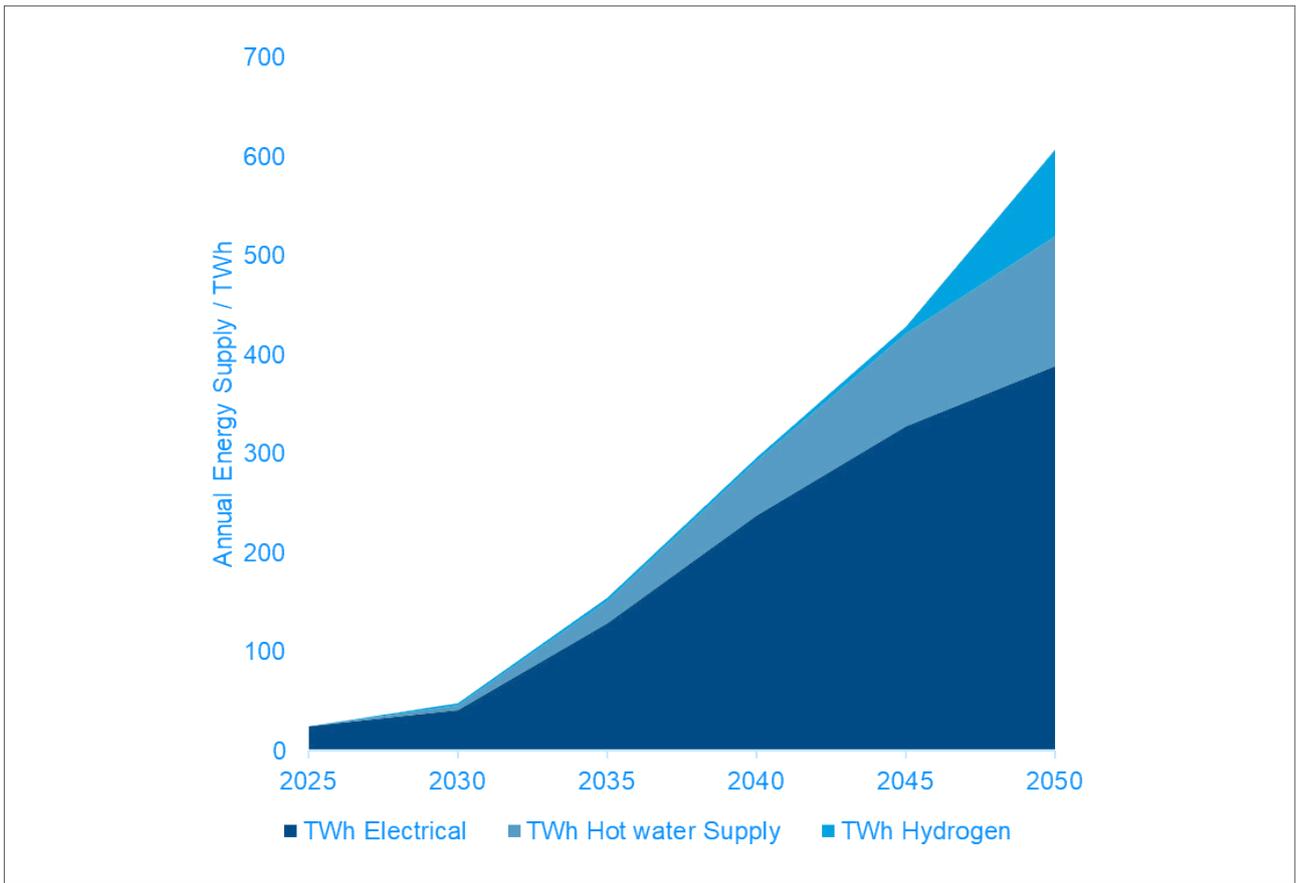
Figure 4 – Annual energy supply (electrical, hot water and hydrogen) for 'higher optimism' scenario, 2020 to 2050

2. Summary

Detailed energy system modelling has been completed to support advanced fuels and fuel cycle technology roadmapping, as well as underpinning fuel cycle modelling. This work is required due to the absence of publicly available detailed full system modelling in a Net Zero world that includes a wider role for nuclear technologies beyond electricity generation. For this reason, the modelling included here is crucial and adds considerably to the developing database of understanding of future UK energy system scenarios.

The modelling provides credible scenarios including a role for large, small and advanced nuclear across electricity, heat and hydrogen. These scenarios are, however, not intended to be predictions of the future but to look at a range of possible future roles for nuclear in a Net Zero 2050 UK energy system. This enables appropriate assessment of potential fuel and fuel cycle technology needs to be considered and investigated. It is also crucial to understand potential future markets for future fuels.

Advanced fuel and fuel cycle technology research, development and demonstration (RD&D) roadmaps will be published (separately) based on the nuclear deployment scenarios outlined.

In addition, detailed ORION fuel cycle modelling (using input data from this energy system modelling work) will be published to understand the potential implications of scenarios that may need to be considered from a UK strategic perspective.

3. Acknowledgements

Thank you to Energy Systems Catapult (ESC) and LucidCatalyst for their expert input to enable this work to be undertaken.

Appendix 1

SUPPLEMENTARY REPORT NO. 1:
ADDITIONAL SCENARIOS

NNL ENERGY SYSTEM MODELLING REPORT

CATAPULT
Energy Systems

LUCID
CATALYST

NATIONAL NUCLEAR
LABORATORY

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1. Executive summary

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme including a Futures Roadmap. NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements. These scenarios are defined through NNL's Energy System Modelling project as:

0. No new nuclear deployment

1. Constrained by policy to a capped level of nuclear deployment

2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral

3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market

4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies new potential pathway options as part of the approach to Net Zero.

These scenarios are partly delivered through ESC's Nuclear for Net Zero technical report which is available to NNL. The balance of the analysis to define these four scenarios is to be delivered through 3 Supplementary Reports. The first element of additional analysis is described in this report as Supplementary Report No.1.

The scope of the analysis in this report delivers the additional scenarios required by the scope of the NNL specification for its Energy System Modelling project. The additional scenarios included examination of Generation IV technology for combined heat and power operations, with heat taken at a lower temperature consistent with the requirement for District Heating (DH) energisation. This enabled comparison with energy system scenarios using Light-Water nuclear Small Modular Reactors (LWSMRs) for Combined Heat and Power (CHP) operations and DH energisation. A further additional scenario was a repeat of the probabilistic (Monte Carlo) analysis described in the Nuclear for Net Zero technical report, but with LWSMRs deployed in electricity only mode rather than for CHP and DH energisation.

The new analysis supports the following conclusions:

Conclusion 1 – Gen IV technologies are equally capable of combined heat and power operations for DH energisation as LWSMRs. In like-for-like comparisons between energy system scenarios, the differences between overall optimisation solutions were small.

Conclusion 2 – the technical performance and economic differences between Gen IV and LWSMR are relatively small when considering their relative merit for CHP configuration for potential DH energisation. Such differences are small when considered against the overall need for market, policy and regulation consideration of whether city scale district heat networks are to be part of the basket of technical solutions to decarbonise space heating and hot water production in larger towns and cities.

Conclusion 3 – a policy decision not to deploy nuclear plants (large Gen III+, LWSMR, or Gen IV) as capable of future energisation of city scale district heating systems is likely to increase demand for hydrogen and electricity generation. Technologies contributing to this increase in installed generating capacity are likely to include wind and nuclear.

Conclusion 4 – the analysis in this report has identified no new Market, Policy or Regulation (MPR) considerations in addition to those identified in the Nuclear for Net Zero technical report.

Conclusion 5 – the nuclear deployment scenarios defined as "constrained" and "base case" as reported in the Nuclear for Net Zero technical report are further supported by the analysis in this report and are therefore unchanged.

This report should be read in conjunction with the ESC Nuclear for Net Zero report which is available within NNL.

2. Introduction

2.1. Introduction to Energy Systems Catapult

Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.

The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research.

We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, to decarbonise the energy system at the lowest cost.

2.2. NNL's Energy System Modelling Project

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme:

1. People
2. Infrastructure
3. Ideas
4. Supply Chain
5. Stakeholder Engagement
6. Industry Alignment
7. International Influence
8. Futures Roadmap

NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements.

2.2.1. NNL's Energy System Modelling Project objective

The objective of NNL's Energy System Modelling project is to inform 5 potential nuclear deployment scenarios defined as:

0. No new nuclear deployment
1. Constrained by policy to a capped level of nuclear deployment
2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral
3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market
4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies potential new pathway options as part of the approach to Net Zero.

Nuclear deployment in a scenario of "no new nuclear" as indicated above is of little benefit to an advanced fuel cycle programme, other than cognisance of the circumstances that could make such a scenario more likely. Such a scenario is defined later in this report in Section 2.2.2 but otherwise not considered further as part of this project.

2.2.2. Technical starting point for NNL's Energy System Modelling Project

ESC owns, operates and maintains a whole energy system model known as Energy System Modelling Environment[1] (ESME) which has been developed over a decade for the purpose of better understanding the pathways and options for decarbonising the UK economy. ESME has been internationally peer reviewed and is used under licence by various organisations. Analysis using ESME has been considered by the Climate Change Committee as part of its deliberations.

The process flow necessary to deliver the 4 nuclear deployment scenarios is illustrated in Figure 1.

Figure 1 – Process flow to deliver four potential UK nuclear deployment scenarios

However, in 2019 ESC launched a programme of projects as part of a Net Zero programme to reflect the amendment in June 2019 to the Climate Change Act 2008. This legislation adjusted the performance objective of 80% decarbonisation compared with historic reference levels to Net Zero by 2050. This ESC programme in response to this new legislation delivered the first step in the process flow illustrated in Figure 1 by delivering four new ESME decarbonisation scenarios:

• FA96 – using core technologies for 80% decarbonisation and stretched to deliver 96%

• TECH100 – introduction of additional speculative technologies to deliver 100% decarbonisation

• SOC100 – introduction of speculative changes to societal behaviours for 100% decarbonisation

• BOB100 – combination of both TECH100 and SOC100

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1. Further information on ESME and the evidence base it incorporates can be found on the ESC website: https://es.catapult.org.uk/brochures/esme-data-references-book/

These new scenarios are described in more detail in ESC's Innovate to Net Zero analysis and report[2], and subsequently used in the IUK WP7 project.

ESC's Net Zero programme was delivered through a project known as the Energy Technology Benchmarking project which was grant funded by Innovate UK (IUK). The scope funded by IUK included a further project known as Innovate UK Work Package 7 (IUK WP7). The scope of IUK WP7 delivered the next two steps in the process flow illustrated in Figure 1. Therefore, the technical starting point for NNL's Energy System Modelling Project is ESC's Nuclear for Net Zero project and associated report[3], otherwise known as IUK WP7. The Nuclear for Net Zero project technical report has been made available to NNL for the purpose of its Energy System Modelling project.

The objective of NNL's Energy System Modelling project will be achieved through a combination of the IUK WP7 project and associated report, and three further Supplementary Reports as illustrated in Figure 2. The Zero Deployment (0) and the Constrained Deployment (1) scenarios are defined within the IUK WP7 project technical report. This report together with Supplementary Report No.1 delivering additional scenarios informs the Base Case (2) Nuclear Deployment scenario. A second Supplementary Report (No.2) will document indicative nuclear deployment with further revised data provided by industry experts at LucidCatalyst to inform a nuclear deployment scenario known as (3) Higher Optimism. A final Supplementary Report (No.3) will document the indicative nuclear deployment levels from adding a new technology type to ESME enabled by low-cost, carbon-free hydrogen. This will inform the final scenario known as (4) Greater Nuclear Ambition. The project outputs to deliver the project objective are summarised in Table 1 below.

Figure 2 – ESC's WP7 project report and the 3 NNL Supplementary Reports combine to define four potential UK nuclear deployment scenarios

2. Innovating to Net Zero. Energy Systems Catapult 10th March 2020.
   https://es.catapult.org.uk/reports/innovating-to-net-zero/

3. Nuclear for Net Zero – A UK Whole Energy System Appraisal. Project Technical Report dated 17th April 2020 by Energy Systems Catapult.

Table 1 – Sequence of project reports leading to nuclear deployment scenarios to deliver the project objective

Project	Report	Scope	Nuclear Deployment Scenarios
ESC project IUK WP7	ESC project report	Overlap with majority of analysis detailed in NNL ITT	1 Constrained
NNL Energy System Modelling project	Supplementary report 1	Balance of analysis required by NNL ITT	2 Base case
	Supplementary report 2	Impact of revised inputs for nuclear technologies	3 Higher optimism
	Supplementary report 3	Additional technology added to and tested in ESME	4 Greater nuclear ambition

2.2.3. Purpose of Supplementary Report No.1

The purpose of Supplementary Report No.1 is to deliver the balance of scope specified for NNL's project and to contribute to the analysis supporting the first two potential nuclear deployment scenarios of "Constrained" and "Base Case".

3. Approach to the analysis for Supplementary Report No. 1

3.1. Gap analysis

A gap analysis was undertaken to compare the detailed scope of work in NNL's project specification of requirements with the scope of work already being delivered as part of IUK WP7. This showed that there are two specific scenarios to be modelled which are not included within the full scope of IUK WP7 but need to be delivered to achieve full compliance with the technical scope of NNL's ITT. These scenarios are:

- AMR high temperature reactors configured to deliver a combination of flexible power generation and low temperature heat production for the energisation of city scale district heating systems

- A probabilistic run (sometimes referred to as a Monte Carlo run) with LWSMR cogeneration switched off (i.e. no heat extraction for the energisation of city scale district heating systems)

These two scenarios are to be undertaken as part of the scope of Supplementary Report No.1. Additionally, there is benefit in providing a brief explanation as to why within the IUK WP7 project ESC elected not to update the model functionality to represent the general direct application of nuclear heat as a potential solution for decarbonising industrial heat demand.

3.2. Approach informed by the gap analysis

The approach to the scope for Supplementary Report No.1 is illustrated in Figure 3 which shows:

- Gap assessment: This identifies the scope of the additional sensitivity runs to be undertaken in ESME

- Update datasets: No additional data is required for this analysis, but Generation IV plants are modelled in a different mode and the Gen IV dataset is reconfigured to reflect this

- Scenario analysis:

  - The first scenario is for the Gen IV plant to be deployed using Base Case data in a cogeneration mode to deliver a combination of flexible power generation and low temperature heat production for the energisation of city scale district heating systems. For direct comparison with specific earlier Runs reported in IUK WP7, this deployment scenario will be tested with decarbonisation scenarios FA96 and TEC100. These Runs will be for cogeneration Gen IV deployed alone without deployment of large Gen III+ or LWSMR

  - The second scenario is a repeat of the probabilistic (Monte Carlo) run reported in IUK WP7 but with LWSMRs configured for the supply of electricity only, with no heat take-off to energise city scale district heating systems.

  - Although not undertaken as a scenario, there is benefit in providing a brief explanation of why, within the IUK WP7 project, ESC elected not to update the model functionality to represent the general direct application of nuclear heat as a potential solution for industrial heat demand.

- Results: Data is extracted from ESME outputs in the form of core charts and the results interpreted to identify any new trends or tipping points from the new scenarios and data.

- Recommendations with respect to Market, Policy or Regulation (MPR): The actions and MPR recommendations from the IUK WP7 technical report are re-visited with the benefit of additional scenarios and data informed by the analysis for Supplementary Report No.1.
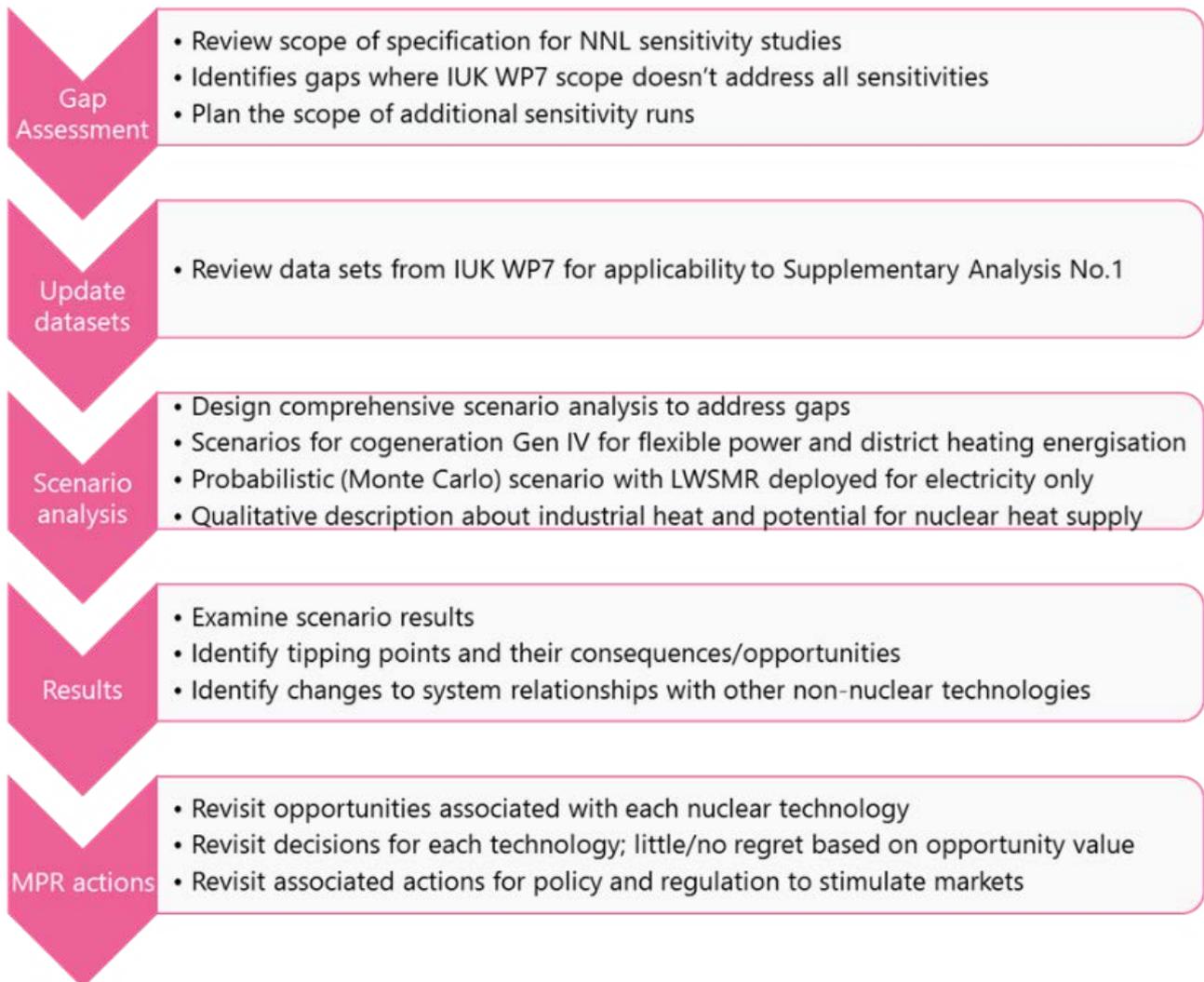
Gap Assessment
- Review scope of specification for NNL sensitivity studies
- Identifies gaps where IUK WP7 scope doesn't address all sensitivities
- Plan the scope of additional sensitivity runs

Update datasets
- Review data sets from IUK WP7 for applicability to Supplementary Analysis No.1

Scenario analysis
- Design comprehensive scenario analysis to address gaps
- Scenarios for cogeneration Gen IV for flexible power and district heating energisation
- Probabilistic (Monte Carlo) scenario with LWSMR deployed for electricity only
- Qualitative description about industrial heat and potential for nuclear heat supply

Results
- Examine scenario results
- Identify tipping points and their consequences/opportunities
- Identify changes to system relationships with other non-nuclear technologies

MPR actions
- Revisit opportunities associated with each nuclear technology
- Revisit decisions for each technology; little/no regret based on opportunity value
- Revisit associated actions for policy and regulation to stimulate markets

Figure 3 – Schematic showing process flow to deliver analysis for Supplementary Report No.1

4. Updated datasets for Supplementary Report No.1

4.1. Datasets for Supplementary Report No.1

Table 2 – Selected key parameters from NFNZ for Gen IV cogen (flexible power and heat for district heating energisation)

Cogen Gen IV Electricity and Hydrogen (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2035	2040 (but 2035 used in ESME runs to reflect a push for commercialization)	2045
Construction Duration (years)	2	3	4
Build Out Rate (GWe/year)	3.0	1.5	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,000/KWe at 2035 reducing to $2,500/KWe by 2050	$3,500/KWe at 2035 reducing to $3,000/KWe by 2050	$4,000/KWe at 2035 reducing to $3,500/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 90% (3) Capex is for cogeneration with heat rejected from power conversion system used for DH energisation with power downrate penalty. Costs include $500/kWe Capex increment for CHP which includes pipe runs circa 10 km to connect plant to city scale DH ring main (4) For electricity only plant remove the $500/KWe CHP increment included in the Capex (5) Full DH energisation across England and Wales equates to 22 GWe of LWSMR in England and Wales from ETI ANT project. This limit retained for Gen IV Cogeneration of power heat and heat for DH energisation. (6) Site capacity limit for England and Wales at 2050 established from the ETI PPSS (7) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The analysis for Supplementary Report No.1 requires no new input data, but the Generation IV plant represented in ESME, with its associated dataset, is deployed in a different operating mode. For ease of reference the key parameters of the Generation IV plant dataset when configured for flexible delivery of power and heat for DH energisation are shown in Table 2. For brevity, the full

dataset and associated supporting assumptions and related data are not repeated here but reported and available in the Nuclear for Net Zero technical report, together with the comparable data for large Generation III+ reactors (above 1.0 GWe), and Light-Water nuclear Small Modular Reactors (LWSMRs).

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 2 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

4.2. Options for decarbonising industrial heat

There are diverse requirements for the use of high temperature heat across the industry sector. The opportunities for decarbonisation of energy use in the industry sector include:

- energy efficiency measures through insulation or process improvement

- CCS emission abatement technology, but many applications of high temperature heat use are unlikely to be in CCS clusters therefore precluding this as a widespread option

- electrification, depending on local infrastructure requirements

- naked flame hydrogen as a replacement for natural gas.

Fuel type	Key	TWh at 2050
Liquid fuel		30
Hydrogen		60
Gas		83
Electricity		95
Coal		4
Biomass		34
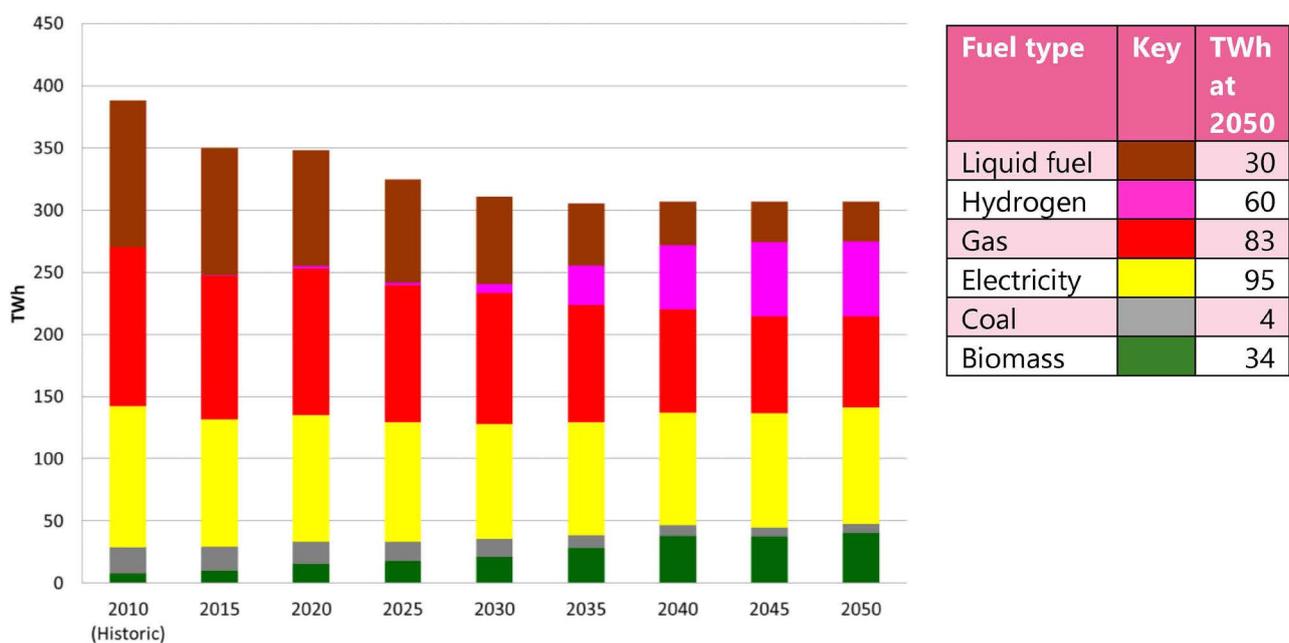
Figure 4 – Industry fuel consumption with scenario TECH100 (Run 1a) from ESC's Nuclear for Net Zero Report

Figure 4 illustrates both how ESME categorises fuel use within the industrial sector and also how ESME approaches the decarbonisation of the industrial use of heat towards 2050. The chart in Figure 4 is from Run 1a using the TECH100 scenario which is described in the Nuclear for Net Zero technical report. Inspection of the sources of fuel for the industry sector in 2050 identifies:

- Continued consumption in some industrial applications of liquid fuels and natural gas, which will make some contribution to gross Green House Gas (GHG) emissions in 2050 Fuel type Key TWh at 2050 Liquid fuel 30

- Use of electricity and hydrogen as low carbon energy vectors, both of which have the potential to be energised by nuclear as described in the Nuclear for Net Zero report

- Potential for further reduction in the use of fossil fuels if the direct supply of high temperature heat from nuclear could be introduced as a further option from this sector

Some vendors of advanced reactor designs are promoting the direct supply of high temperature heat as part of their business proposition to the market. Specific opportunities have been identified where significant energy demand at existing nuclear sites might be cost effectively delivered and decarbonised through the on-site cogeneration of high temperature heat and power. U Battery[4] has promoted this as a potential solution for the energy demand at Urenco's UK uranium enrichment plant at Capenhurst. High temperature heat supply (above 300°C currently achievable with LWRs) is an area of interest for a number of vendors of advanced reactors, either for the embedded heat and power supply within industrial complexes, or for remote off-grid industries and communities.

The decision not to develop ESME within IUK WP7 to specifically introduce the direct supply of nuclear heat to the industrial sector was based on a compromise reflecting 4 factors:

- The complexity and associated necessary effort to specifically introduce the direct supply of nuclear heat to the industrial sector within ESME

- The progress that could be made in decarbonising the industry sector through the potential for increased availability and reduced cost of low carbon electricity and hydrogen as reported in the Nuclear for Net Zero technical report

- Recognition of the potential MPR challenge in realising widespread deployment of nuclear high temperature heat for industrial applications. Much of this challenge is centred on the requirement to introduce additional nuclear licenced sites which is described in detail in section 9.6.5 of the Nuclear to Net Zero technical report

- Balancing the value of impact from effort and recognition that, within IUK WP7, effort invested in tackling the direct supply of nuclear heat to the industry sector would have less impact on overall decarbonisation pathways compared with the benefits of increasing the availability and reducing costs for low carbon electricity, hydrogen, and hot water delivered through district heating networks.

This decision does not mean that nuclear technologies are unable to supply direct high temperature heat for industrial applications and this could be investigated further through ESME if funding is available to do so. But the MPR considerations to enable the widespread deployment of nuclear technologies for this purpose include:

- Designation of additional nuclear sites beyond those identified in NPS – EN6

- A change to the reactor siting criteria relevant to the specific nuclear technologies proposed, to enable co-location with some industrial activities and potentially closer to population centres

- A positive Government policy approach for nuclear licensed sites of "disperse and embed", as opposed to "contain and distribute"

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4. U Battery website: https://www.u-battery.com/

- Regulatory acceptance by safety and environmental regulators of the concept of "remote operational control", which would be driven by the economic requirement to minimise fixed operating costs and reducing the number of licensee personnel permanently based at each location

- In comparison with alternative low carbon energy sources for industrial sector decarbonisation, nuclear technologies must offer sufficient economic and wider benefits to secure the argument for such applications through Regulatory Justification with Parliament (see section 5.4 of the Nuclear for Net Zero technical report for more details).

This collection of MPR challenges for the widespread dispersed direct supply of heat for industry sector applications is much greater than for the cogeneration of power and hydrogen production. From an MPR consideration, it is judged that cogeneration of power and hydrogen probably has greater economic and wider benefits related to Regulatory Justification.

5. ESME analysis and results

The charts and tables shown in section 5 are intended to collate and summarise key information from the many ESME runs across relatively few pages. These results are then interpreted and discussed in Section 6.

A listing of all new scenario runs is provided in Annex 1. To provide a greater level of detail, all the relevant ESME core chart outputs for these Runs are included in Annex 2. Some Runs from the Nuclear for Net Zero report are included for comparison purposes with the new analysis reported here. The relevant ESME core charts for these comparison runs are additionally included within Annex 2 for convenience.

5.1. Electricity capacity and generation

The data associated with new Runs 27 (FA96) and 27a (TECH100) are summarised in comparison with previous Runs 9 and 15 in Table 3 and Runs 9a and 15a in Table 4. These Tables include 2050 levels of nuclear deployment and associated power generation. The three Runs in Tables 3 and 4 are defined as:

- Run 9 – new nuclear deployment limited to LWSMR alone, deployed as cogeneration for heat and power

- Run 27 – new nuclear deployment limited to Gen IV alone, deployed as cogeneration for heat and power

- Run 15 – new nuclear deployment limited to Gen IV alone, deployed as cogeneration power and hydrogen production.

Table 3 – Selected 2050 energy system outputs from selected scenarios using decarbonisation scenario FA96

FA96 Run	Overall Grid Capacity GWe	LWSMR Cogen Power and Heat GWe	Gen IV Cogen Power & Heat GWe	Gen IV Cogen Power & H2 GWe	Nuclear Electricity Generation TWh	Nuclear Heat to DH Network TWh	H2 Supply from Gen IV TWh	LWSMR or Gen IV Energy Supply TWh
Run 9	275	22			156	190		346
Run 27	275		22		173	189		362
Run 15	268			22	14		120	134

Table 4 – Selected 2050 energy system outputs from selected scenarios using decarbonisation scenario TECH100

TECH100 Run	Overall Grid Capacity GWe	LWSMR Cogen Power and Heat GWe	Gen IV Cogen Power & Heat GWe	Gen IV Cogen Power & H2 GWe	Nuclear Electricity Generation TWh	Nuclear Heat to DH Network TWh	H2 Supply from Gen IV TWh	LWSMR or Gen IV Energy Supply TWh
Run 9a	161	22			158	177		335
Run 27a	161		22		173	189		362
Run 15a	165			22	168		4	172

5.2. Supply of lower grade heat for district heating energisation

Energy from nuclear distributed via DH networks is also included in Tables 3 and 4 for Runs 27 and 27a for comparison with previous Runs.

Energy from nuclear distributed via DH networks is also illustrated in Figure 5 which shows Runs 27 and 27a for comparison with previous Runs.
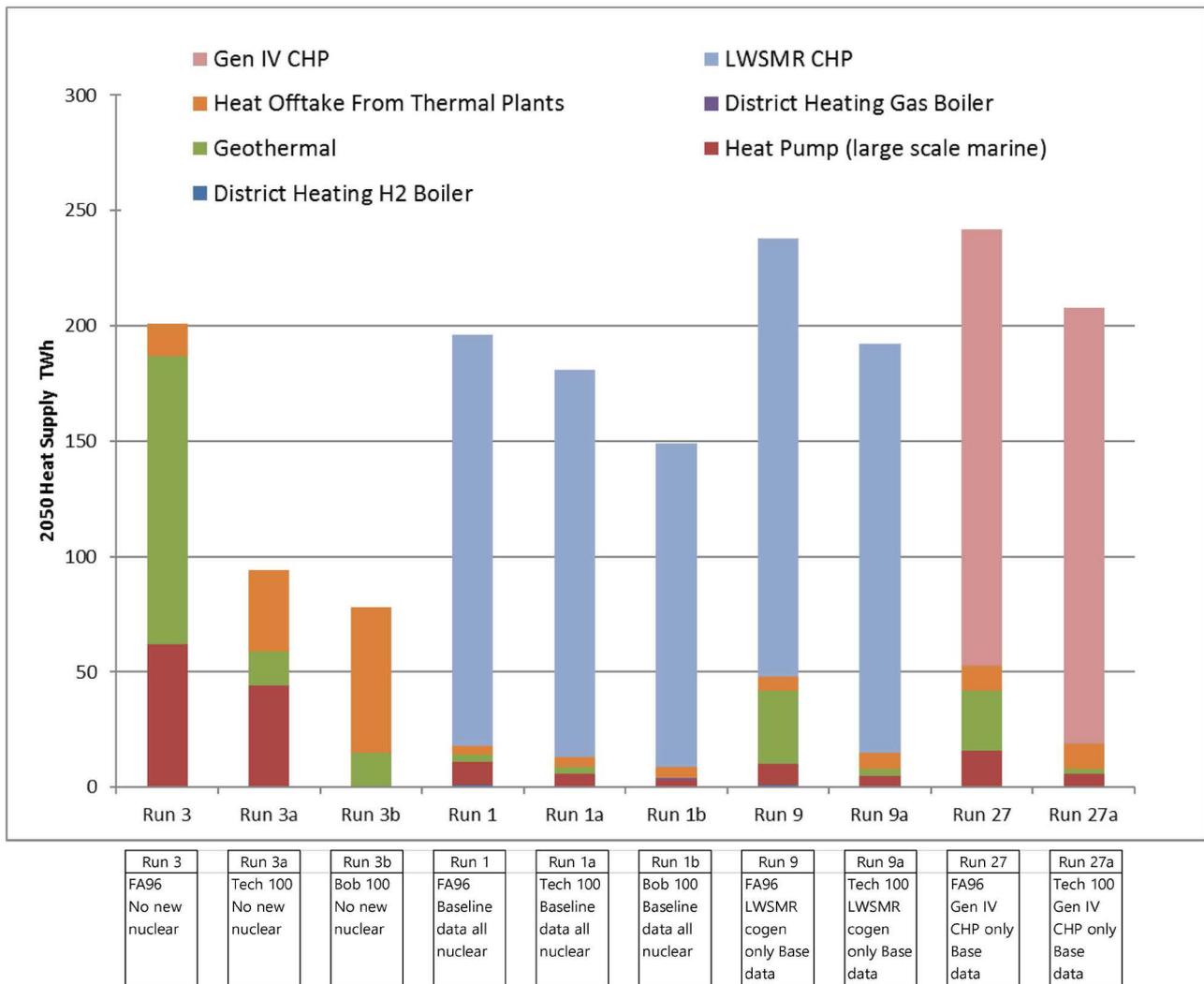
Figure 5 – 2050 hot water network heat supply by technology for a range of scenarios

5.3. Hydrogen consumption and supply

Hydrogen supply from nuclear is also included Tables 3 and 4 for Runs 27 and 27a for comparison with previous Runs.

5.4. Probabilistic (Monte Carlo) assessment
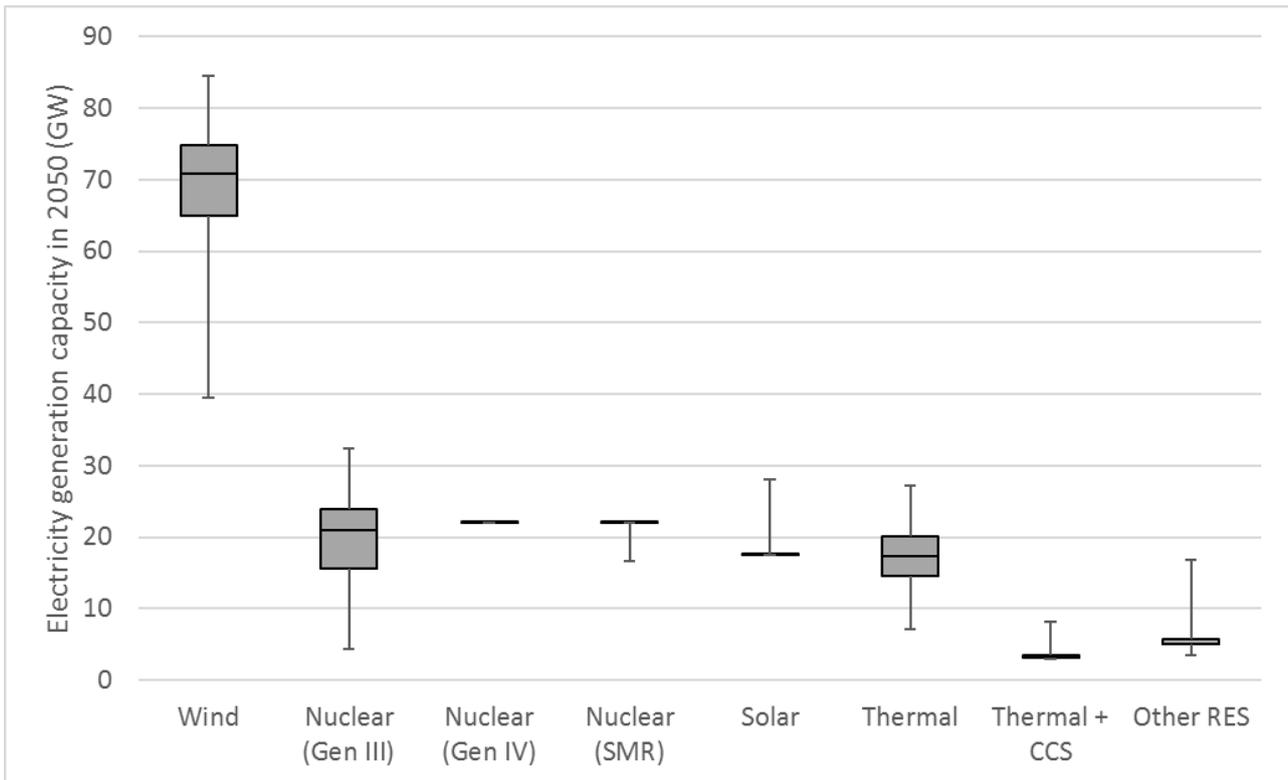
Figure 6 – Probabilistic (Monte Carlo) run showing electricity generation capacity in 2050 – using TECH100 with nuclear base case values but with LWSMR deployed as electricity only
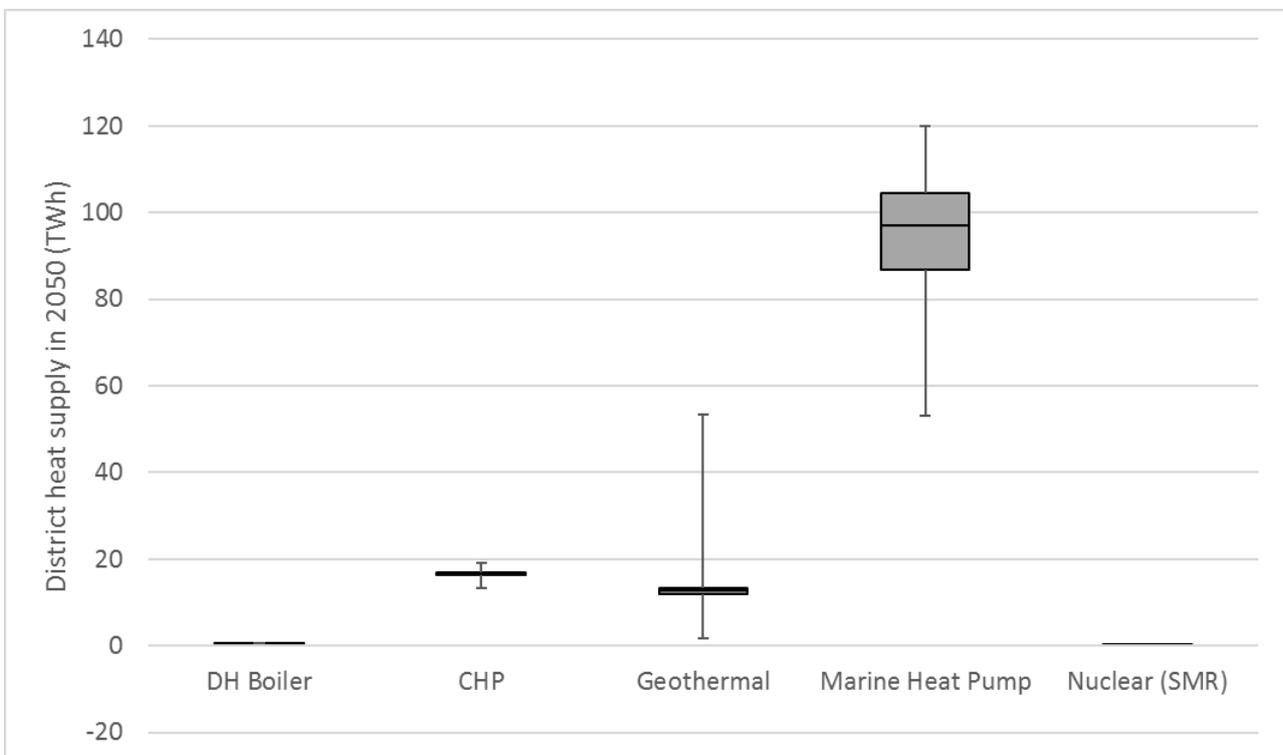
Figure 7 – Probabilistic (Monte Carlo) run showing district heat supply in 2050 – using TECH100 with nuclear base case values but with LWSMR deployed as electricity only

Table 5 – Selected key parameters from Monte Carlo analysis with cogen LWSMR deployed for district heating energisation

Statistical Distribution Level %	2050 Electrical Generation Capacity by Technology (GWe)			
	Wind	Gen III+	LWSMR Cogen CHP	Gen IV Cogen Power and H2
100	83	29	22	22
75	74	21	22	22
50 – median	69	17	22	22
25	64	14	22	22
0	38	4	18	22

Table 6 – Selected key parameters from Monte Carlo analysis with LWSMR deployed as electricity only

Statistical Distribution Level %	2050 Electrical Generation Capacity by Technology (GWe)			
	Wind	Gen III+	LWSMR Electricity Only	Gen IV Cogen Power and H2
100	94	33	22	22
75	85	24	22	22
50 – median	71	21	22	22
25	65	16	22	22
0	39	4	18	22

6. Discussion

6.1. Electricity capacity and generation

Tables 3 and 4 include electrical generation capacity and electricity generation in 2050. Runs 9 and 9a are for LWSMR deployed alone, i.e. without large Gen III+ or Gen IV, using decarbonisation scenarios FA96 and TECH100 respectively. Runs 27 and 27a are for Gen IV CHP deployed alone, i.e. without large Gen III+ or LWSMR, using decarbonisation scenarios FA96 and TECH100 respectively. Finally, Runs 15 and 15a are included for comparison which are for Gen IV cogen power and hydrogen production deployed alone, i.e. without large Gen III+ or LWSMR, using decarbonisation scenarios FA96 and TECH100 respectively.

In these scenarios, the individual technologies are deployed to the limits of build-out rate and site capacity limits in each Run.

Annual power generation levels in 2050 are slightly lower for LWSMR than Gen IV CHP. This is expected to be related to the Nuclear Heat Supply System cycle temperature assumed for Gen IV compared with LWSMR. For the months of the year when LWSMRs are operating in CHP mode, the ESME model applies a power downrate derived from the thermodynamic analysis reported in the ETI's ANT project. This power downrate is influenced by the temperature of the heat leaving the Nuclear Heat Supply System and the temperature of the heat extracted to energise the DH network. Either a decrease in nuclear cycle temperature or an increase in the temperature of heat extraction will cause the power downrate to increase. Overall this effect is relatively small for LWSMRs. The ESME model applies no power downrate to Gen IV because it is assumed that Gen IV is operating with a much higher nuclear cycle temperature associated with many advanced reactors in general, and HTGRs in particular.

Comparison of LWSMR and Gen IV CHP with Gen IV cogeneration of power and hydrogen shows similar levels of electricity generation in Run 15a. Electricity generation is much lower in Run 15 which is associated with a much greater proportion of hydrogen production operation in 2050 associated with the FA96 scenario. The absence of the more speculative measures within FA96 leads to a reduction in emissions headroom in the system, meaning that even the small residual emissions from fossil CCS hydrogen production are prohibitive. In that case, options for hydrogen production are limited to Low Temperature Electrolysis or, in the case of Run 15/15a, nuclear Gen IV.

6.2. Energy supply to hot water networks

The hot water network energy supply chart in Figure 5 shows a number of Runs for comparison.

Runs 3, 3a and 3b are scenarios of no new nuclear deployment for decarbonisation scenarios FA96, TECH100 and BOB100 respectively. Heat networks are still extensively deployed in these scenarios, even in the absence of potential DH energisation from nuclear. In these scenarios the alternative sources of heat supply are heat off-take from other thermal plants and large-scale marine heat pumps. For the FA96 scenario there is also significant deployment of geothermal technologies, but the level of deployment diminishes with TECH100 and BOB100 scenarios.

Runs 1, 1a and 1b are for the same three decarbonisation scenarios but applied with all three nuclear technologies deployed in combination; Gen III+, LWSMR cogen CHP and Gen IV cogeneration of power and hydrogen production. These Runs show extensive deployment of LWSMR for CHP and DH energisation. Deployment erodes slightly in the sequence of FA96 through to BOB100. This is related to other system solutions being found for heating and power generation in response to the emissions headroom created with the introduction of more speculative measures in TECH100. This

is compounded by the reduction in energy demand and pressure on abating emissions due to other societal measures introduced in BOB100. But with the DH modelling assumptions in ESME, there is a strong role across all scenarios for using nuclear energy to energise DH networks.

Runs 9 and 27, and 9a and 27a present like-for-like comparisons between LWSMR CHP and Gen IV CHP. There is little difference between the technologies in terms of technical performance for DH energisation or the level of build out in ESME like-for-like scenarios.

6.3. Hydrogen consumption and supply

From Tables 3 and 4 only Runs 15 and 15a offer a source of hydrogen supply from nuclear. Runs 27 and 27a offer little additional insight into 2050 production or supply of hydrogen.

6.4. Probabilistic (Monte Carlo) assessment

The results from the additional Monte Carlo analysis undertaken to support this report are shown in Figures 6 and 7. These can be compared by inspection with the earlier charts from the Nuclear for Net Zero technical report which are included for ease of reference in Annex 2 as figures A2-39 and A2-40. The key parameters from both Monte Carlo analyses are summarised in Tables 5 and 6.

Figure 7 illustrates that with LWSMR deployed as electricity only instead of CHP, then large scale marine heat pumps become the dominant technology for energising district heat networks, which are still deployed at scale.

At first inspection, Figure 6 showing capacity levels of nuclear technologies deployed for electricity generation appears to have little difference from the previous analysis reported in the Nuclear for Net Zero technical report. Tables 5 and 6 compare the difference in more detail between with Table 5 associated with CHP LWSMR and Table 6 associated with LWSMR deployed for electricity only.

Table 6 shows a number of more subtle effects of removing the heat off-take from LWSMRs for DH energisation:

- High deployment levels remain for LWSMR and Gen IV at or close to deployment limits across the 100 simulations within the Monte Carlo analysis

- Removing the option of nuclear heat supply to energise DH networks results in alternative technologies being deployed to energise DH networks which are still built-out at scale, but less extensively than when a nuclear heat supply was available. Much of this alternative capacity for DH energisation, such as large-scale marine heat pumps, creates additional demand for grid supply. For the heat demand displaced from the hot water network, this heat demand must be satisfied through other technologies such as heat pumps, direct resistive electrical heating and use of hydrogen. These combined effects create additional electricity demand and pressure on emissions

- The overall net effect from removing the option of heat energisation of DH networks through LWSMR CHP is a net increase in deployment of electricity generation technologies to increase overall grid capacity. Table 6 shows this includes additional capacity from wind and additional deployment of Gen III+.

7. Implications for markets, policy and regulation

7.1. Extant MPR commentary from ESC report remains valid

The new analysis indicates four factors for consideration for markets, policy and regulation:

- Removing the optionality of combined heat and power from LWSMR plants or (potentially large Gen III+ plants noting that this option is not currently modelled in ESME) appears a poor policy choice. Heat networks are still extensively deployed in ESME scenario modelling although slightly diminished in scale. The net effect is to increase demand on other low carbon energy vectors including electricity, with implications for grid capacity

- Cogen Gen IV CHP plants are equally capable of energising DH networks as Cogen LWSMR CHP plants

- Nuclear technology deployment for CHP application and, in particular energising city scale DH systems, is most closely linked to policy decisions on whether there is policy support for DH deployment at scale

- Should city-scale DH deployment receive policy support, then potential heat off-take from all thermal plants, including nuclear, will be important. At present the default ESME configuration is that the only nuclear technology enabled for DH energisation is LWSMRs. In further work this should be extended to all nuclear technologies. Actual deployment of CHP capable plants will be strongly influenced by local demand, choices available at a local level, and the proximity of the nearest potential nuclear plant to the nearest potential DH network.

To this extent, the existing MPR recommendations identified in the Nuclear for Net Zero project report remain valid.

Removing the option of DH energisation from nuclear doesn't reduce nuclear deployed capacity from the Monte Carlo analysis. It has the opposite effect and, in leading to an increased demand for electricity, would suggest slightly higher levels of nuclear deployment. Therefore, the nuclear deployment scenarios of "constrained" and "base case" identified in the Nuclear for Net Zero project report remain extant.

7.2. Cogen heat and power – LWSMR or Gen IV?

There are no strong indicators within this analysis which identify whether LWSMR or Gen IV technologies are significantly better than the other for delivering cogeneration heat and power applications. In this analysis the datasets assume that the capex associated with Gen IV is lower than for LWSMR, and the datasets assume that the power downrate in CHP operation of LWSMRs doesn't apply to Gen IV deployed in CHP operations.

These subtle differences are outweighed by two MPR factors identified in the Nuclear for Net Zero technical report:

- Guidance on decarbonising space heating and domestic hot water production and whether city-scale DH is one of the technology options to receive policy support

- The benefit of launching the 3 nuclear programmes; an initial programme of large Gen III+ deployment, with parallel development programmes for LWSMR and Gen IV to establish if either or both can realise the assumed benefits in deployment. Success of either or both of these development programmes is unlikely to be influenced by which technology is better for CHP operations and DH energisation.

8. Conclusions

Context – the new analysis in this report delivers the additional scenarios required by the scope of the NNL specification for its Energy System Modelling project. The additional scenarios included examination of Generation IV technology for combined heat and power operations, with heat taken at a lower temperature consistent with the requirement for DH energisation. This enabled a comparison with energy system scenarios using Light-Water nuclear Small Modular Reactors for CHP operations and DH energisation. A further additional scenario was a repeat of the probabilistic (Monte Carlo) analysis described in the Nuclear for Net Zero technical report, but with LWSMRs deployed in electricity only mode rather than for CHP and DH energisation.

Conclusion 1 – Gen IV technologies are equally capable of combined heat and power operations for DH energisation as LWSMRs. In like-for-like comparisons between energy system scenarios, the differences between overall optimisation solutions were small.

Conclusion 2 – the technical performance and economic differences between Gen IV and LWSMR are relatively small when considering their relative merit for CHP configuration for potential DH energisation. Such differences are small when considered against the overall need for market, policy and regulation consideration of whether city scale district heat networks are to be part of the basket of technical solutions to decarbonise space heating and hot water production in larger towns and cities.

Conclusion 3 – a policy decision not to deploy nuclear plants (large Gen III+, LWSMR, or Gen IV) as capable of future energisation of city scale district heating systems is likely to increase demand for hydrogen and electricity generation. Technologies contributing to this increase in installed generating capacity are likely to include wind and nuclear.

Conclusion 4 – this analysis in this report has identified no new MPR considerations in additions to those identified in the Nuclear for Net Zero technical report.

Conclusion 5 – the nuclear deployment scenarios defined as "constrained" and "base case" as reported in the Nuclear for Net Zero technical report are further supported by the analysis in this report and are therefore unchanged.

9. Acronyms

AFCP	Advanced Fuel Cycle Programme
AMR	Advanced Modular Reactor
ANT	Alternative Nuclear Technologies (Project)
BOB100	Best of Both ESME Scenario designed to achieve 100% decarbonisation based on speculative behavioural change affecting demand and emissions
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DH	District Heat (System)
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment (a whole energy system model)
FA96	Further Ambition 96 (% decarbonisation scenario)
GHG	Green House Gas
Gen III+	Generation III+ nuclear reactor
Gen IV	Generation IV nuclear reactor
GWe	Giga-Watt electric
ITT	Invitation to Tender
IUK WP7	Innovate UK Work Package 7 (of the Energy Technologies Benchmarking Project)
LWSMR	Light-Water (Nuclear) Small Modular Reactor
MPR	Markets, Policy and Regulation
NNL	National Nuclear Laboratory
NPS	National Policy Statement
RES	Renewable Energy Source
TECH100 ESME	Scenario designed to achieve 100% decarbonisation using speculative technologies

10. Annexes

Annex 1 – List of ESME sensitivity runs for Supplementary Report No.1

Table A1-1 – Run summary from SR No.1 sensitivity studies

Run	Scenario	Sensitivity Criteria Applied	Notes
		Gen IV deployment only; no large Gen III+ deployment or light-water SMRs	
27	FA96	Gen IV Cogeneration power and heat for District Heat energisation only; no Gen III+ or light-water SMR. Base case data.	Reflects scenario where Gen IV is reconfigured from Cogen power and hydrogen to Cogen (CHP) for power and lower grade heat for DH energisation
27a	Tech100	Gen IV Cogeneration power and heat for District Heat energisation only; no Gen III+ or light-water SMR. Base case data.	Reflects scenario where Gen IV is reconfigured from Cogen power and hydrogen to Cogen (CHP) for power and lower grade heat for DH energisation
M/C	Tech100	All nuclear new build technologies enabled for deployment alongside nuclear legacy. Large Gen III+ plants for flexible power; light-water nuclear SMR for electricity generation only; Gen IV advanced nuclear plants as Cogen power and hydrogen production. Baseline data but with -25%+40% spread applied to baseline CAPEX.	The M/C analysis applies elements of uncertainty to individual technologies in ESME. For nuclear (excluding legacy) this uncertainty is applied to overnight capital cost (CAPEX). For all new nuclear technologies in the M/C analysis the CAPEX is expressed as a range around a central value. The central value for each new nuclear technology is the Base Case value for CAPEX, with the lowest value being Base Case minus 25%, and the upper value being Base Case plus 40%. This range is intentionally greater than the range between low (optimistic) CAPEX and high (pessimistic) CAPEX used in the deterministic scenarios.

Table A1-2 – Run summary of NFNZ runs included for comparison

Run	Scenario	Sensitivity Criteria Applied	Notes
15	FA96	Gen IV Cogeneration power and hydrogen deployment only; no Gen III+ or light-water SMR. Base case data.	Reflects scenario where insufficient support is provided to deployment of Gen III+, in anticipation and hope that Gen IV can be brought to market to the claimed timeline and with viable economics.
15a	Tech100	Gen IV Cogeneration power and hydrogen deployment only; no Gen III+ or light-water SMR. Base case data.	Reflects scenario where insufficient support is provided to deployment of Gen III+, in anticipation and hope that Gen IV can be brought to market to the claimed timeline and with viable economics.
9	FA96	Light-water SMR deployment only; no Gen III+ or Gen IV. Base case data.	Reflects scenario where insufficient support is provided to deployment of Gen III+, in anticipation and hope that light-water SMRs can be brought to market to the claimed timeline and with viable economics.
9a	Tech100	Light-water SMR deployment only; no Gen III+ or Gen IV. Base case data.	Reflects scenario where insufficient support is provided to deployment of Gen III+, in anticipation and hope that light-water SMRs can be brought to market to the claimed timeline and with viable economics.
M/C	Tech100	All nuclear new build technologies enabled for deployment alongside nuclear legacy. Large Gen III+ plants for flexible power; light-water nuclear SMR for cogeneration of flexible power and heat for DH energisation; Gen IV advanced nuclear plants as Cogen power and hydrogen production. Baseline data but with -25%+40% spread applied to baseline CAPEX.	The M/C analysis applies elements of uncertainty to individual technologies in ESME. For nuclear (excluding legacy) this uncertainty is applied to overnight capital cost (CAPEX). For all new nuclear technologies in the M/C analysis the CAPEX is expressed as a range around a central value. The central value for each new nuclear technology is the Base Case value for CAPEX, with the lowest value being Base Case minus 25%, and the upper value being Base Case plus 40%. This range is intentionally greater than the range between low (optimistic) CAPEX and high (pessimistic) CAPEX used in the deterministic scenarios.

Annex 2 – Selected ESME outputs for Supplementary Report No.1

The columns below are the colour coded legends for the respective ESME generic output core charts which follow.

Primary Resource Consumption
Wave
Tidal Stream
Tidal Range
Hydro
Solar
Wind (deep offshore)
Wind (shallow offshore)
Wind (onshore)
Nuclear
Geothermal Heat
Wet Waste
Dry Waste Resource
Dry Waste
Biomass
UK Biomass
Biomass Imports
Coal
Gas
GasTS
GasLDN
Gas_Zeb_Import
Gas_UKCS_Import
Gas_TTF_Import
Gas_NCS_Import
Gas_LNG_Import
Biofuel Imports
Liquid Fuel
Diesel
Petrol
Aviation Fuel
Hydrogen
Electricity_DX_LV
Electricity_DX_HV
Electricity_TX

Net CO2 Emissions
GasTS
Biomass
Hydrogen
Electricity
CapturedCO2
Retroplus
Retrofix
PC Coal CCS Retrofit
PC Coal Biomass Retrofit
IGCC Coal CCS Retrofit
CCGT CCS Retrofit
Energy Storage
Industry
International A & S
Transport Sector
Buildings Sector
Power Sector
Other Conversion Sector
Industry Sector (combustion)
Industry Sector (process CO2)
Other CO2
Biogenic credits
Wood in Construction
Waste incineration
Settlements
Peatland
LULUCF Other
Industry
IGCC Coal with CCS - 99pct CCR
H2 Plant (SMR with CCS) - 99pct CCR
H2 Plant (Biomass Gasificn. with CCS) - 99pct CCR
Forest land
Energy crops, agroforestry, hedges
Converted Biomass Plant (Drax)
CCGT with CCS - 99pct CCR
CO2 Processing for synfuel
Biopetrol Production with CCS - 99pct CCR
Biokerosine Production with CCS - 99pct CCR

Electricity Generation Cap. & Annual Generation
Geothermal Plant (HSA) Electricity & Heat
Geothermal Plant (EGS) Electricity & Heat
Wave Power
Tidal Stream
Tidal Range
Severn Barrage
Hydro Power
Solar PV (Domestic)
Solar PV (Farm)
Offshore Wind (floating)
Offshore Wind (fixed)
Onshore Wind
Micro Wind
Micro CHP - Space Heat
Micro CHP - Hot Water
H2 Turbine
ATC of Waste
Anaerobic Digestion CHP Plant
Incineration of Waste
IGCC Biomass with CCS
Biomass Fired Generation with CCS
Biomass Macro CHP
IGCC Biomass
Converted Biomass Plant
Biomass Fired Generation
Nuclear Gen III Hinkley Point C
Nuclear Gen IV Hydrogen only
Nuclear Gen IV Elec only
Nuclear SMR Elec only
Nuclear (SMR)
Nuclear (Gen IV)
Nuclear SMR Cogen Power and Heat (DH)
Nuclear Gen IV Cogen Power and H2
Nuclear (Gen III)
Nuclear (Legacy)
Waste Gasification with CCS
Waste Gasification
CCGT with CCS
CCGT
IGCC Coal with CCS
IGCC Coal
PC Coal with CCS
PC Coal
OCGT
Gas Macro CHP
Oil Fired Generation
Interconnector Nordel (Electricity)
Interconnector Ireland (Electricity)
Interconnector France (Electricity)
Interconnector Benelux-Germany (Electricity)
CCGT with CCS - 99pct CCR
Converted Biomass Plant (Drax)
IGCC Coal with CCS - 99pct CCR

Space Heat Capacity & Space Heat Generation

H2 Micro CHP - Space Heat
H2 Boiler - Space Heat
Heat Pump (Ground Source, Space Heat)
Heat Pump (Air Source, Space Heat)
Electric Resistive Heating - Space Heat
Biomass Boiler - Space Heat
Micro CHP - Space Heat
Gas Boiler - Space Heat
Oil Boiler - Space Heat
DH for Dwelling (LD, ThP)
DH for Dwelling (LD, ThP with Retroplus)
DH for Dwelling (LD, ThP with Retrofix)
DH for Dwelling (LD, ThM)
DH for Dwelling (LD, ThM with Retroplus)
DH for Dwelling (LD, ThM with Retrofix)
DH for Dwelling (LD, ThG)
DH for Dwelling (LD, ThE)
DH for Dwelling (MD, ThP)
DH for Dwelling (MD, ThP with Retroplus)
DH for Dwelling (MD, ThP with Retrofix)
DH for Dwelling (MD, ThM)
DH for Dwelling (MD, ThM with Retroplus)
DH for Dwelling (MD, ThM with Retrofix)
DH for Dwelling (MD, ThG)
DH for Dwelling (MD, ThE)
DH for Dwelling (HD, ThP)
DH for Dwelling (HD, ThP with Retroplus)
DH for Dwelling (HD, ThP with Retrofix)
DH for Dwelling (HD, ThM)
DH for Dwelling (HD, ThM with Retroplus)
DH for Dwelling (HD, ThM with Retrofix)
DH for Dwelling (HD, ThG)
DH for Dwelling (HD, ThE)
District Heating (Public floorspace)
District Heating (Commercial floorspace)
Solid Fuel Boiler - Space Heat

Hydrogen Production

Nuclear Gen IV Hydrogen only
Nuclear Gen IV Cogen Power and H2
H2 Plant (Biomass Gasification with CCS)
H2 Plant (Biomass Gasification)
H2 Plant (SMR with CCS)
H2 Plant (SMR)
H2 Plant (Coal Gasification with CCS)
H2 Plant (Electrolysis)
H2 Plant (Biomass Gasification with CCS) - 99pct CCR
H2 Plant (SMR with CCS) - 99pct CCR
Nuclear H2 Gigafactory

Network Hot Water Production

District Heating H2 Boiler
Heat Pump (Large Scale Marine)
Geothermal Plant (EGS) Electricity & Heat
Geothermal Plant (HSA) Electricity & Heat
Geothermal Plant (HSA) Heat Only
District Heating Gas Boiler
Gas Macro CHP
District Heating Biomass Boiler
Biomass Macro CHP
Anaerobic Digestion CHP Plant
Nuclear SMR Cogen Power and Heat (DH)
Nuclear (SMR)
Heat Offtake for District Heat Network

Industry Fuel Consumption

Industry - Liquid Fuel
Industry - Hydrogen
Industry - GasTS
Industry - Electricity
Industry - Coal
Industry - Biomass

Hydrogen Consumption

Hydrogen Distribution Network
H2 Turbine
Bus (Hydrogen FCV)
MGV
HGV
LGV (Hydrogen ICE)
Car Hydrogen ICE (C/D Segment)
Car Hydrogen ICE (A/B Segment)
LGV (Hydrogen FCV)
Car Hydrogen FCV (C/D Segment)
Car Hydrogen FCV (A/B Segment)
Industry
Wheeled Excavator (H2)
Medium Wheel Loader (H2)
Medium Articulated Truck (H2)
Maritime (Ammonia International)
Maritime (Ammonia Domestic)
Large Articulated Truck (H2)
Industry I8 SpH Hyd Sw
Industry I7 SpH Hyd Sw
Industry I7 DaS Hyd Sw
Industry I6 SpH Hyd Sw
Industry I6 DaS Hyd Sw
Industry I5 SpH Hyd Sw
Industry I5 DaS Hyd Sw
Industry I4 LTP Hyd Sw
Industry I4 DaS Hyd Sw
Industry I3 SpH Hyd Sw
Industry I2 SpH Hyd Sw
Crawler Excavator (H2)
Agricultural Vehicle (H2)

Run 27 FA96 – Gen IV cogeneration electricity and heat for DH energisation without Gen III+ or LWSMR deployment; base case data
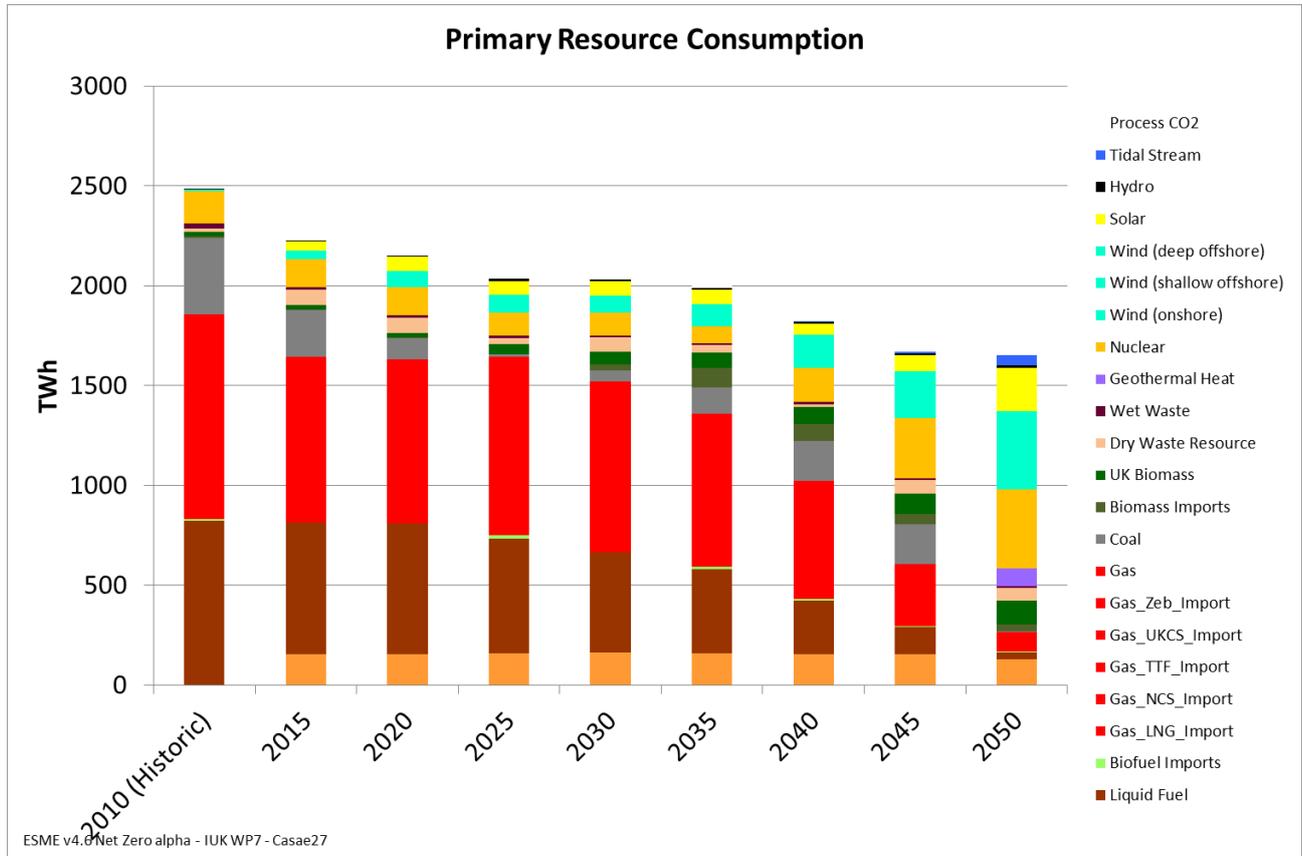
Figure A2-1 – Run 27 primary resource consumption
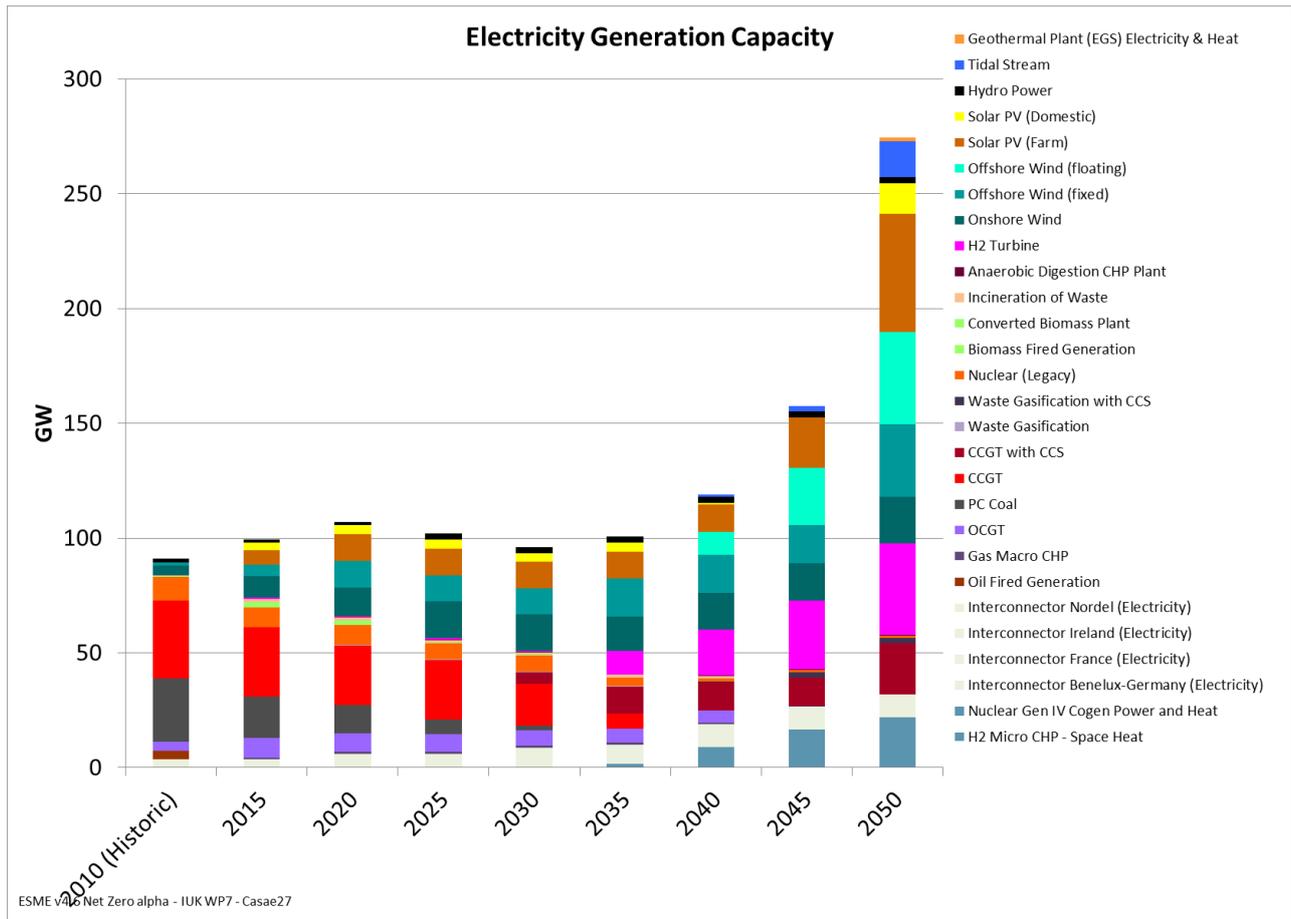
Figure A2-2 – Run 27 electricity generation capacity
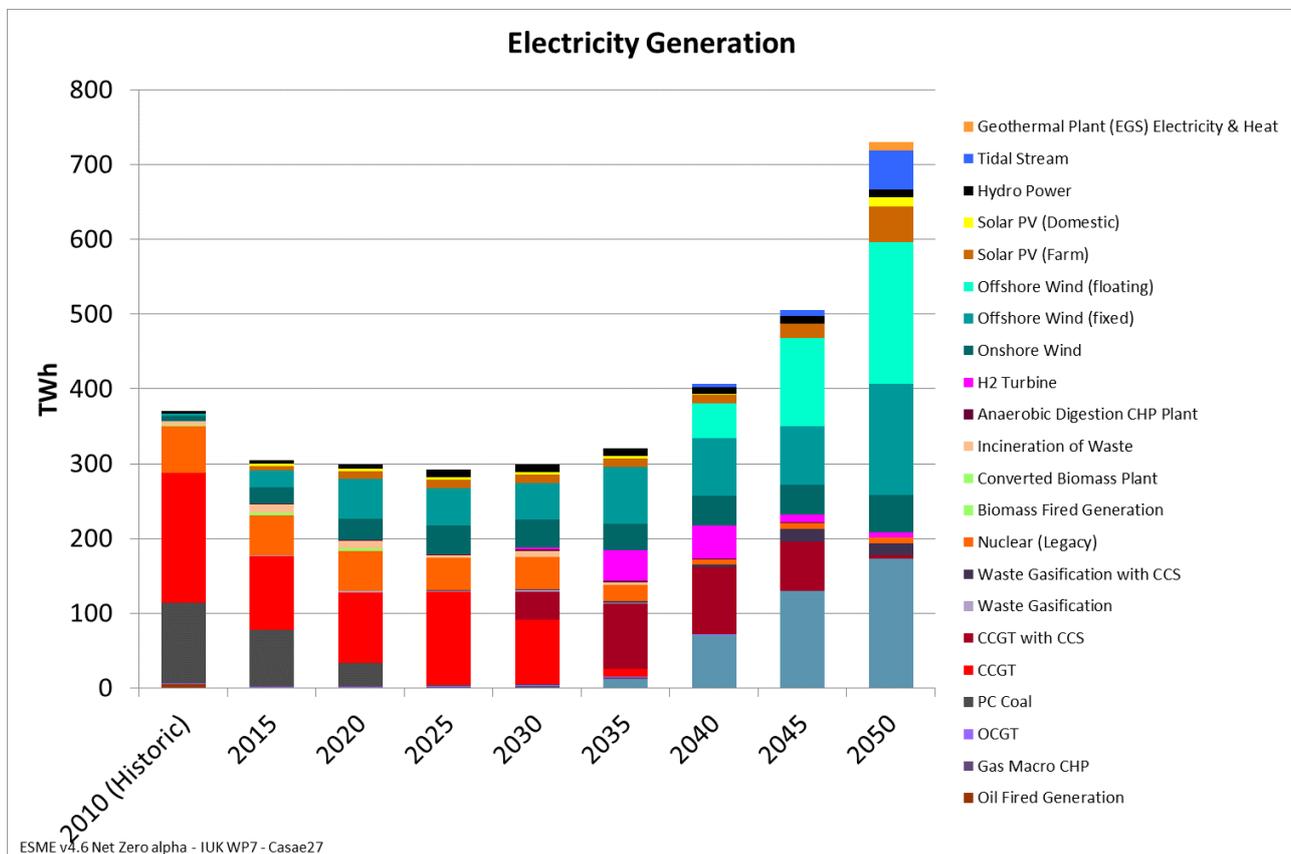
Figure A2-3 – Run 27 electricity generation
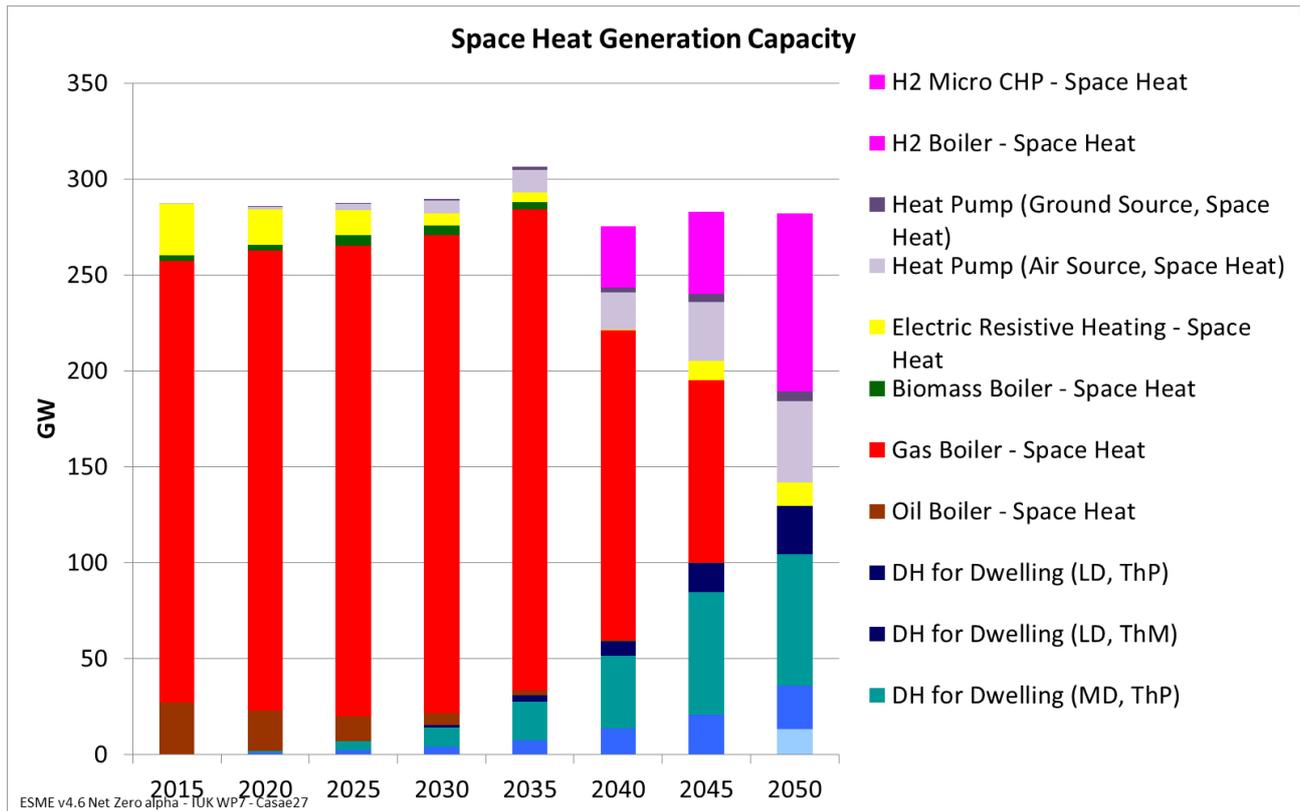
Figure A2-4 – Run 27 space heat generation capacity
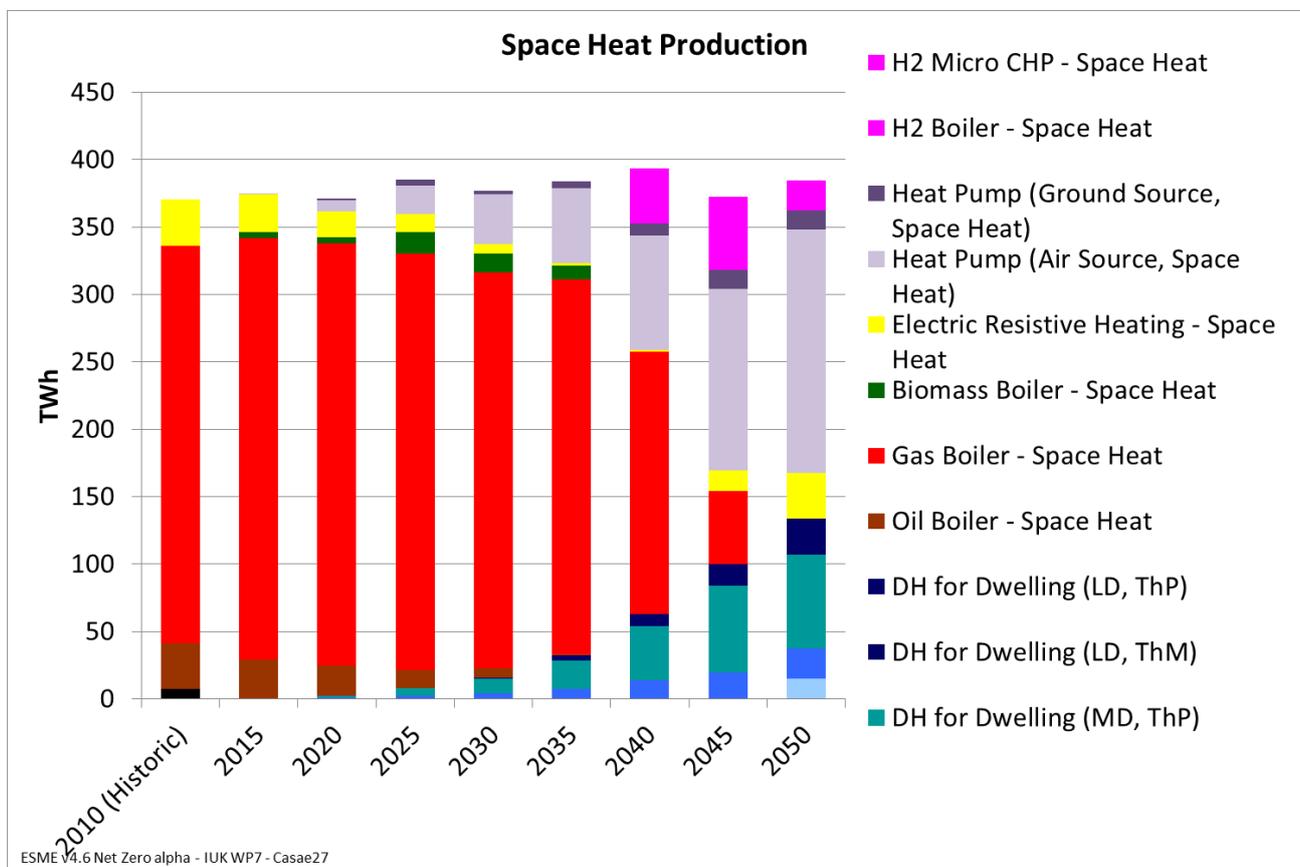
Figure A2-5– Run 27a space heat production
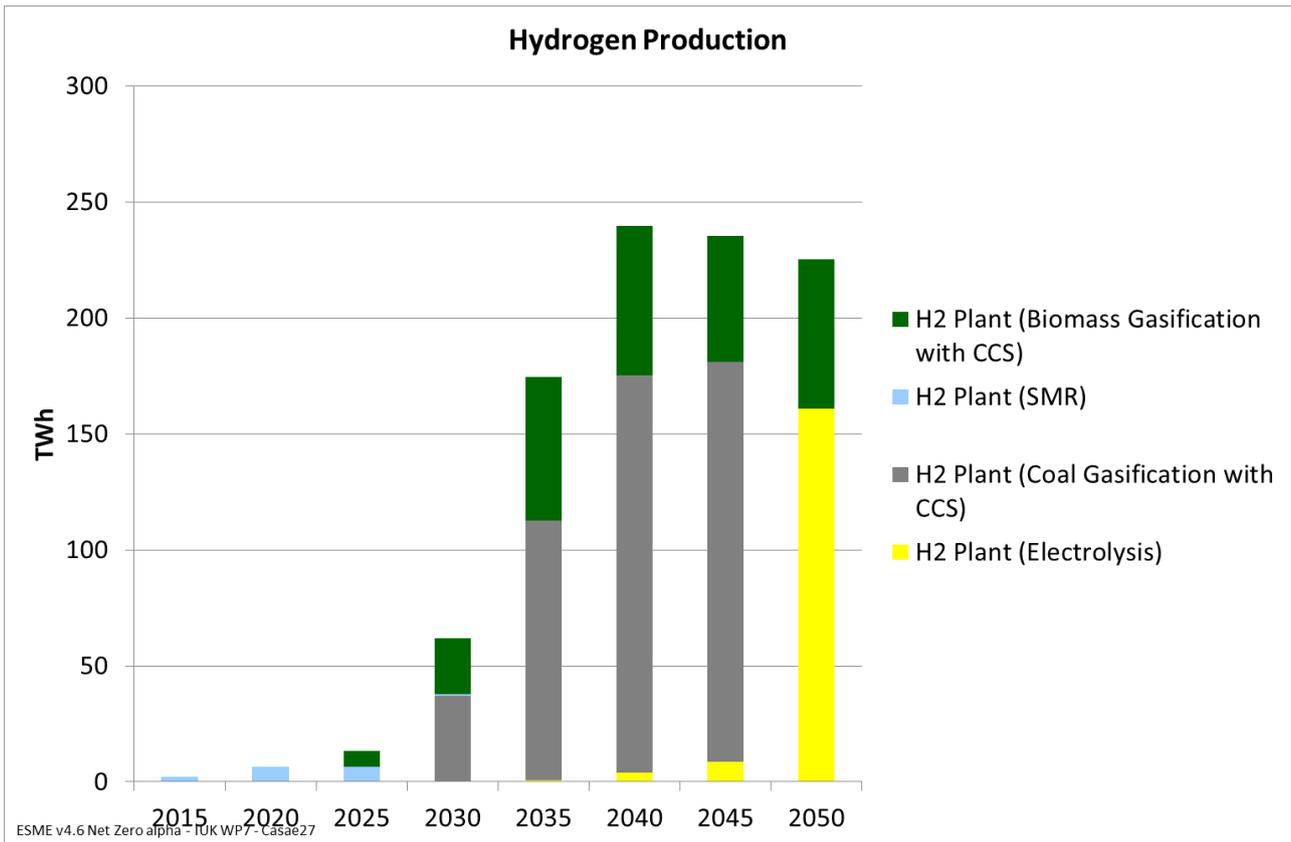
Figure A2-6 – Run 27 hydrogen production
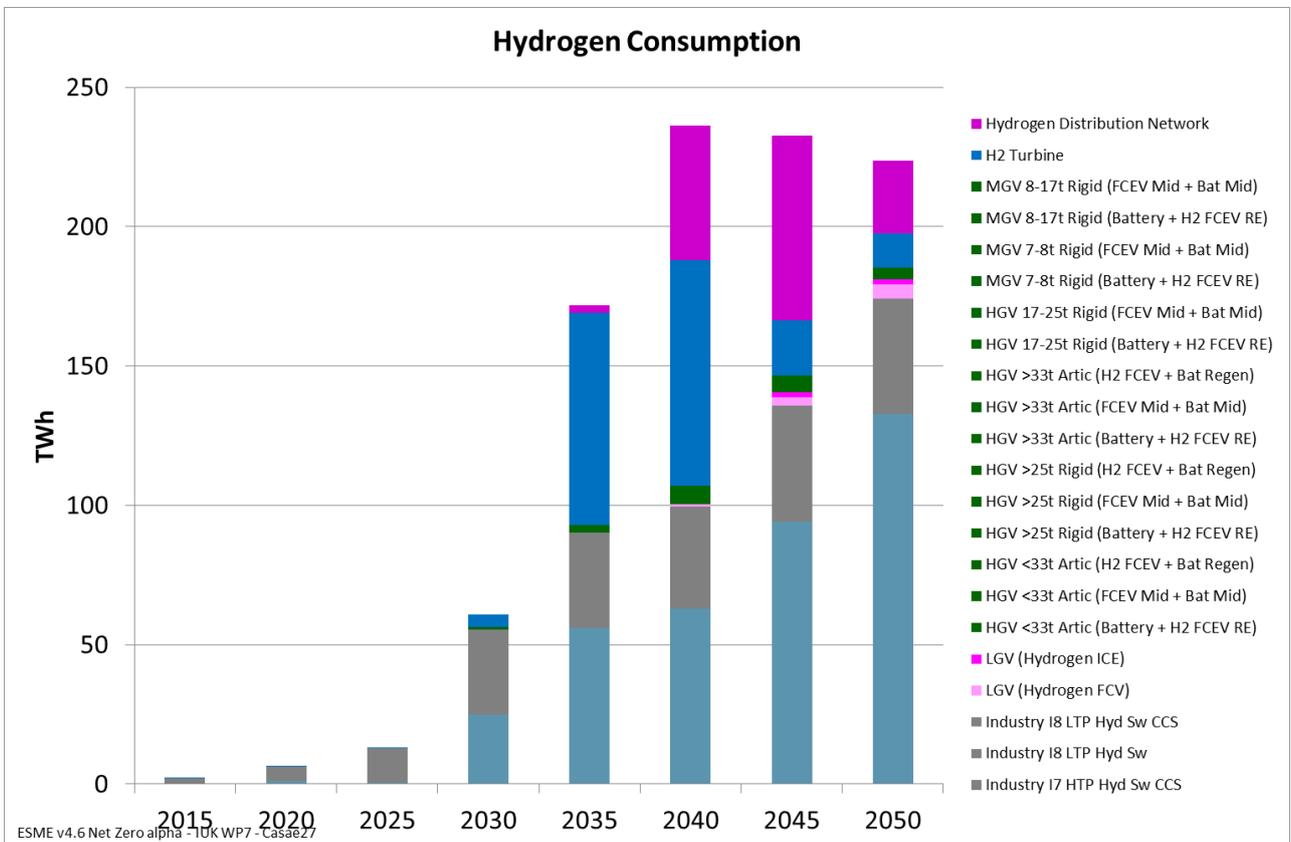
Figure A2-7 – Run 27 hydrogen consumption
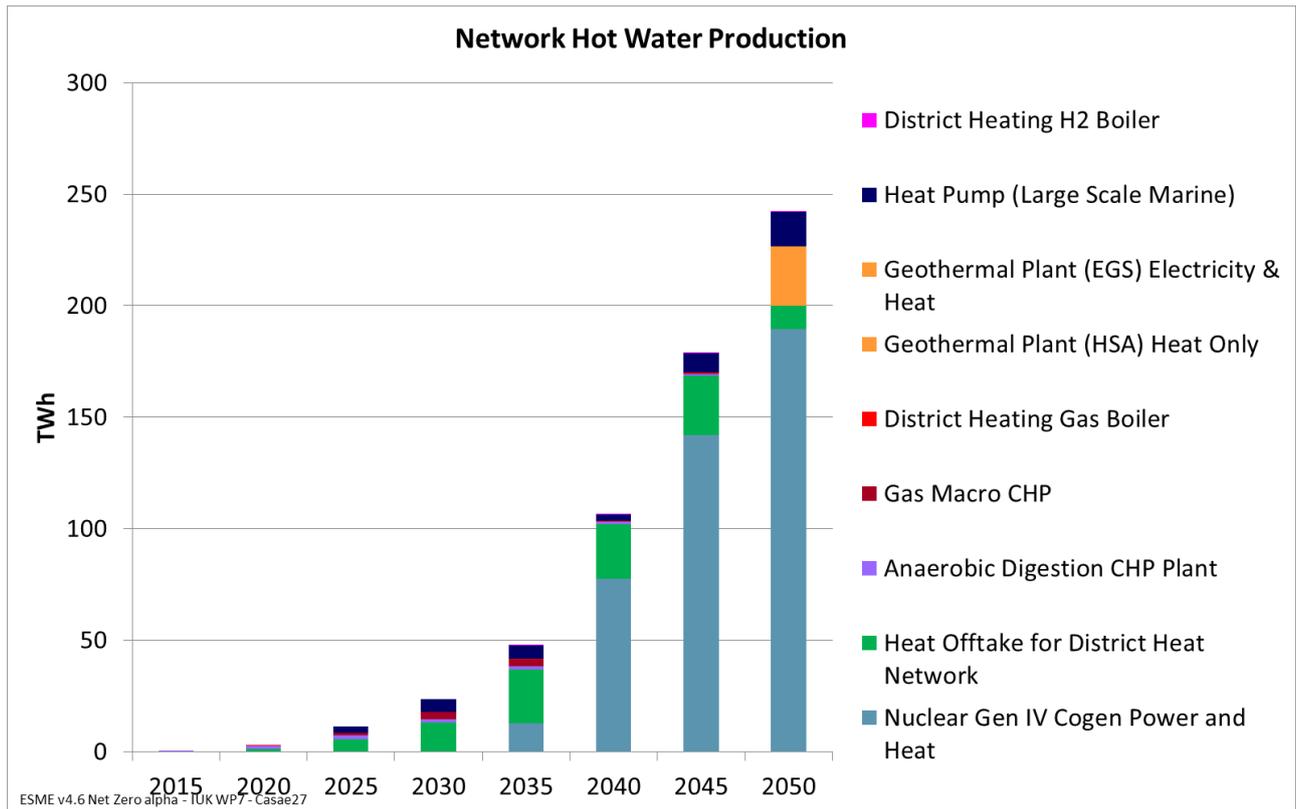
Figure A2-8 – Run 27 network hot water production
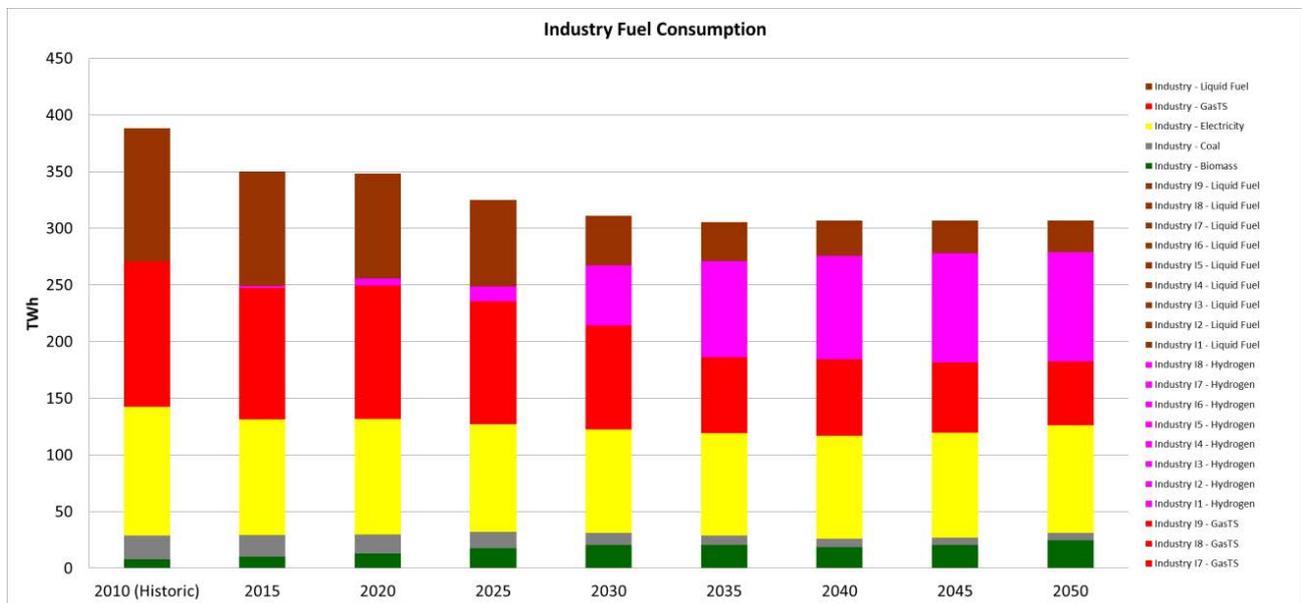
Figure A2-9 – Run 27 industry fuel consumption

Run 27a TECH100 – Gen IV cogeneration electricity and heat for DH energisation without Gen III+ or LWSMR deployment; base case data
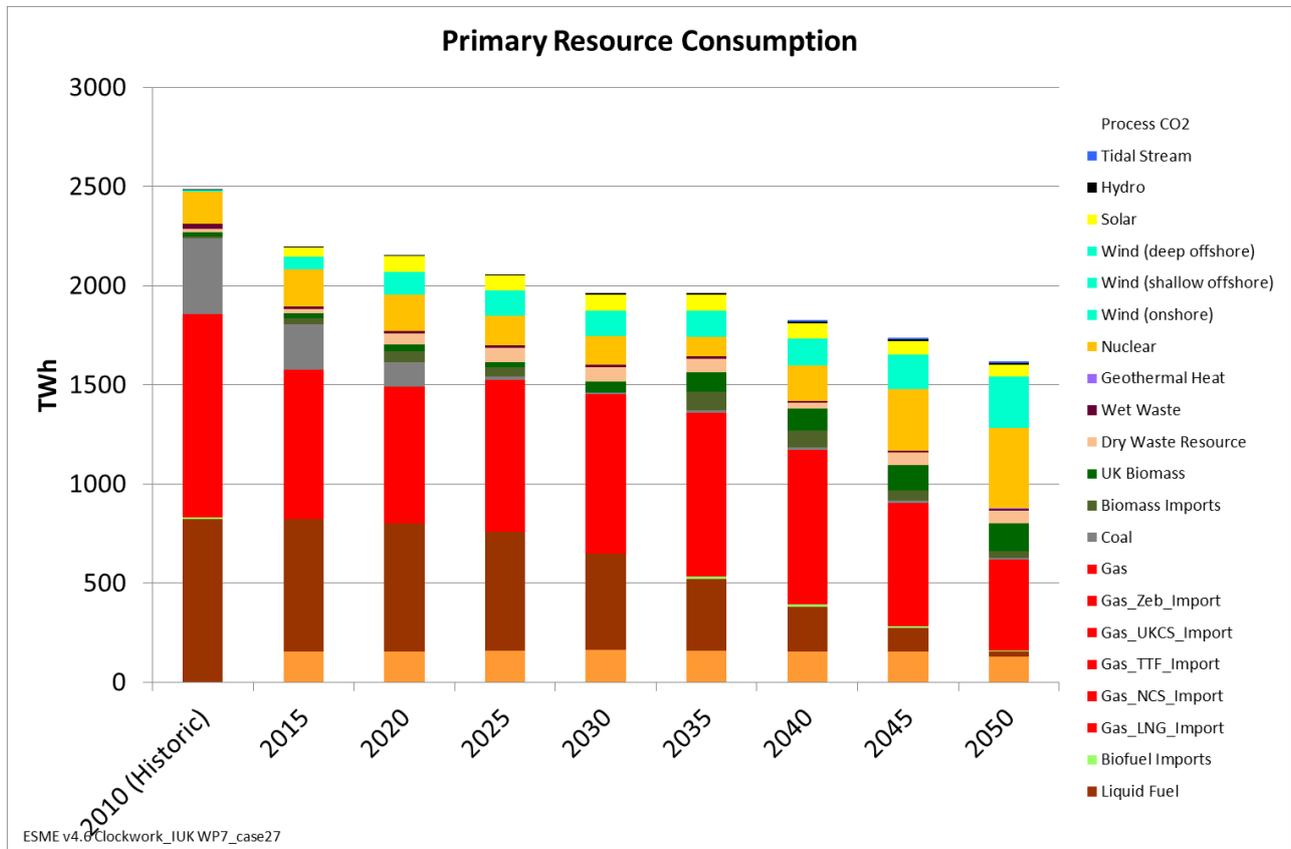
Figure A2-10 – Run 27a primary resource consumption
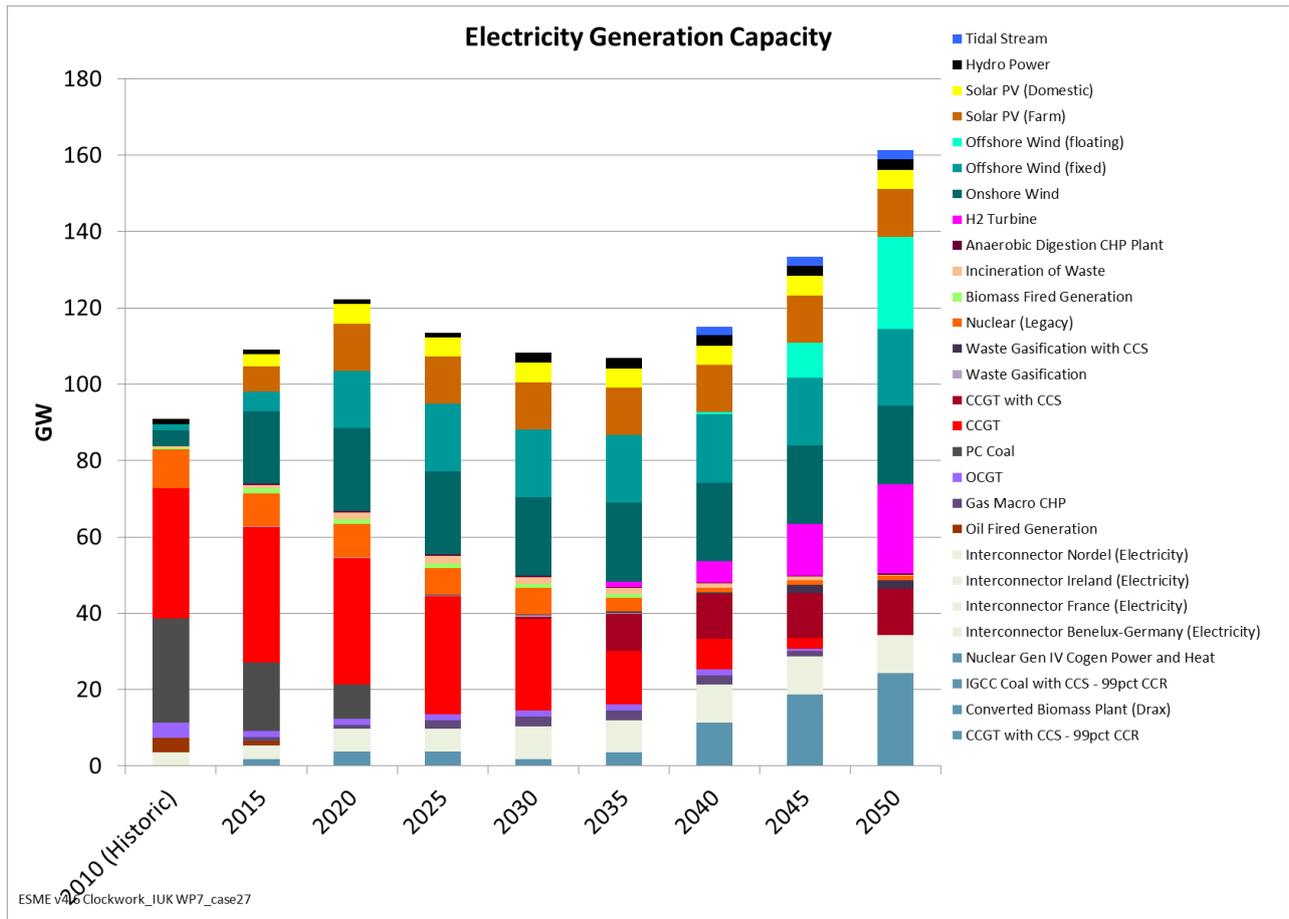
Figure A2-11 – Run 27a electricity generation capacity
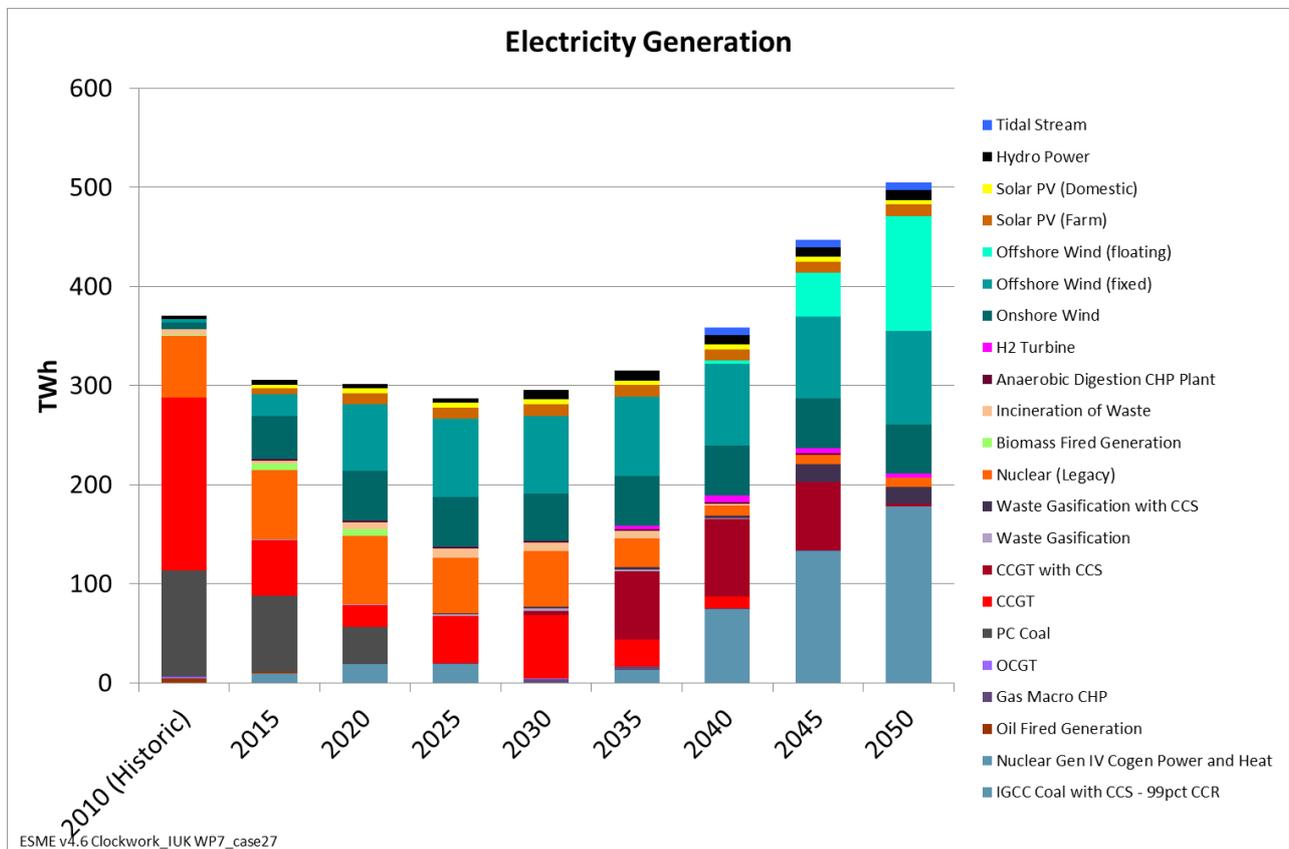
Figure A2-12 – Run 27a electricity generation
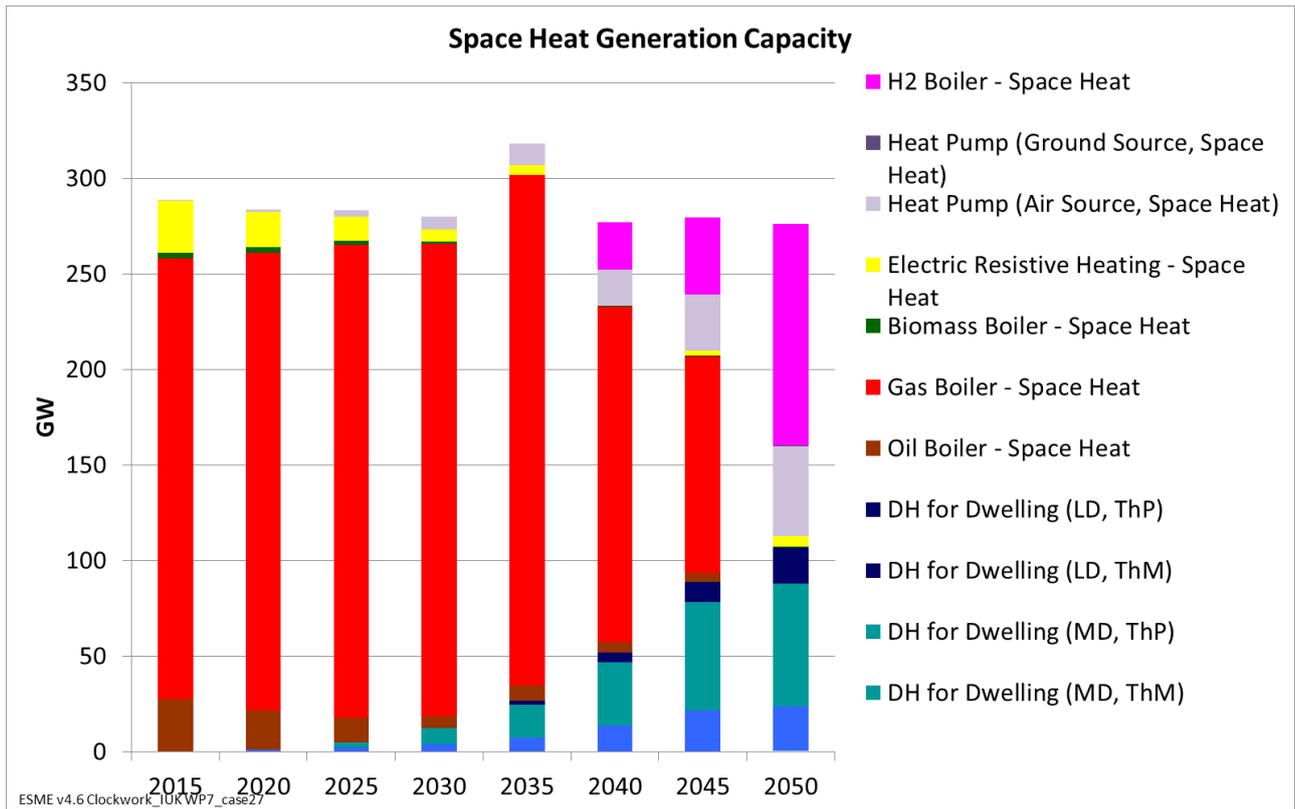
Figure A2-13 – Run 27a space heat generation capacity
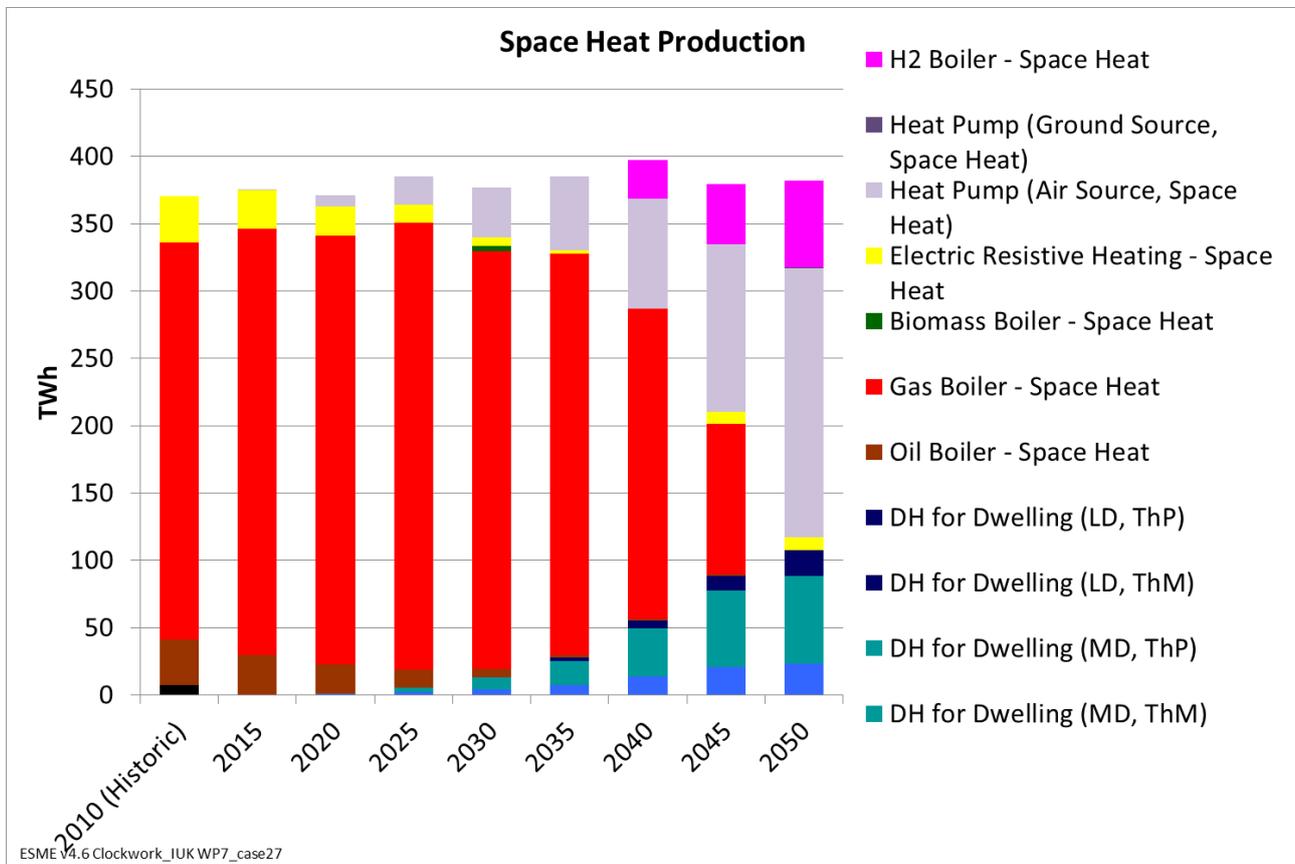
Figure A2-14– Run 27 space heat production
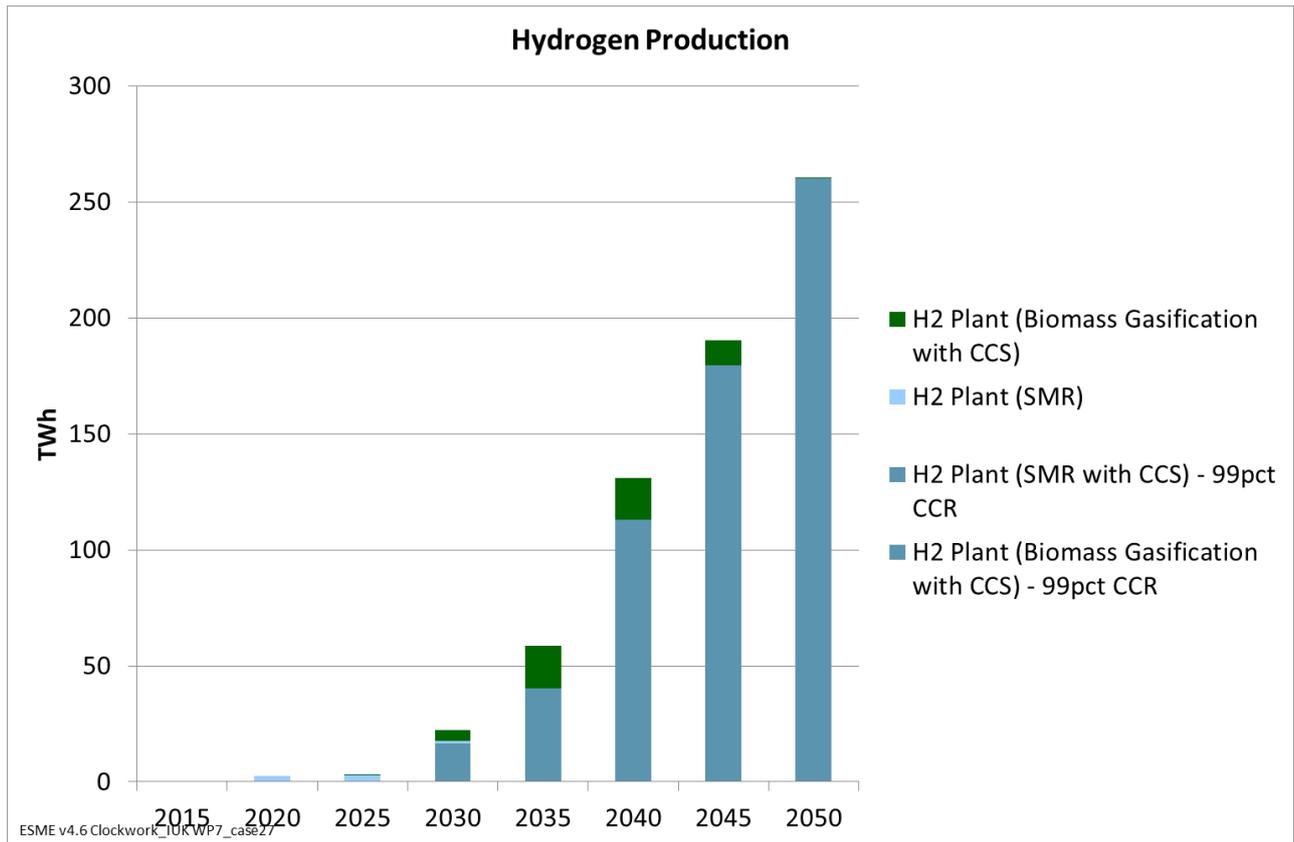
Figure A2-15 – Run 27a hydrogen production
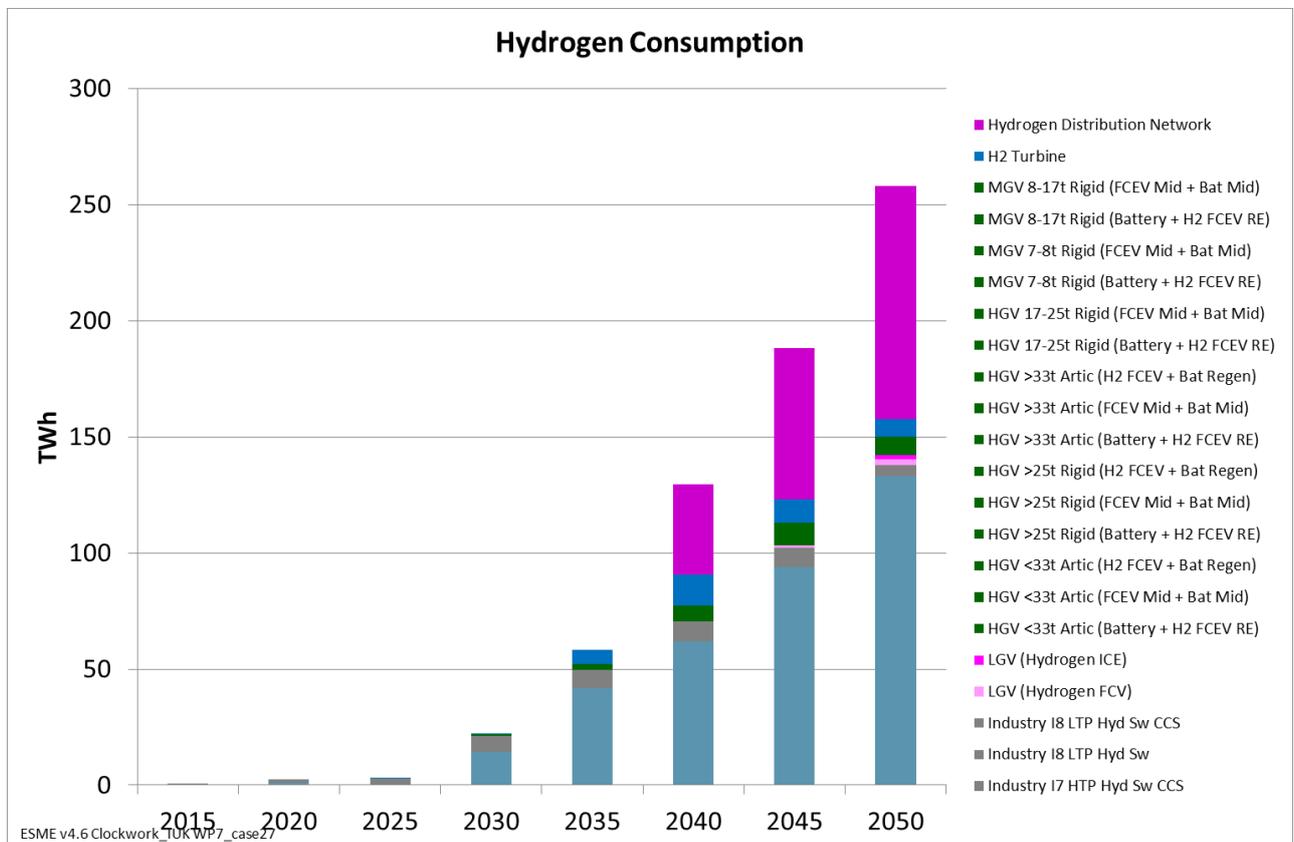
Figure A2-16 – Run 27a hydrogen consumption
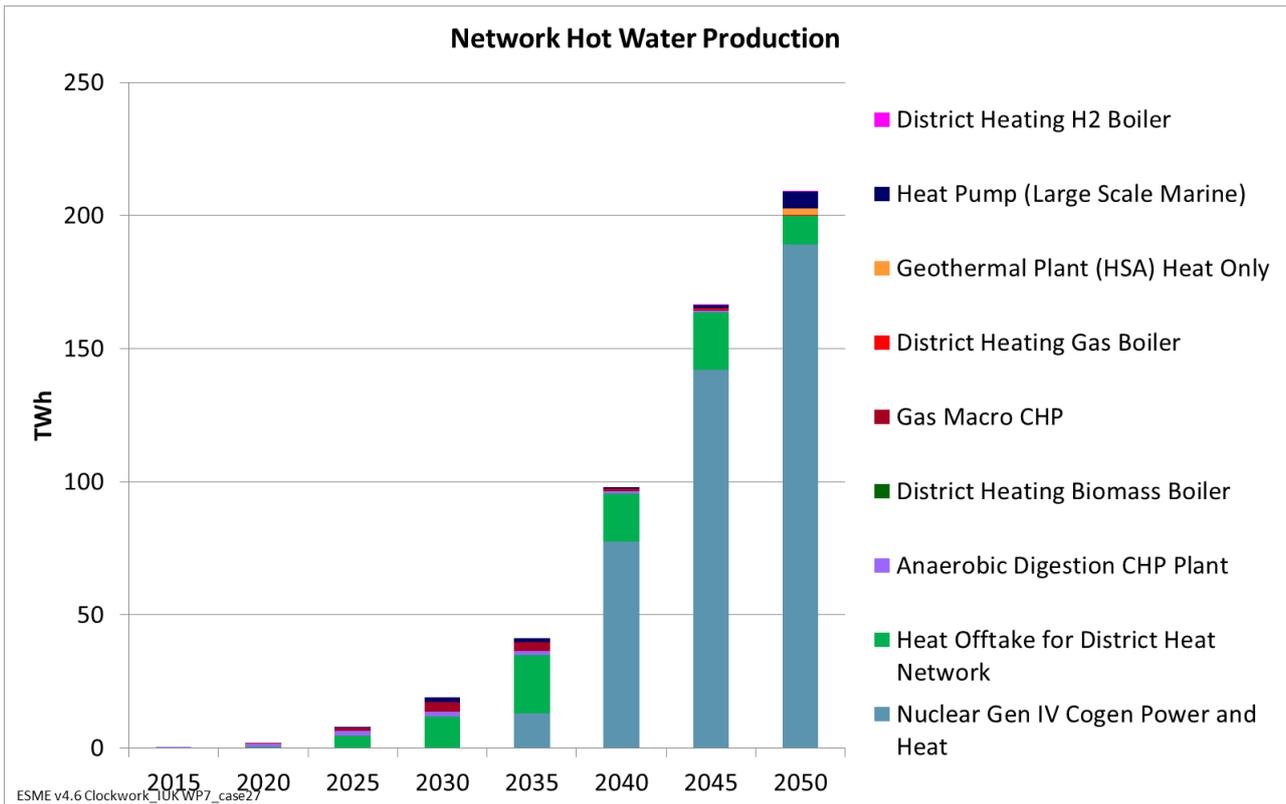
Figure A2-17 – Run 27a network hot water production
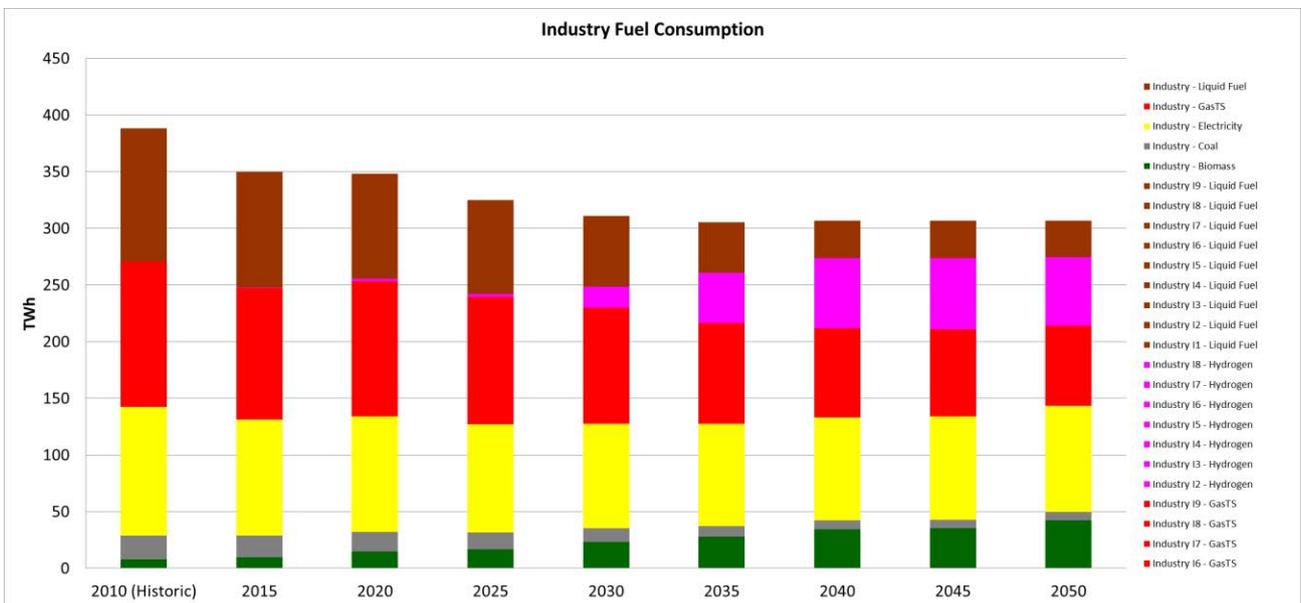
Figure A2-18 – Run 27a industry fuel consumption

Monte Carlo Run TECH100 – All nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR deployed as electricity only; Gen IV advanced nuclear plants as cogen power and hydrogen production; baseline data with -25%/+40% spread applied to capex for all nuclear new build technologies
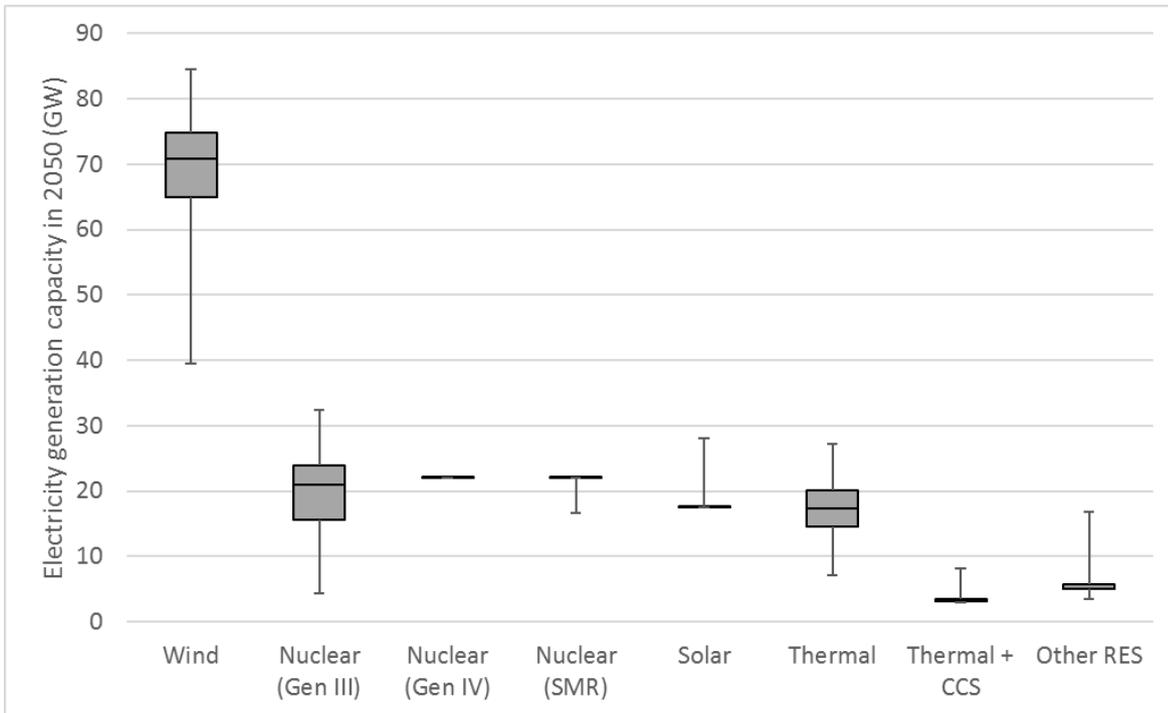
Figure A2-19 – Probabilistic (Monte Carlo) run showing electricity generation capacity in 2050–using TECH100 with nuclear base case values
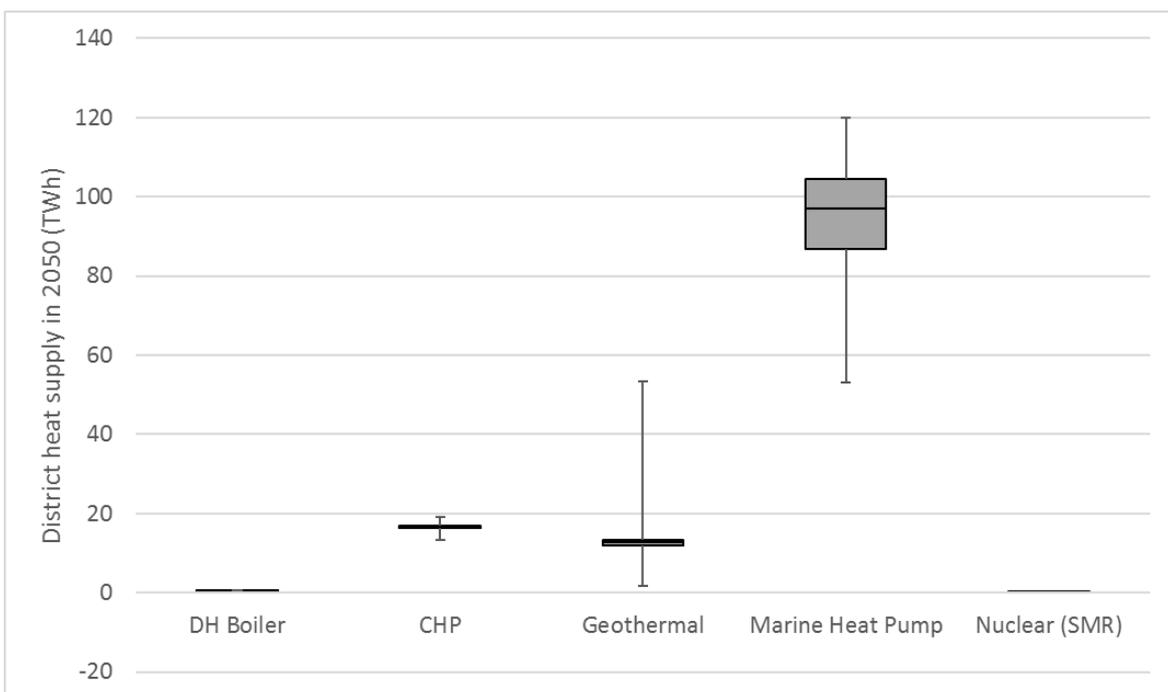
Figure A2-20 – Probabilistic (Monte Carlo) run showing district heat supply in 2050–using TECH100 with nuclear base case values

Run 15 FA96 – Gen IV cogeneration power and hydrogen deployment only; no Gen III+ or light-water SMR; base case data
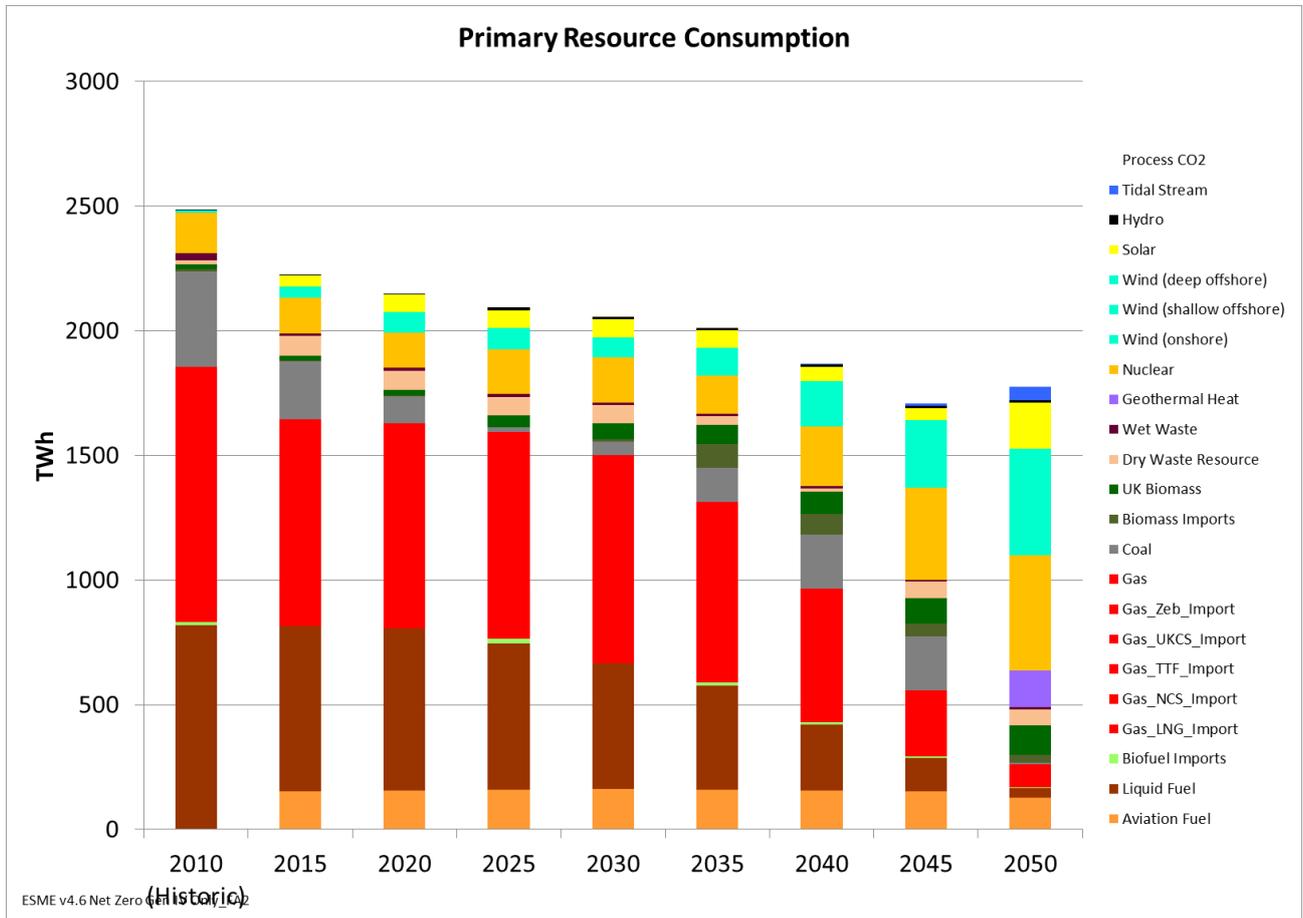
Figure A2-21 – Run 15 primary resource consumption
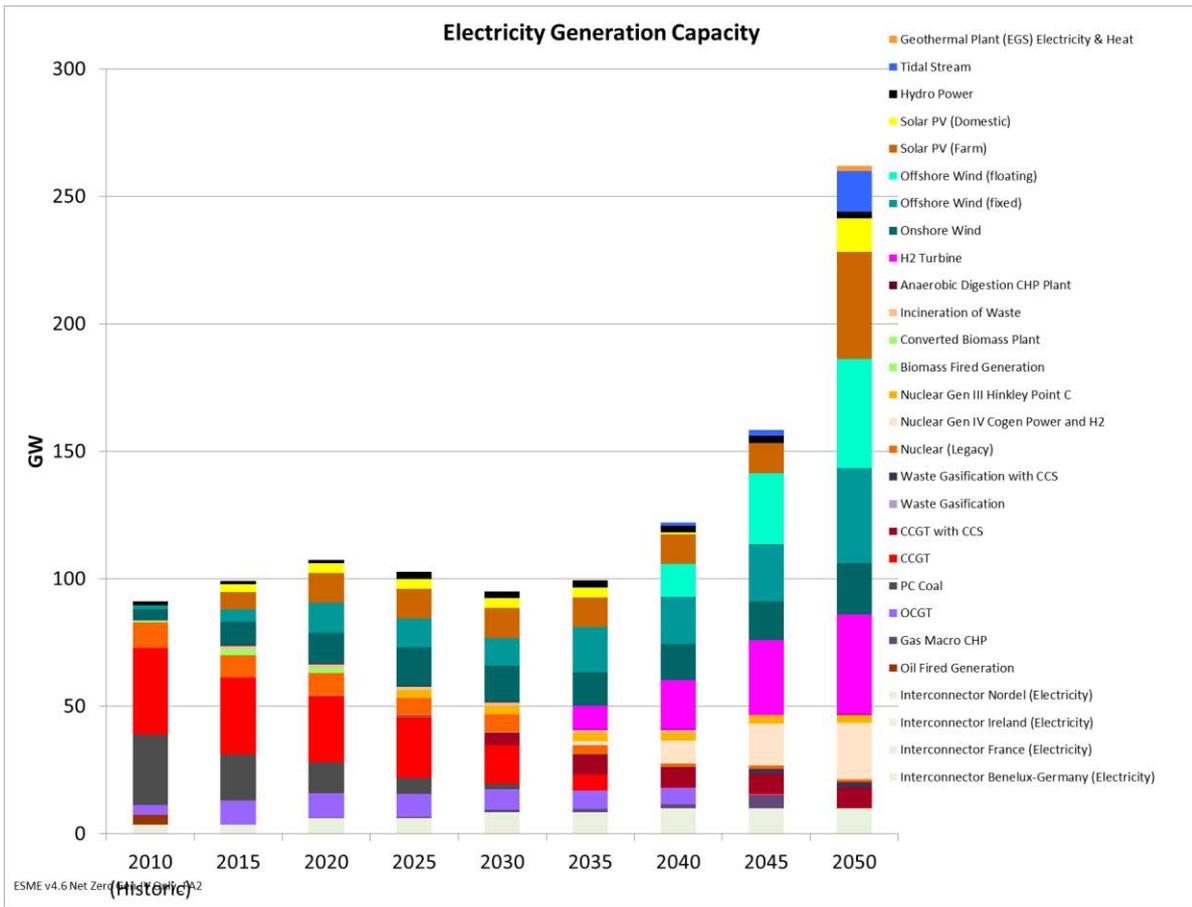
Figure A2-23 – Run 15 electricity generation
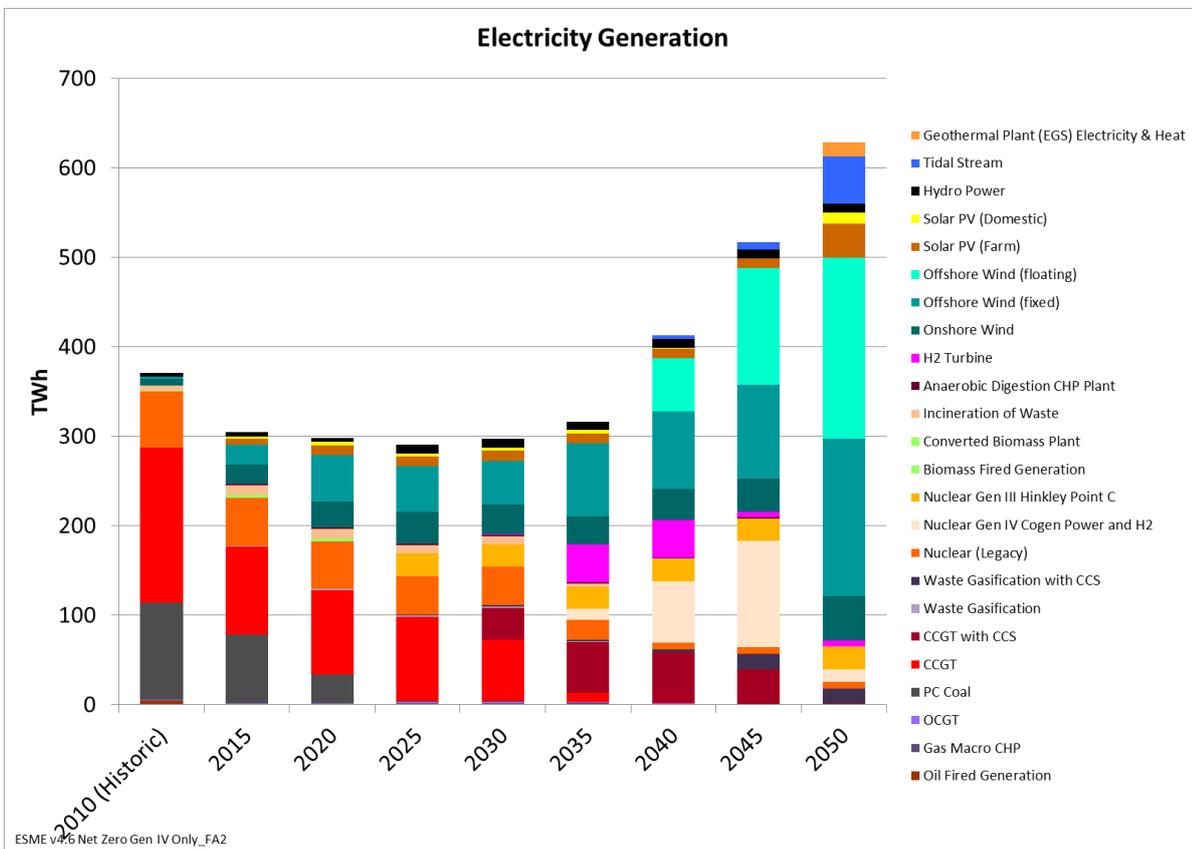
Figure A2-23 – Run 15 electricity generation
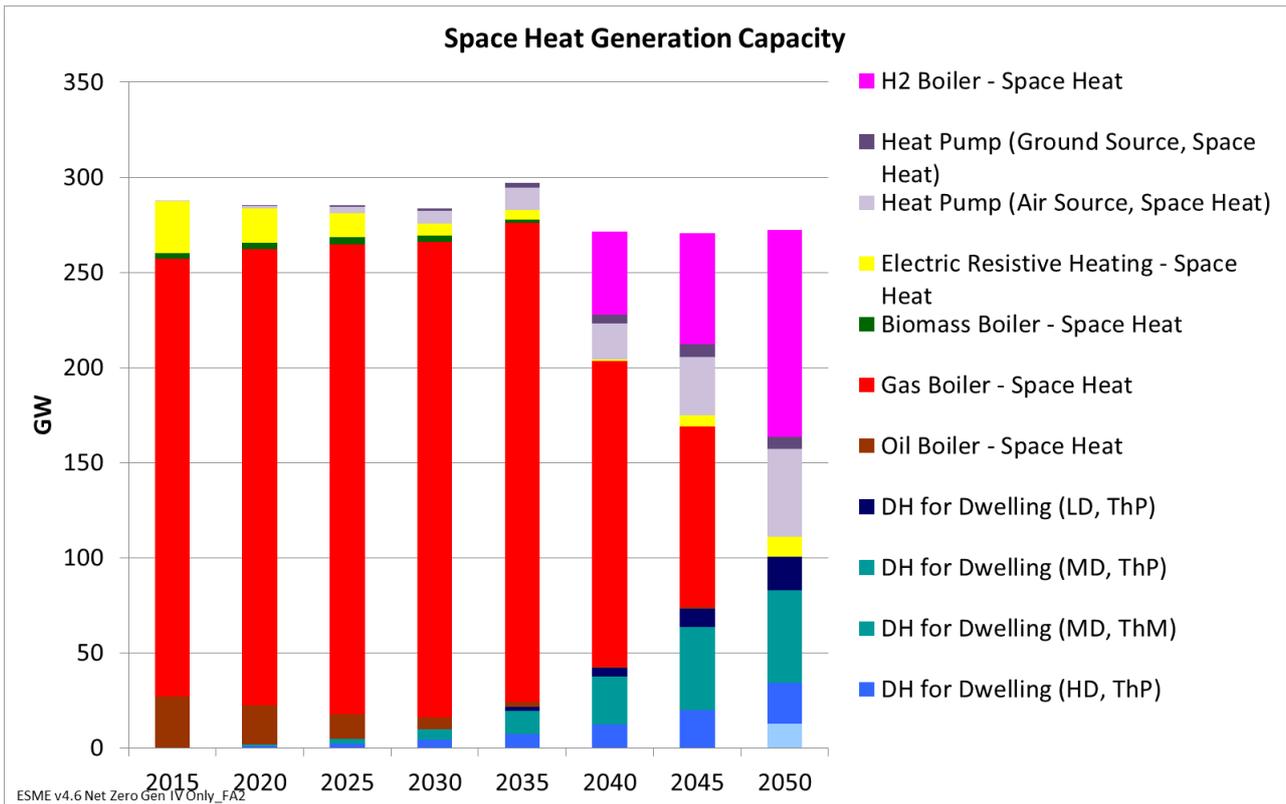
Figure A2-24 – Run 15 space heat generation capacity
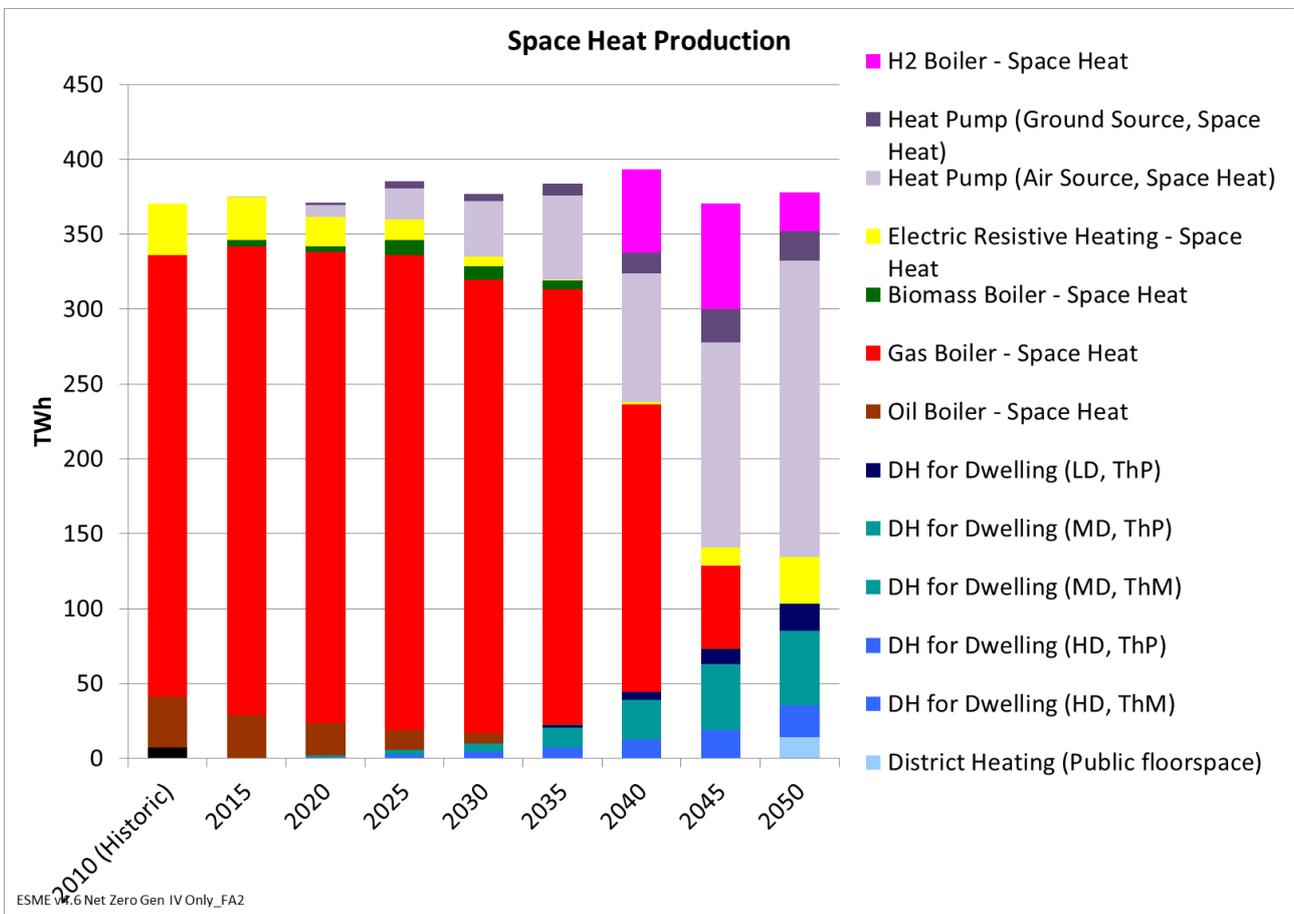
Figure A2-25 – Run 15 space heat production
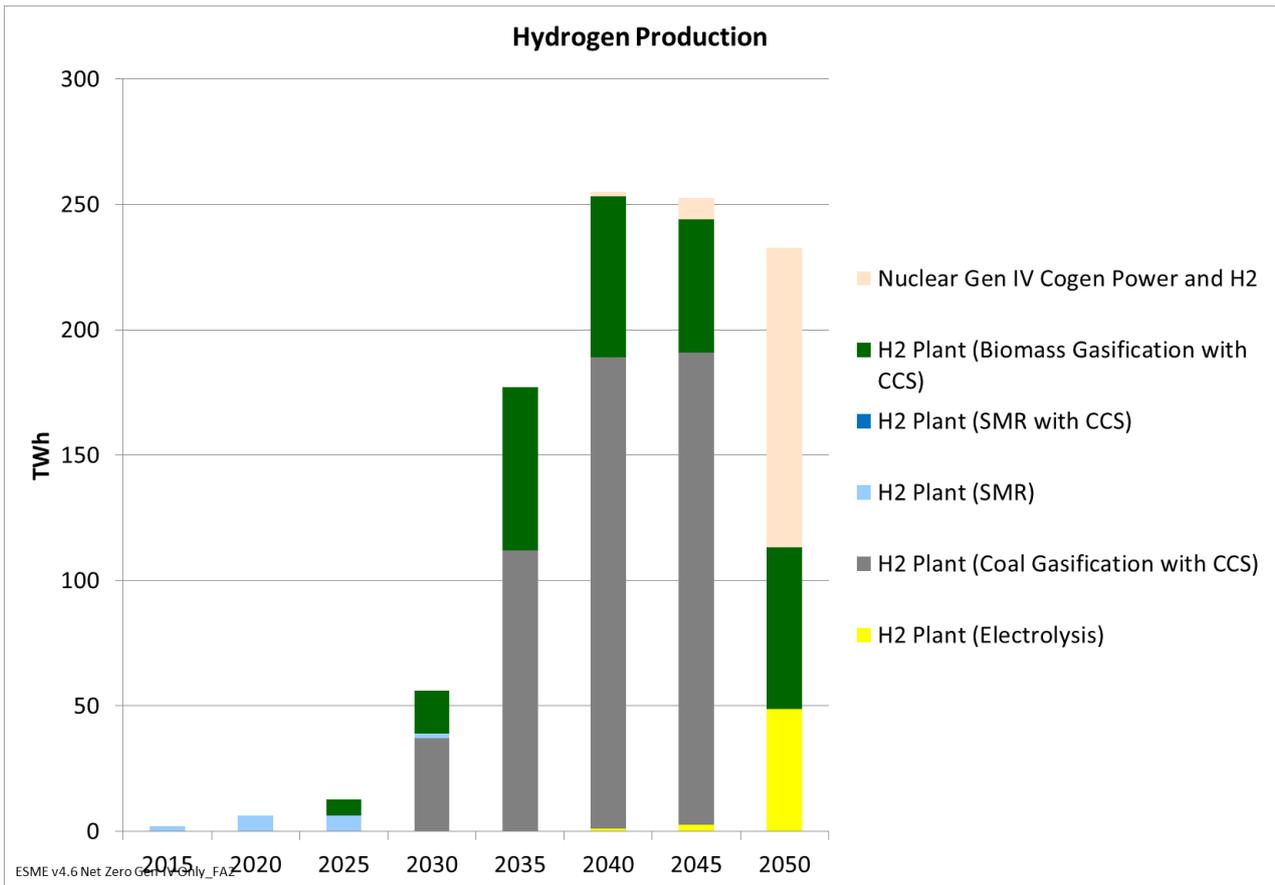
Figure A2-26 – Run 15 hydrogen production
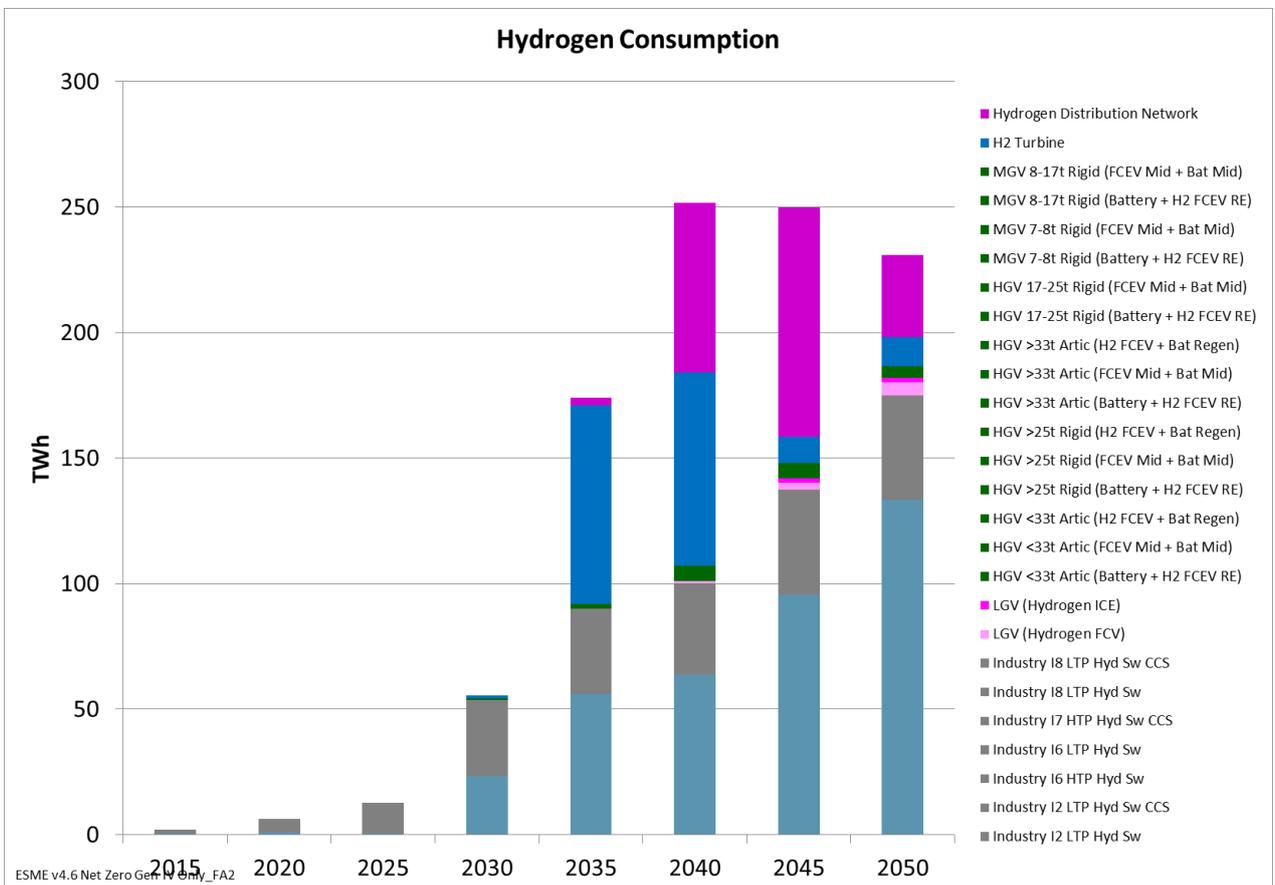
Figure A2-27 – Run 15 hydrogen consumption
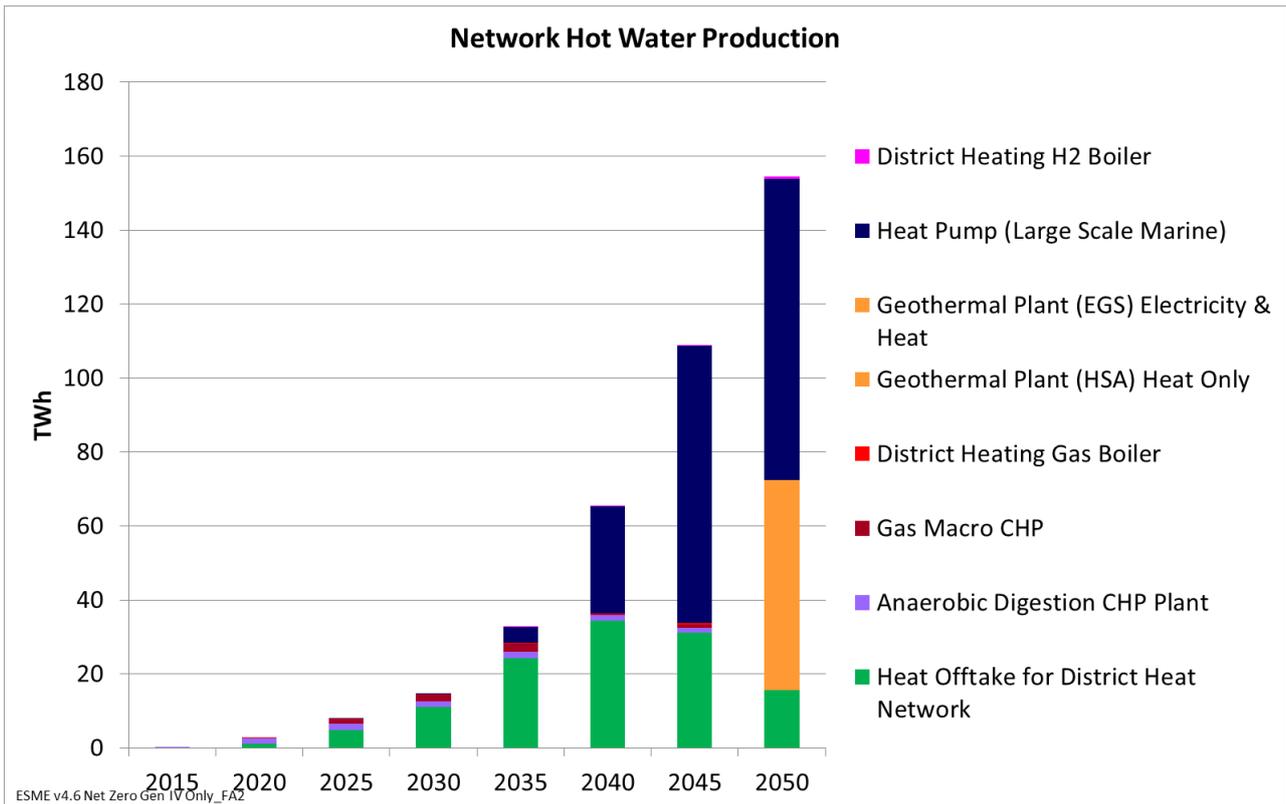
Figure A2-28 – Run 15 network hot water production
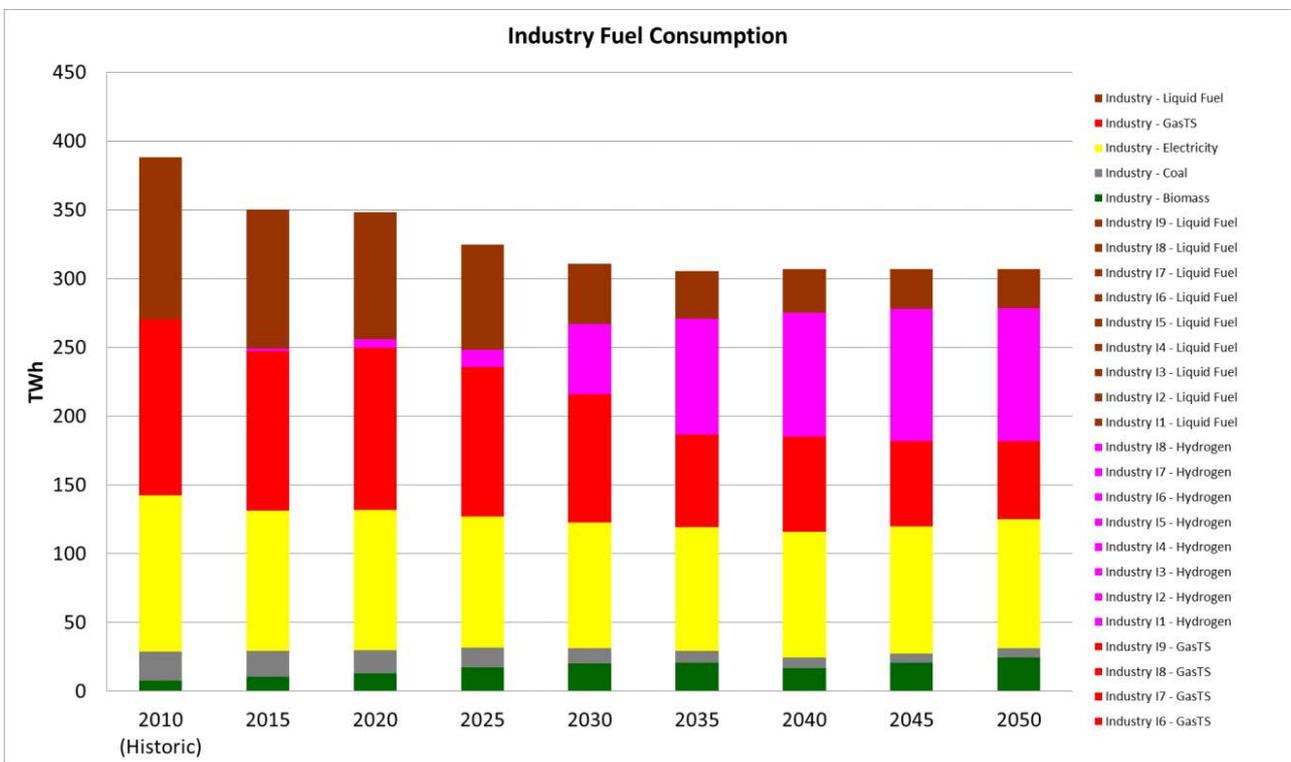
Figure A2-29 – Run 15 industry fuel consumption

Run 15a TECH100 – Gen IV cogeneration power and hydrogen deployment only; no Gen III+ or light-water SMR; base case data
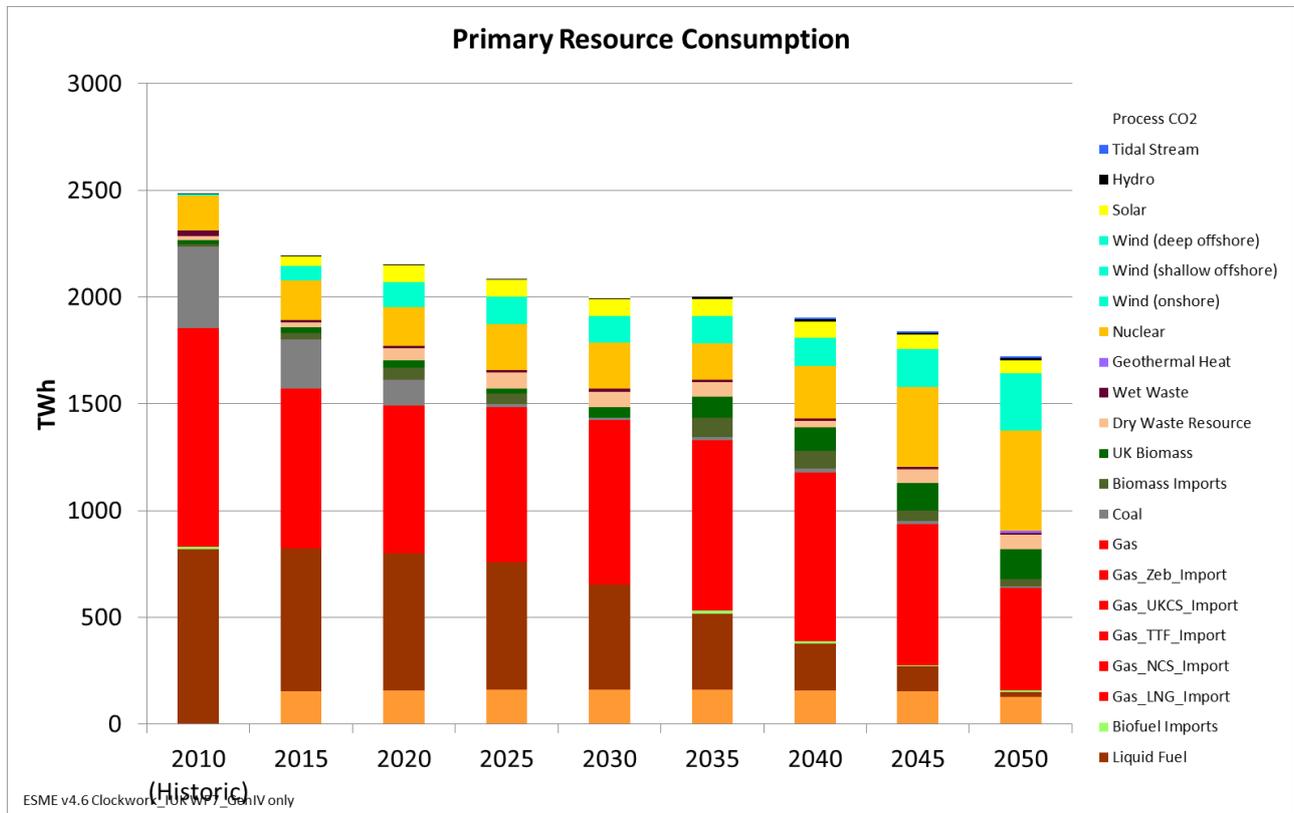
Figure A2-30 – Run 15a primary resource consumption
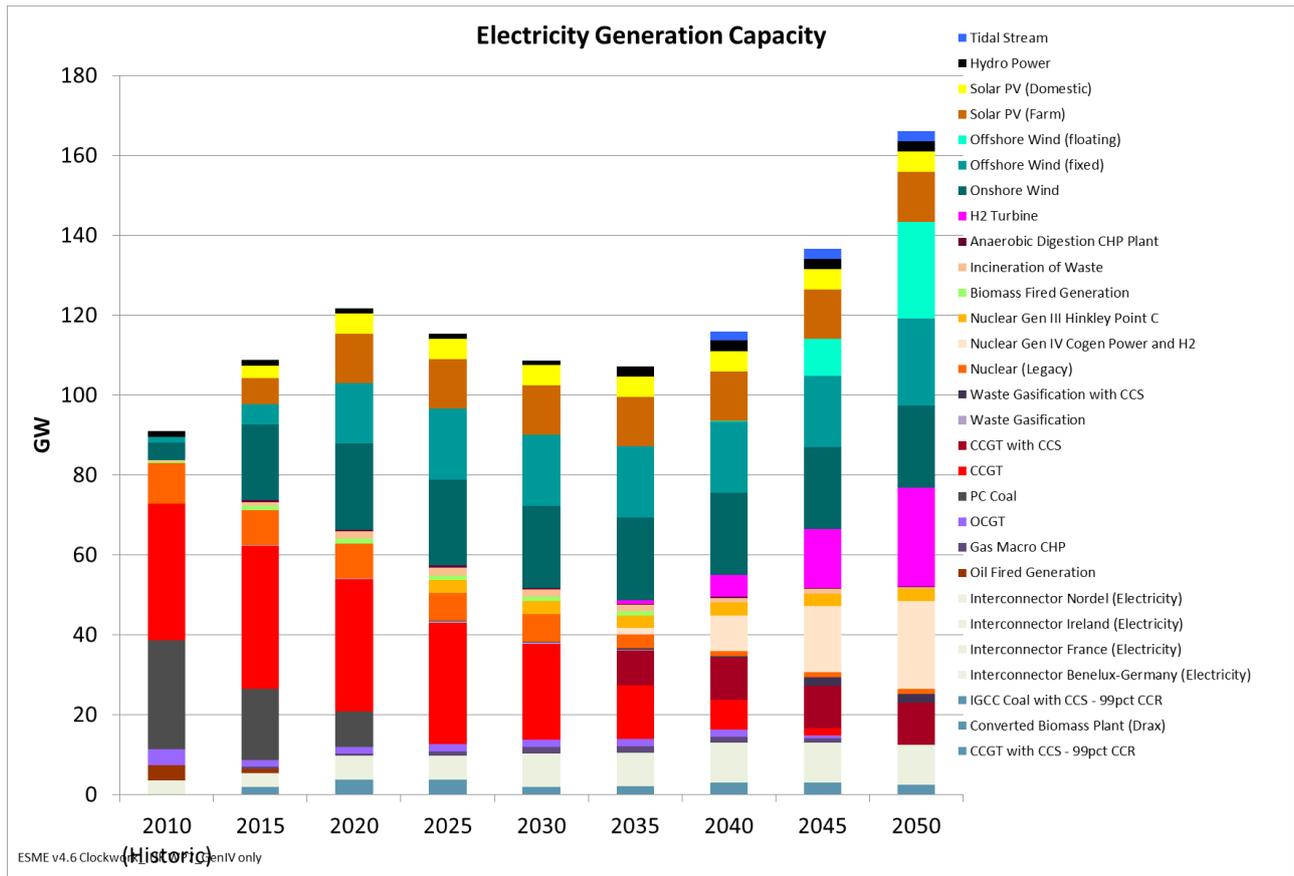
Figure A2-31 – Run 15a electricity generation capacity
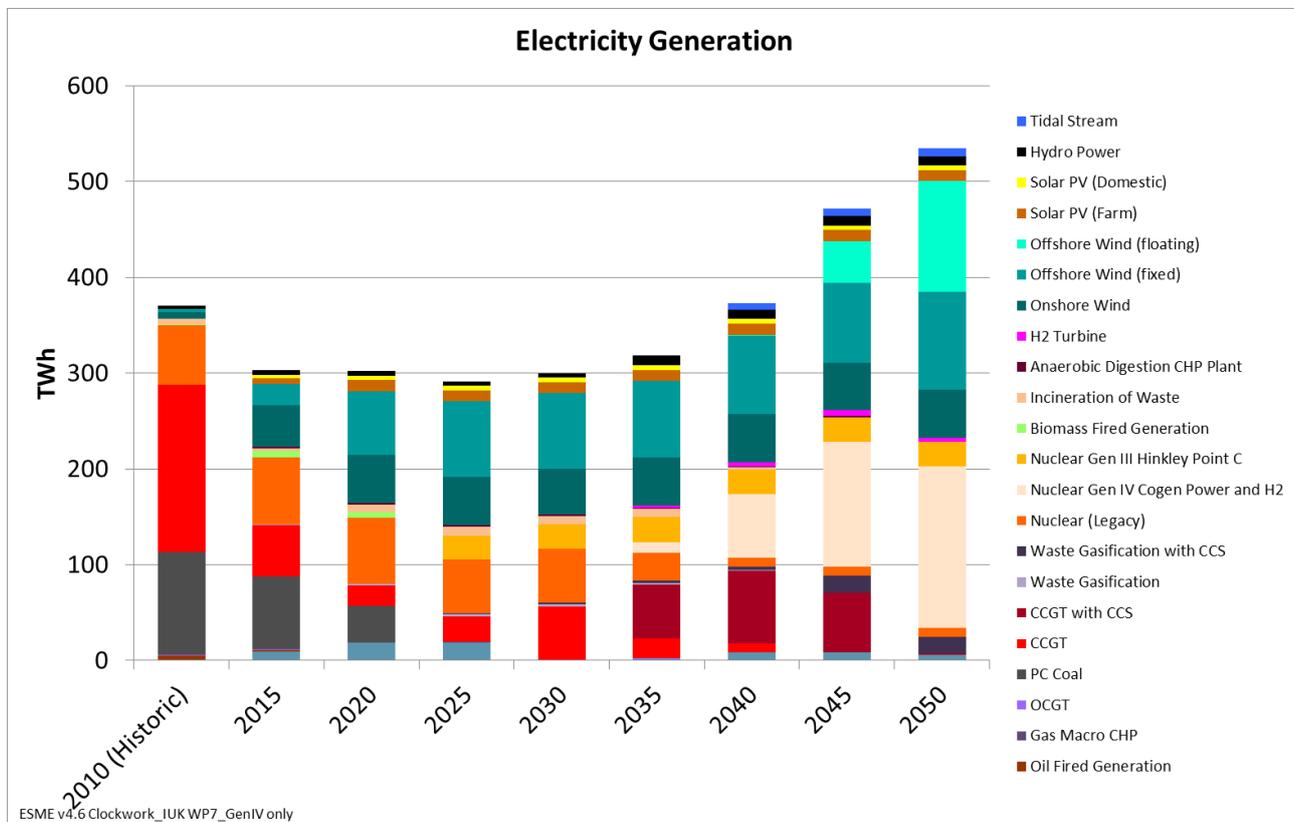
Figure A2-32 – Run 15a electricity generation
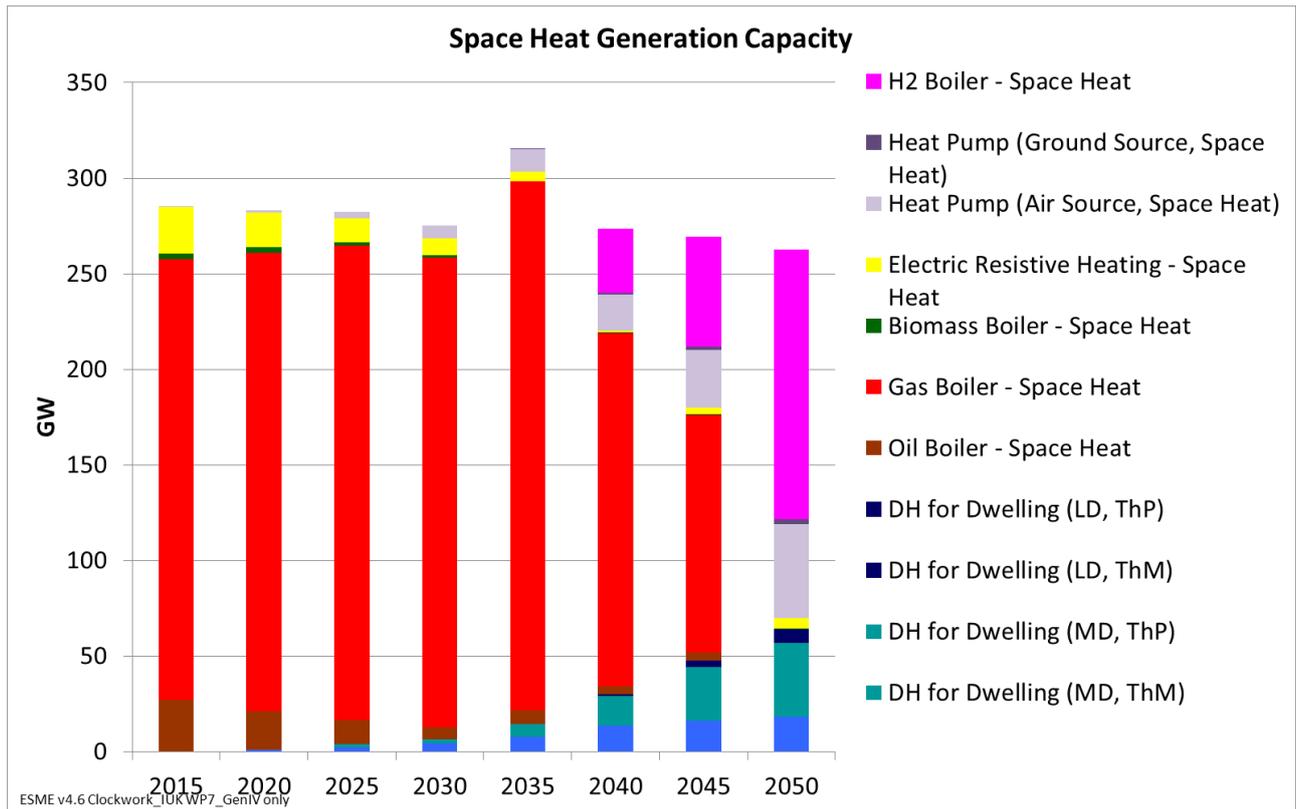
Figure A2-33 – Run 15a space heat generation capacity
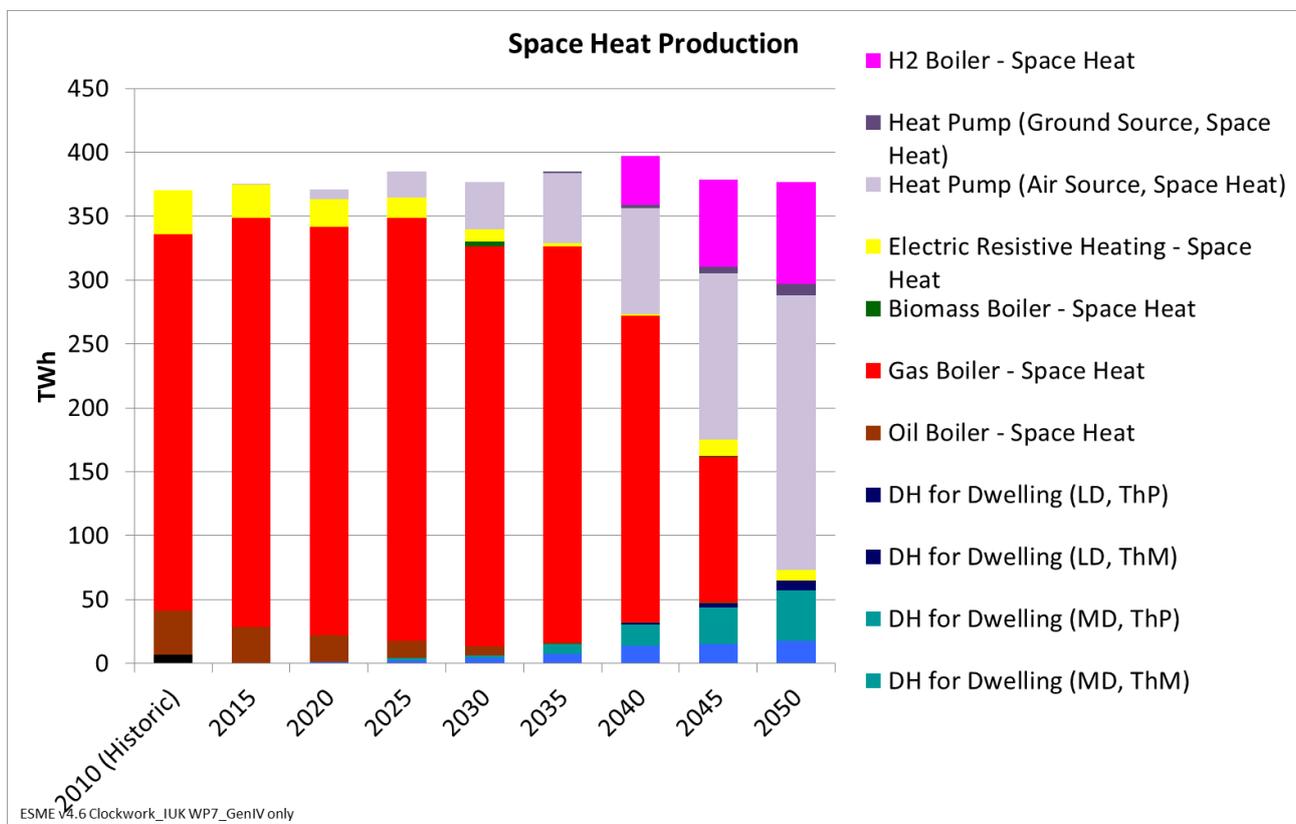
Figure A2-34 – Run 15a space heat production
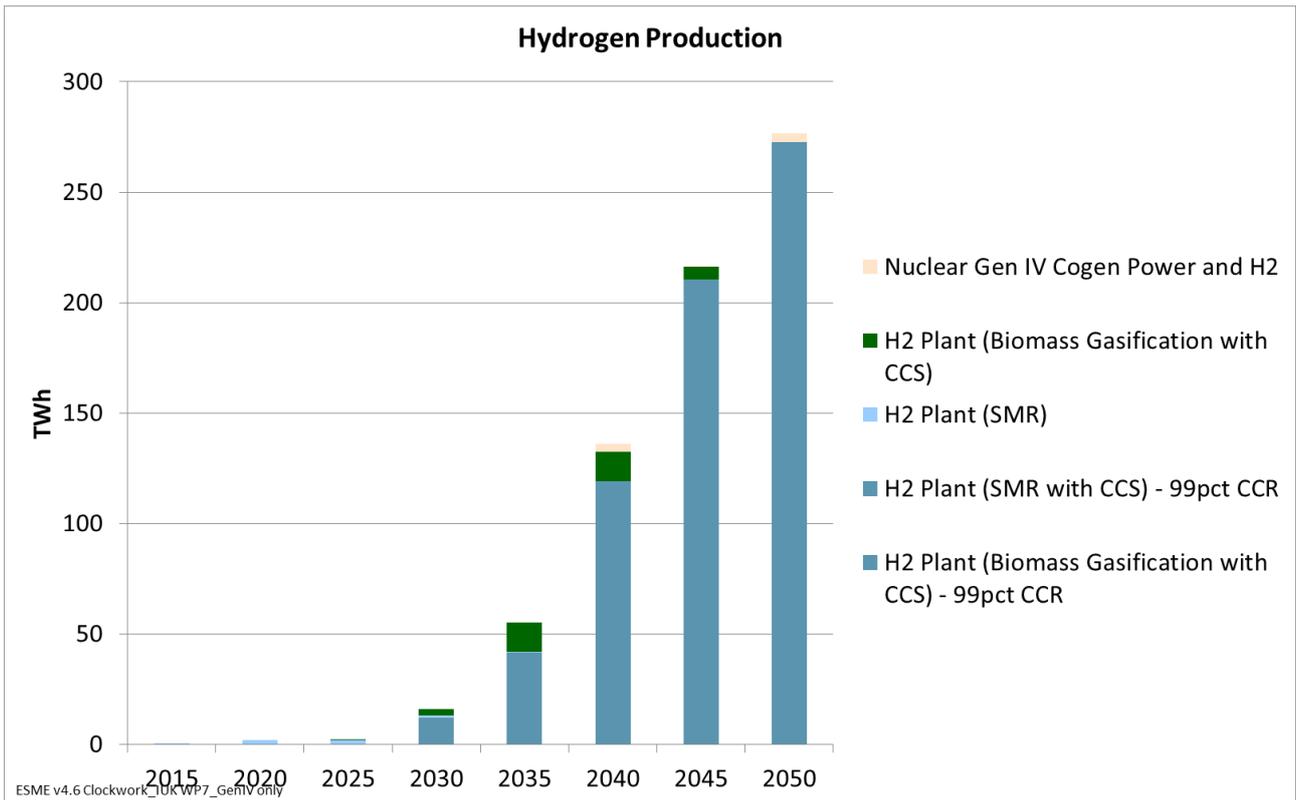
Figure A2-35 – Run 15a hydrogen production
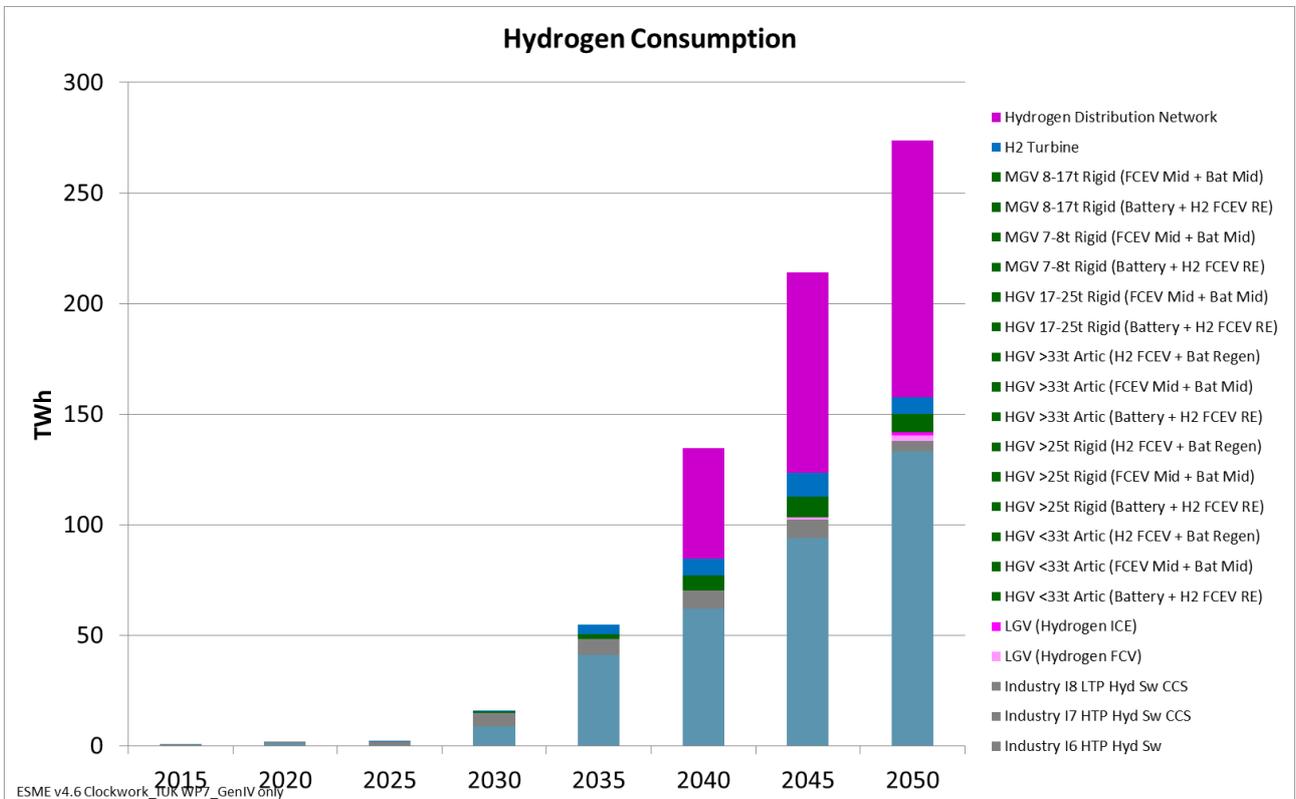
Figure A2-36 – Run 15a hydrogen consumption
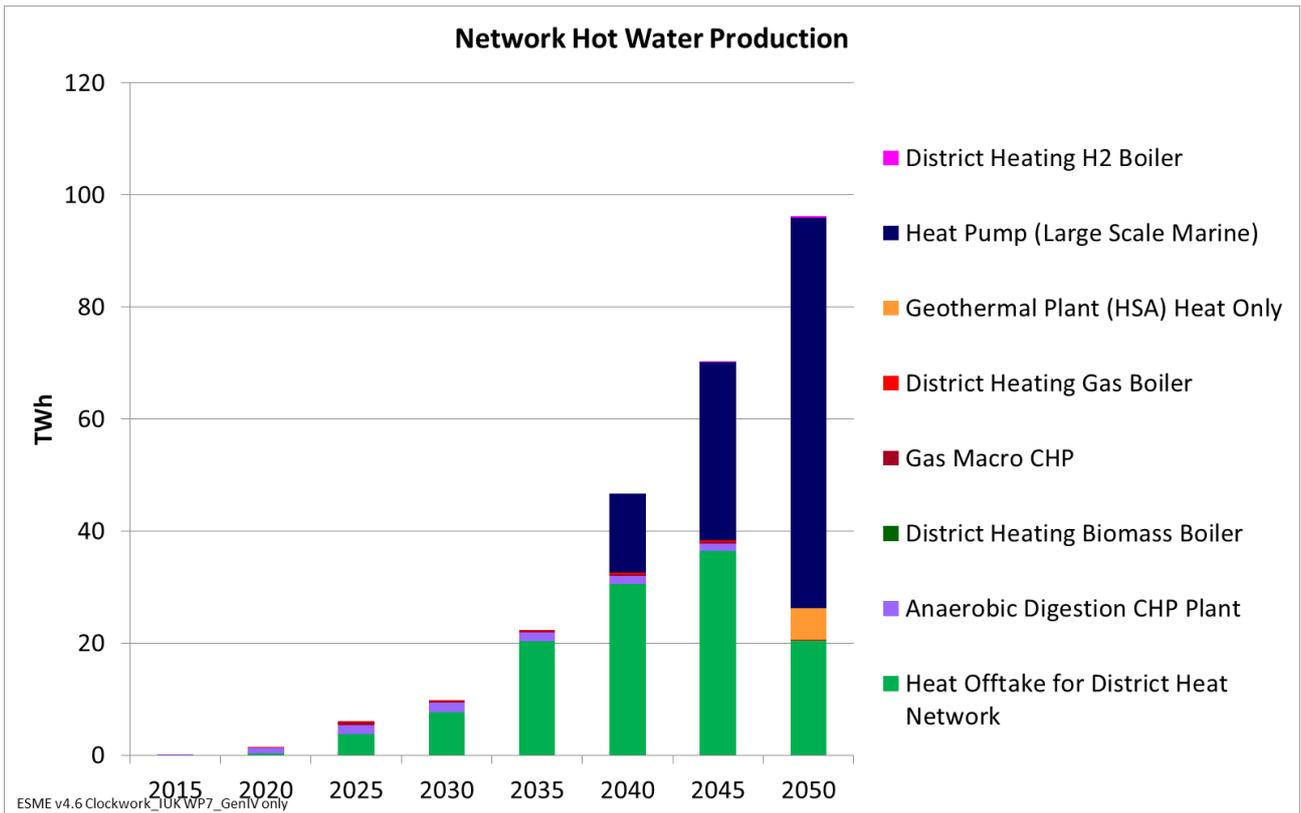
Figure A2-37 – Run 15a network hot water production
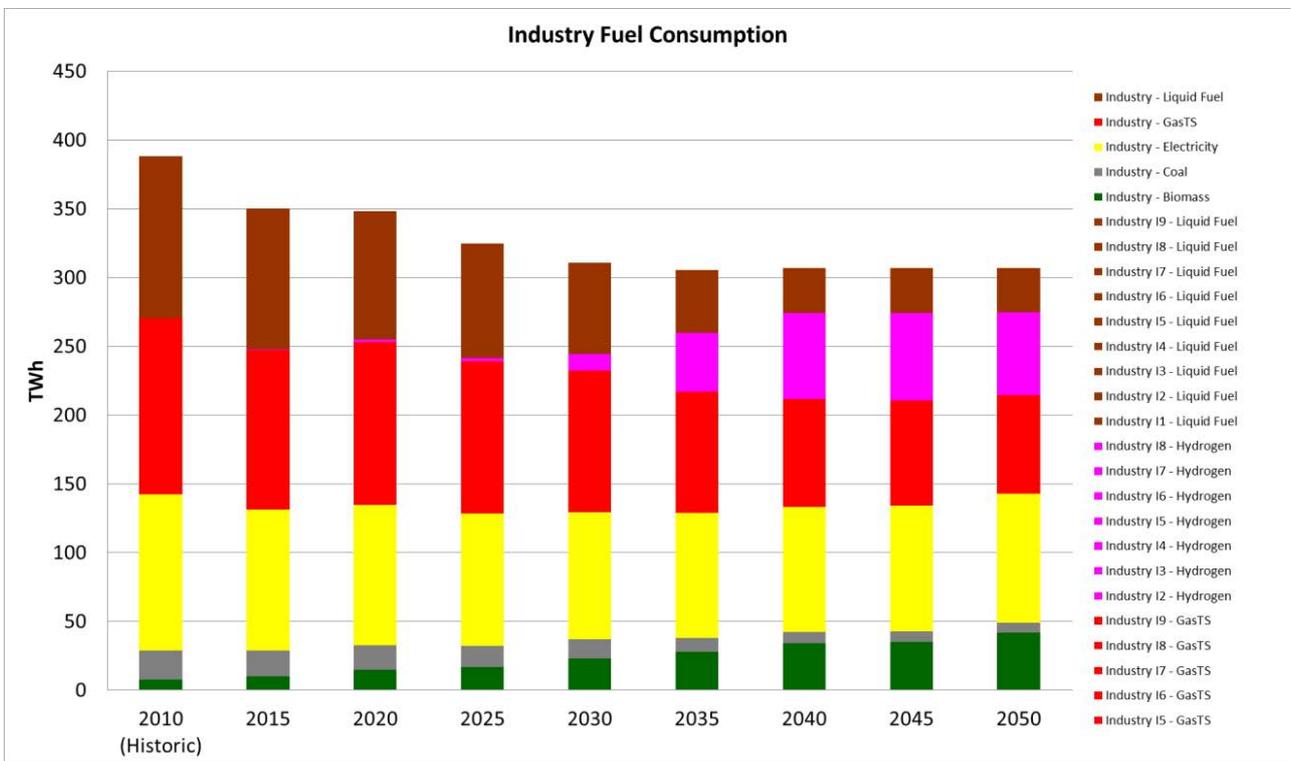
Figure A2-38 – Run 15a industry fuel consumption

Monte Carlo Run TECH100 – All nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR for cogeneration of flexible power and heat for DH energisation; Gen IV advanced nuclear plants as cogen power and hydrogen production; baseline data with -25%/+40% spread applied to capex for all nuclear new build technologies
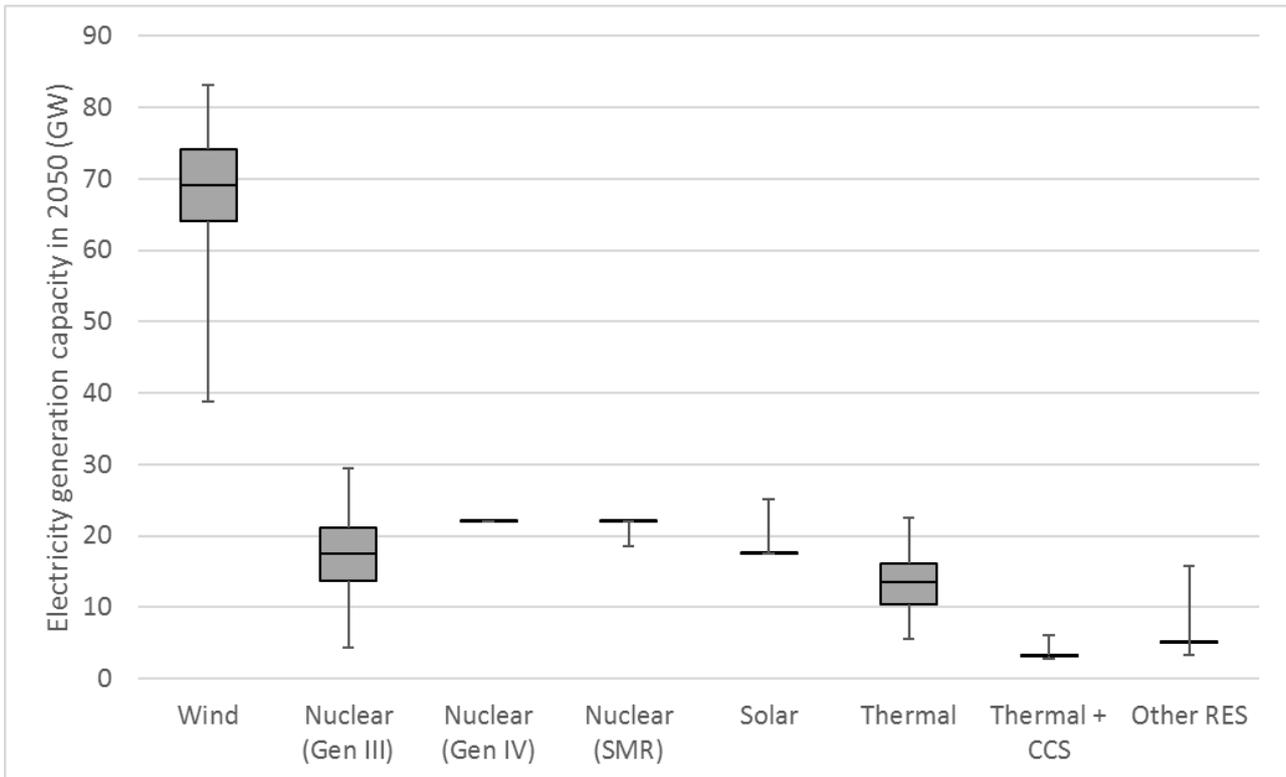
Figure A2-39 – Probabilistic (Monte Carlo) run showing electricity generation capacity in 2050 – USING TECH100 with nuclear base case values

Figure A2-40 – Probabilistic (Monte Carlo) Run showing district heat supply in 2050 – using TECH100 with nuclear

Appendix 2

SUPPLEMENTARY REPORT NO.2:
REVISED DATASETS REFLECTING HIGHER OPTIMISM

NNL ENERGY SYSTEM MODELLING REPORT

Contents

1. Executive summary

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme including a Futures Roadmap. NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements. These scenarios are defined through NNL's Energy System Modelling project as:

0. No new nuclear

1. Constrained by policy to a capped level of nuclear deployment

2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral

3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market

4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies new potential pathway options as part of the approach to Net Zero.

These scenarios are partly delivered through ESC's Nuclear for Net Zero (NFNZ) technical report which is available to NNL. The balance of the analysis to define these four scenarios is to be delivered through 3 Supplementary Reports. The second element of additional analysis is described in this report as Supplementary Report No.2. The analysis in this report delivers additional scenarios using revised nuclear technology datasets based on expert input from LucidCatalyst. The revised nuclear technology datasets incorporate:

- An increase in N'th-of-a-Kind (NOAK) construction duration for Gen III+ from 5 years to 5.5 years

- A reduction in the NOAK cost for Light-Water Small Modular Reactor (LWSMR) with an increase in learner effect through to 2050

- An advance of the first UK operations date of a commercial High Temperature Gas Reactor from 2035 to 2030 with an increase in learner effect through to 2050.

The conclusions are summarised as follows:

Conclusion 1 – lower costs for Gen IV and LWSMR and an earlier deployment date for Gen IV combine to increase deployment levels for both these technologies, with some reduction in deployment of Gen III+.

Conclusion 2 – where a common nuclear heat supply system is deployed both as cogeneration of heat and power and cogeneration of power and hydrogen, the hydrogen variant is deployed at higher levels.

Conclusion 3 – for the nuclear data assumed in this analysis, levels of nuclear deployment were consistently significant, independent of whether heat networks were widely deployed at city-scale, or whether heat networks were supplied with nuclear heat.

Conclusion 4 – minimising the capital and operating costs for nuclear is expected to involve multi-unit deployment at each site; this should be a consideration for siting policy and the future designation of sites.

Conclusion 5 – a siting approach with fewer sites and more units per site is consistent with the initial exploitation of nuclear new build locations adjacent to existing nuclear licensed sites.

Conclusion 6 – reactor deployment at industrial brownfield sites in locations of heat and hydrogen demand may require the review and development of current siting policy; this pathway may be easier for safety and environmental regulators for HTGRs than for light-water reactors.

Conclusion 7 – a new nuclear deployment scenario of "higher optimism" has been defined, and the deployment scenarios for "constrained" and "base case" have been updated.

Conclusion 8 – the suggested approach previously identified in the NFNZ report of an initial Gen III+ programme alongside stage-gated development programmes for LWSMR and Gen IV is further supported by the analysis in Supplementary Report No.2.

Conclusion 9 – the HTGR technology has many advantages amongst the family of advanced nuclear technologies which makes it a good choice for UK Gen IV development.

2. Introduction

2.1. Introduction to Energy Systems Catapult

Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.

The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research.

We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, to decarbonise the energy system at the lowest cost.

2.2. NNL's Energy System Modelling Project

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme:

1. People
2. Infrastructure
3. Ideas
4. Supply Chain
5. Stakeholder Engagement
6. Industry Alignment
7. International Influence
8. Futures Roadmap.

NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements.

2.2.1. NNL's Energy System Modelling Project objective

The objective of NNL's Energy System Modelling project is to inform 5 potential nuclear deployment scenarios defined as:

0. No new nuclear deployment
1. Constrained by policy to a capped level of nuclear deployment
2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral
3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market
4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies potential new pathway options as part of the approach to Net Zero.

Nuclear deployment in a scenario of "no new nuclear" as indicated above is of little benefit to an advanced fuel cycle programme, other than cognisance of the circumstances that could make such a scenario more likely. Such a scenario is defined later in this report in Section 2.2.2 but otherwise not considered further as part of this project.

2.2.2. Technical starting point for NNL's Energy System Modelling Project

ESC owns, operates and maintains a whole energy system model known as Energy System Modelling Environment[1] (ESME) which has been developed over a decade for the purpose of better understanding the pathways and options for decarbonising the UK economy. ESME has been internationally peer reviewed and is used under licence by various organisations. Analysis using ESME has been considered by the Committee on Climate Change as part of its deliberations.

The process flow necessary to deliver the 4 nuclear deployment scenarios is illustrated in Figure 1.

Figure 1 – Process flow to deliver four potential UK nuclear deployment scenarios

However, in 2019 ESC launched a programme of projects as part of a Net Zero programme to reflect the amendment in June 2019 to the Climate Change Act 2008. This legislation adjusted the performance objective of 80% decarbonisation compared with historic reference levels to Net Zero by 2050. This ESC programme in response to this new legislation delivered the first step in the process flow illustrated in Figure 1 by delivering four new ESME decarbonisation scenarios:

- F A96 – using core technologies for 80% decarbonisation and stretched to deliver 96%
- TECH100 – introduction of additional speculative technologies to deliver 100% decarbonisation
- SOC100 – introduction of speculative changes to societal behaviours for 100% decarbonisation
- BOB100 – combination of both TECH100 and SOC100

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1   Further information on ESME and the evidence base it incorporates can be found on the ESC website:
    https://es.catapult.org.uk/brochures/esme-data-references-book/

These new scenarios are described in more detail in ESC's Innovating to Net Zero analysis and report[2], and subsequently used in the IUK WP7 project.

ESC's Net Zero programme was delivered through a project known as the Energy Technology Benchmarking project which was grant funded by Innovate UK (IUK). The scope funded by IUK included a further project known as Innovate UK Work Package 7 (IUK WP7). The scope of IUK WP7 delivered the next two steps in the process flow illustrated in Figure 1. Therefore, the technical starting point for NNL's Energy System Modelling Project is ESC's Nuclear for Net Zero (NFNZ) project and associated report[3], also known as IUK WP7. The Nuclear for Net Zero project technical report has been made available to NNL for the purpose of its Energy System Modelling project.

The objective of NNL's Energy System Modelling project will be achieved through a combination of the NFNZ project and associated report, and three further Supplementary Reports as illustrated in Figure 2. The Zero Deployment (0) and the Constrained Deployment (1) scenarios are defined within the NFNZ project technical report. This report together with Supplementary Report No.1 delivering additional scenarios informs the Base Case (2) Nuclear Deployment scenario. A second Supplementary Report (No.2) will document indicative nuclear deployment with further revised data provided by industry experts at LucidCatalyst to inform a nuclear deployment scenario known as (3) Higher Optimism. A final Supplementary Report (No.3) will document the indicative nuclear deployment levels from adding a new technology type to ESME enabled by low-cost carbon free hydrogen. This will inform the final scenario known as (4) Greater Nuclear Ambition. The project outputs to deliver the project objective are summarised in Table 1 below.

Table 1 – Sequence of project reports leading to nuclear deployment scenarios to deliver the project objective

Project	Report	Scope	Nuclear Deployment Scenarios
ESC NFNZ project	ESC project report	Overlap with majority of analysis detailed in NNL ITT	1 Constrained
NNL Energy System Modelling project	Supplementary report 1	Balance of analysis required by NNL ITT	2 Base case
	Supplementary report 2	Impact of revised inputs for nuclear technologies	3 Higher optimism
	Supplementary report 3	Additional technology added to and tested in ESME	4 Greater nuclear ambition

2.2.3. Purpose of Supplementary Report No.2

The purpose of Supplementary Report No.2 is to test the impact of revised nuclear technology datasets available from LucidCatalyst and to inform the analysis supporting the third nuclear deployment scenario known as "Higher Optimism".

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2. Innovating to Net Zero. Energy Systems Catapult 10th March 2020.
    https://es.catapult.org.uk/reports/innovating-to-net-zero/

3. Nuclear for Net Zero – A UK Whole Energy System Appraisal. Project Technical Report dated 17th April 2020 by Energy Systems Catapult.

3. Approach to the analysis for Supplementary Report No.2

3.1. Alternative datasets available through LucidCatalyst

From its ongoing research and operational activities, LucidCatalyst is able to develop an alternative view of potential pathways to commercialisation and associated costs for advanced nuclear technologies, as well as learning from large reactor projects in development and deployment. The interest in these alternative datasets is not simply whether UK Net Zero can be achieved at lower net cost, but whether alternative datasets open-up new insights regarding potential Market, Policy or Regulatory action by policymakers for introducing new technologies. Additionally, new datasets have the potential to introduce additional pathways in the transition to UK Net Zero.

For Supplementary Report No.2, the updated datasets comprise:

- An increase in NOAK construction duration for Gen III+ from 5 years to 5.5 years
- A reduction in the NOAK cost for LWSMR with an increase in learner effect through to 2050
- An advance of the first UK operations date of a commercial HTGR from 2035 to 2030 with an increase in learner effect through to 2050.

These updated datasets are described in more detail later in Section 4 and Annex 1.

3.2. Approach informed by the alternative datasets

The approach to the scope for Supplementary Report No.2 is illustrated in Figure 3 which shows:

- Updated datasets applied to all new nuclear technologies of Gen III+, LWSMR and Gen IV, with LWSMR still deployed as cogeneration for flexible electricity generation and lower grade heat for district heating and Gen IV deployed as cogeneration for flexible electricity generation and hydrogen production.

- Scenario analysis:
  - The first group of scenarios is to test the nuclear technologies in combination for the 3 Net Zero scenarios of FA96, TECH100 and BOB100
  - The second group uses FA96 and TECH100 to test the resilience of nuclear deployment to higher and lower capex levels
  - The third group tests Gen IV plant deployment without Gen III+ beyond HPC and without LWSMR, using base case values
  - Given the earlier first operations date of Gen IV in the updated dataset, the fourth group tests Gen IV deployment with a higher site capacity limit of 55 GWe and a higher build-out rate. Scenarios FA96 and TECH100 are used with base case values, and higher and lower capex values
  - The fifth group tests the impact of a potential policy choice of whether district heating should be deployed at scale. The intention is to test resilience of nuclear deployment when the energy system is optimised to deliver space heating without district heating available as an energy vector

- The sixth group tests the impact of Gen IV deployment as low-cost "hydrogen only" plants to explore the impact of increased supply of low-cost hydrogen on the optimisation of the energy system.

- Results: Data is extracted from ESME outputs in the form of core charts and the results interpreted to identify any new trends or tipping points from the new scenarios and data.

- Recommendations with respect to Market, Policy or Regulation (MPR): The actions and MPR recommendations from the NFNZ technical report are re-visited with the benefit of additional scenarios and data informed by the analysis for Supplementary Report No.2.

Update datasets
- Update ESME nuclear technology datasets for based on expert input from LucidCatalyst
- Apply as appropriate to Gen III+, LWSMR and GenIV
- Design sensitivity analyses to explore impact of updated datasets

Scenario analysis
- Gen IV technology tested for role and value to the whole energy system
- Sensitivity studies with/without widespread deployment of district heating
- Combined assessment to test impact and value of all nuclear options together
- Repeated probabilistic analysis to address uncertainties

Results
- Examine multi-vector impacts; power, heat and hydrogen production
- Identify tipping points and their consequences/opportunities
- System relationships with other non-nuclear technologies

MPR actions
- Identification of opportunities associated with each nuclear technology
- Decisions for each technology; little/no regret based on opportunity value
- Associated actions for policy and regulation to stimulate markets

Figure 3 – Schematic showing process flow to deliver analysis for Supplementary Report No.2

4. Updated datasets for Supplementary Report No.2

4.1. Dataset for large Gen III+

Table 2 – Large Gen III+ selected key parameters applied for Supplementary Report No.2

Gen III+ Electricity Generation (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2025	2025	2030
Construction Duration (years)	4.5	5.5	7
Build Out Rate (GWe/year)	2.1	1.4	0.7
Overnight Capital Cost ($/KWe in 2017 dollars)	$4,000/KWe at 2025 reducing to $3,500/KWe by 2050	$4,500/KWe at 2025 reducing to $4,000/KWe by 2050	$5,500/KWe at 2030 reducing to $5,000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The dataset for large Gen III+ has been updated for Supplementary Report No.2. For ease of reference the key parameters are shown in Table 2. For brevity, the full dataset and associated supporting assumptions and related data are not detailed here but included in Annex 1.

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 2 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

4.2. Dataset for LWSMR

Table 3 – LWSMR cogen (flexible power and heat for district heating energisation) selected key parameters applied for Supplementary Report No.2

Cogen LWSMR Electricity and Heat (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2028	2030	2035
Construction Duration (years)	3	4	5
Build Out Rate (GWe/year)	2.7	1.2	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,000/KWe at 2028 reducing to $2,000/KWe by 2050	$4,000/KWe at 2030 reducing to $3,000/KWe by 2050	$5,000/KWe at 2035 reducing to $4,000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Capex is for cogeneration with heat rejected from power conversion system used for DH energisation with power downrate penalty. Costs include $500/kWe Capex increment for CHP which includes pipe runs circa 10 km to connect plant to city scale DH ring main (4) For electricity only plant remove the $500/KWe CHP increment included in the Capex (5) Full DH energisation across England and Wales equates to 22 GWe of LWSMR in England and Wales from ETI ANT project. (6) Site capacity limit for England and wales at 2050 established from the ETI PPSS (7) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The dataset for LWSMR has been updated for Supplementary Report No.2. For ease of reference the key parameters are shown in Table 3. For brevity, the full dataset and associated supporting assumptions and related data are not detailed here but included in Annex 1.

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 3 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

4.3. Dataset for Gen IV cogeneration for electricity and hydrogen

Table 4 – Gen IV cogen (flexible power and hydrogen production) selected key parameters applied for Supplementary Report No.2

Cogen Gen IV Electricity and Hydrogen (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2030	2030	2035
Construction Duration (years)	2	3	4
Build Out Rate (GWe/year)	3.0	1.5	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,000/KWe at 2030 reducing to $2,000/KWe by 2050	$4,000/KWe at 2030 reducing to $3,000/KWe by 2050	$5,000/KWe at 2035 reducing to $4,000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 90% (3) Capex is for cogeneration of electricity and hydrogen production. Costs include $500/kWe Capex increment for co-located hydrogen production plant (4) For electricity only plant remove the $500/KWe hydrogen production increment included in the Capex (5) Full DH energisation equated to 22 GWe of LWSMR in England and Wales from ETI ANT project. This limit retained for LWSMR and the "twice-over" PPSS site capacity allocated to Advanced Gen IV high temp. If large reactor Gen III+ sites un-used then this underutilised capacity could be available to LWSMR or Advanced Gen IV high temp in additional sensitivity studies (6) Site capacity limit for England and Wales at 2050 established from the ETI PPSS (7) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The dataset for Gen IV has been updated for Supplementary Report No.2. For ease of reference the key parameters are shown in Table 4. For brevity, the full dataset and associated supporting assumptions and related data are not detailed here but included in Annex 1.

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 4 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

5. ESME analysis and results

The charts and tables shown in section 5 are intended to collate and summarise key information from the many ESME runs across relatively few pages. These results are then interpreted and discussed in Section 6. A listing of all new scenario runs is provided in Annex 2. All ESME Runs undertaken for Supplementary Report No.2 are numbered sequentially from 201 to distinguish them from earlier runs for NFNZ and Supplementary Report No.1. To provide a greater level of detail, all the relevant ESME core chart outputs for these Runs are included in Annex 3.

5.1. Electricity capacity and generation

Figure 4 – Electricity generating capacity installed in 2050 from NFNZ for a range of scenarios

Run 25	Run 1	Run 26	Run 25a	Run 1a	Run 26a	Run 1b
FA96 Lower CAPEX all nuclear	FA96 Baseline data all nuclear	FA96 Higher CAPEX all nuclear	Tech 100 lower CAPEX all nuclear	Tech 100 Baseline data all nuclear	Tech 100 Higher CAPEX all nuclear	Bob 100 Baseline data all nuclear

Figure 5 – Electricity generation in 2050 from NFNZ for a range of scenarios

Figure 6 – Electricity generating capacity in 2050 from Supplementary Report No.2 analysis for a range of scenarios

Run 204	Run 201	Run 206	Run 205	Run 202	Run 207	Run 203
FA96 Lower CAPEX all nuclear	FA96 Baseline data all nuclear	FA96 Higher CAPEX all nuclear	Tech100 Lower CAPEX all nuclear	Tech100 Baseline data all nuclear	Tech100 Higher CAPEX all nuclear	Bob 100 Baseline data all nuclear
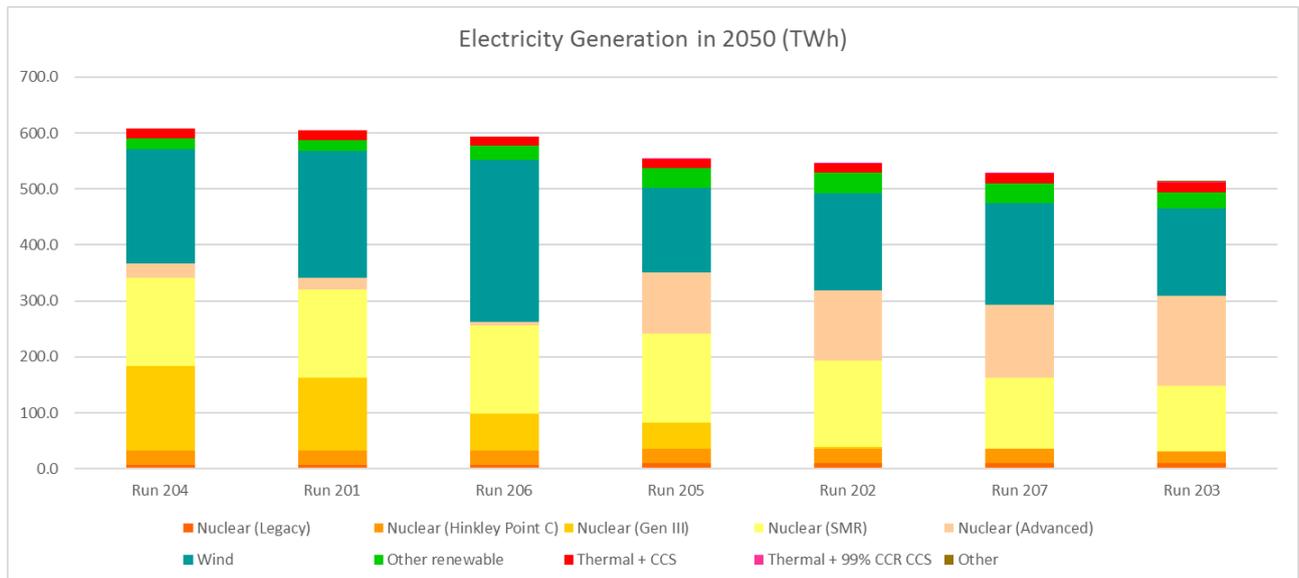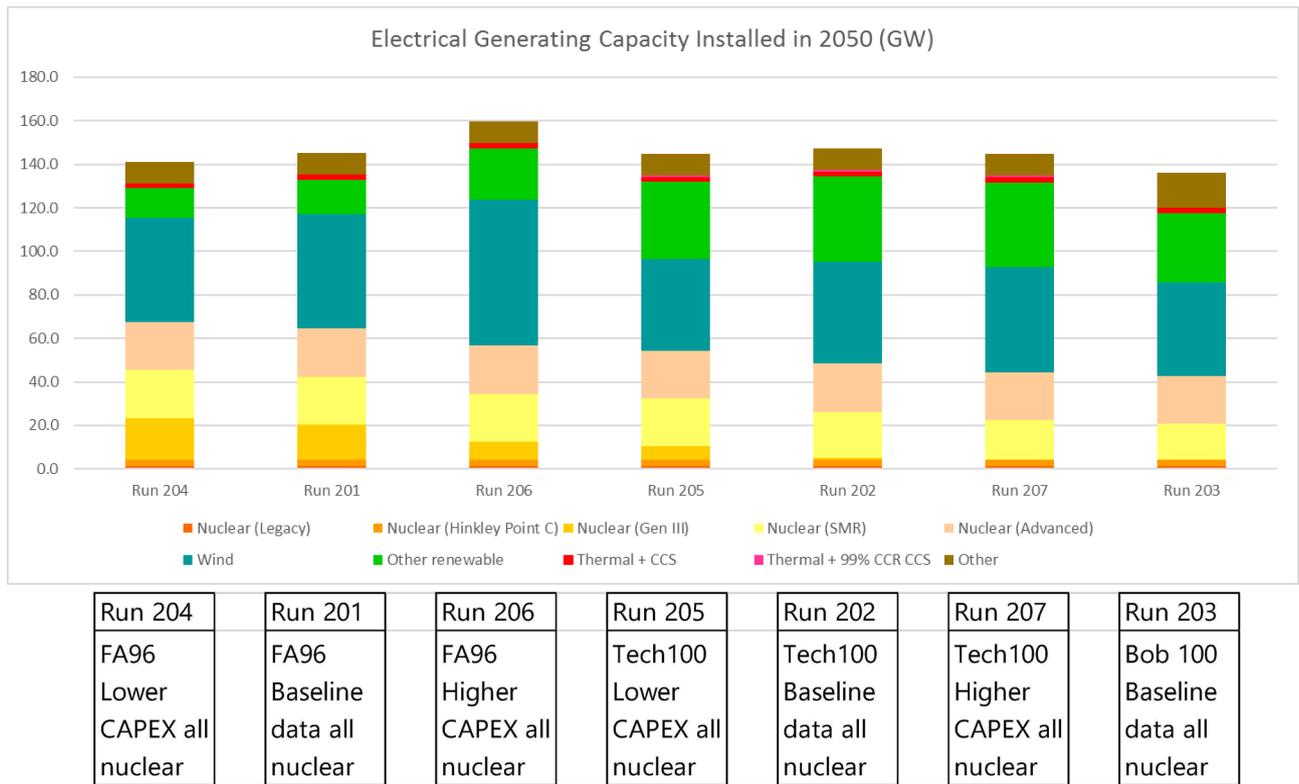
Figure 7 – Electricity generation in 2050 from Supplementary Report No.2 analysis for a range of scenarios

5.2. Hydrogen consumption and supply

Hydrogen consumption and supply is shown in Figures 8 and 9 for comparison against previous scenario Runs from NFNZ.

Figure 8 – Hydrogen consumption in 2050 from NFNZ for a range of scenarios
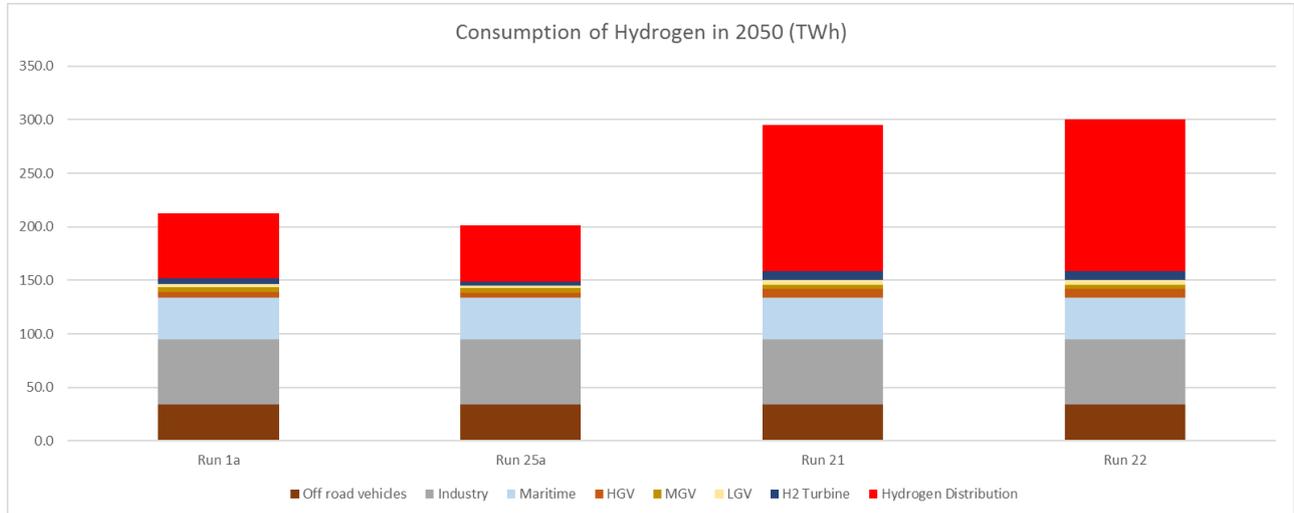
Run 1a		Run 25a		Run 21		Run 22
Tech 100 Baseline data all nuclear		Tech 100 lower CAPEX all nuclear		Tech 100 Only Gen IV H2; higher roll out and base CAPEX		Tech 100 Only Gen IV H2; higher roll out lower CAPEX
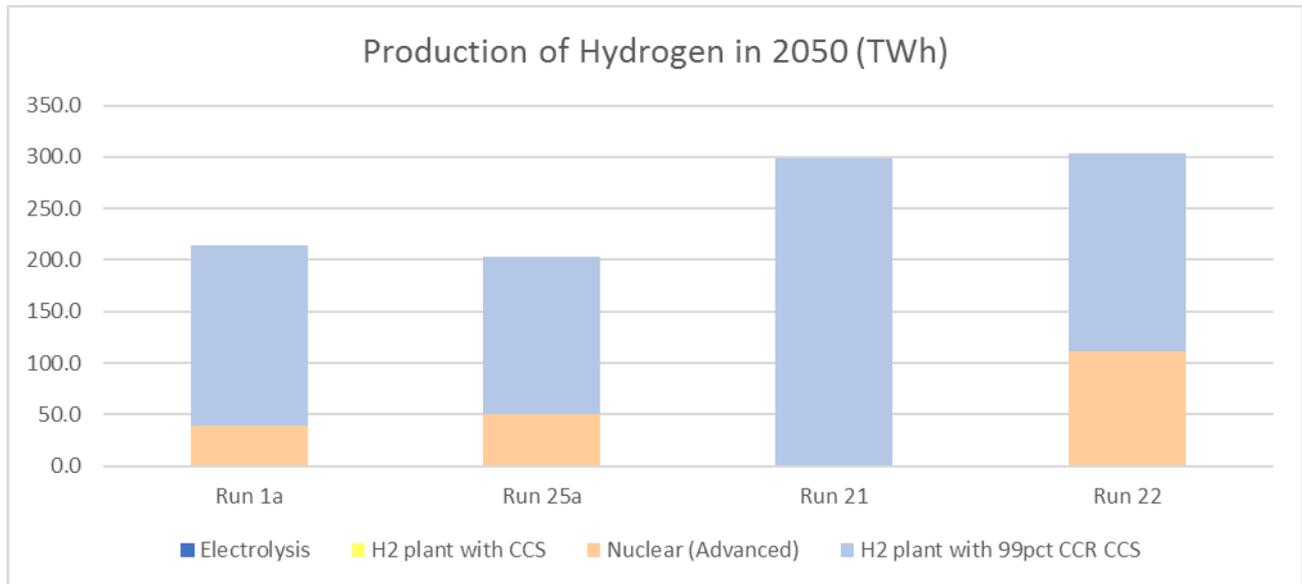
Figure 9 – Hydrogen production in 2050 from NFNZ for a range of scenarios

Figure 10 – Hydrogen consumption in 2050 from Supplementary Report No.2 analysis for a range of scenarios
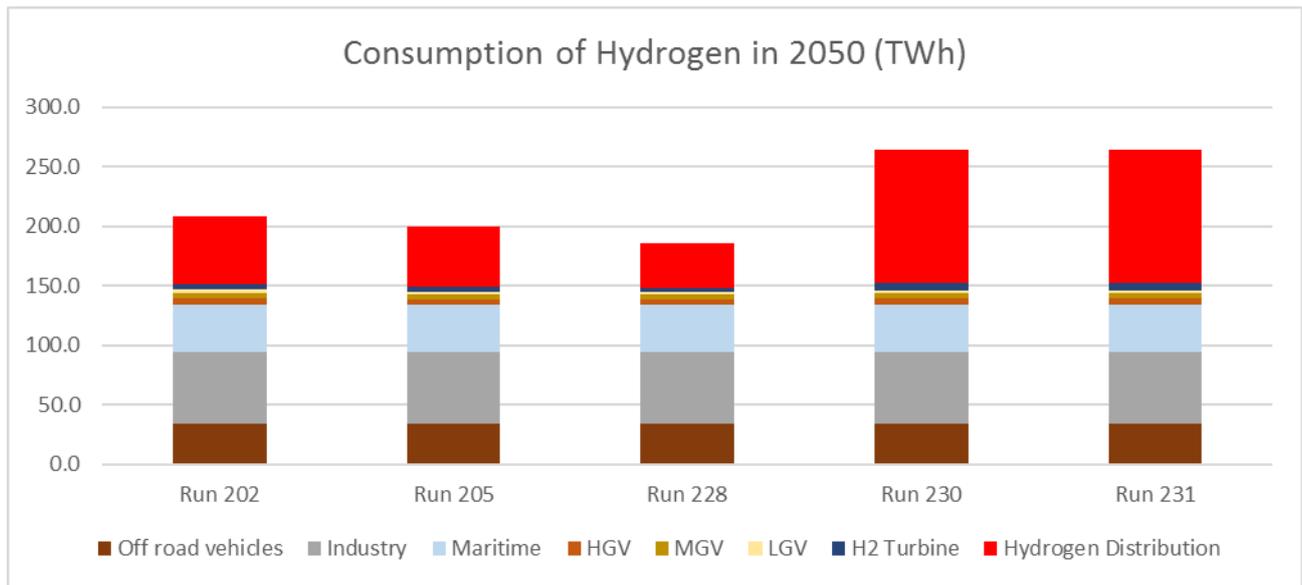
Run 202		Run 205		Run 228		230		Run 231
Tech100 Baseline data all nuclear		Tech100 All nuclear; lower CAPEX values		Tech 100 Baseline data all nuclear but higher roll out Gen IV		Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Higher roll out and base CAPEX Gen IV for H2 only		Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only and higher roll out and lower CAPEX Gen IV for H2 only
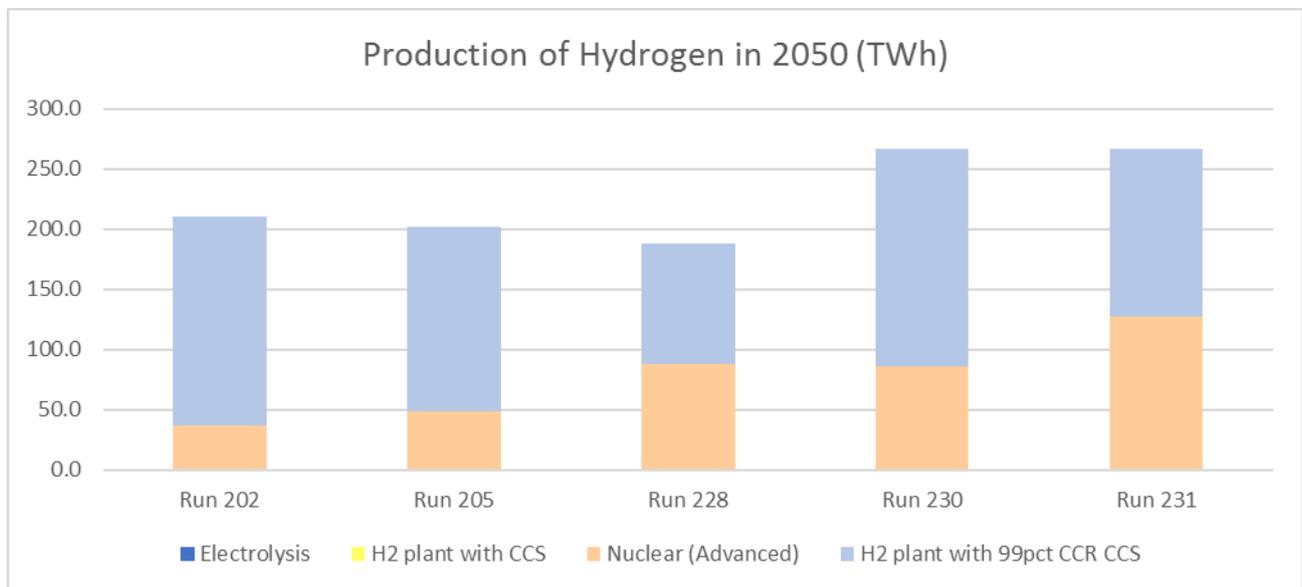
Figure 11 – Hydrogen production in 2050 from Supplementary Report No.2 analysis for a range of scenarios

5.3. Heat networks and energy supply from nuclear

Figure 12 – Nuclear contribution to energy supply including heat networks in 2050 for a range of scenarios

Run 201	Run 202	Run 203	Run 227	Run 228
FA96 Baseline data all nuclear	Tech100 Baseline data all nuclear	Bob 100 Baseline data all nuclear	FA96 Baseline data all nuclear but higher roll out Gen IV	Tech 100 Baseline data all nuclear but higher roll out Gen IV
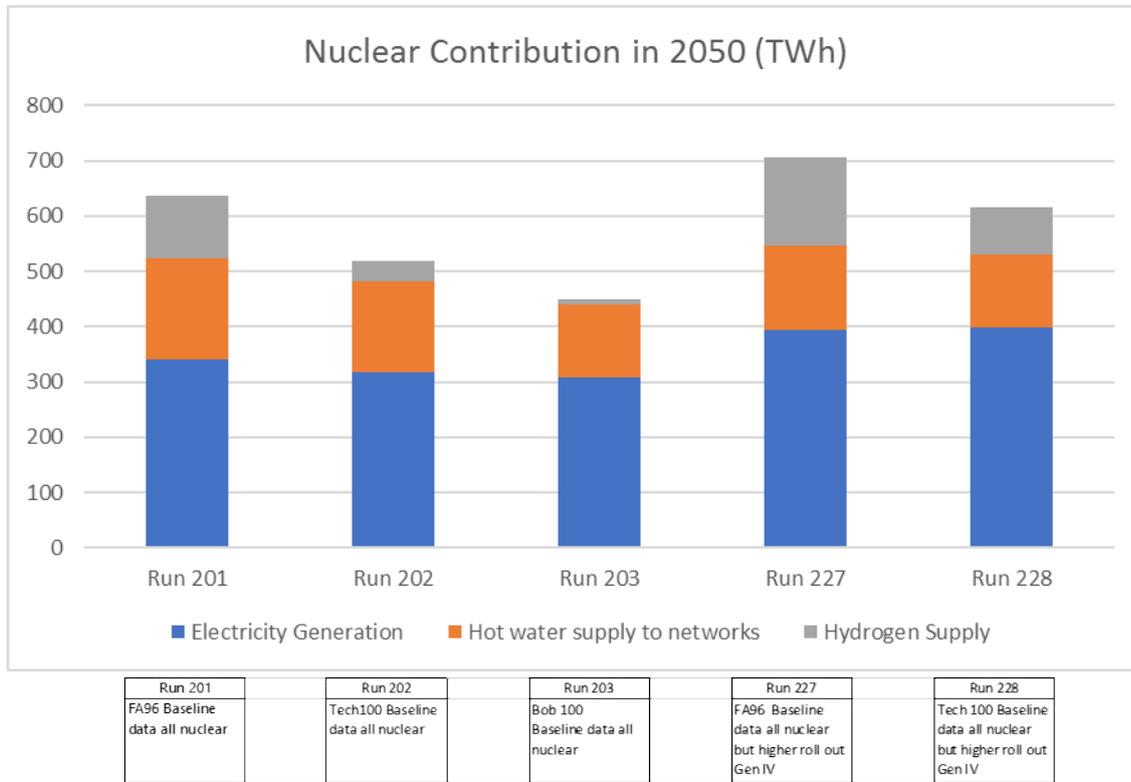
Figure 13 – Nuclear contribution to energy supply without heat networks in 2050 for a range of scenarios

Run 221	Run 222	Run 224	Run 225	Run 230	Run 231
FA96 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Gen IV cogen.	Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Gen IV cogen.	FA96 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Higher roll out for Gen IV cogen.	Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Higher roll out for Gen IV cogen.	Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only. Higher roll out and base CAPEX Gen IV for H2 only.	Tech 100 Baseline data all nuclear with ESME DH switched off. LWSMR as electricity only and higher roll out and lower CAPEX Gen IV for H2 only

5.4. Potential Gen IV contribution to 2050 energy supply

Figure 14 – Potential Gen IV contribution to energy supply in 2050 for a range of scenarios
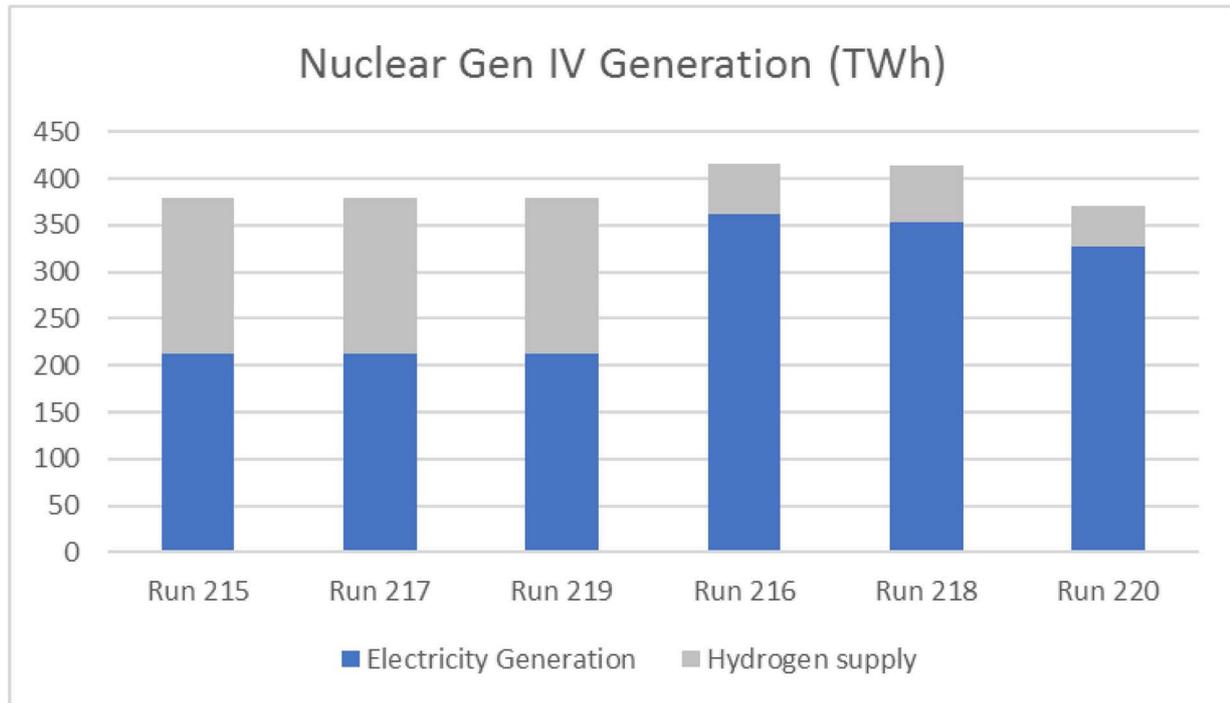
Run 215	Run 217	Run 219	Run 216	Run 218	Run 220
FA96 HPC and GenIV cogen only; higher roll out rate and base CAPEX	FA96 HPC and GenIV cogen only; higher roll out rate and lower CAPEX	FA96 HPC and GenIV cogen only; higher roll out rate and higher CAPEX	Tech100 HPC and GenIV cogen only; higher roll out rate and base CAPEX	Tech100 HPC and GenIV cogen only; higher roll out rate and lower CAPEX	Tech100 HPC and GenIV cogen only; higher roll out rate and higher CAPEX

5.5. Selection of Run 228 as basis for Monte Carlo analysis

Deterministic Run 228 was selected as the basis for the probabilistic (Monte Carlo) Run for Supplementary Report No.2. This run is listed in Annex 2 with a selection of ESME core output charts in Annex 3 at Figures A3-244 to A3-252. For ease of reference the charts for electrical generation capacity and generation are repeated in Figures 15 and 16, and hydrogen consumption and production in Figures 17 and 18. Additionally the utilisation charts for LWSMR cogeneration and Gen IV cogeneration are shown in Figures 19 and 20.
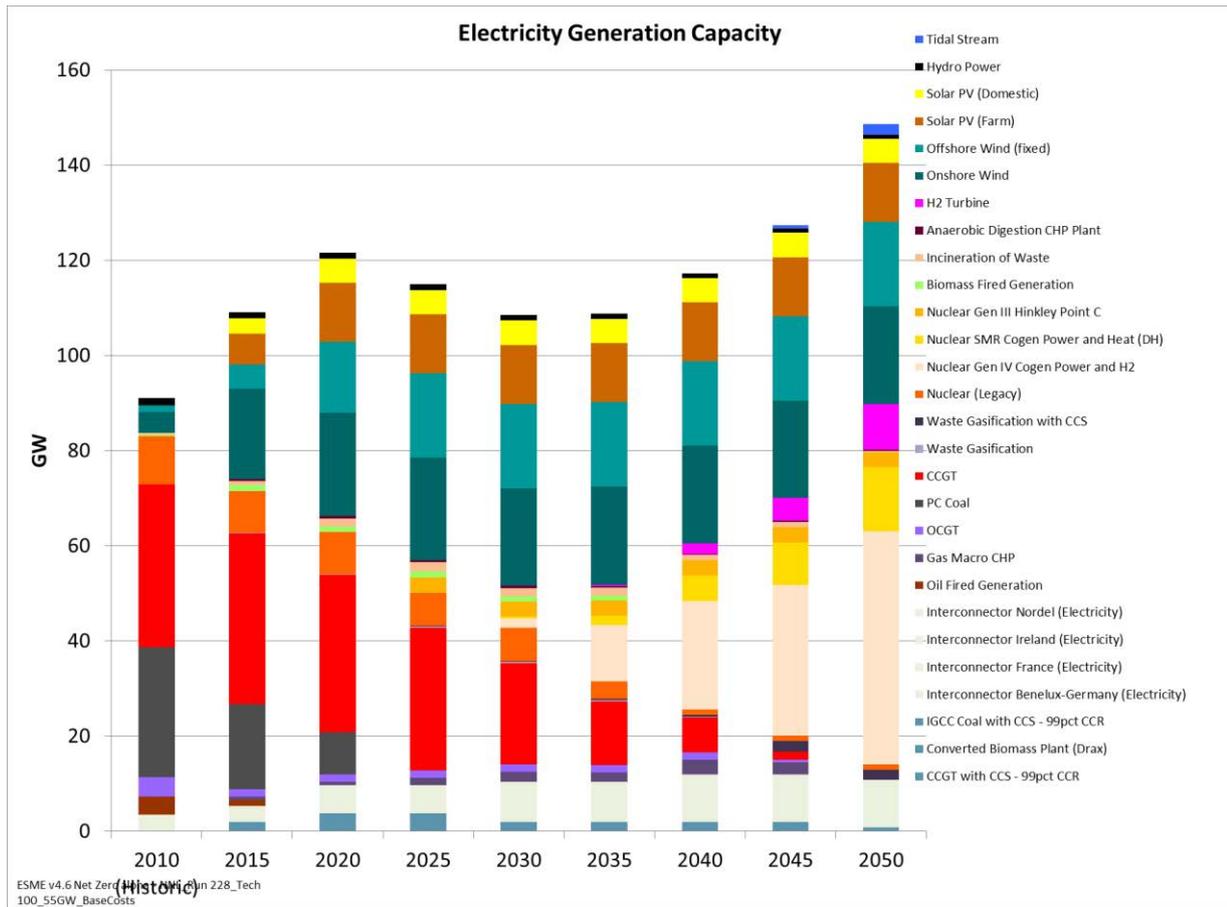
Figure 15 – Electricity generation capacity from Run 228 (TECH100)
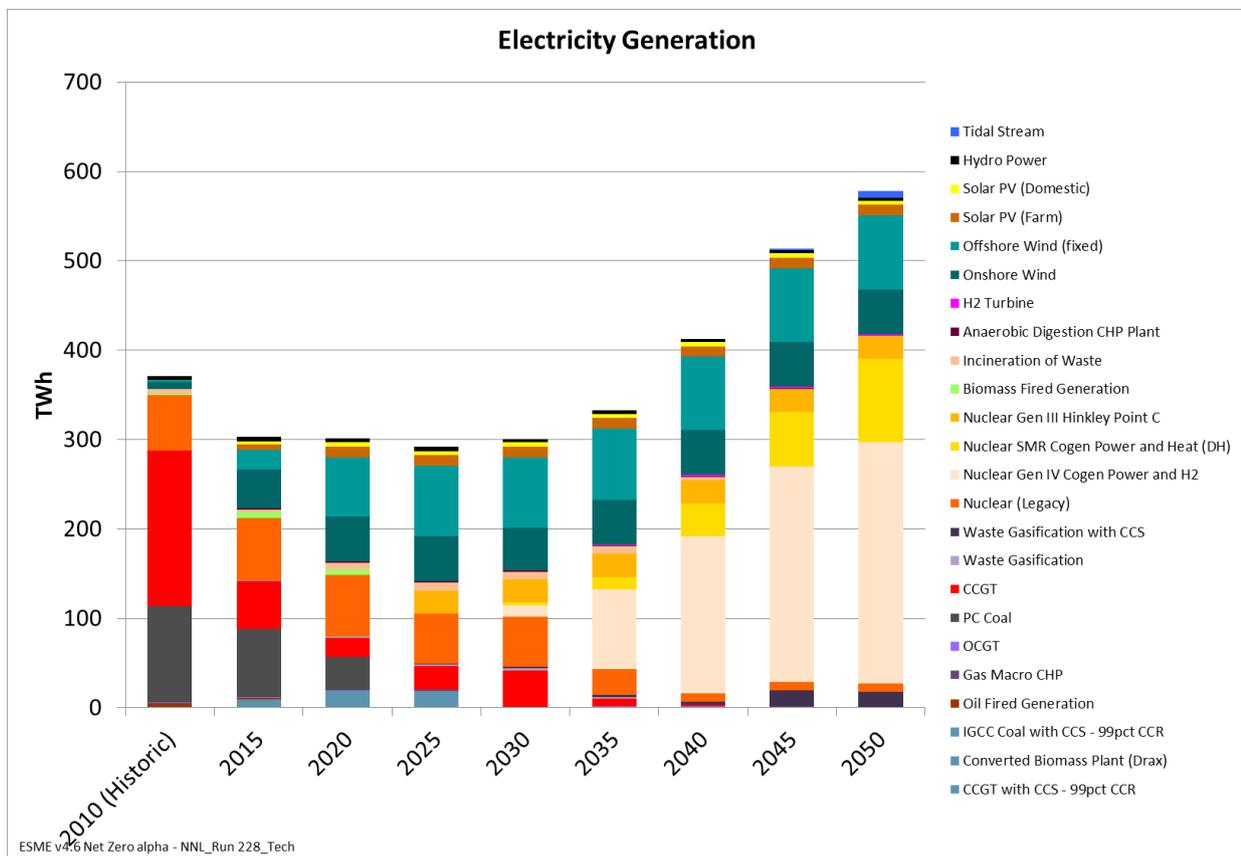
Figure 16 – Electricity generation from Run 228 (TECH100)
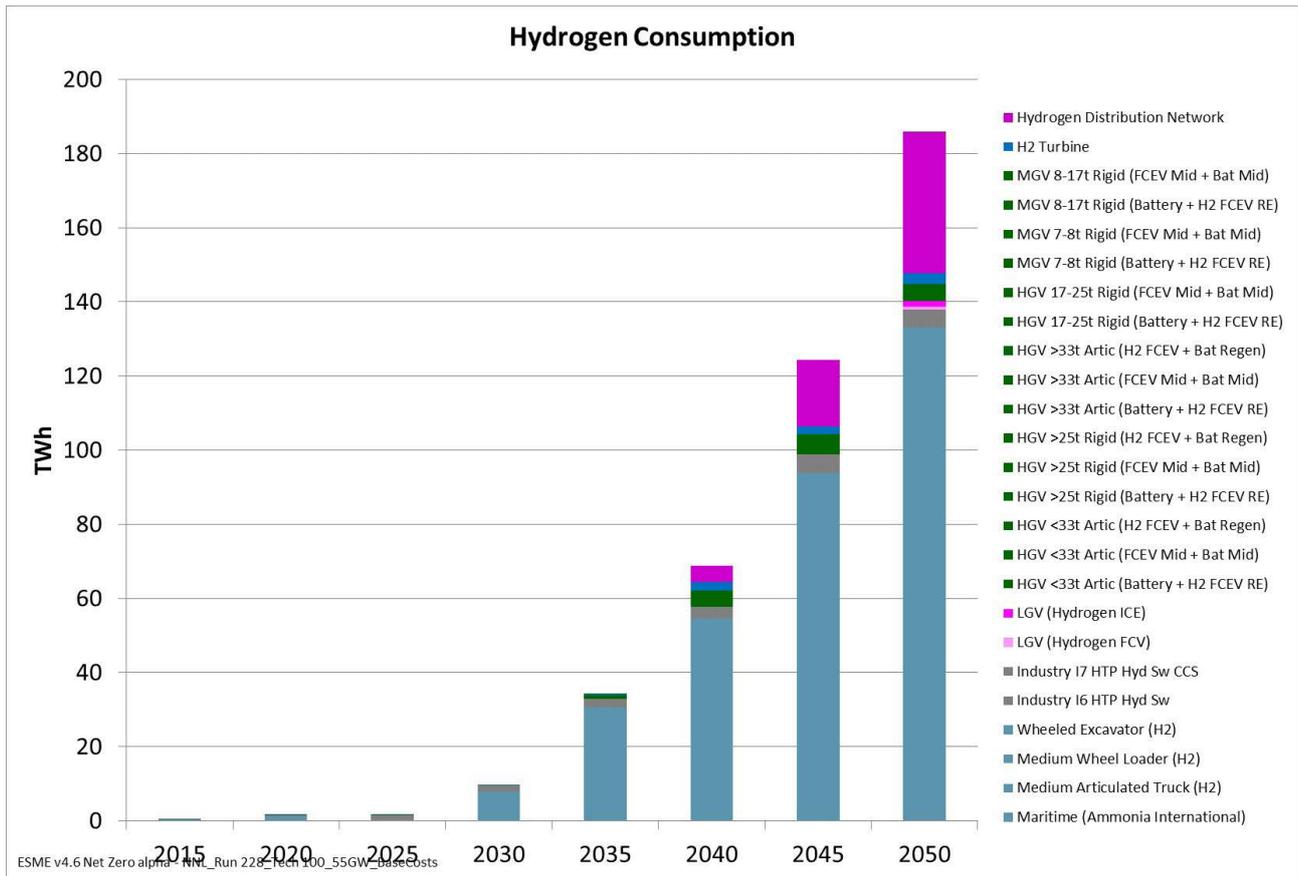
Figure 17 – Hydrogen consumption from Run 228 (TECH100)
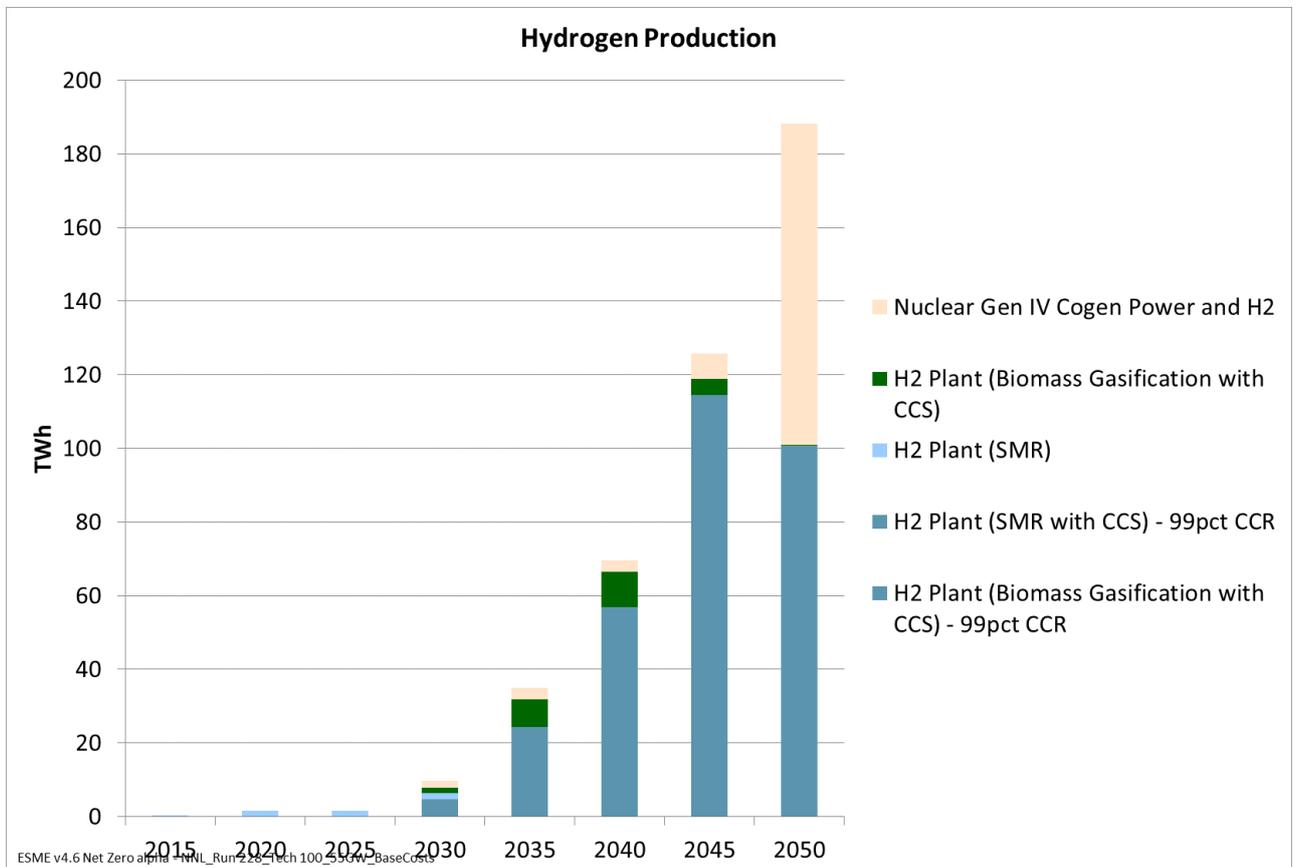
Figure 18 – Hydrogen production from Run 228 (TECH100)
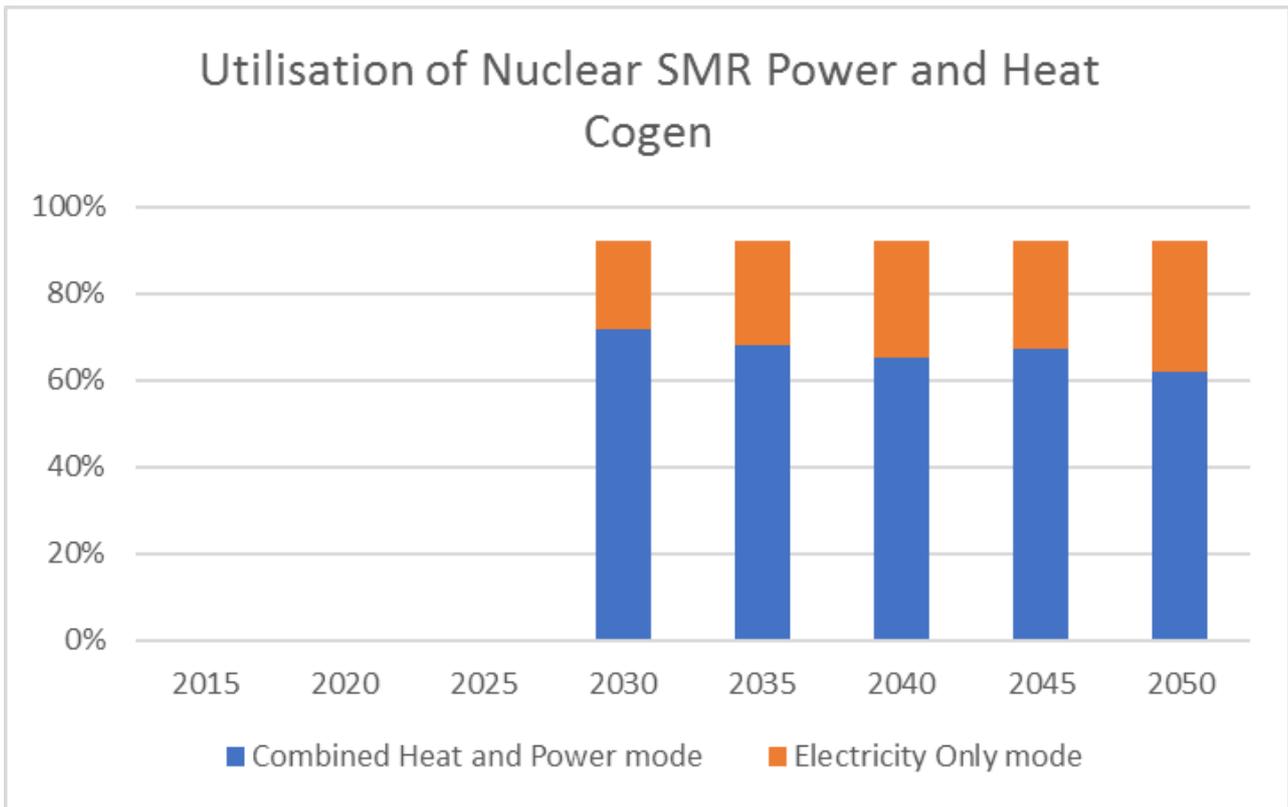
Figure 19 – LWSMR utilisation in 2050 from Run 228 (TECH100)
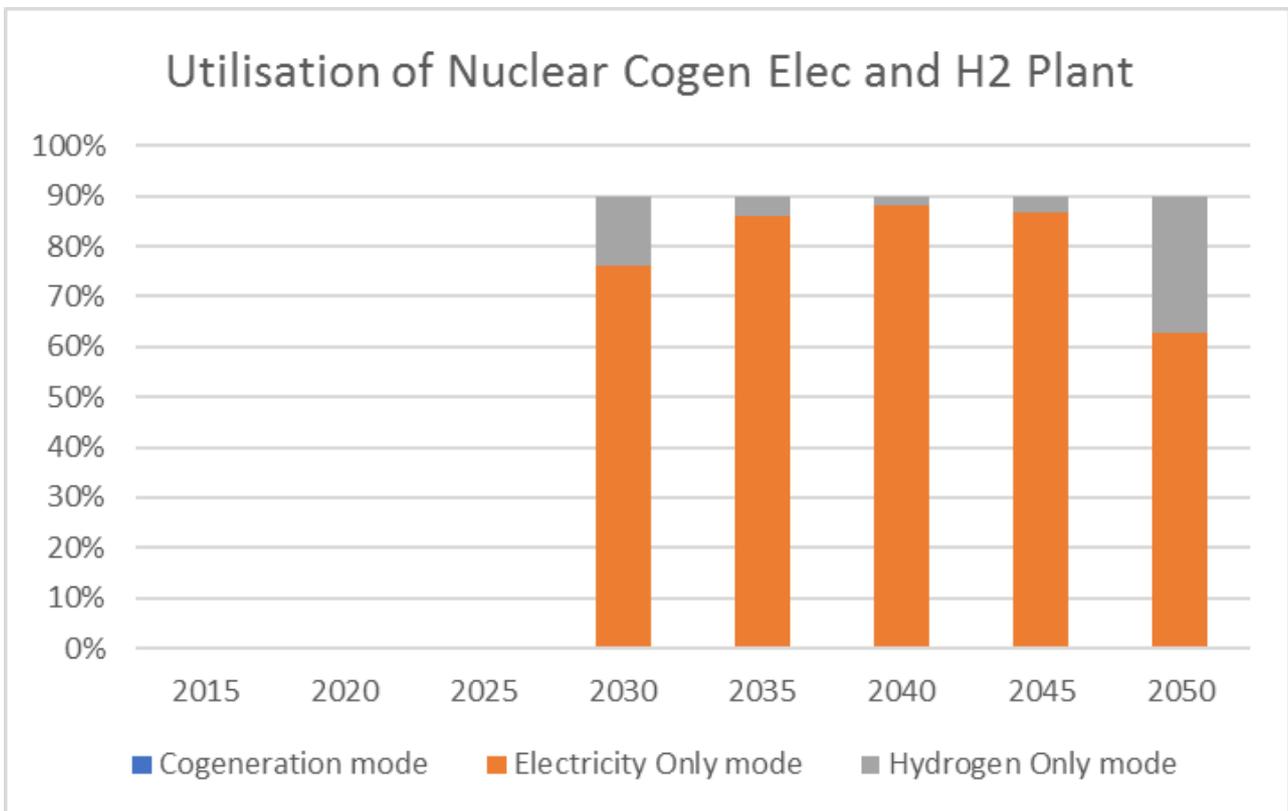
Figure 20 – Gen IV utilisation in 2050 from Run 228 (TECH100)

5.6. Probabilistic (Monte Carlo) assessment
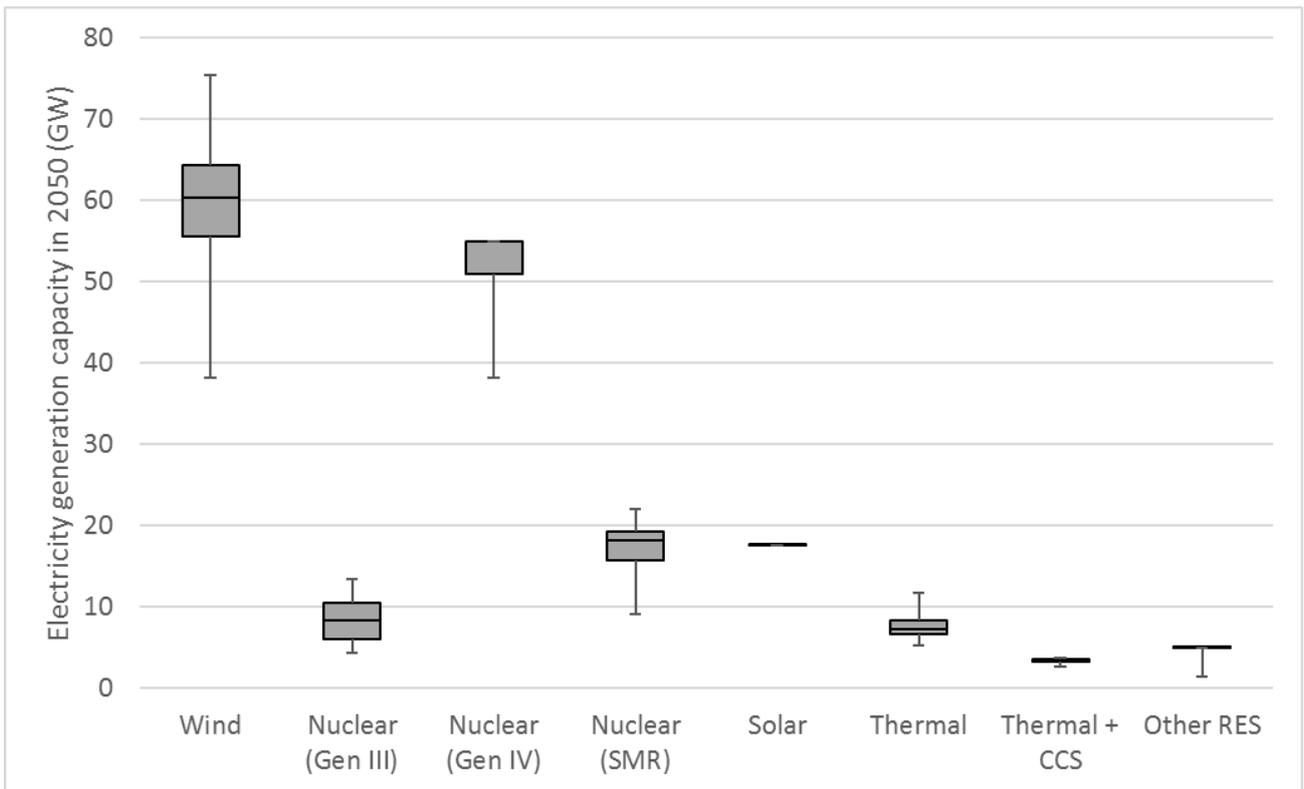
Figure 21 – Probabilistic (Monte Carlo) Run showing electricity generation capacity in 2050 – using TECH100 with nuclear technologies deployed in combination as per Run 228
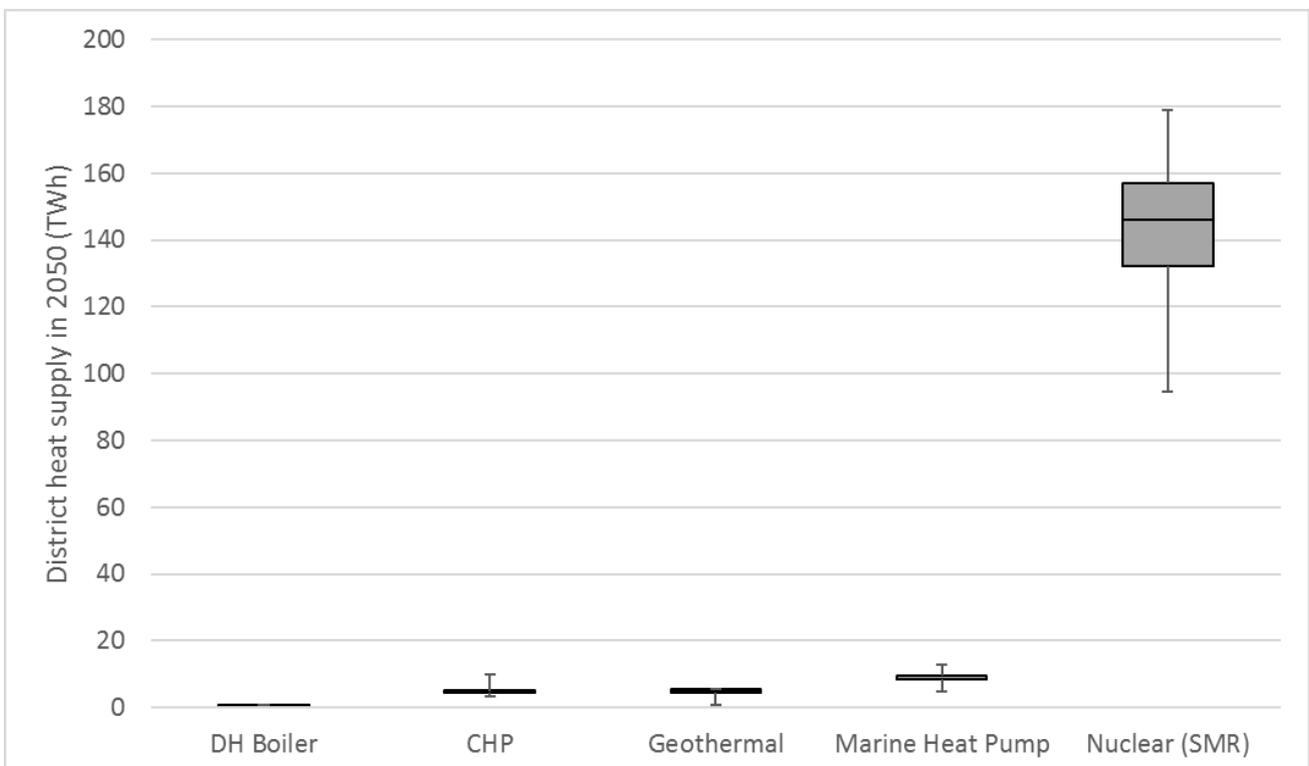
Figure 22 – Probabilistic (Monte Carlo) Run showing district heat supply in 2050 – using TECH100 with nuclear technologies deployed in combination as per Run 228
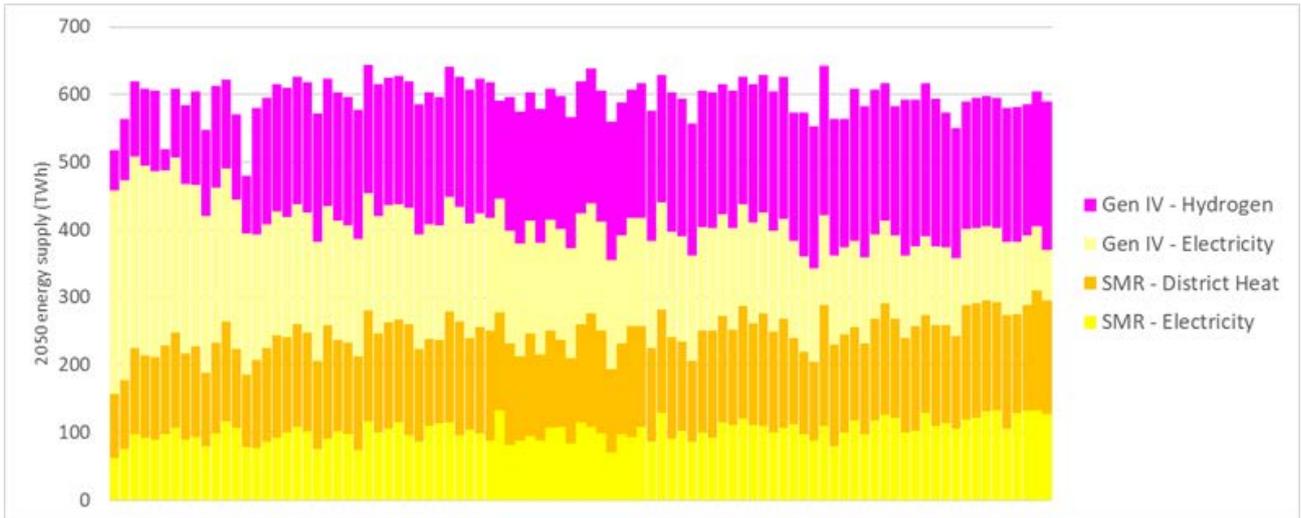
Figure 23 – Probabilistic (Monte Carlo) Run showing LWSMR electricity and heat supply together with Gen IV electricity and hydrogen production in 2050 – using TECH100 with nuclear technologies deployed in combination as per Run 228

6. Discussion

6.1. Electricity capacity and generation

Figures 6 and 7 show the electrical generating capacity and annual electricity generation in 2050 for a range of scenarios and a range of capex values for nuclear. These charts from the analysis supporting Supplementary Report No.2 can be compared with Figures 4 and 5 which are the equivalent charts from NFNZ. The comparison confirms some common features:

- Grid capacity at 2050 is typically around 140 GWe except for BOB100 where energy demand, electricity consumption and installed capacity is slightly lower, and in scenarios using higher nuclear capex values where there are more renewables and grid capacity is slightly higher

- Electricity generation values at 2050 are typically higher with FA96 scenarios compared with TECH100. This is because without the additional speculative technologies, emissions headroom is limited in FA96, allowing less hydrogen production with CCS technologies operating with 95% carbon capture rates. The balance of hydrogen production is from low temperature electrolysis using electricity from renewables. Total electricity generation in BOB100 is slightly lower, reflecting slightly lower demand

- Total nuclear deployed capacity from 42 to 66 GWe across the scenarios in Figures 4 and 6, and 2050 electricity generation 270 to 390 TWh across the same scenarios in Figures 5 and 7

- Deployment levels at 2050 of large Gen III+ are sensitive to the level of achievement of long-term cost reduction and the success in implementing the speculative technologies at the level of technical and cost performance assumed in the analysis. In FA96 without speculative technologies, electricity demand is higher and more hydrogen is produced via low temperature electrolysis. This combination sustains higher levels of large Gen III+ deployment. With the introduction of speculative technologies in the TECH100 scenario, continued large Gen III+ deployment beyond HPC only occurs with Runs 25a and 205 which use lower levels of capex for nuclear.

These trends are also evident in Run 228 with the associated electrical generation capacity and electricity generation charts shown in Figures 15 and 16 respectively.

6.2. Hydrogen consumption and supply

The 2050 hydrogen consumption and hydrogen supply charts for a range of scenarios from NFNZ are shown in Figures 8 and 9 respectively. These charts illustrate that in these runs the significant demand variable is the level of hydrogen consumption through the hydrogen network which will include uses for space heating and domestic hot water production. The supply variable is the balance between hydrogen from steam methane reformation with 99% Carbon Capture Rate (CCR) CCS and hydrogen from cogeneration Gen IV. In these runs there is no hydrogen supply from low temperature electrolysis or hydrogen production technologies with 95% CCR CCS.

Run 25a illustrates that with a lower capex for all nuclear, nuclear deployment increases with lower costs corresponding with a slightly lower demand in network hydrogen. Lower nuclear deployment costs also result in a small increase in nuclear share of hydrogen production.

Run 21 illustrates a scenario of no new nuclear deployment other than for hydrogen production. A shortfall in firm electricity demand shifts heating demand to the hydrogen network, but at the level of performance and costs assumed in Run 21, then hydrogen with 99% CCR CCS is the preferred source of hydrogen supply. When this analysis is repeated with lower capex values for nuclear in Run 22, some hydrogen production is displaced from technologies with 99% CCR CCS to Gen IV hydrogen production.

The runs for Supplementary Report No.2 for hydrogen consumption and supply in 2050 are shown in Figures 10 and 11 respectively. Runs 202, 205 and 228 together infer that the supply of hydrogen from Gen IV is limited by the Gen IV build-out rate. With the higher build out rate in Run 228, the volume of hydrogen production in 2050 is doubled in comparison with Runs 202 and 205.

Runs 230 and 231 were designed to explore the tipping point where the availability of high-volume low-cost hydrogen with low carbon footprint begins to drive the hydrogen economy rather than merely supply it. In Runs 230 and 231 system-wide DH deployment within ESME was switched off, Gen IV was deployed as hydrogen only, and LWSMR and large Gen III+ were available to meet system electrical generation demand if required. There are 3 learning points from this analysis:

- network hydrogen demand increased when district heating was unavailable as a vector for decarbonising space heating

- reducing the cost of hydrogen from nuclear resulted in a greater hydrogen supply from Gen IV and a corresponding reduction from hydrogen production technologies using 99% CCR CCS

- there may be a constraint in ESME limiting the growth in hydrogen demand that could otherwise have been expected when comparing Runs 230 and 231. This is to be explored further in Supplementary Report No.3.

Finally, in respect of hydrogen production, most runs show the two key technologies for hydrogen production are the group of technologies using 99% CCR CCS, and low-cost nuclear combined with the most cost-effective higher temperature hydrogen production process. In terms of reducing risk to the achievement of UK Net Zero by 2050, it could make sense to advance the development for commercial deployment of both of these technologies as a hedge that either technology may fail to fulfil its potential.

6.3. Energy supply to heat networks

The design of the sensitivity tests for Supplementary Report No.2 was described in section 3.2. The fifth group of tests was intended to explore the sensitivity of nuclear technology deployment to the scale of district heating deployment.

Figure 12 illustrates the nuclear 2050 contribution to energy supply from a range of scenarios. This chart shows the separate elements electricity generation, hot water supply to energise district heating networks, and hydrogen supply. The results in this chart can be compared with Figure 13 which show ESME runs with two changes consistently applied:

- LWSMR deployment as electricity only rather than cogen power and heat

- all district heating deployment within ESME disabled.

The comparison between Figures 12 and 13 shows some common features:

- the highest levels for nuclear energy supply in each chart are with FA96 scenarios, which excludes the more speculative technology solutions

- on a like-for-like scenario comparison with the corresponding scenario, when DH deployment is switched off and LWSMR deployed for electricity only, then overall electricity supply and hydrogen supply from nuclear increases

- scenarios of up to 22 GWe of Gen IV cogen deployment in Runs 221, 222, 201 and 202 can be compared with equivalent scenarios of up to 55 GWe of Gen IV cogen deployment in Runs 224, 225, 227 and 228. Where the availability of Gen IV is greater through a higher site capacity limit and a higher build-out rate, then more Gen IV is deployed for increased electricity and hydrogen production irrespective of DH deployment.

The ability to potentially energise city scale district heating networks with relatively low-grade heat represents an opportunity to use a "by-product" associated with energy production from nuclear. Consistent with the technical and cost assumptions for nuclear within this analysis, nuclear deployment levels remain high without the use of this nuclear "by-product". This point is also illustrated through Figure 14 with the common scenario of Hinkley Point C (HPC) plus Gen IV cogeneration deployment of up to 55 GWe at the higher build-out rate. The first three Runs 215, 217 and 219 are FA96 scenarios with base, lower and higher levels of capex respectively. The second three Runs 216, 218 and 220 are TECH100 scenarios with base, lower and higher levels of capex respectively. Figure 14 confirms the previously identified trend for Gen IV cogeneration in that operation for hydrogen production is more frequent in FA96 scenarios than for TECH100, but high levels of Gen IV cogeneration are commonly deployed across all scenarios.

6.4. Probabilistic (Monte Carlo) assessment

Deterministic Run 228 was selected as the basis for the probabilistic (Monte Carlo) analysis. Run 228 comprises with the following elements:

- All nuclear technologies available for deployment with base case values

- Large Gen III+ key parameters as defined in Table 2

- LWSMR deployed as cogeneration for flexible power and heat for district heat energisation with key parameters as defined in Table 3

- Gen IV deployed as cogeneration for flexible power and hydrogen production. Site capacity limit increased to 55 GWe and build-out rate increased to create the potential for 55 GWe deployment by 2050. Otherwise key parameters as defined in Table 4.

Deterministic Run 228 is listed in Annex 2 with a selection of ESME core output charts in Annex 3 at Figures A3-244 to A3-252. For ease of reference the charts for electrical generation capacity and generation are repeated in Figures 15 and 16, and hydrogen consumption and production in Figures 17 and 18. Additionally the utilisation charts for LWSMR cogeneration and Gen IV cogeneration are shown in Figures 19 and 20.

The Monte Carlo Run uses a spread on all nuclear technology capital costs of -25%/+40% applied to base capital costs across 100 simulations. The outputs are shown in Figures 21, 22 and 23.

Figure 22 confirms that LWSMRs remain the technology of choice for energising city-scale district heating systems but there is more statistical spread across levels of deployment.

Figure 21 re-confirms that wind is an important renewable technology for decarbonising power.

The category of Gen III+ deployment includes HPC (already committed) and Sizewell B (SZB) life extension (1.2 GWe expected to operate from 2035 to 2055); these two elements together deliver the minimum level of deployment shown in the output from the probabilistic analysis. But within the statistical variation within the simulations the median, 75% quartile and 100% distribution levels are 8, 10 and 14 GWe respectively, showing the potential for further Gen III+ construction beyond HPC until lower cost nuclear alternatives are available.

For LWSMR deployment levels remain close to the modelled site deployment constraint of 22 GWe but with some spread below 22 GWe.

Figure 23 presents a different visualisation of the probabilistic results showing 2050 energy supply from LWSMR and Gen IV across the 100 simulations. The simulations on the left of the chart are more like TECH100 (Run 202) which involve high volumes of Gen IV electricity: the simulations further to the right on the chart shows more like a 50:50 split between hydrogen and electricity production and thus a more balanced energy vector mix is deployed to displace the fossil-based systems.

Table 5 summarises the results from the Monte Carlo analysis reported in NFNZ. This can be compared with the results summarised for the Monte Carlo analysis reported in Section 5.6 and summarised in Table 6.

Table 5 – Selected key parameters from Monte Carlo analysis from NFNZ with cogen LWSMR deployed for district heating energisation

Statistical Distribution Level %	2050 Electrical Generation Capacity by Technology (GWe)			
	Wind	Gen III+	LWSMR Cogen CHP	Gen IV Cogen Power and H2
100	83	29	22	22
75	74	21	22	22
50 – median	69	17	22	22
25	64	14	22	22
0	38	4	18	22

Comparison between Tables 5 and 6 show a reduction in wind capacity of around 10 GWe at median, upper quartile and 100% levels. The detail within the probabilistic analysis indicates a corresponding reduction of around 6 GWe in hydrogen turbines, which are the dispatchable electrical generation technology to back up the intermittency of renewables. There is also a reduction of around 10 to 15 GWe in the higher levels of Gen III+ deployment.

For Gen IV, the combination of an earlier first operations date and raising the site capacity limit to 55 GWe with a matching build out rate results in consistent higher levels of deployment in the probabilistic analysis. This reflects the value of the nuclear technology dataset used to represent Gen IV:

- low-cost supply of electricity

- low-cost supply of hydrogen

- the ability to switch between energy vectors to complement electricity supply from renewables such that when margins are tight and prices high, then Gen IV plants will deliver electricity to the grid, and when margins are high are prices are low, then Gen IV plants will deliver hydrogen for use with the excess sent to store for inter-seasonal use.

Table 6 – Selected key parameters from Monte Carlo analysis with scenario inputs as per deterministic Run 228

Statistical Distribution Level %	2050 Electrical Generation Capacity by Technology (GWe)			
	Wind	Gen III+	LWSMR Cogen CHP	Gen IV Cogen Power and H2
100	76	14	22	55
75	64	10	19	55
50 – median	60	8	18	55
25	56	6	16	51
0	39	4	9	38

Overall, this probabilistic analysis still supports the approach described in NFNZ. An initial optimised programme of around 10 GWe of new Gen III+ capacity beyond HPC remains a decision of low or no regret provided construction duration and costs continue to reduce as predicted by the findings of the ETI Nuclear Cost Drivers project. This additional capacity can be expected to potentially commence operations between 2028 and 2035 if suitable projects are committed at the right time. Over the next 5 years, staged gated reviews of LWSMR and Gen IV development programmes would provide a clearer indication of the likelihood of realising the anticipated benefits from these two technologies. This additional understanding, accompanied by progress in the development of other low carbon energy technology programmes, would support further periodic policy reviews and decisions in the period 2025 to 2035 regarding policies for deployment of LWSMR, Gen IV, and the continued deployment of Gen III+ with reducing costs. Provided that costs continue to reduce for Gen III+, the deployment decision is not when to start but when to stop.

6.5. Nuclear deployment scenario 3 – Higher optimism

The Monte Carlo analysis has been built around Run 228 with the results summarised in Table 6.

To maintain transparency, it is simpler if each of the nuclear deployment scenarios is associated with a specific deterministic ESME Run. For this reason it is simpler if the constrained and base cases are now redefined to be associated with earlier NFNZ Runs for:

- Constrained – Run 5

- Base case – Run 26a

The redefined nuclear deployment scenarios are summarised in Table 7. Supplementary Report No.3 will inform and define the nuclear deployment scenario of Greater Nuclear Ambition.

Table 7 – Potential nuclear deployment scenarios with values shown at 2050

Nuclear Deployment Scenario (TECH100)	Overall Grid Capacity GWe	Gen III+ Installed Capacity GWe	LWSMR Cogen Power and Heat GWe	Gen IV Cogen Power & H_2 GWe	Nuclear Electricity Generation TWh	Nuclear Heat to DH Network TWh	H_2 Supply from Gen IV TWh	Total Nuclear Energy Supply TWh
No Nuclear (Run 3a)	203	0	0	0	0	0	0	0
Constrained (Developed from Run 5)	177	14	0	0	154	0	0	154
Base Case (Run 26a)	144	4	19	22	298	167	33	498
Higher Optimism (Run 228)	148	4	13	49	399	131	87	617
Greater Nuclear Ambition	Supplementary Report No.3							

7. Implications for markets, policy and regulation

7.1. Speed to commercial deployment and subsequent build-out

It is evident that advancing the first UK operations date for Gen IV from 2035 to 2030 combined with a higher build-out rate has a significant impact in the technology mix when considered from a perspective of technology and policy neutrality. This effect is more significant than the long-term ratcheting between technology groups through design innovation and anticipated cost reduction. A technology which addresses the two real needs of low-cost dispatchable electricity generation and low-cost hydrogen production is a genuinely new addition to the basket of new technologies potentially important in realising the transition to UK Net Zero by 2050.

This reinforces that if advanced nuclear technologies are to deliver a beneficial and significant impact in the transition to UK Net Zero then the stage gated development, demonstration and deployment of such technologies should be measured against criteria including:

- early UK commercial deployment

- early achievement of a sustainable drumbeat for manufacture, installation, commissioning and operation

- low installed cost with designs optimised to deliver this

- compatible with options for higher temperature and higher efficiency hydrogen production technologies.

From a policy perspective this stage-gated development needs to be progressed vigorously and urgently to support early commercial deployment.

7.2. Cost effective hydrogen supply

At a system level, the Gen IV cogeneration technology is attractive because of its low-cost electricity supply, its low-cost hydrogen supply and the potential to switch between these two vectors. In all the ESME runs in this and previous reports, hydrogen supply from nuclear has complemented other hydrogen supply technologies using 99% CCR CCS.

To minimise the cost of hydrogen supply from nuclear, it will be necessary to optimise both the plant design and how it is deployed. Learning from the ETI nuclear cost drivers project confirmed the economic benefits of installing multiple units per site with the following effects:

- reducing capex per unit by spreading site development and permitting costs across multiple units

- reducing capex per unit by spreading site infrastructure costs across multiple units, e.g. spent fuel storage and export facilities, training facilities, workshops etc.

- maximising site construction learner effect from multiple units per site

- reducing operating costs per unit with more units per site, e.g. multiple unit surveillance from a single control room, a dedicated local maintenance team for multiple units, and security staff and assets associated with fewer sites.

7.3. Low-cost electricity generation

To minimise the cost of electricity supply will require similar characteristics of multi-unit deployment per site as for low-cost hydrogen supply. This level of cost reduction is unlikely to be realised at sites with deployment of only 1 or 2 units per site.

7.4. Cogeneration or single vector energy supply?

The cogeneration nuclear technology variants modelled in this report (and previous reports NFNZ and Supplementary Report No.1) each incurred an additional capex increment of $500/kWe for this dual vector capability. If the nuclear technologies could be utilised close to their Design Capacity Factor within an energy system that requires output through a single energy vector, then this could have the potential to further reduce system costs, albeit with the loss of some flexibility.

Plants deployed for hydrogen production alone might first be deployed at locations with high levels of industrial demand for hydrogen. Subsequent plants could support hydrogen production for hydrogen turbines for peaking power generation, and continued growth in hydrogen supply and availability could enable the growth of a hydrogen network and national transmission system for use of hydrogen boilers for space heating and domestic hot water production.

More work is needed to better understand how increasing availability and reducing cost of hydrogen with a low carbon footprint would incrementally develop the growth of the hydrogen economy. This will be explored in Supplementary Report No.3.

Simplified dedicated plants for electricity generation would benefit from cost reduction and removal of the $500/kWe increment for cogeneration. The system effects should be explored to establish whether there are more cost-effective solutions for energy storage to address periods of potential over-supply from renewables, and periods when generation margins are tight in winter when it is dark with no wind. More work is needed on this element of optimisation.

7.5. Siting policy and designation of nuclear development sites

For ease of reference, section 9.6.5 from the NFNZ technical report is repeated below:

"The list of sites designated in NPS EN-6 is sufficient for a new nuclear build programme with a capacity cap of up to around 16 GWe, and UK Government has consulted on the potential process for updating NPS EN-6 for deployment from 2025 onwards of nuclear power with single reactor capacity greater than 1 GWe. These designations are relatively specific in terms of the size and type of nuclear power plants that can be built together with timescales for their development. Further policy work is needed should:

- the requirement for the number of sites change
- the timeframe for development change
- there be a change to the proposed type of nuclear technology to be deployed at one or more of these sites.

The summarised learning from the ETI's Power Plant Siting Study is that:

- the site capacity for large reactors in England and Wales is limited
- there is additional site capacity potentially suitable for smaller reactors which is unsuitable for GWe units.

If the scale of nuclear deployment and generation is to increase beyond historic levels, then a strategy for designating further sites will require consideration of the following:

- the hierarchy articulated in the Jackson report based on planning considerations of (1) existing nuclear generation sites, (2) other nuclear licensed sites, (3) brownfield sites and (4) greenfield sites

- the largest permissible generation capacity at a single site, which recognises system vulnerabilities from loss of generation due to localised external hazards e.g. weather or other natural events. Planned multi-unit development at a single site is demonstrated to be effective in accelerating cost reduction

- the expectation that all designs (GWe Gen III+, light-water SMR and Gen IV) will initially be deployed at "remote" sites consistent with existing siting policy. In effect this means adjacent to existing Magnox licensed sites

- the limited choices for deployment sites for GWe Gen III+ in England and Wales

- the benefits to reactor vendors and potential developers through clarity from UK Govt on two likely opposing policy options:

  - "disperse and embed"; applicable to future designs of around 300 MWe or less to enable energy to be created close to where it is needed

  - "Contain and distribute"; applicable to all designs where the intent is to minimise the number of licensed sites, but each site developed with multiple units per sites, and use distribution systems (power, heat and hydrogen) to deliver the energy to where it is required.

There is time to develop this strategic approach and framework to the next phase of nuclear siting consideration because the list of sites in the current version of NPS EN-6, subject to the addition of a new site adjacent to the existing decommissioning Magnox reactors at Trawsfynydd, is likely to be sufficient until around 2025. But it will be necessary to show that there is active policy development on further site designation to maintain investor confidence amongst vendors, developers and associated supply chains."

The judgement from this new analysis combined with the learning from the ETI NCD project is that accessing very low-costs is more challenging for deployment of just 1 or 2 units per site, particularly for advanced nuclear technologies. This is because indirect costs as a proportion of project Total Capital Cost would increase as direct costs associated with technology series production effects continue to reduce. These "one-off" site specific indirect costs include:

- Site licensing with associated consultation, site establishment and institutional control by a licensee

- Site preparation including surveys, groundworks and platform formation, local infrastructure improvements, and fuel route access for new fuel and export of spent fuel

- Installation and removal of temporary works and equipment associated with advanced modular construction

- Construction or installation of facilities for cooling (typically direct cooling with sea water or evaporative cooling away from the coast) or for power evacuation via a grid connection.

Similar arguments apply for operating costs. New technologies can be expected to be designed to minimise the requirements for frequent inspection or preventative maintenance. But a minimum level of plant support for operations and maintenance can be delivered more cost effectively across a site with multiple units than a site with just 1 or 2 units.

This judgement therefore suggests that deployment at sites with few units per site will be unable to access the low level of hydrogen or electricity costs associated with multiple units per site. At the same time, the social barriers associated with realising many but smaller nuclear licensed sites are probably more challenging than realising the development of fewer but larger nuclear licensed sites. Public engagement and consultation are more effectively directed towards locations where there is likely to be a system need for energy production and communities more likely to be open to considering the socio-economic benefits of long-term higher-skilled employment. Taken together, this suggests that a siting designation policy of "contain and distribute" as described above as a better policy choice than the alternative of "distribute and embed".

A policy of "contain and distribute" would translate into new nuclear deployment at three types of site:

- LWRs for electricity generation adjacent to existing nuclear sites

- HTGRs for electricity generation at sites either adjacent to existing nuclear sites or at brownfield locations which may or may not be suitable for LWRs

- HTGRs at sites where there is an industrial demand for high-temperature energy or hydrogen production which are probably unsuitable for LWRs.

HTGR technology benefits from the high temperature stability of the core, which should make it easier through consideration of siting policy to deploy HTGRs at locations less suitable for LWRs.

A suggested approach to designating future nuclear development sites would comprise:

- A number of locations in England and Wales are identified within the PPSS as meeting current siting criteria and capable of supporting multi-unit deployment (4 units per site). These locations are prioritised for near-term deployment of large Gen III+.

- Further locations identified in England and Wales are identified as expected to meet siting criteria either for large Gen III+ or LWSMR. These locations are either adjacent to existing nuclear licensed sites or at brownfield sites previously used for power generation. These are prioritised for HTGR deployment for electricity generation where capable of supporting multi-unit deployment (at least 4 units per site).

- Further locations in England and Wales are identified on the basis of industrial clusters with the need for high temperature heat of hydrogen to support the decarbonisation of current industrial activity, or to support the growth of new or replacement industrial activity. These are expected to be brownfield sites. Some locations may meet the existing siting criteria, but not all. HTGRs offer the potential for a level 3 Probabilistic Safety Analysis with negligible levels of off-site release. It would therefore be beneficial to Initiate a review of siting policy based on the design, demonstrated fuel integrity, and operating history of High Temperature Gas Reactors. Such a review should be led by Safety Regulators.

The development of such a siting approach requires further work over a number of years and would be subject to consultations both nationally led by Government regarding policy and locally led by developers for proposed projects as per the current NPS – EN6.

7.6. District heating deployment

The earlier discussion at sections 7.1 to 7.5 has little direct relevance to district heating deployment. The NFNZ report demonstrated that the economics of district heating deployment are largely dominated by building density and the cost of installing the associated pipework. In the ESME model runs reported in NFNZ, significant deployment of DH occurs even with the scenarios of no new nuclear.

The NFNZ report did illustrate that a nuclear plant which is in reasonably close proximity to a city scale DH system could provide a very low-cost supply of low carbon heat, provided that the cost of pipework to connect the plant to the network was not prohibitive.

It would make sense that all future nuclear plant, whether for the production of electricity, hydrogen or heat for industry, should be designed with the potential for future upgrade to enable the off-take of low grade heat for energisation of DH networks. The ETI Alternative Nuclear Technologies (ANT) project reports demonstrated that the cost of providing this future optionality was very low, provided that it was designed in at the time of initial plant construction.

More work would be needed to model this approach in ESME because this is very regionally-specific and better considered through the process of local area energy planning. The current approach of allocating an average cost associated with pipework installation to national level deployment of LWSMRs would no longer apply.

8. Conclusions

Context – the new analysis in this report delivers additional scenarios using revised nuclear technology datasets based on expert input from LucidCatalyst. The revised datasets are summarised in section 4 and detailed in Annex 1. The revised nuclear technology datasets incorporate:

- An increase in NOAK construction duration for Gen III+ from 5 years to 5.5 years
- A reduction in the NOAK cost for LWSMR with an increase in learner effect through to 2050
- An advance of the first UK operations date of a commercial HTGR from 2035 to 2030 with an increase in learner effect through to 2050.

The conclusions are as follows:

Conclusion 1 – lower costs for Gen IV and LWSMR and an earlier deployment date for Gen IV combine to increase deployment levels for both these technologies, with some reduction in deployment of Gen III+. Application of these revised base case nuclear technology parameters results in reductions in deployment of Gen III+ and increases in deployment of LWSMR and Gen IV within the site capacity limits and build out constraints. With base case values it is evident that the energy system is "under-supplied" with firm and mid-merit electricity to complement renewables.

Conclusion 2 – where a common nuclear heat supply system is deployed both as cogeneration of heat and power and cogeneration of power and hydrogen, the hydrogen variant is deployed at higher levels. The revised datasets bring LWSMR and Gen IV into alignment regarding costs and date of first UK operations. This alignment can be used to interpret the results as a common nuclear heat supply system being deployed in two separate configurations: cogeneration for flexible electricity generation and lower grade heat for DH energisation; and cogeneration for flexible electricity generation and hydrogen production. A group of scenarios were explored with raised site capacity limits and build out rate for Gen IV. In these deterministic runs the system was balancing and optimising with nuclear technology deployment within the applied site capacity limits (Run 228) and consistent with nuclear site capacity indicated by the ETI Power Plant Siting Study. Levels of technology deployment for cogeneration for hydrogen production were higher than for cogeneration for DH energisation.

Conclusion 3 – for the nuclear data assumed in this analysis, levels of nuclear deployment were consistently significant, independent of whether heat networks were widely deployed at city-scale, or whether heat networks were supplied with nuclear heat. A group of scenarios were explored to test the impact of a policy decision not to support the widespread deployment of city-scale district heating systems. The net effect is that space heating requirements are delivered through other technologies and vectors including increased deployment of heat pumps, direct resistive heating and use of the hydrogen network. Levels of nuclear deployment remained resilient in these scenarios, with nuclear technologies contributing to the increased demand for electricity generation and hydrogen supply. The purpose of this group of scenarios was to test the reliance of nuclear deployment, rather than to actively explore a policy choice regarding DH deployment. Locations of high building density and occupancy are economically favourable for DH deployment; the uncertainty is the extent to which these heat networks might grow.

Conclusion 4 – minimising the capital and operating costs for nuclear is expected to involve multi-unit deployment at each site; this should be a consideration for siting policy and the future designation of sites. To access the low levels of cost used in this analysis relies on cost reduction strategies identified in the ETI Nuclear Cost Drivers report. These include multiple-unit deployment (4 or more) per site to minimise both capex and operating costs. This approach is not consistent

with a nuclear siting approach of "disperse and embed" which equates to a large number of nuclear licensed sites with relatively few units per site. Delivering lower costs is consistent with a nuclear siting approach of "contain and distribute" with higher levels of nuclear deployment at fewer sites.

Conclusion 5 – a siting approach with fewer sites and more units per site is consistent with the initial exploitation of nuclear new build locations adjacent to existing nuclear licensed sites.
A siting approach of "contain and distribute" could be combined with nuclear sites of up to 5 GWe (or equivalent for hydrogen production) comprising:

- Large Gen III+ electricity generation plants at sites adjacent to existing nuclear licensed sites

- Gen IV electricity generating plants either at sites adjacent to existing nuclear licensed sites or at locations not traditionally associated with nuclear energy

- Gen IV heat supply and hydrogen production plants at locations not traditionally associated with nuclear energy where there is a socio-economic pull for energy supply associated with industrial use of heat or hydrogen.

Conclusion 6 – reactor deployment at industrial brownfield sites in locations of heat and hydrogen demand may require the review and development of current siting policy; this pathway may be easier for safety and environmental regulators for High Temperature Gas Reactors than for light-water reactors.
The High Temperature Gas Reactor genre, as a Gen IV nuclear heat supply technology, is a potentially valuable technology. The relatively high nuclear cycle temperature is a good combination with higher temperature and more efficient hydrogen production technologies. The structural resilience and integrity of the reactor core through high temperature abnormal transient conditions create the expectation that it would be simpler and easier for safety regulators to support development of UK reactor siting policy with HTGRs than for light-water reactor technologies.

Conclusion 7 – A new nuclear deployment scenario of "higher optimism" has been defined, and the deployment scenarios for "constrained" and "base case" have been updated.
The analysis in Supplementary Report No.2 supports the definition of nuclear deployment scenario of "higher nuclear optimism". This is based on deterministic Run 228. The two previously defined nuclear deployment scenarios of "policy constrained" and "base case" have been updated:

- No new nuclear – zero

- Constrained – 154 TWh per annum by 2050

- Base case – 498 TWh per annum by 2050

- Higher optimism – 617 TWh per annum by 2050

- Greater nuclear ambition – to be defined through Supplementary Report No.3.

Conclusion 8 – the suggested approach previously identified in the NFNZ report of an initial Gen III+ programme alongside stage-gated development programmes for LWSMR and Gen IV is further supported by the analysis in Supplementary Report No.2.
The probabilistic (Monte Carlo) analysis associated with deterministic Run 228 further demonstrated the resilience in deployment of Gen IV reactor technology. This should be interpreted as illustrating the system value of a low-cost technology capable of delivering dispatchable low carbon electricity or hydrogen alongside energy from wind. The probabilistic analysis also continues to support the approach described in the NFNZ report:

- Commit to an intentional programme of around 10 GWe beyond HPC

- Launch a stage-gated development and deployment programme for UK deployment of LWSMR technology

- Launch a parallel stage-gated development, demonstration and deployment programme for HTGR technology

- With regular reviews in the period 2025 to 2035, and informed by the ongoing development and deployment of other low carbon technologies, then review and update optimised planned deployment levels of Gen III+, LWSMR and Gen IV in the UK transition to Net Zero

- The decision for large Gen III+ is not when to start, but when to stop.

Conclusion 9 – the High Temperature Gas Reactor technology has many advantages amongst the family of advanced nuclear technologies which makes it a god choice for UK Gen IV development.
The ESME analysis using the Gen IV technology dataset is blind to the particular type of Nuclear Heat Supply System, but parallel technical assessment suggests that this is most likely to be a High Temperature Gas Reactor because of the simpler design, fewer components and fewer safety systems compared with Gen III+. It is also the technology with significant development and operating experience and closest to commercial deployment amongst the Gen IV group or reactor technologies. Because of the high temperature structural resilience and integrity of the core, the route to developing UK long term reactor siting policy will probably be easier for HTGRs than for light-water reactors.

9. Acronyms

AFCP	Advanced Fuel Cycle Programme
ANT	Alternative Nuclear Technologies (Project)
BOB100	Best of Both ESME Scenario designed to achieve 100% decarbonisation based on the combination of TECH100 and SOC100
CCR	Carbon Capture Rate – typically associated with CCS
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DH	District Heat (System)
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment (a whole energy system model)
ETI	Energy Technologies Institute
FA96	Further Ambition 96 (% decarbonisation scenario)
FOAK	First of a Kind
Gen III+	Generation III+ nuclear reactor
Gen IV	Generation IV nuclear reactor
GWe	Giga-Watt electric
HPC	Hinkley Point C Project
HTGR	High Temperature Gas Reactor
IUK WP7	Innovate UK Work Package 7 (of the Energy Technologies Benchmarking Project)
LWR	Light-Water Reactor
LWSMR	Light-Water (Nuclear) Small Modular Reactor
MPR	Market, Policy and Regulatory (considerations)
MWe	Mega Watt electrical
NCD	ETI's Nuclear Cost Drivers project
NFNZ	Nuclear For Net Zero
NNL	National Nuclear Laboratory
NOAK	N'th of a Kind
NPS	National Policy Statement
PPSS	The ETI's Power Plant Siting Study
SOC100	ESME scenario designed to achieve 100% decarbonisation using speculative changes in societal behaviour which reduce or restrict the growth of emissions
SZB	Sizewell B nuclear power station
TECH100	ESME Scenario designed to achieve 100% decarbonisation using speculative technologies
TWh	Terra Watt hour

10. Annexes

Annex 1   Revised datasets for Supplementary Report No.2

Annex 2   List of ESME sensitivity runs

Annex 3   Selected ESME core chart outputs

Annex 1 – Revised datasets for Supplementary Report No.2

This Annex has been carried forward from the ESC Nuclear for Net Zero report. The nuclear technology datasets have been updated with expert input from LucidCatalyst. Where narrative has been added by LucidCatalyst to support these changes, this additional narrative is show in bold font.

Cost conversion

Costs are shown here in 2017 dollars for consistency with the reporting cost base of the Nuclear Cost Drivers study. The price base for ESME is 2010 pounds. The combined conversion rate $2017 to £2010 applied is 0.665.

Gen III+ light water reactor contemporary designs for power generation

ESME data set; large contemporary Gen III+ for power generation. Assumptions:

- First operations date 2025

- Construction period 5.5 years from 2025

- Technical and economic life of 60 years

- Design capacity factor 92%

- Site capacity limit 35 GWe with distribution as currently embedded in ESME

- Roll out rate 1.4 GW/yr equivalent to two sites developed in parallel. If there is a need for sensitivity runs:

  - Reduce to 0.7 GWe/yr which is equivalent to series construction, ie there isn't a second site or technology being deployed in parallel

  - Increase to 2.1 GWe/yr which is equivalent to three concurrent construction sites at a time (and perhaps 3 different technologies in the UK).

- Overnight NOAK capex:

- $4500/kWe ($2017) at 2025 reducing to $4000/kWe ($2017) by 2050 (BASE).

- Sensitivity runs:

  - Higher costs. $5500/kWe ($2017) at 2035 reducing to $5000/kWe ($2017) by 2050 (PESS).

  - Lower costs. $4000/kWe ($2017) at 2035 reducing to $3500 /kWe ($2017) by 2050 (OPT)

- Opex 2017 dollars:

  - Fixed OPEX to 2050 excluding fuel and waste – $101/kW-year

  - Variable OPEX to 2050 excluding fuel and waste – $2.32/MWh

  - Fuel and associated disposal cost to 2050 – $10/MWeh

First operations date

This is benchmarked by unit 1 of Hinkley Point C.

Construction period

The construction period for Gen III+ LWRs in the UK would depend on several factors, especially the plant design that would be built and the construction techniques that would be used. LucidCatalyst specified three construction period parameters for the BASE, OPTIMISTIC, and PESSIMISTIC scenarios to reflect the possible ranges for these key factors. The range of construction periods in this analysis mirrors the historical observed range of nuclear projects around the world.

For the BASE scenario, LucidCatalyst specified a construction period of 5.5 years, a somewhat longer time than the IUK WP7 value of 5 years. The updated parameter reflects the 'middle-of-the-road' experience among recent nuclear projects, such as the four units at the Barakah plant in the United Arab Emirates[4]. These units use the Korean APR-1400 design and are being built by a vendor consortium with extensive experience constructing plants in Korea. The UAE project benefits from unit-to-unit learning effects but is the first experience with the APR-1400 (or any other nuclear plant) in the country. An LWR project in the UK could have a similar construction period for a first-in-country plant design and conventional construction techniques. The BASE period of 5.5 years corresponds to average cost driver score of -1.0 from ETI NCD study.

For the OPTIMISTIC scenario, LucidCatalyst retained the IUK WP7 parameter of 4.5 years. This period reflects the fastest nuclear projects in global historical experience, such as the ABWRs in Japan in the 1990's and various plant designs in China from the 1980's to the 2000's[5]. This shorter period also mirrors the 'best experience' case from the US Energy Economic Data Base, which represented the subset of fast and low-cost US projects in the 1970's and 1980's[6]. The shorter construction period in this scenario can occur in the UK through effective use of modularity and design-for-manufacturing. Innovative construction techniques can also hasten progress, such as advanced concrete and other materials, virtual reality practice and wearable technologies for work crews, and automation of inspection and qualification[7]. Achieving this scenario's shorter period in the UK would require following the best practices identified in the ETI NCD study, including design completion before construction start and collaborative interactions with regulators, as in the Sizewell B project in the early 1990s[8].

For the PESSIMISTIC scenario, LucidCatalyst specified a construction period of 7 years, a shorter time than the IUK WP7 value of 8 years. This scenario reflects the long experiences among recent projects in Europe and the US. The EPR projects in Finland and France began in 2005 and 2007, respectively, and the two AP-1000 units in Georgia (US) began in 2013. As a group, these European and US projects have an average period over 10 years, but the assumption for this scenario is not as long because future UK LWRs could presumably learn from Hinkley Point C and other projects to avoid such adverse outcomes. Moreover, this modelling exercise out to 2050 should provide ample time for UK plants to enhance productivity and adopt best practices. Nevertheless, factors that could lead to long projects in the UK include first-in-country plant designs and conventional stick-built construction practices without the innovative techniques and best practices outlined above.

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4   UAE nuclear energy unit 1 construction completed. Trade Arabia. 26th March 2018.
     http://www.tradearabia.com/news/CONS_338321.html

5   International Atomic Energy Agency's Power Reactor Information System.
     https://pris.iaea.org/PRIS/home.aspx

6   US Energy Economic Data Base. 1986. https://www.osti.gov/biblio/6927146/

7   Dominion Engineering and LucidCatalyst for the Electric Power Research Institute. Advanced Nuclear Technology:
     Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction. 2019.
     https://www.epri.com/#/pages/product/000000003002015935/?lang=en-US

8   ETI NCD study. 2017.
     https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf

Technical and economic life

Many Gen II and Gen III reactors were designed for an initial technical life of 40 years. Most Gen III+ reactors are now designed for and technical and economic life of 60 years.

Several power plants in the US have received multiple life extensions and a number of reactors are already licensed for 80 years of operation, as reported by World Nuclear News[9].

Design capacity factor

The design capacity factor for many Gen III+ designs is around 92%. This reflects operating experience feedback on factors influencing unscheduled outages from existing operating reactors into current designs. Achieving this level of load factor depends on two factors:

- The operator maintaining this level of plant availability through well managed outages for refuelling operations, scheduled maintenance and safety case related inspections
- The electricity grid demand and management such that the plant can continuously run at design load

The latter factor will be indicated through ESME scenario modelling to show how closed the modelled load factor comes to the design capacity factor.

The former factor is influenced by outage management, avoidance on unplanned reactor trips, the regulatory requirement for any additional safety inspections, and to an extent any particular regulatory requirements related to the sequencing and hold points in a refuelling outage which may influence its duration. This is not the same for all reactor designs with refuelling process differences between BWRs and PWRs. The UK Advanced Gas-cooled Reactors (AGRs) were designed for refuelling on-line.

As the AGR fleet is now well into its life-extension programme, the inspection requirements have increased particularly for the known life limiting components and systems. This has had the effect of reducing the reported load factor.

Despite an ageing US reactor fleet, the industry achieved an average capacity factor of 92.6%[10] in 2018. Newer light-water reactors with improved design should be capable of matching this performance.

Capacity limit

This is derived from the ETI PPSS and reflects an upper bound of around 35 GWe based on the use of locations adjacent to existing licensed sites, and additional brownfield and greenfield sites which met the criteria. This capacity limit reflects reactors deployed in pairs (or potentially singly) to reflect developer proposals made through the Strategic Siting Assessment process managed by UK Government.

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9   Second US plant licensed for 80 year operation. World Nuclear News 9th March 2020.
    https://www.world-nuclear-news.org/Articles/Second-US-plant-licensed-for-80-year-operation

10 US nuclear generation peaked in 2018, says IEA. World Nuclear News 22nd March 2019.
    https://www.world-nuclear-news.org/Articles/US-nuclear-generation-peaked-in-2018-EIA reflect developer proposals made through the Strategic Siting Assessment process managed by UK Government

Other scenarios could influence the increase or decrease of this upper bound site capacity limit for the UK. Multi-unit deployment (more than 2 reactors per site) is an established approach to reduce the average capital cost per unit. Four units on a single site delivers lower average costs than two twin reactors deployed on separate site. Recent experience from Barakah as reported in the ETI NCD project is a demonstration of how effective this approach is in reducing costs. As well as absorbing site related fixed costs across more units, the continuous workflow from unit to unit with the same supply chain and workforce reveals a substantial site related learner effect. More policy work is needed in this area.

Roll out rate

There are underlying assumptions supporting the roll out rates:

- Within a nuclear deployment programme one of the key factors is the ability of the supply chain to sustain construction operations associated with projects at a scale of nationally significant infrastructure. A single supply chain can support a sequence of twin reactor construction at a first site and then demobilises to support construction at a subsequent site. This drumbeat broadly equates to a new reactor being subsequently connected to the grid every two years.

- A second supply chain associated with a second developer could operate in the same way with a combined drumbeat of a new reactor being connected to the grid every year.

- In 2018 when EDF, CGN, NuGen and Horizon all had active development plans, the scheduling of their plans combined with associated reactor generating capacity was averaged to yield a connection rate of 1.4 GWe/year. This is the logic for the BASE roll out rate.

- Lower, base and higher roll out rates relate to 1, 2, or 3 concurrent developer supply chains.

In the UK, the AGR plants were developed by the CEGB in pairs apart from the lead plant at Dungeness B. Each AGR is a twin reactor unit. Although the scale of contemporary light-water reactors is bigger than the UK AGRs, there is a precedent in the UK of two supply chains supporting concurrent construction at two locations in the UK.

Capex

The BASE capex rate is set at $4500 /kWe ($2017) at 2025 reducing to $4000/kWe ($2017) by 2050. The root assumption for this is that following an optimised programme of deployment the supply chain in the UK could deliver NOAK reactor plants with an average cost driver score of minus 1.0. The chart extracted from the ETI NCD summary report equates this with an overnight capital cost value of $4386/kWe.

The experience at Sizewell B with Nuclear Electric's plans for follow on units at the same site suggest that this is not an overly optimistic assumption, although multi-unit deployment at a single site with its accelerated rate of cost reduction should be better considered in terms of a site average. A subsequent site in a multi-site development programme could be expected to yield a lower average cost per unit, but the costs for unit 1 at this next site should be expected to be higher than last unit at the previous site. This is because there are site costs to be repeated at each site associated with achieving a Development Consent Order and supply chain mobilisation.

The ETI NCD project is built with a reference benchmark of the US median experience referenced from the US EEDB database version VIII. A later and final version of this database included a subset of data for "better experience" in delivery plants. There is a summary description of the background to this better experience data in section 2.3 of a PhD thesis report[11] by Robbie Lyons and recently published by Cambridge University. When brought to the common benchmark of ETI NCD data by converting

to 2017 dollars and using an interest rate of 7%, the Total Capital Cost (TCC) of the median of $6780/kWe falls to $3951/kWe from the better experience data in EEDB version IX. This equates to an average cost driver score of below minus 1.0.

A modest long-term learner rate is applied. This is consistent with the research by Lovering[12] published in 2016 which identified that for a stable long- term construction programme evidenced by experience in Korea could yield an annual cost reduction factor of 2%

For other reference points it is useful to note that the World Nuclear News identified an EDF estimate from July 2019 that construction of a further 6 EPR units in France would cost $51Bn, equivalent to a specific capex of $5150/kWe. This cost is an average across 6 units and therefore does not reveal the cost of the sixth unit on the downward trajectory towards NOAK.

The optimistic capex cost draws on the US EEDB version IX data for the group of US nuclear construction projects with the 'better experience' (mentioned above). The pessimistic cost, by contrast, draws on the group of projects with the 'median experience'. The pessimistic case also reflects fewer units per plant site and minimal learner effects.

Opex

Opex data is based on earlier ESME version values and benchmarked with data from the ETI NCD database.

Light water SMRs for power generation and/or cogeneration of power and DH energisation

ESME data Set; LWR SMRs for flexible cogeneration of power and heat for district heating energisation. Assumptions:

- First operations date 2030 (BASE)

- Construction period 4 years

- Technical and economic life of 60 years

- Design capacity factor 92%

- Site capacity limit 22 GWe with distribution as currently embedded in ESME

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11 The effect of supply chain configuration on small modular reactor economics. PhD thesis by Robbie Lyons at Cambridge University dated September 2019.
https://www.repository.cam.ac.uk/handle/1810/302392

12 Historical construction costs of global nuclear power reactors. Jessica Lovering et al. 2nd February 2016.
https://www.researchgate.net/profile/Jessica_Lovering/publication/292964046_Historical_construction_costs_of_global_nuclear_power_reactors/links/56cf5bce08ae85c82344a585/Historical-construction-costs-of-global-nuclear-power-reactors.pdf?origin=publication_detail

- Roll out rate 1.2 GWe/yr (BASE) from 2030 (equivalent to four 300 MWe units per year). If there is a need for sensitivity runs:
  - Reduce to 0.6 GWe/yr (PESS) which is equivalent to two units per year
  - Increase to 2.7 GWe/yr (OPT) which is equivalent to nine units per year with concurrent deployment at two sites at time.
- Overnight NOAK capex (includes $500/kWe for CoGen which could be removed for electricity only deployment):
  - $4000/kWe ($2017) at 2030 reducing to $3000/kWe ($2017) by 2050 (BASE).
  - Sensitivity runs:
    - Higher costs. $5000/kWe ($2017) at 2035 (first operations date) reducing to $4000/kWe ($2017) by 2050 (PESS).
    - Lower costs. $3000/kWe ($2017) at 2028 (first operations date) reducing to $2000 /kWe ($2017) by 2050 (OPT)
- Opex 2017 dollars:
  - Fixed OPEX to 2050 excluding fuel and waste – $152/kW-year
  - Variable OPEX to 2050 excluding fuel and waste – $2.32/MWh
  - Fuel and associated disposal cost to 2050 – $7/MWeh

For light water SMRs additional data was provided for extracting heat at 98 deg C for district heating energisation including upgrade to a plant designed "for but not with" this capability. The upgrade included plant pipework and a representative distance of long-distance pipe for connecting a plant at a typical distance from a conurbation to a district heating ring main. Costs include notional additional increment of $500/kWe for steam extract piping, heat exchangers and countryside "cut and cover" pipe run of 10 km to connect to a DH ring main or spur. Periods of extracting heat are associated with a simultaneous power down rate of around 20% at maximum steam extraction.

First operations date

2030 as a first operations date for the base case remains consistent with the ETI reports from ANT phase 2 and the SDE project. Government facilitation through an enabling policy framework and associated actions is the minimum necessary to realise this date. In parallel this is consistent with a first UK operations date of 2028 being forecast by the UK SMR consortium.

NuScale is forecasting[13] operation of its FOAK modular PWR design in 2026 at the site of the Idaho National Laboratory as part of the UAMPS carbon free project.

Another emerging design is GE's BWRX-300 which a 300 MWe boiling water reactor. This is one of the technologies being considered in an SMR study[14] for potential deployment in Estonia with a 2030 deployment horizon.

The optimistic case uses 2028 as the potential date of first operations in line with the UK SMR consortium. The pessimistic case uses 2035 to represent a possible longer period until first deployment.

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13 NuScale's website at 22nd March 2020. https://www.nuscalepower.com/Projects/Current-Projects/United-States

Construction period

LucidCatalyst specified 4 years as the construction period for LW SMRs for the BASE scenario, 3 years for the OPTIMISTIC scenario, and 5 years for the PESSIMISTIC scenario. This range of potential construction periods reflects various approaches to SMR designs and delivery. For example, some SMR designs are being intentionally optimized for streamlined construction. Some SMRs are similar to conventional nuclear plants at smaller scale, with relatively long construction through conventional stick-built construction. Other SMRs are fully modular and could be installed quickly after arriving at the site via rail or lorry. The GEH BWRX-300 planning team is aiming for 3 years (mirrored in the OPTIMISTIC scenario) through simplified plant systems with fewer parts, pre-packaged tools and pieces for each day's shift (similar to IKEA assembly kits in plastic bags), and fully integrated project management schemes to minimise delays. In addition, SMR construction period depends on greenfield or brownfield site and number of units per site, as well as sequential or simultaneous build programme. Relative to the IUK WP7 study, LucidCatalyst has extended the construction periods for the BASE and PESSIMISTIC scenarios for realism because plant construction as fast as the BWRX-300 goal have not yet been demonstrated in the UK or elsewhere in the world.

Plant Life and capacity factor

As large Gen III+.

Site capacity limit

If light-water nuclear SMRs are deployed in the UK for the purpose of Cogen and district heating energisation, the majority of plants need to be at sites closer to centres of heat demand than the UK's existing licensed sites. The majority would be deployed at brownfield or greenfield sites which could only be enabled by associated policy action. The ETI PPSS phases 1 and 2 was designed to address this issue and through the "twice-over" analysis demonstrates a diversity of locations necessary to delivers 22 GWe of capacity equivalent to 40 GWth of district heating energisation.

To test a scenario with no deployment of Gen III+, the site capacity limit nominally allocated to large Gen III+ can be reallocated to LWSMRs in addition to the SMR only site capacity from the "twice-over" analysis. This is the basis of the SMR electricity only site capacity limit of 55 GWe.

Roll out rate

Vendor forecasts of roll out rate must be considered with caution; such forecasts need to be market led. With a first operations date of 2030, a roll out rate of just under 1.2 GWe per year can deliver 22 GWe by 2050. This is the basis for the roll out rate. It is the equivalent of connecting 4 units per year of nominal capacity of 300 MWe. For multi-unit construction per site with much of the assembly and integration taking place in bespoke factories, this assumption is not unreasonable.

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14 Vattenfall involved in Estonian study on SMRs. World Nuclear News 19th March 2020.
    https://www.world-nuclear-news.org/Articles/Vattenfall-involved-in-Estonian-study-on-SMRs

Using the same methodology, the roll out rate for 55 GWe of electricity only operations would be just over 2.7 GWe per year. For 300 MWe units this is 9 per year or one reactor connected to the grid every 6 weeks. Such a scenario might involve more than one design and associated modular manufacturing eco-system. Deployment would be concurrent on multiple sites.

Capex

The approach in the ANT project was to establish the value for an economically viable specific capex. For electricity only applications this was derived at around £3,600/kWe (around $4,700/kWe). With a CHP or Cogen SMR, the value attributed to potential sales indicated that a higher capex could be economically sustainable at £6,500/kWe, or reducing to £5,000/kWe (around $6,500/kWe) if more pessimistic assumptions were used.

The equivalent capex figure in the ETI NCD cost driver model for light-water SMR electricity only operations is around $4,500/kWe.

In a Bloomberg article dated 6th December 2019, the Rolls-Royce CEO was reported as giving a brief to the Aviation Club in London. The plan described in this brief involved 16 reactors at sites adjacent to existing UK nuclear licensed sites. This deployment would be delivered between 2030 and 2050 at a cost of $2.4 Bn/plant. This would comprise a programme of around 8 GWe. With a plant electrical output in the range 400 to 450 MWe, and assuming these are overnight capex estimates rather than Total Capital Cost including financing, this infers a specific capex in the range $5300 to $6000/kWe. The Bloomberg article also refers to R-R's interest in co-locating the power plants with synthetic fuel plants as a means of producing carbon-neutral synthetic fuel for the aviation industry.

It is noteworthy that the M-Power SMR progressed no further with the realisation that its design was unlikely to yield overnight capex costs of less than $5,000/kWe.

NuScale's website[15] projects a FOAK capex of $3Bn. For a net power output of 684 MWe this is equivalent to a specific capex for FOAK at $4,385/kWe.

GE's cost reduction target for its BWRX-300 boiling water reactor is more ambitious than the ETI NCD cost model datapoint, given the recognition that its product must be commercially attractive to developers in a financially tough US electricity market. GE's cost estimate is awaited, along with a credible design and deployment story to support their cost projection.

With ESME application of light-water SMRs for cogeneration, the capex figure used in ESME must include an increment to upgrade from electricity only application to combined heat and power with connection to a city-scale district heating ring main or spur. In the ETI ANT project this increment was estimated at £300/kWe for FOAK and £200/kWe for NOAK. The requirement to revisit this in more detail was part of the scope of ANT phase 3. The ANT project report and associated ETI nuclear insight paper each report a revised estimate and confirms that this increment should be greater. Incremental costs are dominated by costs associated with the pipeline connection. Accordingly, this increment has been increased to $500/kWe for a NOAK SMR.

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15 NuScale's website at 22nd March 2020.
    https://www.nuscalepower.com/benefits/cost-competitive

LucidCatalyst specified capex parameters of $4,000/kWe in 2030, reducing to $3,000/kWe in 2050, for LW SMRs for power generation and/or cogeneration for the BASE scenario. For the OPTIMISTIC scenario, the lower capex parameters are $3,000/kWe initially, reducing to $2,000/kWe in 2050. For the PESSIMISTIC scenario, the higher capex parameters are $5,000/kWe initially, reducing to $4,000/kWe in 2050. These parameters reflect the range of publicly available cost estimates from SMR developers, as well as the various possible contingencies and construction project outturns. As examples of publicly available SMR cost estimates, NuScale's website[16] projects a FOAK capex of $3Bn. For a net power output of 684 MWe, this is equivalent to a specific capex for FOAK at $4,385/kWe, which is near the initial capex parameter for the BASE scenario. GEH[17] aims for a capex below $3,000/kWe for NOAK plants for its BWRX-300, which is within the range for the OPTIMISITC scenario. The PESSIMISTIC scenario represents SMR designs without optimised design and delivery. LucidCatalyst has lowered SMR capex parameters relative to IUK WP7 to capture the low range of published cost estimates as well as the possibility of undertaking innovative strategies to minimise schedule and cost, such as the BWRX-300 measures described above.

The SMR capex parameters also reflect learning effects that could lead to significant reductions in cost per kWe by 2050 after deployment of many units. Learning effects stem from efficiency improvements over time across the nuclear project team, from reactor designers and supporting vendors to work crews, supervisors, and regulators. In their analysis of historical nuclear costs in various costs, Lovering et al.[18] found substantial reductions in Japan and Korea from the 1990's to the 2010's, but rising costs in the US and Europe from the 1970's to the 1980's. The main reason for improvements in Japan and Korea is that these countries undertook multi-unit build programmes reusing the same plant designs, vendors, and work crews. The project participants learned lessons and honed their skills over sequential projects, leading to long-term declines in capex. Learning effects should be especially pronounced for SMRs because their smaller size means that more projects are undertaken to reach a certain total installed capacity. LucidCatalyst's capex parameters decline by $1,000/kWe by 2050 in all three scenarios because construction of many UK SMRs in decades ahead should also benefit from learning effects, especially if designs are frequently reused and individuals on project teams are redeployed from unit to unit and site to site.

Advanced nuclear – Cogen HTGR for power and hydrogen production

Source of technical data

It is important that the technical concepts are traceable to a credible technical source. Selected for this purpose are the technical parameters from JAEA conceptual design report 21/07/2011 "Status report 101 – Gas Turbine High Temperature Reactor (GTHTR300C)". https://slidelegend.com/gthtr300c-iaea-aris_59e609571723dd528389e770.html

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16 NuScale's website at 22nd March 2020.
    https://www.nuscalepower.com/benefits/cost-competitive

17 GEH website at 7th May 2020.
    https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300

18 Lovering et al., 'Historical construction costs of global nuclear power reactors', Energy Policy, April 2016.
    https://www.sciencedirect.com/science/article/pii/S0301421516300106

The reference concept design is optimised for routine cogeneration as the middle column in the table below. The design point is optimised for the long-term cogeneration of hydrogen and power at an optimised design point for long term thermal efficiency. The plant is designed to be capable of moving with reasonable notice (ie not fast response) away from this design point to:

- Maximise power generation when electricity demand and prices are high and reduce hydrogen production to zero if needed

- Minimise net power generation to zero when prices are low and instead divert the reactor thermal energy into maximum hydrogen production

There is a link therefore between power generation and hydrogen production in the same way that there is a connection between heat off-take and power down rate in the Light Water Small Modular Reactor representation in ESME. In this concept design, the switch between nominal cogeneration and maximum hydrogen can be made quickly because the reactor coolant flows and temperatures are the same. For the switch between nominal cogeneration and maximum electricity generation there is an increase in reactor coolant flow and pressure together with a reduction in coolant outlet temperature from 950 deg C to 850 deg C. To avoid thermal stresses in the reactor this transient is limited to 15 deg C per hour. In practical terms this a relatively quick response across the range zero to 174 MWe net electrical output, but six and a half hours in moving between 174 MWe net and 274 MWe net. Weather forecasting 24 hrs ahead is now good enough to give a firm forecast from renewables which are weather dependent as well as those which depend on tides or daylight hours. This means that the practicalities of planning "a day ahead" for such a plant are entirely achievable.

Table A1-1 – Gen IV cogen design parameters

Parameter	GTHTR300C Maximised Power	GTHTR300C Cogeneration	GTHTR 300C Maximised Hydrogen
Reactor thermal power	600 MWt/module	600 MWt/module	600 MWt/module
Reactor lifetime	60 years	60 years	60 years
Plant availability	90%+	90%+	90%+
Reactor fuel cycle	LEU, MOX, others	LEU, MOX, others	LEU, MOX, others
Reactor fuel design	TRISO coated particles	TRISO coated particles	TRISO coated particles
Reactor pressure vessel	SA508/SA533 steel	SA508/SA533 steel	SA508/SA533 steel
Reactor core coolant	Helium gas	Helium gas	Helium gas
Core coolant flow	403 kg/s	324 kg/s	324 kg/s
Core inlet temperature	663 deg C	594 deg C	594 deg C
Core outlet temperature	950 deg C	950 deg C	950 deg C
Core coolant pressure	6.9 MPa	5.1 MPa	5.1 MPa
Core power density	5.4 W/cc	5.4 W/cc	5.4 W/cc

Average fuel burnup	120 GWd/ton	120 GWd/ton	120 GWd/ton
Refuelling interval	18 months	18 months	18 months
GT conversion cycle	Non-intercooled direct Brayton cycle	Non-intercooled direct Brayton cycle	Non-intercooled direct Brayton cycle
GT cycle pressure ratio	2.0	2.0	1.5
Power generation efficiency	51%	47%	38%
Net electricity output (Max 300 MWe gross)	276 MWe. 24 MWe for internal plant load	178 MWe (202 gross; 24 MWe for internal plant load and hydrogen production)	Nil. 34 MWe for internal plant load and hydrogen production
Hydrogen plant effective heat rate	n/a	165 MWt (220 MWt in paper is prob. in error)	505 MWt
Hydrogen conversion process	n/a	Thermochemical or hybrid	Thermochemical or hybrid
Hydrogen conversion efficiency	n/a	43%	41%
Hydrogen production	n/a	58 tonnes/day	126 tonnes/day
Total plant efficiency (net)	50%	45%	40%

ESME data set; modular HTGR construction assumptions:

- First operations date 2030
- Construction period 3 years
- Technical and economic life of 60 years
- Design capacity factor 90%
- Site capacity limit 22 GWE with same distribution as Cogen LWSMR
- Roll out rate 1.5 GW/yr (5 of 300MWe units per year). Sensitivity runs:
  - Allocate LWSMR capacity of 22 GWe to advanced nuclear giving uplift from 22 GWe to 44 GWe. Increase roll out rate from 1.5 GWe/yr to 3.0 GWe/yr
  - Allocate 33 GWe of 35 GWe from large Gen III+ to advanced nuclear giving uplift from 22 GWE to 55 GWe. Increase roll out rate from 1.5 GWe/yr to 3.6 GWe/yr
- Overnight NOAK capex:
  - Assume deployed in quads for site productivity effects. Sites would take one or more quads.
  - $4000/kWe ($2017) at 2030 (first operations date) reducing to $3000/kWE ($2017) by 2050 (BASE). Basis is JAEA NOAK estimate of $2000/kWE plus $500 allowance to bring basis of estimate to that of ETI NCD plus $500/kWe for hydrogen plant plus $1000/kWe for UK licensing and lower productivity at site
- Sensitivity runs:
  - Higher costs. $5000/kWe ($2017) at 2035 (first operations date in this scenario) reducing to $4000/kWE ($2017) by 2050 (PESS).
  - Lower costs. $3000/kWe ($2017) at 2030 (first operations date) reducing to $2000 / kWE ($2017) by 2050 (OPT)
- Opex 2017 dollars:
  - Fixed OPEX to 2050 excluding fuel and waste – $62/kW-year
  - Variable OPEX to 2050 excluding fuel and waste – $2.32/MWh
  - Fuel and associated disposal cost to 2050 – $8/MWeh or $16/MWthh to allow for cogen

For potential sensitivity test of Cogen heat and power:

Table A1-2 – Parameters for sensitivity testing of cogen heat and power

Average fuel burnup	120 GWd/ton	120 GWd/ton	120 GWd/ton
Refuelling interval	18 months	18 months	18 months
GT conversion cycle	Non-intercooled direct Brayton cycle	Non-intercooled direct Brayton cycle	Non-intercooled direct Brayton cycle
GT cycle pressure ratio	2.0	2.0	1.5
Power generation efficiency	51%	47%	38%
Net electricity output (Max 300 MWe gross)	276 MWe. 24 MWe for internal plant load	178 MWe (202 gross; 24 MWe for internal plant load and hydrogen production)	Nil. 34 MWe for internal plant load and hydrogen production
Hydrogen plant effective heat rate	n/a	165 MWt (220 MWt in paper is prob. in error)	505 MWt
Hydrogen conversion process	n/a	Thermochemical or hybrid	Thermochemical or hybrid
Hydrogen conversion efficiency	n/a	43%	41%
Hydrogen production	n/a	58 tonnes/day	126 tonnes/day
Total plant efficiency (net)	50%	45%	40%

- Costs: For Cogen heat and power, the $500/kWe increment for hydrogen production is removed and the $500/kWe increment is added for district heat network energisation (heat extraction via additional heat exchangers and representative typical pipe runs to connect plant to city scale DH system). So overall the costs of Cogen power and hydrogen are modelled the same as the costs for Cogen power and heat.

First operations date

For the HTGR's BASE scenario, LucidCatalyst specified a first operations date of 2030 in light of three main considerations: (1) the near-term need for low-cost hydrogen, ammonia, and synthetic hydrocarbons from HTGRs to decarbonise the UK's oil and gas consumption; (2) significant progress to date on HTGR technology by the Japanese Atomic Energy Agency; and (3) progress on licensing TRISO fuel.

Regarding the first consideration, two forthcoming studies by LucidCatalyst show the cost competitiveness of clean and scalable energy from nuclear-produced hydrogen for addressing the 'hard-to-decarbonise' non-electricity sectors fuelled by oil and gas[19]. In order for the UK to reduce CO_2 emissions in a climate-relevant timeline and reach Net Zero by mid-century, HTGRs for hydrogen, ammonia, and synthetic hydrocarbon production will need to be planned in the mid 2020's for deployment in 2030 and beyond. The DECC SMR TEA Emerging Technologies Project 3 report[20] also

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19 Decarbonizing Prosperity: Hydrogen Enabled Synthetic Fuels, for the Nuclear Energy Institute (NEI); Clean and Scalable Synthetic Fuels: Enabled by Innovative Delivery Models for Advanced Heat Sources, for the Electric Power Research Institute (EPRI)

20 DECC SMR TEA – Emerging Technologies Assessment Project 3. NNL 15th March 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665274/TEA_Project_3_-_Assessment_of_Emerging_SMR_Technologies.pdf

highlighted small modular HTGRs, with potential deployment around 2030, as the best prospect for decarbonising high-temperature industrial processes based on the operating temperature of the nuclear heat supply system and the least challenges on costs and timescales.

The Japanese Atomic Energy Authority (JAEA) has had an active HTGR development programme for many decades with its High Temperature Test Reactor having begun operations in 1999. Many JAEA presentations and papers at conferences and elsewhere identify the potential for commercial deployment in the early 2020's[21]. TRISO fuel for HTGRs is being developed and licensed through programmes at Idaho National Laboratory, and nuclear start-ups such as X-energy and Kairos are making progress on this fuel type for near-term use as well[22].

LucidCatalyst specified HTGR first operations dates of 2030 as well for the OPTIMISTIC scenario and 2035 for the PESSIMISTIC scenario to capture the range of potential schedule outcomes. A supportive UK Government policy and a collaborative approach would help ensure that HTGRs play an important role beginning approximately ten years from now to deliver clean energy for the electricity sector and other fossil fuel applications.

There are two pebble bed HTGRs installed[23] at the Shidaowan site in China. These have a design operating temperature of 750oC and each have a generation capacity of 210 MWe. They are expected to begin critical operations as part of commissioning during 2020.

Construction period

The construction period for HTGRs would depend on the design and delivery details for each plant, with the same important factors identified above for Gen III+ LWRs and LW SMRs, such as design completion before construction start and learning effects through multi-unit build-outs. LucidCatalyst specified 3 years as BASE for construction period for HTGRs, 2 years for the OPTIMISTIC scenario, and 4 years for the PESSIMISTIC scenario. As discussed above, a large amount of hydrogen and derivative clean fuels from HTGRs could be deployed in the UK to decarbonise oil and natural gas consumption outside the electricity sector. The large number of HTGR units implies many opportunities for efficiency improvements from project to project through learning effects over the analysis horizon.

Plant life and capacity factor

The reference JAEA paper states 60 years and 90%.

Site capacity limit

For the purpose of the IUK WP7 project and associated sensitivity study, the second tranche of "twice-over" SMR capacity has been allocated to Gen IV.

To test a scenario with no deployment of Gen III+ or LWSMRs, the site capacity limit nominally allocated to large Gen III+ can be reallocated to Gen IV in addition to the Gen IV SMR only site capacity from the "twice-over" analysis. This is the basis of the Gen IV electricity only site capacity

21 Toshiba and JAEA, 'Expectation to HTGR Deployment', 18th July 2019.
    https://www.jaea.go.jp/04/kokusaibu/ja/event/20190918/4-Presentation.pdf

22 US Department of Energy, 'TRISO Particles: The Most Robust Nuclear Fuel on Earth,' 9th July 2019.
    https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth

23 HTR PM steam generator passes pressure tests. World Nuclear News 2nd October 2018
    https://www.world-nuclear-news.org/Articles/HTR-PM-steam-generator-passes-pressure-tests

limit of 55 GWe. All these locations have some access to cooling (direct or indirect) and so also have access to a water supply for hydrogen production. This is the basis for site capacity for hydrogen-only Gen IV.

Roll out rate

Vendor forecasts of roll out rate must be considered with caution; such forecasts need to be market led. With a first operations date of 2035, a roll out rate of just under 1.5 GWe per year can deliver 22 GWe by 2050. This is the basis for the roll out rate. It is the equivalent of connecting 5 units per year of nominal capacity of 300 MWe. For multi-unit construction per site with much of the assembly and integration taking place in bespoke factories, this assumption is not unreasonable.

Using the same methodology, the roll out rate for 55 GWe of electricity only operations would be just over 3.7 GWe per year. For 300 MWe units this is 12 per year or one reactor connected to the grid every 4 weeks. Such a scenario might involve more than one design and associated modular manufacturing eco-system. Deployment would be concurrent on multiple sites.

Capex

LucidCatalyst specified an initial capex for HTGRs of $4,000/kWe for the BASE scenario, with a lower value of $3,000/kWe for the OPTIMISTIC scenario and higher value of $5,000/kWe for the PESSIMISTIC scenario. In each scenario, capex would decline by $1,000/kWe by 2050 due to learning effects as described above. These capex values are intended to span the potential range of HTGR costs depending on design and delivery strategies for each plant. The overnight capex figure for HTGRs from the ETI NCD cost model is $3350/kWe, which lies between the initial values for the BASE and OPTIMISTIC scenario. There is also a JAEA case study in the ETI NCD project technical report. This identifies that production-ready quotes from suppliers suggest around $2,500/kWe capex for a 4 unit 1,100 MWe plant (4 x 275 MWe). UK nuclear construction would likely be more costly than the Japanese basis for this estimate because of different wage rates and productivity levels[24], but the OPTIMISTIC scenario would decrease to this level or below late in the analysis period.

Capex increment for hydrogen production

A recent report[25] from the Idaho National Laboratory identifies a range of processes for producing hydrogen from light-water reactors. There are estimates for small plants and larger plants, both for low temperature electrolysis and higher temperature electrolysis. Based on the cost estimates in this paper, $500/kWe is a generous provision to allow for additional capex for hydrogen production plant. A cost estimate for a sulphur iodine hydrogen production plant has been difficult to find.

Opex

From ETI NCD cost model and reports.

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24 UK Office of National Statistics, 'International comparisons of UK productivity (ICP),
    final estimates: 2016', website accessed 7th May 2020.
    https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/bulletins/
    internationalcomparisonsofproductivityfinalestimates/2016
    Evaluation on non-electric market options for a light-water reactor in the mid-West dated August 2019.
    https://lwrs.inl.gov/systems%20analysis%20and%20emerging%20issues/forms/allitems.aspx

Table A1-3 – ESME dataset summaries for new nuclear technologies Gen III+, cogen LWSMR and cogen Gen IV

Technology Type	First Operations Date	Construction Duration	Build Out Rate GWe/yr	O/N cost (2017)	Notes
Large light-water reactors. Baseload power generation Economic life 60 years.	2025 (OPT)	4.5 (OPT)	2.1 GWe/yr (OPT) Deployed Capacity against O/B/P first ops dates of 35/35/35 GWe	$4000/kWe ($2017) at 2025 reducing to $3500/kWE ($2017) by 2050 (OPT)	Electricity only; no heat recovery. Different roll out rates reflect (1) construction at one site at a time, (2) concurrent construction at two sites at a time, (3) concurrent construction at 3 sites at a time. Site capacity constraint of 35 GWe new nuclear build by 2050 in England and Wales. Costs reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies. **The OPT cost draws on the US Department of Energy's Best Experience (BE) data from the Energy Economic Database version 9. The PESS cost draws on the median experience (from US in early 1980s) in this source, also assuming only two units per site (rather than more than two) and a greater proportion of EPRs. LucidCatalyst has extended BASE construction duration based on UAE Barakah plant experience (about 65 months per unit) LucidCatalyst has raised overnight costs for BASE (initial level) and PESS for realism in light of recent and ongoing nuclear projects in Europe and US and due**
	2025 (BASE)	5.5 (BASE)	1.4 (BASE) Deployed Capacity against O/B/P first ops dates of 35/35/28 GWe	$4500/kWe ($2017) at 2025 reducing to $4000/kWE ($2017) by 2050 (BASE)	
	2030 (PESS)	7 (PESS)	0.7 (PESS) Deployed Capacity against O/B/P first ops dates of 18/18/14 GWe (PESS)	$5500/kWe ($2017) at 2030 reducing to $5000/kWE ($2017) by 2050 (PESS)	

					to longer construction schedule.
LWSMR UK application of alternative source of nuclear power generation and/or cogeneration of power and low grade heat for district heating energisation. Economic life 60 years.	2028 (OPT)	3 (OPT)	2.7 GWe/yr (OPT) Deployed capacity against O/B/P first ops dates of 22/22/22 GWe	$3000/kWe ($2017) at 2028 reducing to $2000 /kWE ($2017) by 2050 (BASE)	Capable of electricity only or cogeneration with steam extraction for DH energisation (power downrate penalty). Capex increment for upgrade from electricity only to CHP of additional $500/kWe (includes pipe runs circa 5 to 10 km to connect to city scale DH ring main.) Note industry target cost of $2,000/kWe for electricity only (GE BWR) driven by challenging US market conditions. ETI PPSS established 67 GWe SMR capacity in England and Wales without finding capacity limit. Analysis based on twice over district heating energisation with pumping evaporative cooling make up and purge up to 30 km (average distance less than 10 km). Full DH energisation equated to 22 GWe of LWSMR. This limit retained for LWSMR and the "twice-over" allocation allocated to Advanced Gen IV high temp. If Large Gen III sites un-used then this underutilised capacity could be available to LWSMR or Advanced Gen IV high temp in additional sensitivity study. **LucidCatalyst has extended BASE and PESS construction durations for realism. LucidCatalyst has lowered capital costs to reflect substantial**
	2030 (BASE)	4 (BASE)	1.2 GWe/yr (BASE) Deployed capacity against O/B/P first ops dates of 22/22/18 GWe	$4000/kWe ($2017) at 2030 reducing to $3000/kWE ($2017) by 2050 (BASE)	
	2035 (PESS)	5 (PESS)	0.6 GWe/yr (PESS) Deployed capacity against O/B/M first ops dates of 13/12/9 GWe	$5000/kWe ($2017) at 2035 reducing to $4000/kWE ($2017) by 2050 (BASE)	

					learning effects over many units by 2050 and strategies being incorporated into GEH SMR (BWRX-300).
Advanced Nuclear with Gen IV nuclear heat supply system. Could be a range of technologies but data applied here from JAEA HTGR research and development. Assumed UK application of flexible cogeneration of power and hydrogen with plant design enabling migration between full power with no hydrogen to maximum hydrogen production with no net power export to meet needs of energy system predicted 24 hours ahead. Economic life 60 years.	2030 (OPT)	2 (OPT)	3.0 GWe/yr (OPT) Deployed capacity against O/B/P first ops dates of 22/22/9 GWe	$3000/kWe ($2017) at 2030 reducing to $2000 /kWE ($2017) by 2050 (OPT)	This group could include HTGR or small modular fusion reactors. Industry target O/N cost of $2,000/kWE. (JAEA GT-HTGR300). Capable of power (50% thermal efficiency) and cogeneration of hydrogen (sulphur iodine process 40% overall thermal efficiency). Potential heat extraction for salination or DH energisation with zero power downrate). Rollout rates: (1) 2 units per year, (2) 5 units per year, (3) 10 units per years (second technology variant?) Assume modular addition for hydrogen production at $500/kWe. Assume in this mode no power down rate and regarding flexibility hydrogen and power production are linked when reactor thermal output is maintained at maximum (noting that operationally the reactor can be "throttled back" to enable independent supply of power and hydrogen below the limit of maximum core power). Peak power (net) is 276 MWe and peak hydrogen production is 126 tonnes/day from reactor heat and internal electricity demand of 34 MWe. Design point is 178 MWe (net) and 58 tonnes per day of hydrogen. Given water demand to enable hydrogen

				118	production, then place these at the "twice-over" locations for LWSMR with a notional capacity limit of 22 GWe. If Large Gen III sites un-used then this underutilised capacity could be available to LWSMW or Advanced Gen IV high temp in additional sensitivity study. **LucidCatalyst has pulled forward the first operations dates for Gen IV because HTGR fuel (TRISO) has already made progress on licensing, and waiting till 2035/2040/2045 seems unrealistically long**

Annex 2 – List of ESME sensitivity runs for Supplementary Report No.2

For base, lower and higher values refer to the datasets for Supplementary Report No.2 listed in Annex 1.

Table A2-1 – Run summary from SR No.2 sensitivity studies

Run	Scenario	Sensitivity Criteria Applied	Notes
		Gen IV deployment only; no large Gen III+ deployment or light-water SMRs	
201	FA96	All nuclear technologies available for deployment in combination. Base case data.	
202	TECH100	All nuclear technologies available for deployment in combination. Base case data.	
203	BOB100	All nuclear technologies available for deployment in combination. Base case data.	
204	FA96	All nuclear technologies available for deployment in combination. Lower CAPEX data.	
205	TECH100	All nuclear technologies available for deployment in combination. Lower CAPEX data.	
206	FA96	All nuclear technologies available for deployment in combination. Higher CAPEX data.	
207	TECH100	All nuclear technologies available for deployment in combination. Higher CAPEX data.	
		Gen IV cogen deployment only; no large Gen III+ beyond HPC or light-water SMRs	
208	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Base case data.	
209	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Base case data.	
210	BOB100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Base case data.	
211	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Lower CAPEX data.	
212	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Lower CAPEX data.	
213	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Higher CAPEX data.	
214	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Higher CAPEX data.	
215	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity limit raised to 55 GWe with build-out rate to match. Base CAPEX data.	
216	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity limit raised to 55 GWe with build-out rate to match. Base CAPEX data.	
217	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity	

		limit raised to 55 GWe with build-out rate to match. Lower CAPEX data.	
218	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity limit raised to 55 GWe with build-out rate to match. Lower CAPEX data.	
219	FA96	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity limit raised to 55 GWe with build-out rate to match. Higher CAPEX data.	
220	TECH100	Gen IV cogen deployment only, i.e. no Gen III+ beyond HPC, and no LWSMR. Gen IV site capacity limit raised to 55 GWe with build-out rate to match. Higher CAPEX data.	
		Sensitivity runs with DH system deployment disabled for space heating	
221	FA96	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen. Otherwise data from base case.	There is a wariness detected amongst some policy officials to set policy to implement large scale DH deployment as retrofit in cities and towns. An expanded hydrogen economy is seen as more attractive because of less challenge and disruption to city/town dwellers and an easier "sell" to taxpayers and consumers associated with replacing natural gas domestic boilers for hydrogen units. The runs with DH turned off test this policy thinking.
222	TECH100	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen. Otherwise data from base case.	
223	BOB100	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen. Otherwise data from base case.	
224	FA96	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen; deployment capacity limit raised to 55GWe with build-out rate to match. Otherwise data from base case.	
225	TECH100	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen; deployment capacity limit raised to 55GWe with build-out rate to match. Otherwise data from base case.	
226	BOB100	Switch DH deployment off within ESME. Remove CAPEX increment from LWSMR for cogen deployment so deployed as electricity only. Gen IV remains Cogen power and hydrogen; deployment capacity limit raised to 55GWe with build-out rate to match. Otherwise data from base case.	
		Sensitivity Runs with DH system deployment re-enabled for space heating for comparison	
227	FA96	Switch ESME DH deployment back on. Re-instate the CAPEX increment for LWSMR for cogen	Runs 227, 228 and 229 represent a policy neutral fight

		deployment so deployed as cogen power and heat for DH energisation. Gen IV remains Cogen power and hydrogen. Gen IV deployment raised to 55 GWE with build out rate to match. Otherwise base Case data.	for domestic space heating between DH with LWSMR cheap heat, and greater availability of low-cost hydrogen for the hydrogen economy through Gen IV.
228	TECH100	Switch ESME DH deployment back on. Re-instate the CAPEX increment for LWSMR for cogen deployment so deployed as cogen power and heat for DH energisation. Gen IV remains Cogen power and hydrogen. Gen IV deployment raised to 55 GWE with build out rate to match. Otherwise base Case data.	
229	BOB100	Switch ESME DH deployment back on. Re-instate the CAPEX increment for LWSMR for cogen deployment so deployed as cogen power and heat for DH energisation. Gen IV remains Cogen power and hydrogen. Gen IV deployment raised to 55 GWE with build out rate to match. Otherwise base Case data.	
	Sensitivity Runs to Test Impact of reduced hydrogen costs with DH deployment disabled		
230	TECH100	Switch ESME DH deployment off within ESME. Remove $500/kWe increment from LWSMR for Cogen deployment so deployed as electricity only. Remove $500/kWe CAPEX increment from Gen IV so as deployed as hydrogen production only. Gen IV deployment capacity limit raised to 55 GWe with build out rate to match. Otherwise data from base case.	The analysis for Supplementary Report No.1 demonstrated that Gen IV could do district heating energisation just as well as LWSMR. The Lucid-Catalyst data suggests that Gen IV and LWSMR could be available in a similar timeframe and with similar costs. This analysis could represent the same plant design being deployed into two single vector markets, with the potential for the electric only plants to be upgraded to DH energisation capable at a later date should this market emerge. Otherwise the scenario represents a very low level of DH deployment and space heating either via hydrogen boilers through the hydrogen distribution network, or electricity through direct resistive heating or heat pumps.
231	TECH100	Switch ESME DH deployment off within ESME. Remove $500/kWe increment from LWSMW for Cogen deployment so deployed as electricity only. Remove $500/kWE CAPEX increment from Gen IV so as deployed as hydrogen production only. Gen IV deployment capacity limit raised to 55 GWe with build out rate to match. For Gen IV only use lower CAPEX levels (hydrogen only), i.e. $2,500/KWe reducing to $1,500/KWe by 2050. Otherwise data from base case for all technologies.	
	Monte Carlo Run to Recognise Uncertainties		
	M/C	Probabilistic Run with the inputs as per deterministic Run 228. Cost spread for new nuclear technologies is -25% to +40% of Base Case	

Annex 3 – Selected ESME outputs for Supplementary Report No.2

The columns below are the colour coded legends for the respective ESME generic output core charts which follow.

Primary Resource Consumption
- Wave
- Tidal Stream
- Tidal Range
- Hydro
- Solar
- Wind (deep offshore)
- Wind (shallow offshore)
- Wind (onshore)
- Nuclear
- Geothermal Heat
- Wet Waste
- Dry Waste Resource
- Dry Waste
- Biomass
- UK Biomass
- Biomass Imports
- Coal
- Gas
- GasTS
- GasLDN
- Gas_Zeb_Import
- Gas_UKCS_Import
- Gas_TTF_Import
- Gas_NCS_Import
- Gas_LNG_Import
- Biofuel Imports
- Liquid Fuel
- Diesel
- Petrol
- Aviation Fuel
- Hydrogen
- Electricity_DX_LV
- Electricity_DX_HV
- Electricity_TX

Net CO2 Emissions
- GasTS
- Biomass
- Hydrogen
- Electricity
- CapturedCO2
- Retroplus
- Retrofix
- PC Coal CCS Retrofit
- PC Coal Biomass Retrofit
- IGCC Coal CCS Retrofit
- CCGT CCS Retrofit
- Energy Storage
- Industry
- International A & S
- Transport Sector
- Buildings Sector
- Power Sector
- Other Conversion Sector
- Industry Sector (combustion)
- Industry Sector (process CO2)
- Other CO2
- Biogenic credits
- Wood in Construction
- Waste incineration
- Settlements
- Peatland
- LULUCF Other
- Industry
- IGCC Coal with CCS - 99pct CCR
- H2 Plant (SMR with CCS) - 99pct CCR
- H2 Plant (Biomass Gasificn. with CCS) - 99pct CCR
- Forest land
- Energy crops, agroforestry, hedges
- Converted Biomass Plant (Drax)
- CCGT with CCS - 99pct CCR
- CO2 Processing for synfuel
- Biopetrol Production with CCS - 99pct CCR
- Biokerosine Production with CCS - 99pct CCR

Electricity Generation Cap. & Annual Generation
- Geothermal Plant (HSA) Electricity & Heat
- Geothermal Plant (EGS) Electricity & Heat
- Wave Power
- Tidal Stream
- Tidal Range
- Severn Barrage
- Hydro Power
- Solar PV (Domestic)
- Solar PV (Farm)
- Offshore Wind (floating)
- Offshore Wind (fixed)
- Onshore Wind
- Micro Wind
- Micro CHP - Space Heat
- Micro CHP - Hot Water
- H2 Turbine
- ATC of Waste
- Anaerobic Digestion CHP Plant
- Incineration of Waste
- IGCC Biomass with CCS
- Biomass Fired Generation with CCS
- Biomass Macro CHP
- IGCC Biomass
- Converted Biomass Plant
- Biomass Fired Generation
- Nuclear Gen III Hinkley Point C
- Nuclear Gen IV Hydrogen only
- Nuclear Gen IV Elec only
- Nuclear SMR Elec only
- Nuclear (SMR)
- Nuclear (Gen IV)
- Nuclear SMR Cogen Power and Heat (DH)
- Nuclear Gen IV Cogen Power and H2
- Nuclear (Gen III)
- Nuclear (Legacy)
- Waste Gasification with CCS
- Waste Gasification
- CCGT with CCS
- CCGT
- IGCC Coal with CCS
- IGCC Coal
- PC Coal with CCS
- PC Coal
- OCGT
- Gas Macro CHP
- Oil Fired Generation
- Interconnector Nordel (Electricity)
- Interconnector Ireland (Electricity)
- Interconnector France (Electricity)
- Interconnector Benelux-Germany (Electricity)
- CCGT with CCS - 99pct CCR
- Converted Biomass Plant (Drax)
- IGCC Coal with CCS - 99pct CCR

Space Heat Capacity & Space Heat Generation

- H2 Micro CHP - Space Heat
- H2 Boiler - Space Heat
- Heat Pump (Ground Source, Space Heat)
- Heat Pump (Air Source, Space Heat)
- Electric Resistive Heating - Space Heat
- Biomass Boiler - Space Heat
- Micro CHP - Space Heat
- Gas Boiler - Space Heat
- Oil Boiler - Space Heat
- DH for Dwelling (LD, ThP)
- DH for Dwelling (LD, ThP with Retroplus)
- DH for Dwelling (LD, ThP with Retrofix)
- DH for Dwelling (LD, ThM)
- DH for Dwelling (LD, ThM with Retroplus)
- DH for Dwelling (LD, ThM with Retrofix)
- DH for Dwelling (LD, ThG)
- DH for Dwelling (LD, ThE)
- DH for Dwelling (MD, ThP)
- DH for Dwelling (MD, ThP with Retroplus)
- DH for Dwelling (MD, ThP with Retrofix)
- DH for Dwelling (MD, ThM)
- DH for Dwelling (MD, ThM with Retroplus)
- DH for Dwelling (MD, ThM with Retrofix)
- DH for Dwelling (MD, ThG)
- DH for Dwelling (MD, ThE)
- DH for Dwelling (HD, ThP)
- DH for Dwelling (HD, ThP with Retroplus)
- DH for Dwelling (HD, ThP with Retrofix)
- DH for Dwelling (HD, ThM)
- DH for Dwelling (HD, ThM with Retroplus)
- DH for Dwelling (HD, ThM with Retrofix)
- DH for Dwelling (HD, ThG)
- DH for Dwelling (HD, ThE)
- District Heating (Public floorspace)
- District Heating (Commercial floorspace)
- Solid Fuel Boiler - Space Heat

Hydrogen Production

- Nuclear Gen IV Hydrogen only
- Nuclear Gen IV Cogen Power and H2
- H2 Plant (Biomass Gasification with CCS)
- H2 Plant (Biomass Gasification)
- H2 Plant (SMR with CCS)
- H2 Plant (SMR)
- H2 Plant (Coal Gasification with CCS)
- H2 Plant (Electrolysis)
- H2 Plant (Biomass Gasification with CCS) - 99pct CCR
- H2 Plant (SMR with CCS) - 99pct CCR
- Nuclear H2 Gigafactory

Network Hot Water Production

- District Heating H2 Boiler
- Heat Pump (Large Scale Marine)
- Geothermal Plant (EGS) Electricity & Heat
- Geothermal Plant (HSA) Electricity & Heat
- Geothermal Plant (HSA) Heat Only
- District Heating Gas Boiler
- Gas Macro CHP
- District Heating Biomass Boiler
- Biomass Macro CHP
- Anaerobic Digestion CHP Plant
- Nuclear SMR Cogen Power and Heat (DH)
- Nuclear (SMR)
- Heat Offtake for District Heat Network

Industry Fuel Consumption

- Industry - Liquid Fuel
- Industry - Hydrogen
- Industry - GasTS
- Industry - Electricity
- Industry - Coal
- Industry - Biomass

Hydrogen Consumption

- Hydrogen Distribution Network
- H2 Turbine
- Bus (Hydrogen FCV)
- MGV
- HGV
- LGV (Hydrogen ICE)
- Car Hydrogen ICE (C/D Segment)
- Car Hydrogen ICE (A/B Segment)
- LGV (Hydrogen FCV)
- Car Hydrogen FCV (C/D Segment)
- Car Hydrogen FCV (A/B Segment)
- Industry
- Wheeled Excavator (H2)
- Medium Wheel Loader (H2)
- Medium Articulated Truck (H2)
- Maritime (Ammonia International)
- Maritime (Ammonia Domestic)
- Large Articulated Truck (H2)
- Industry I8 SpH Hyd Sw
- Industry I7 SpH Hyd Sw
- Industry I7 DaS Hyd Sw
- Industry I6 SpH Hyd Sw
- Industry I6 DaS Hyd Sw
- Industry I5 SpH Hyd Sw
- Industry I5 DaS Hyd Sw
- Industry I4 LTP Hyd Sw
- Industry I4 DaS Hyd Sw
- Industry I3 SpH Hyd Sw
- Industry I2 SpH Hyd Sw
- Crawler Excavator (H2)
- Agricultural Vehicle (H2)

## Run 201 FA96 – All nuclear technologies; base case data
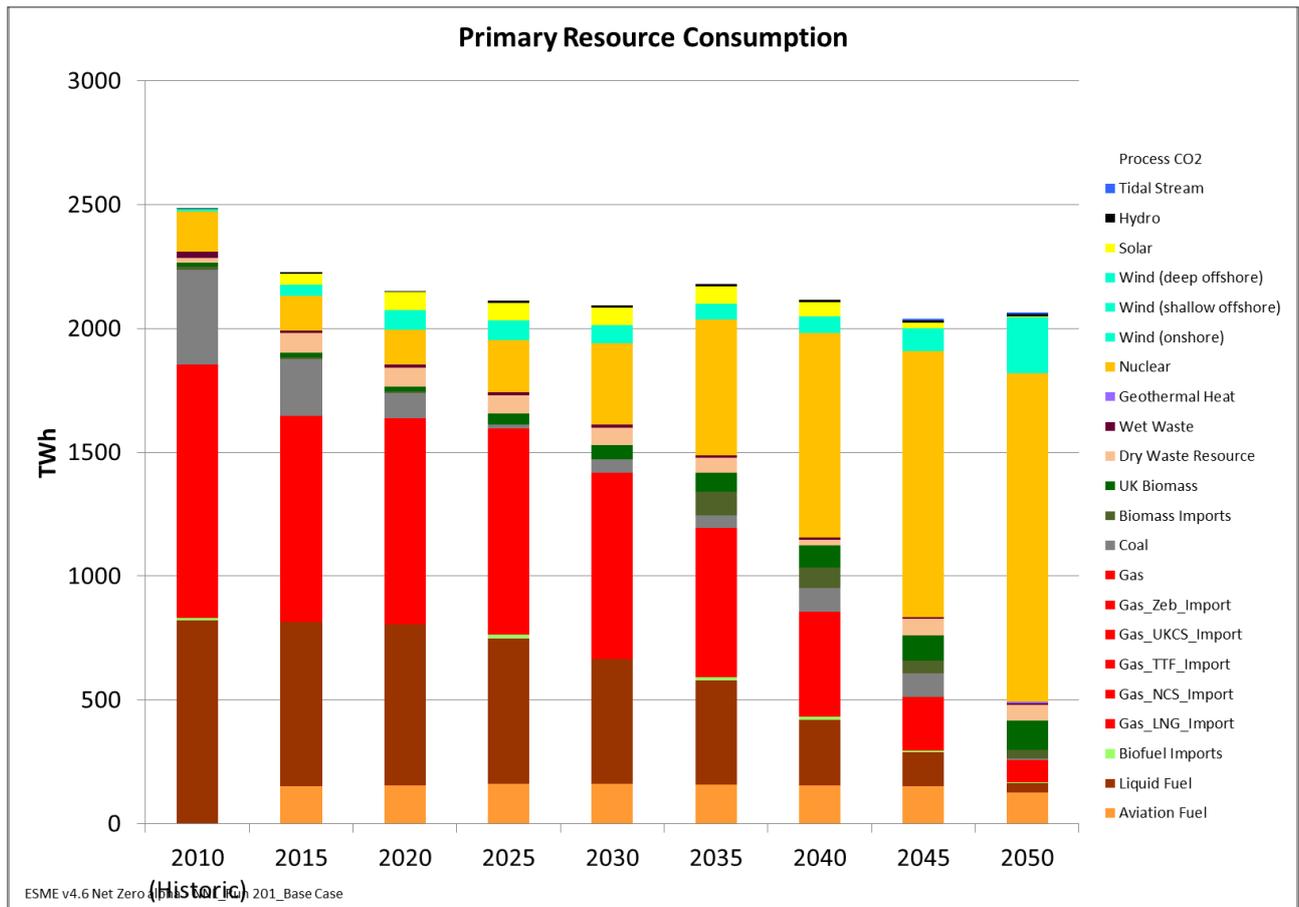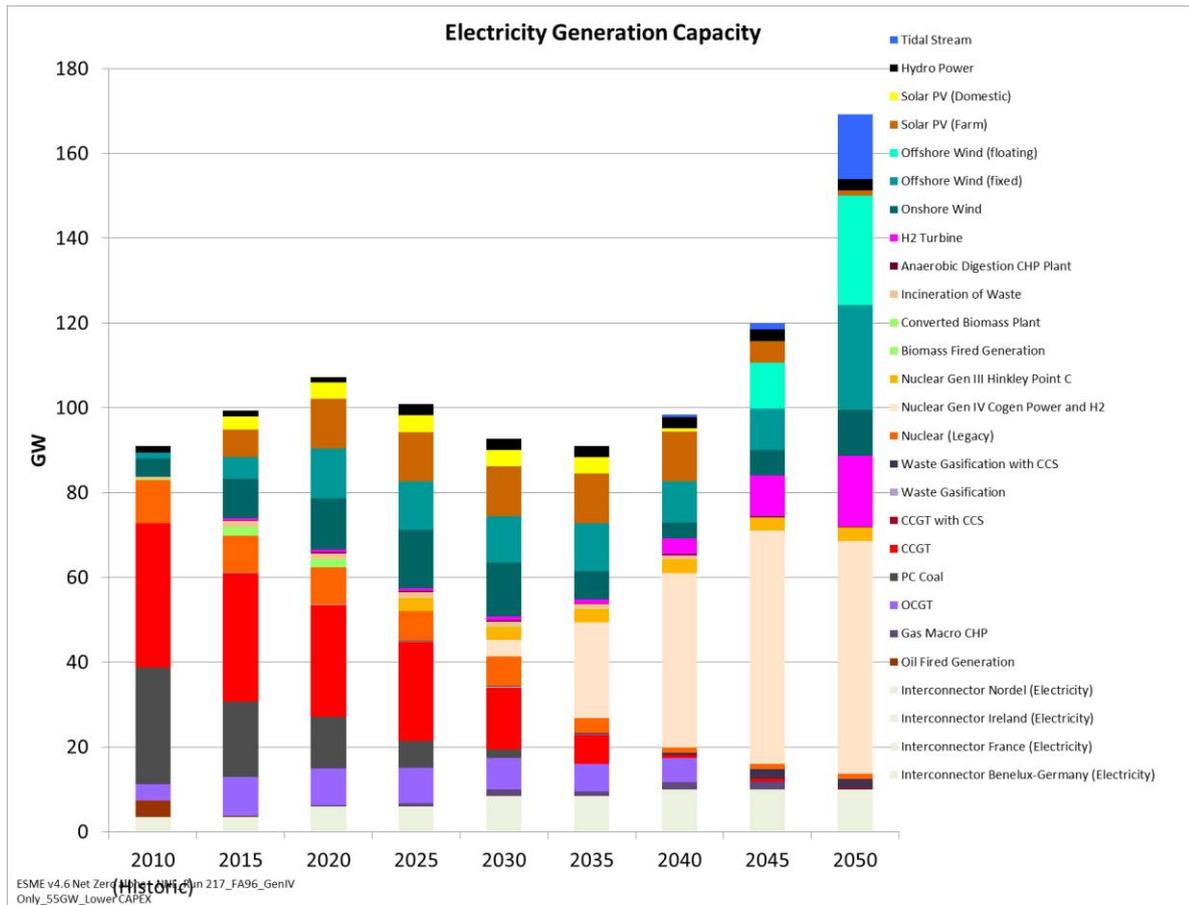

Figure A3-1 – Run 201 primary resource consumption
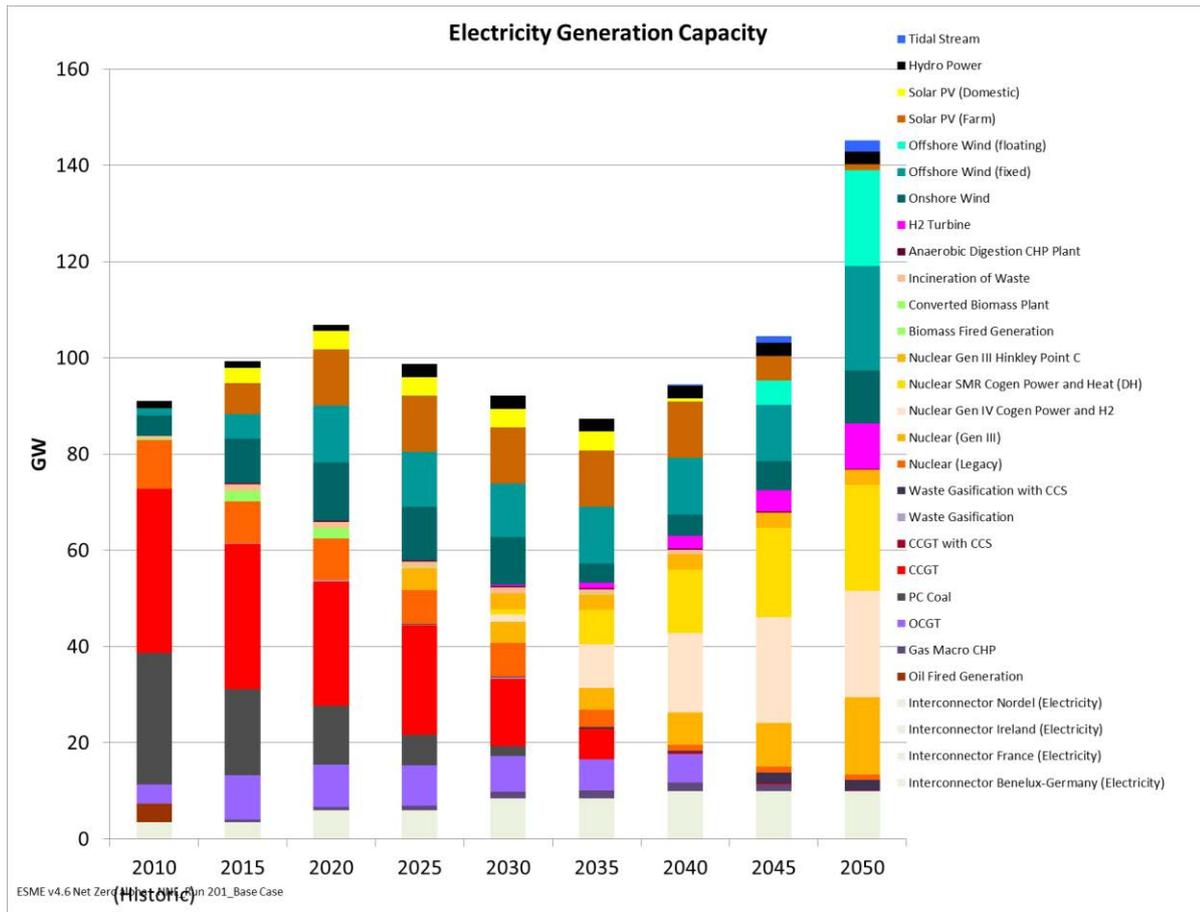
Figure A3-2 – Run 201 electricity generation capacity
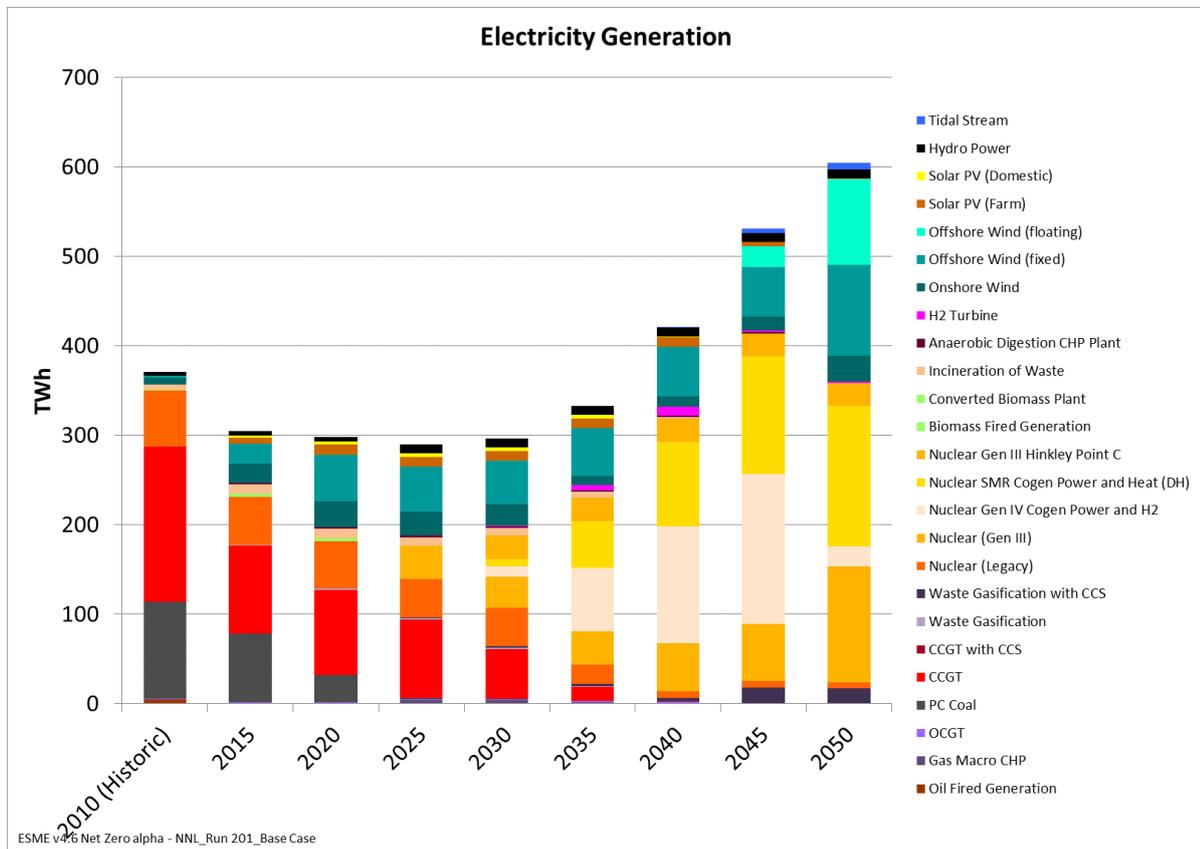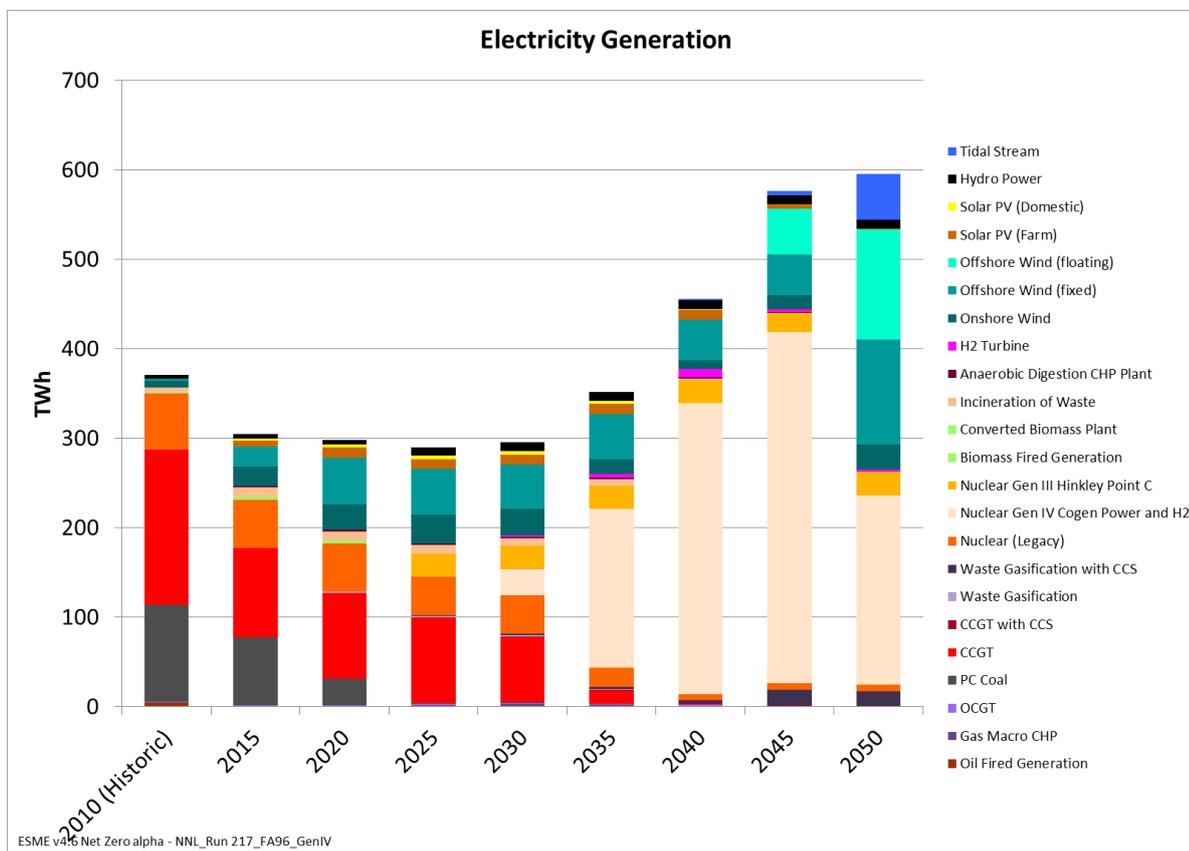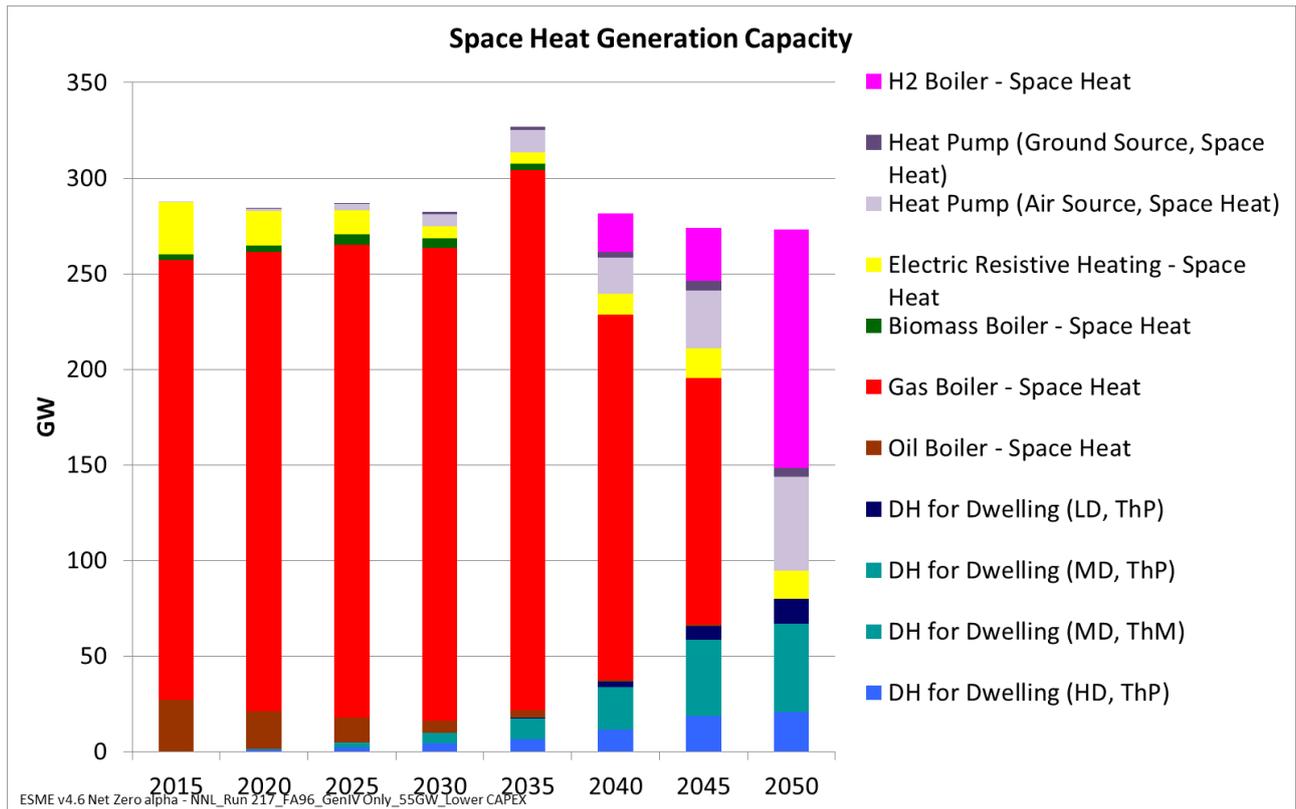

Figure A3-3 – Run 201 electricity generation
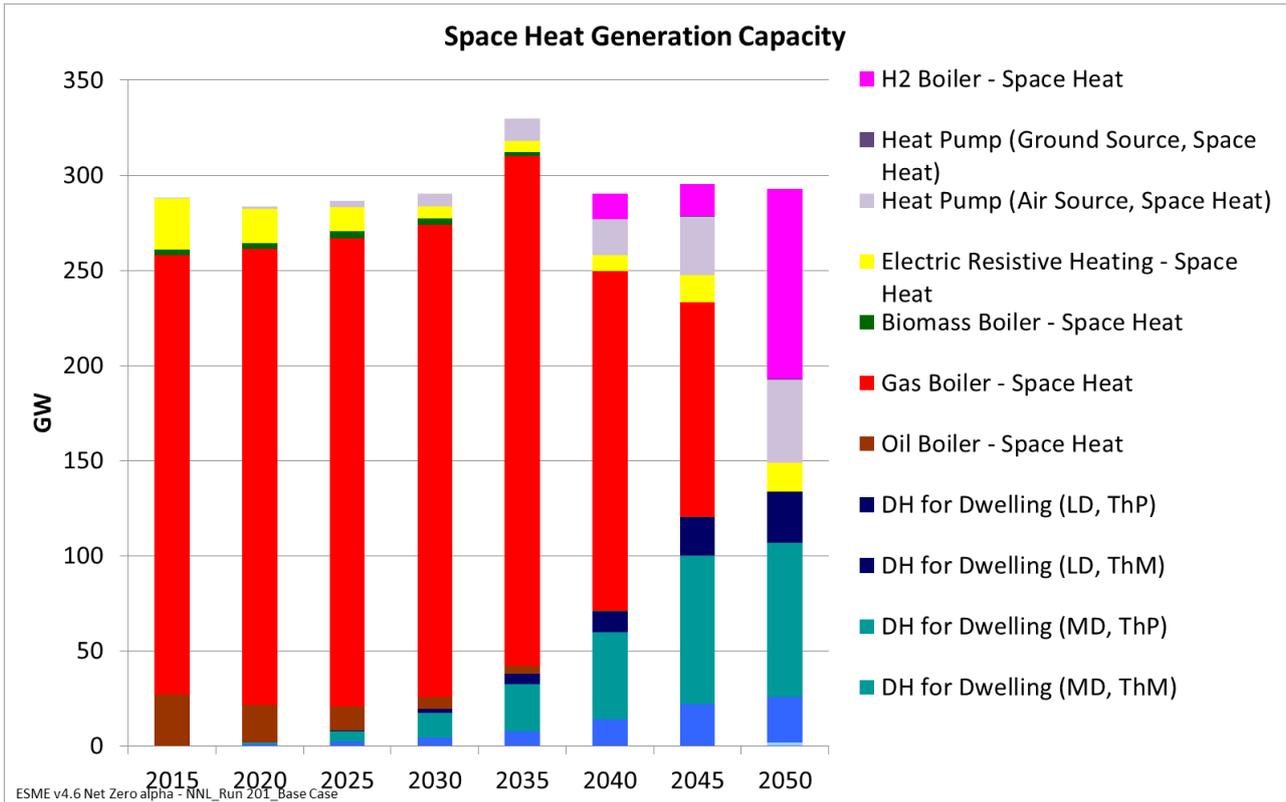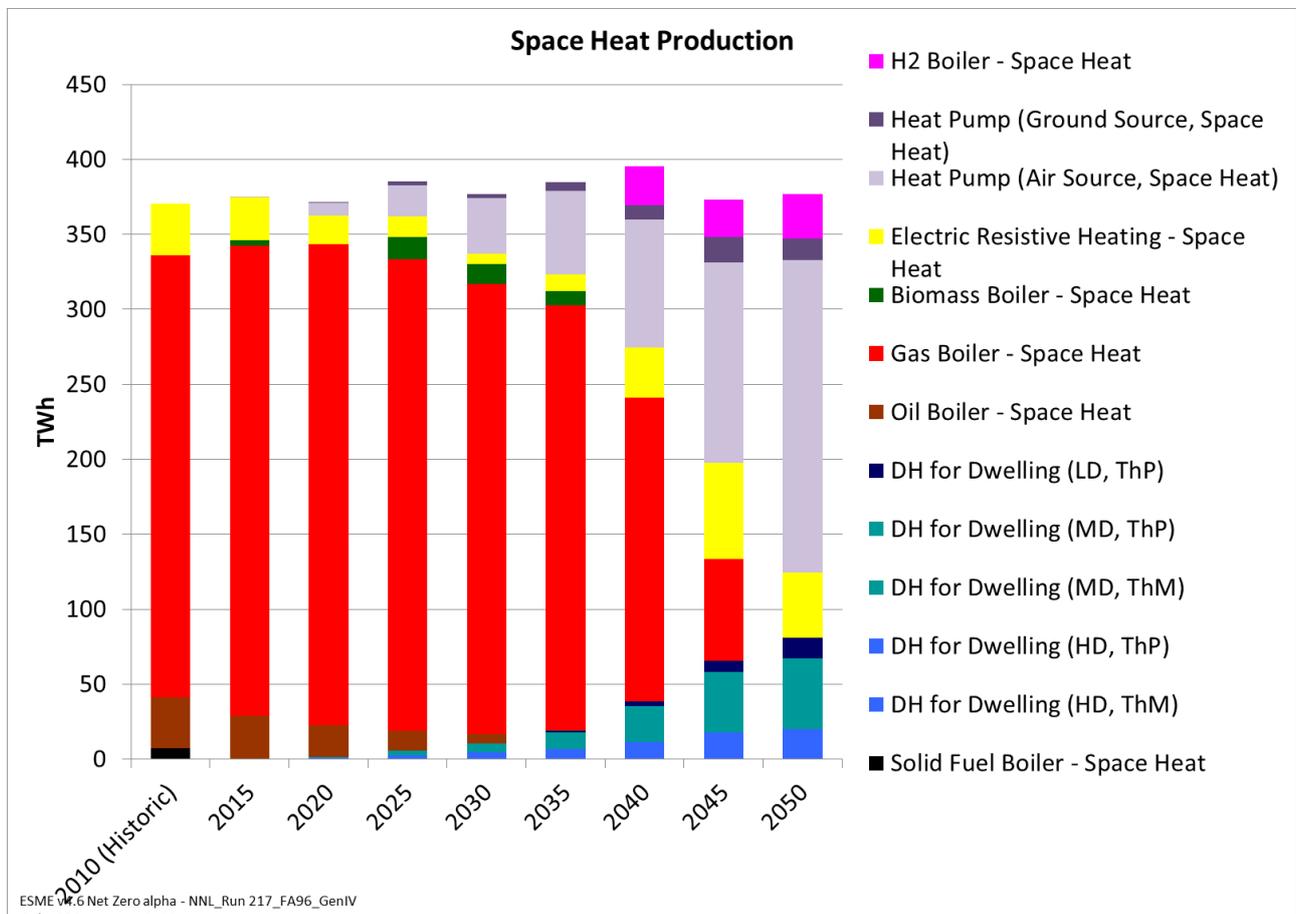
Figure A3-4 – Run 201 space heat generation capacity
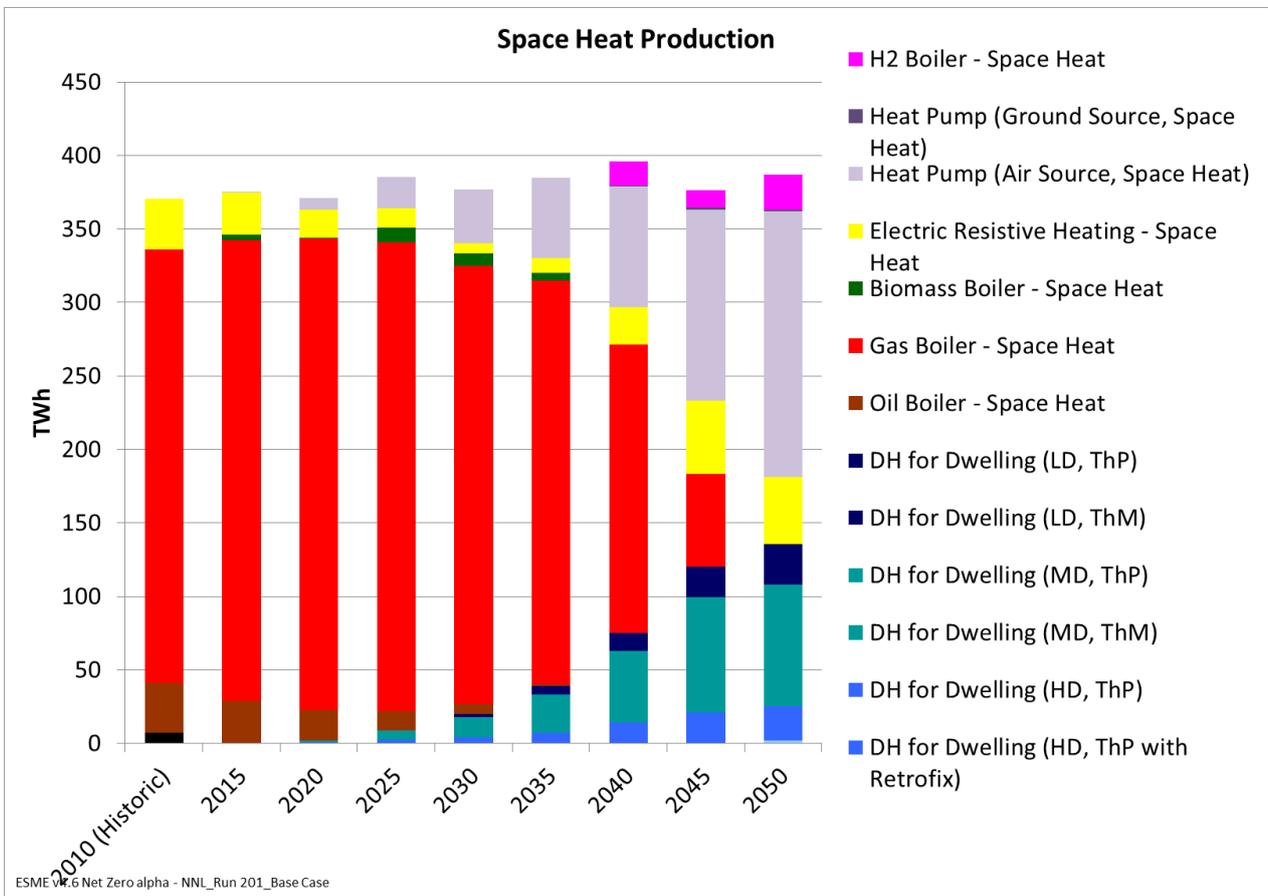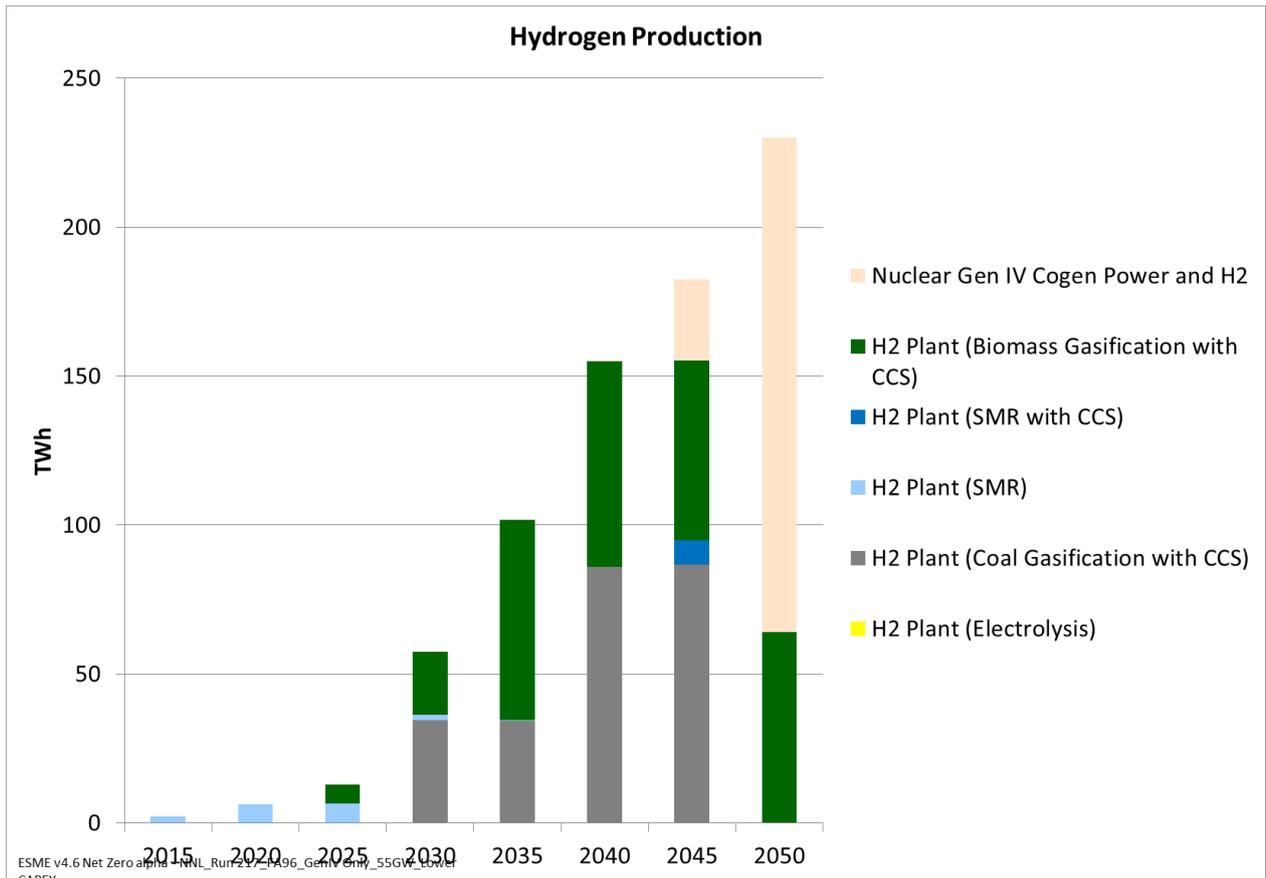

Figure A3-5 – Run 201 space heat production
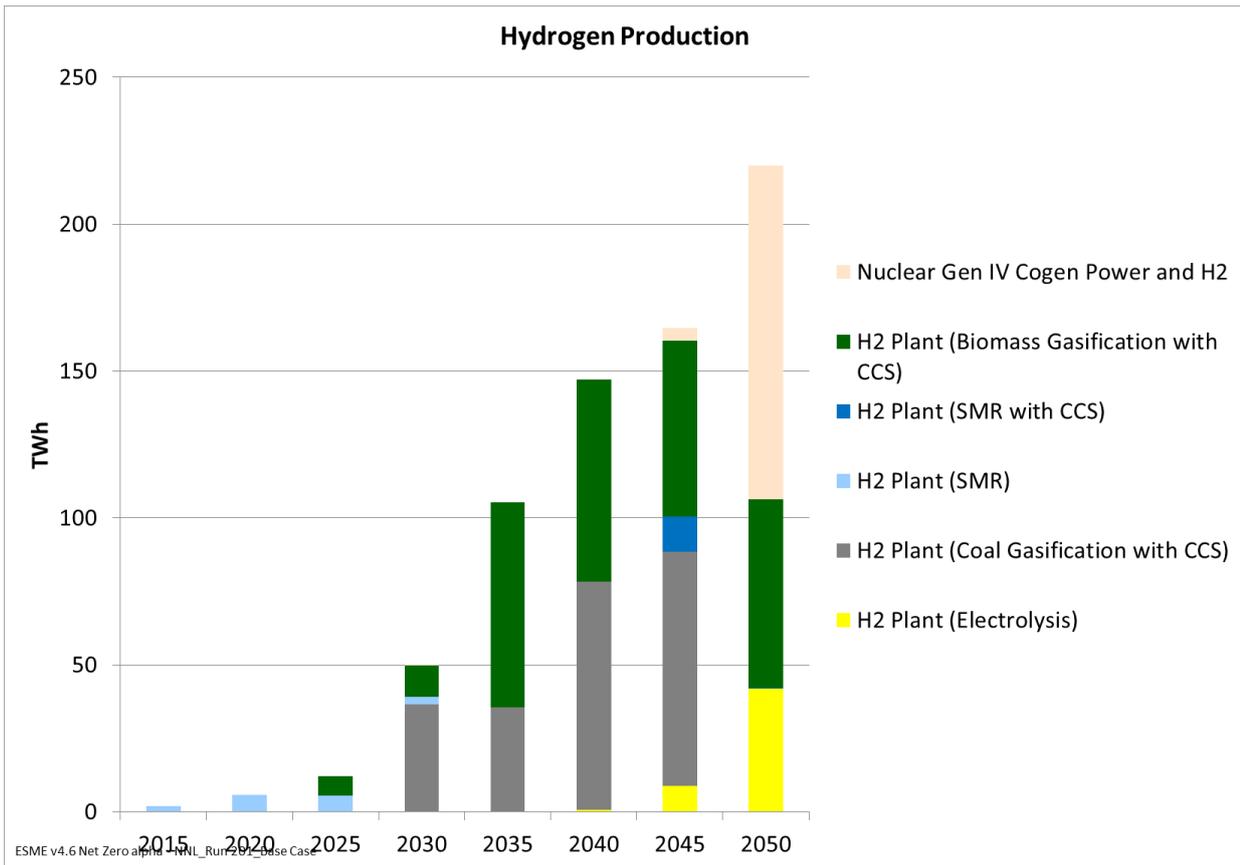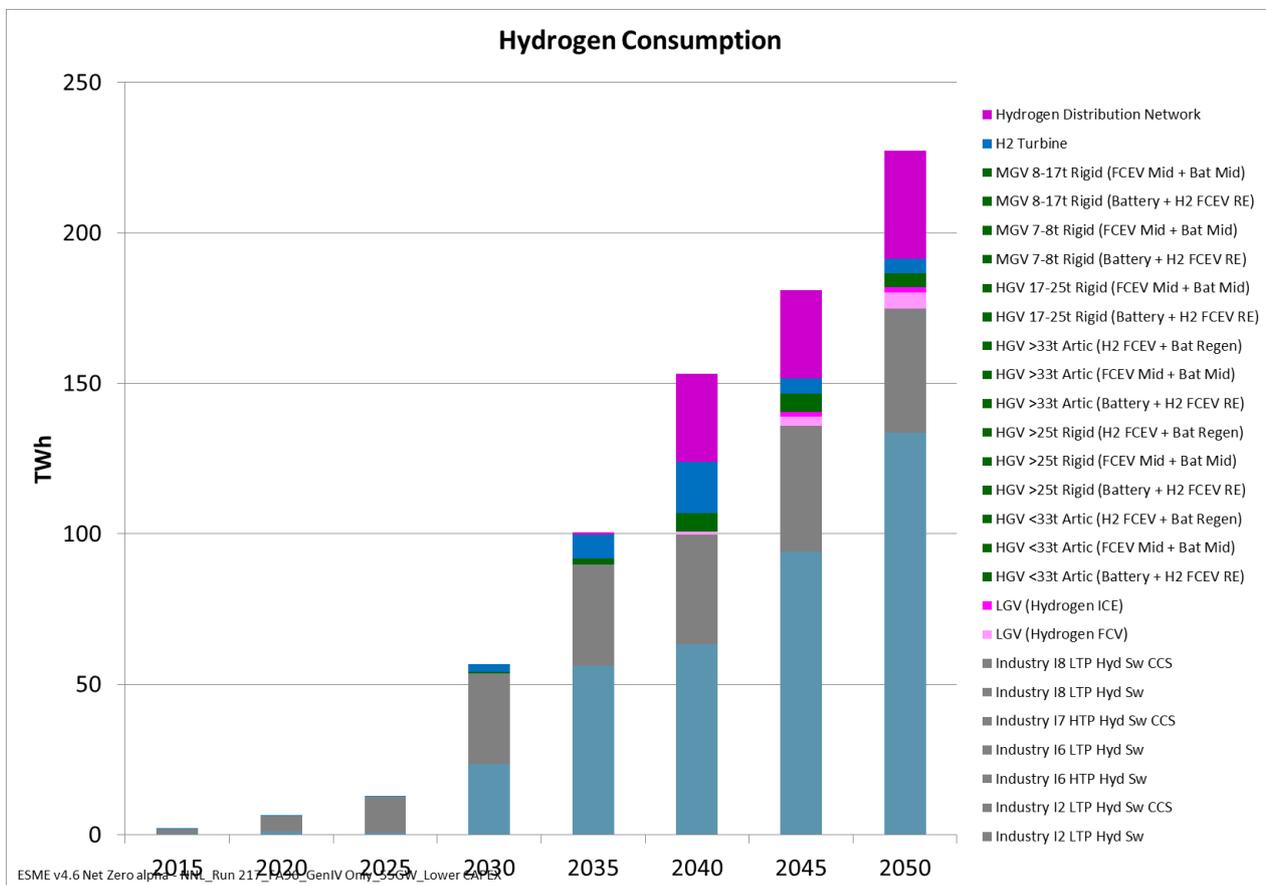
Figure A3-6 – Run 201 hydrogen production
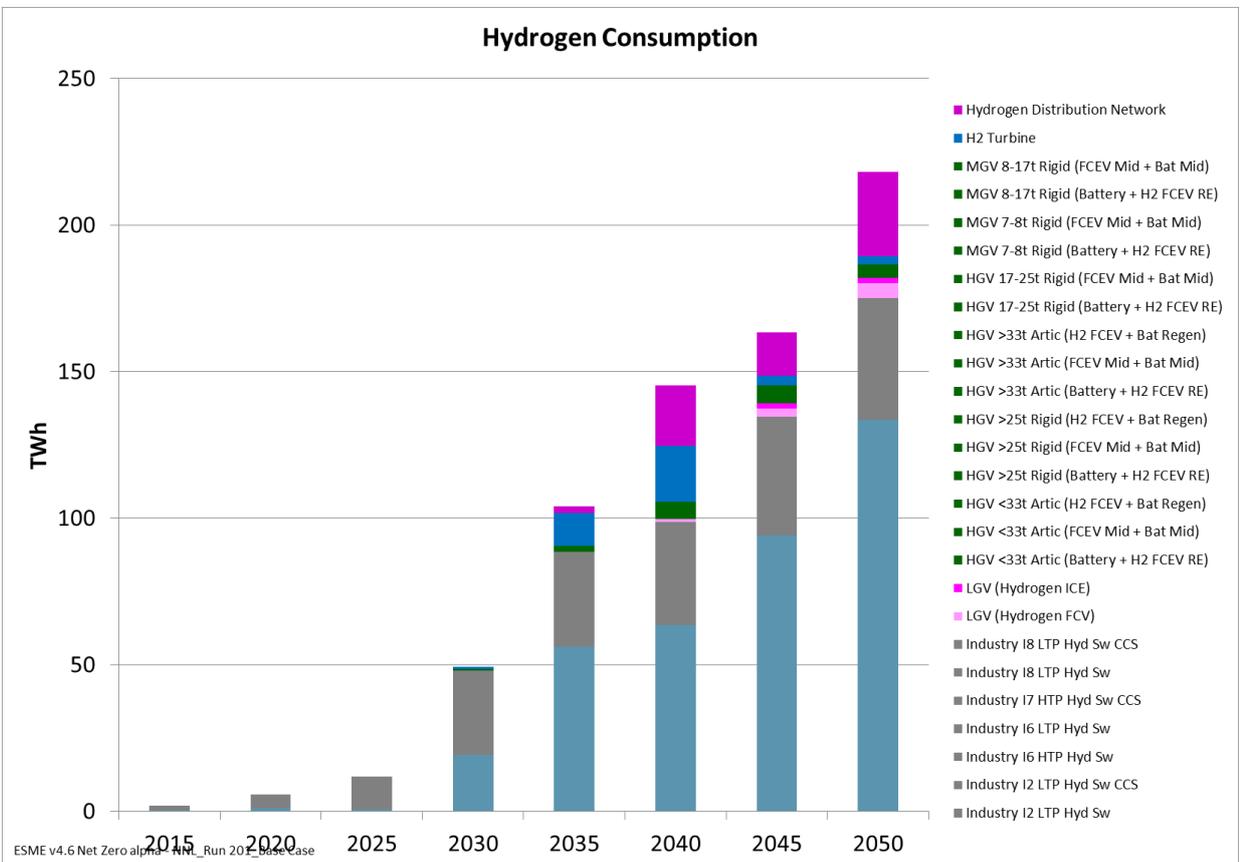

Figure A3-7 – Run 201 hydrogen consumption
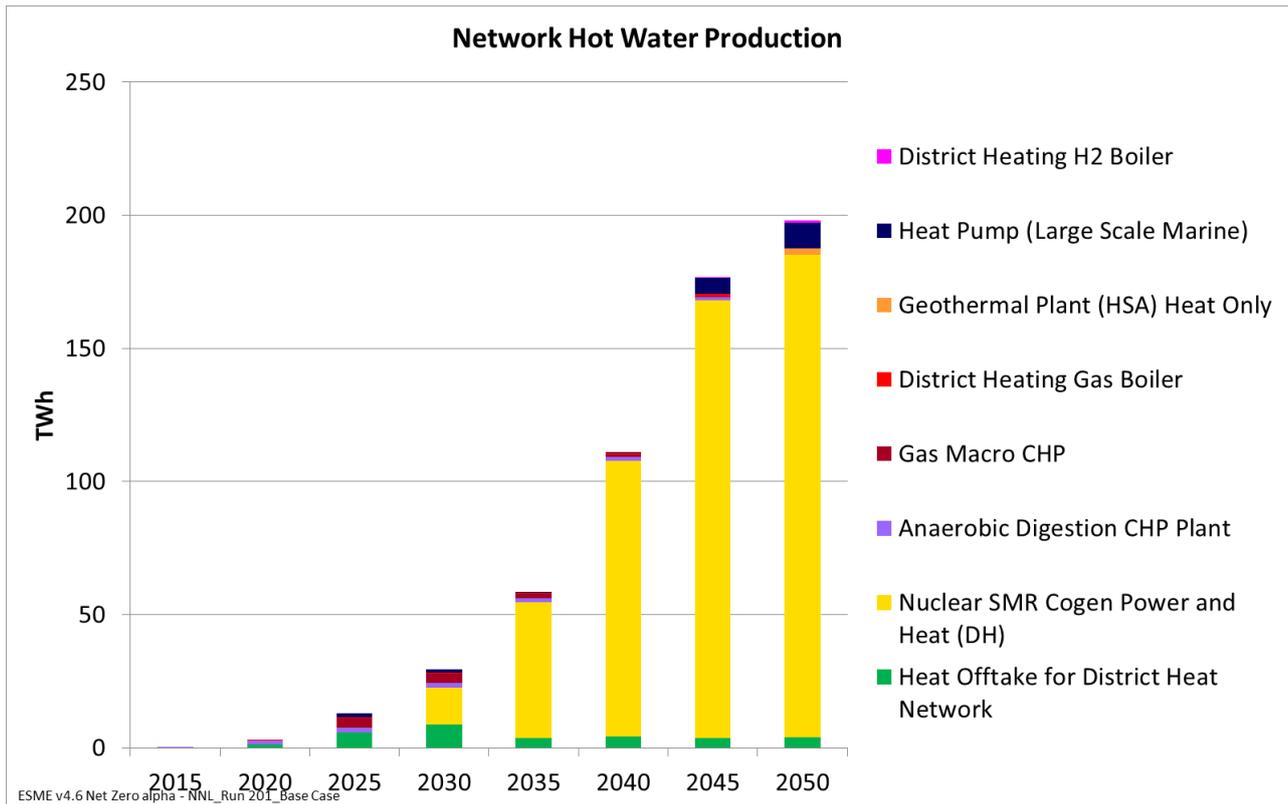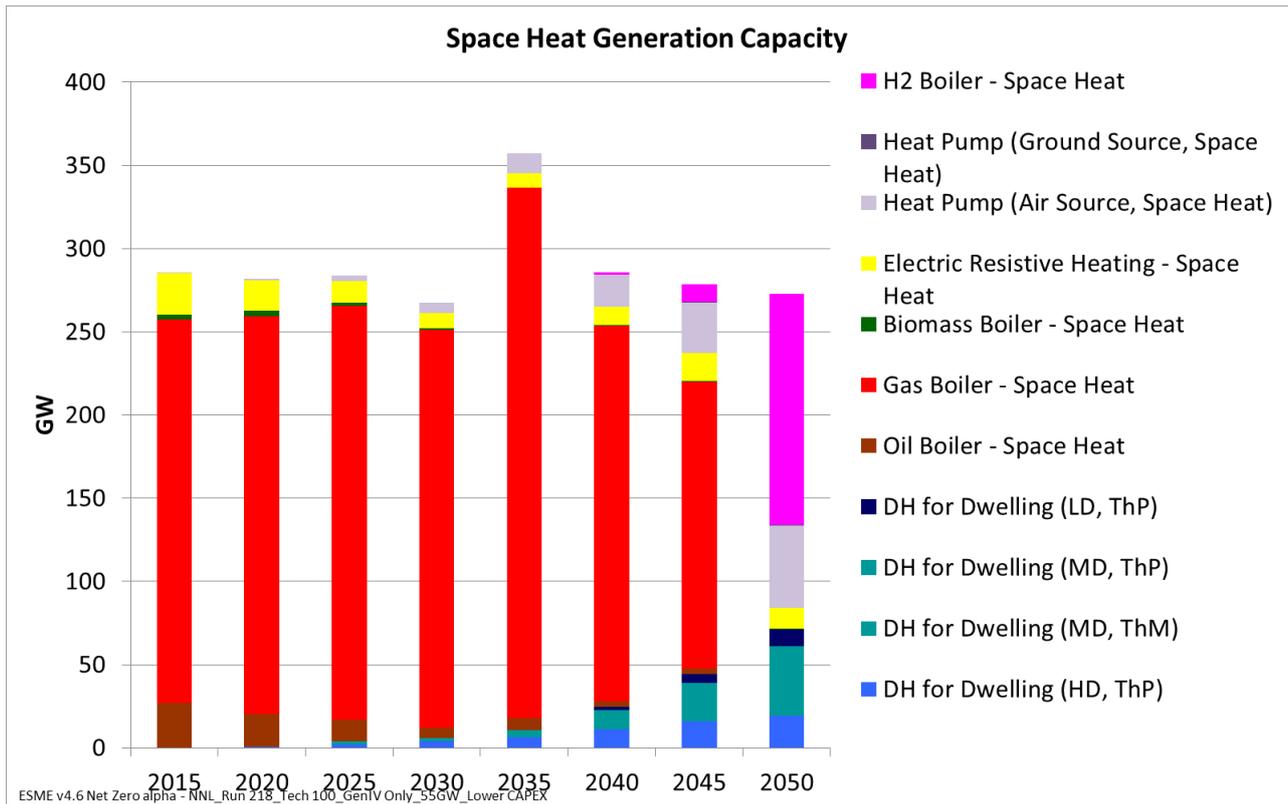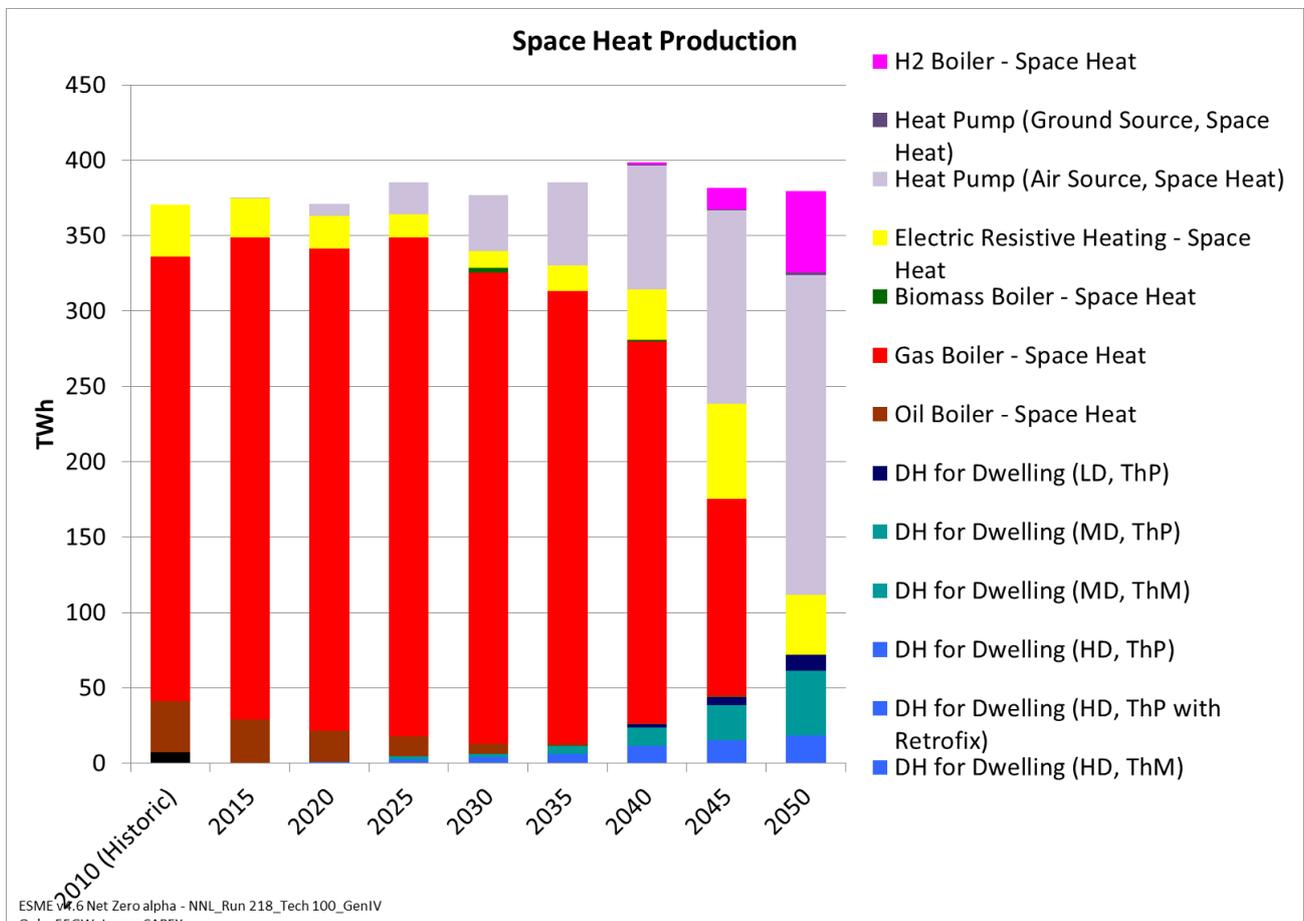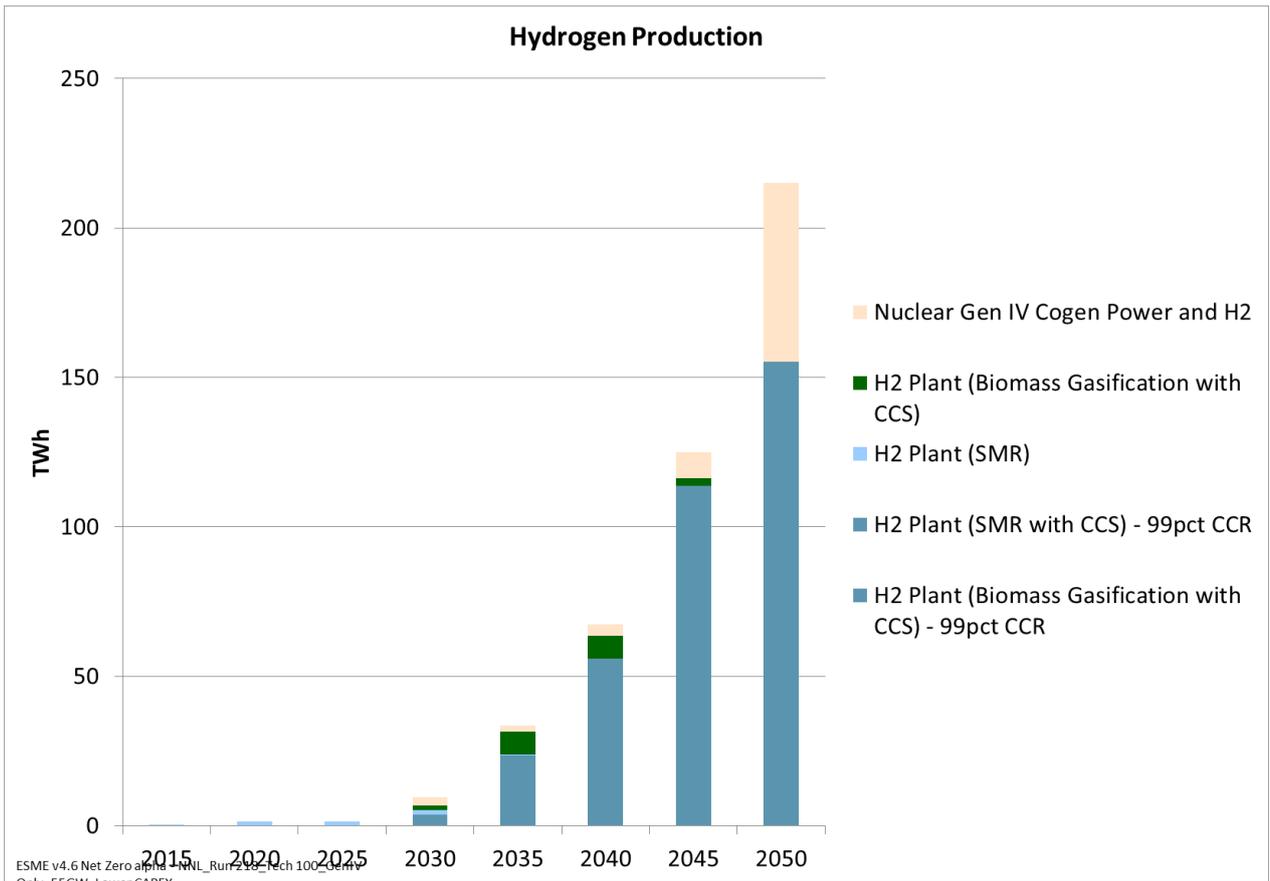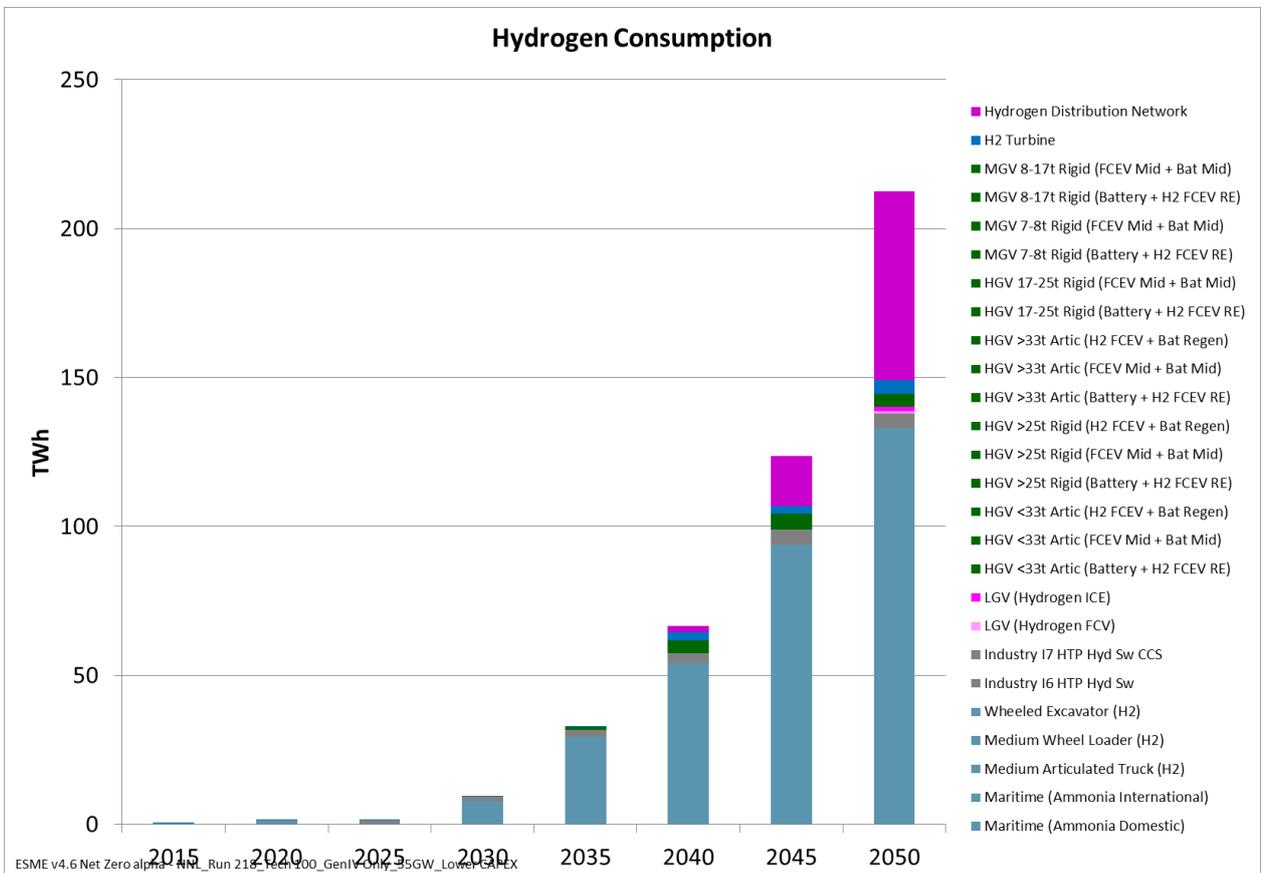
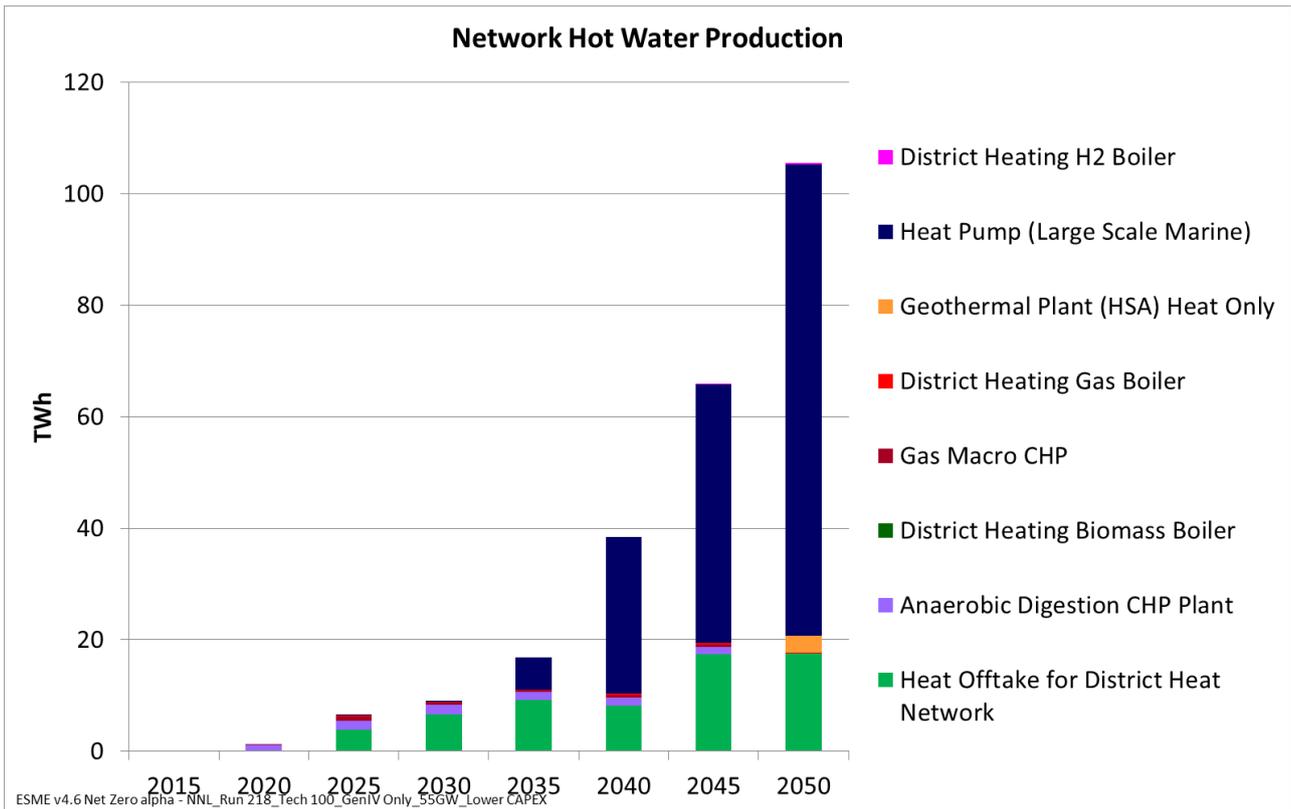Figure A3-8 – Run 201 network hot water production
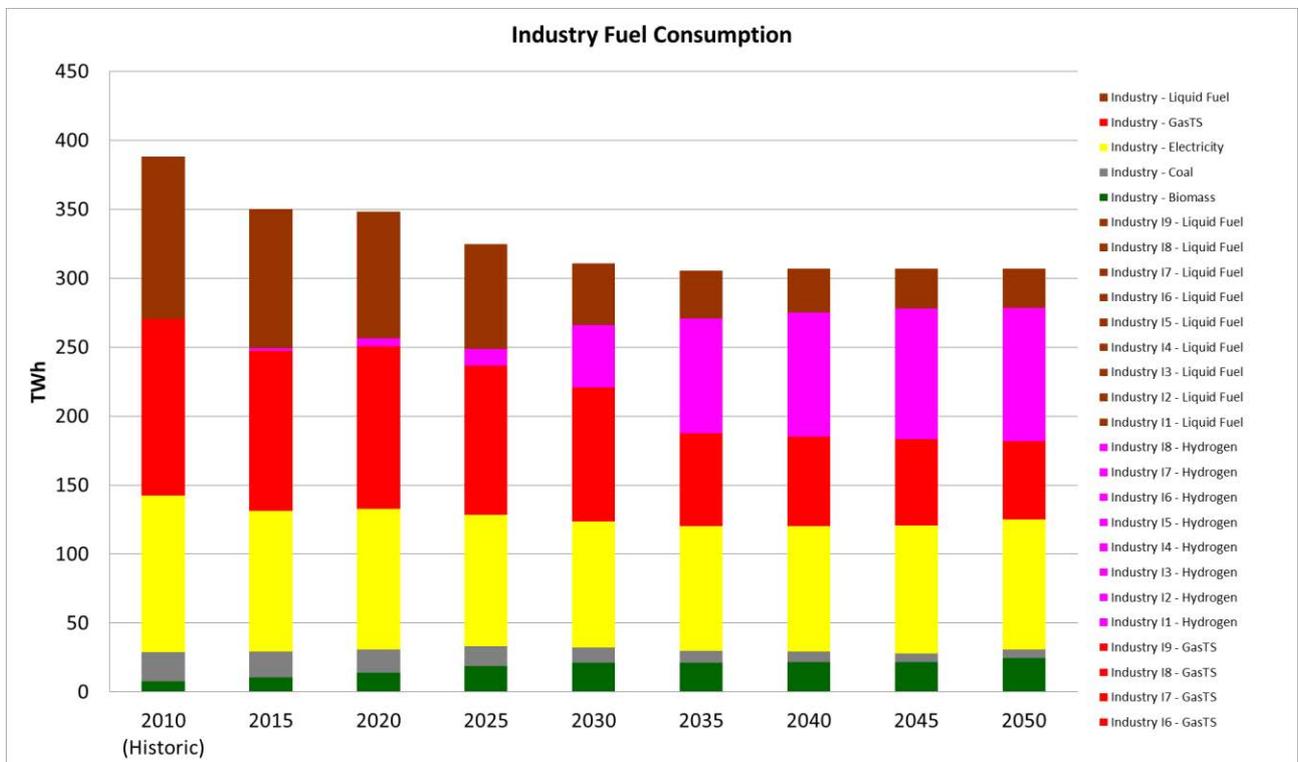
Figure A3-9 – Run 201 industry fuel consumption

## Run 202 TECH100 – All nuclear technologies; base case data
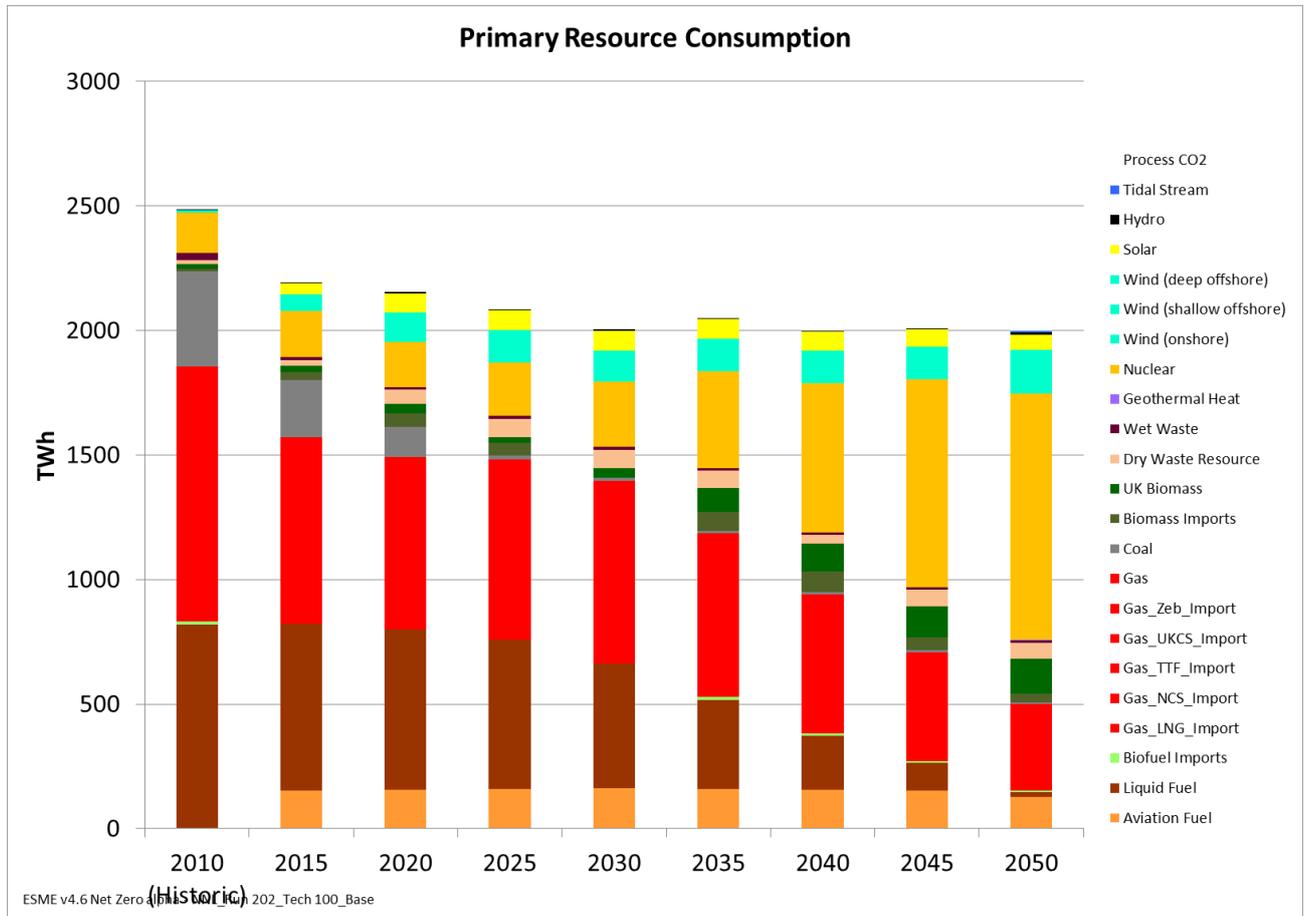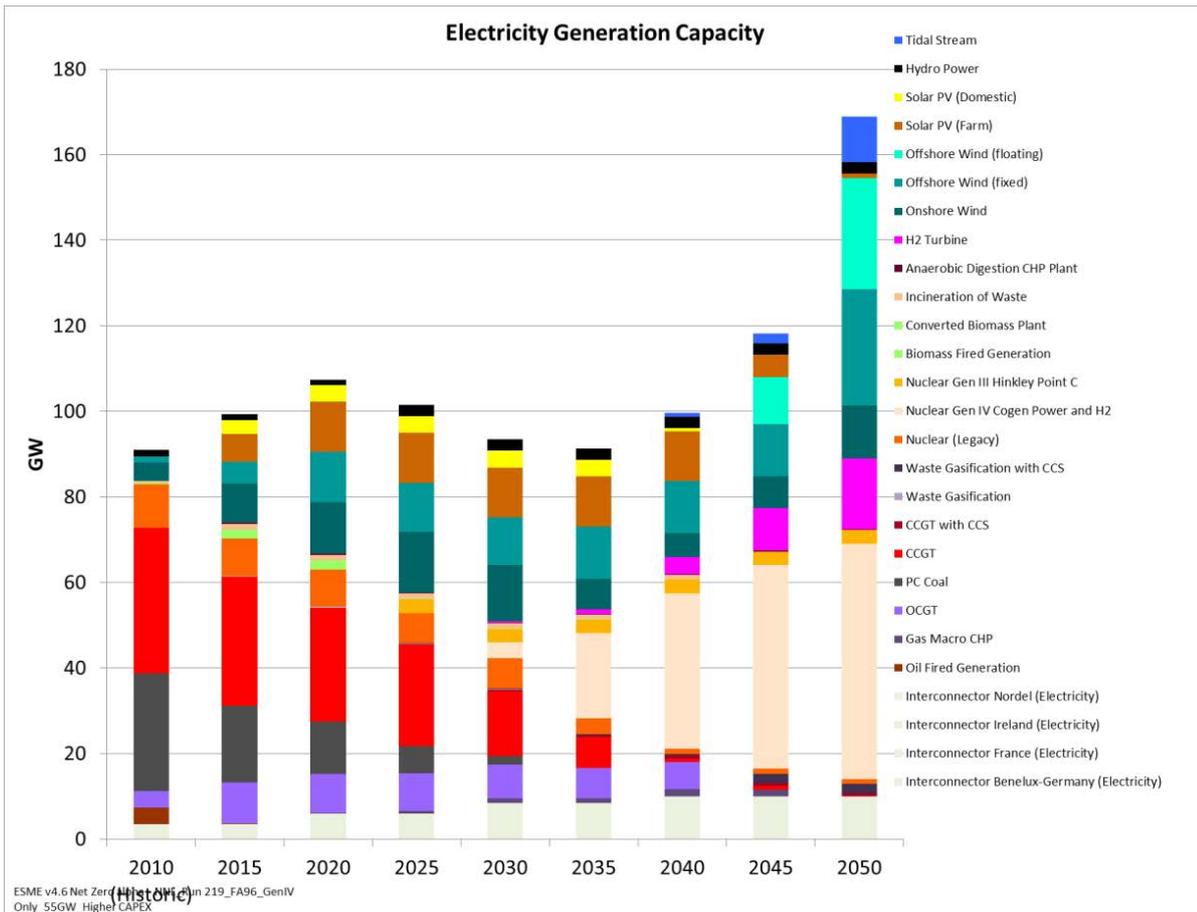

Figure A3-10 – Run 202 primary resource consumption
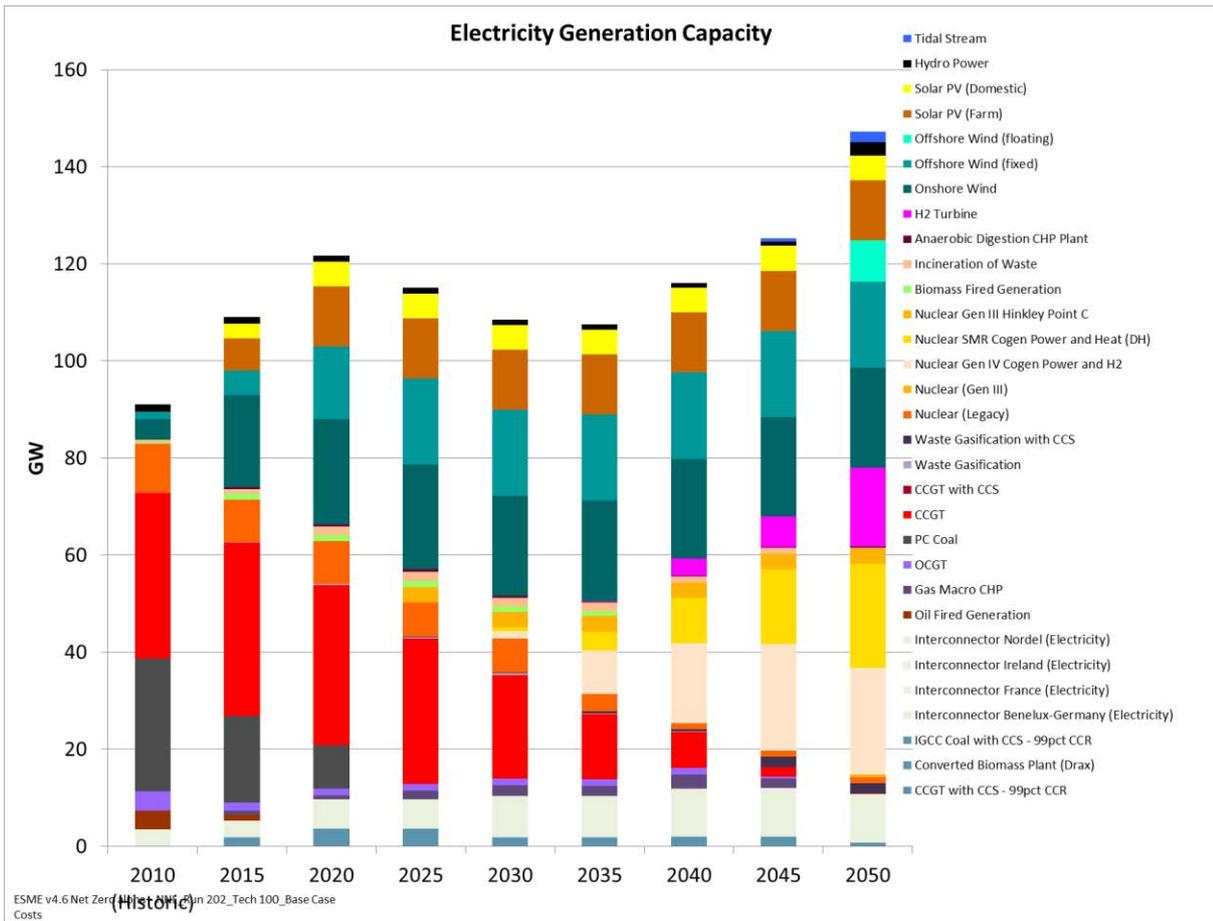
Figure A3-11 – Run 202 electricity generation capacity
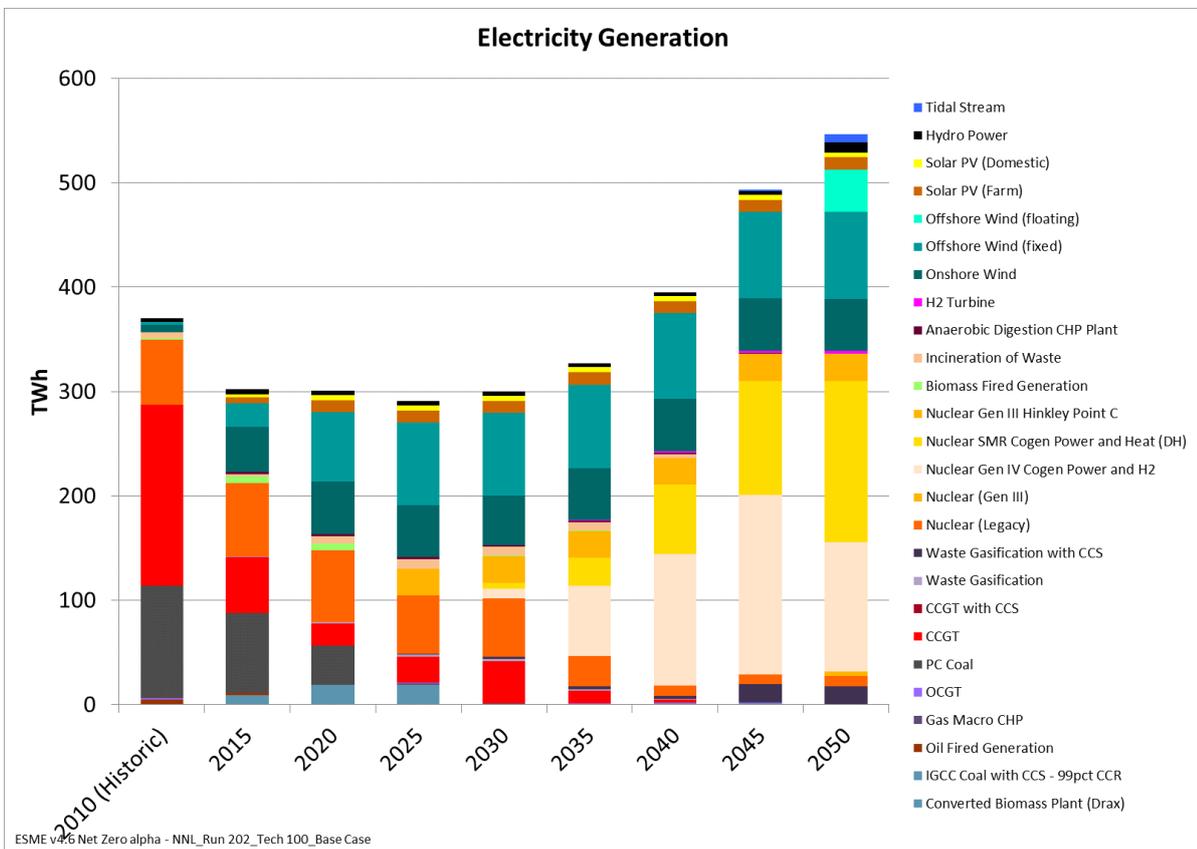
Figure A3-12 – Run 202 electricity generation
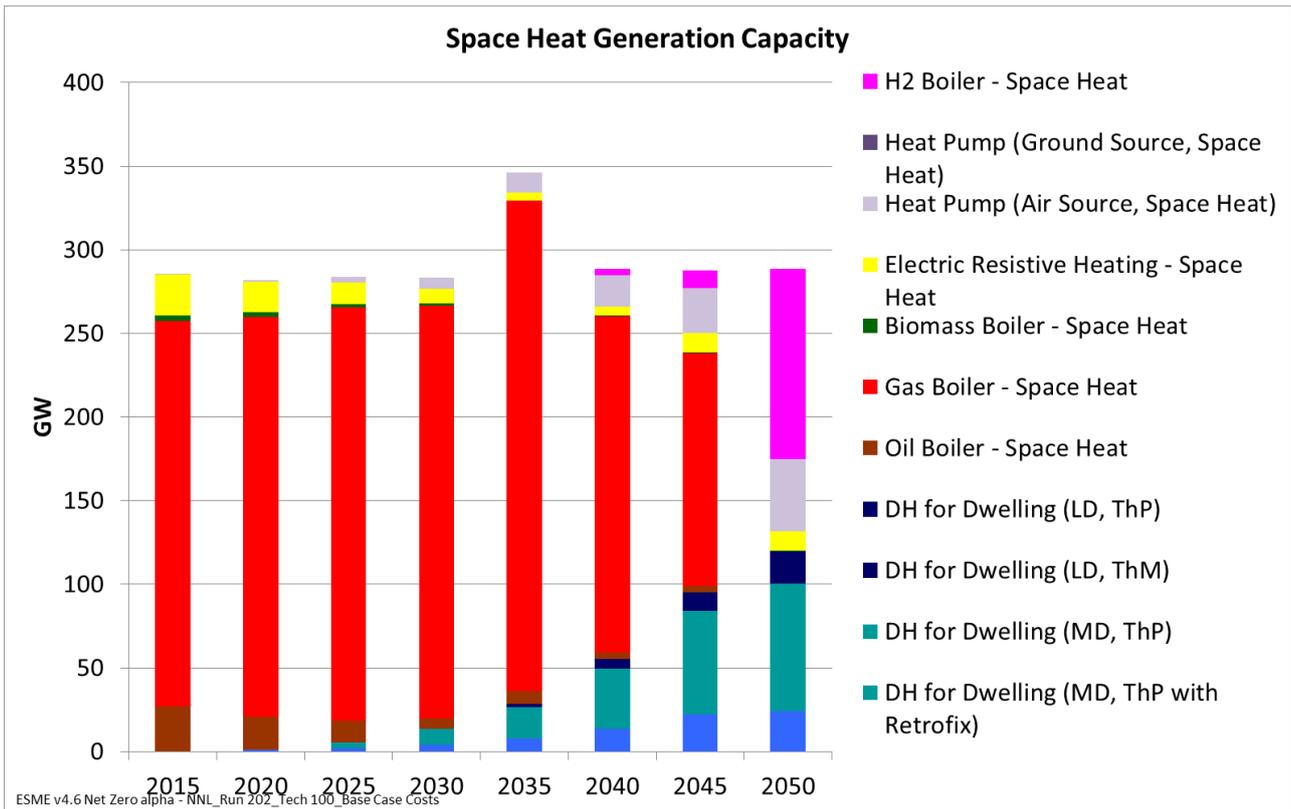
Figure A3-13 – Run 202 space heat generation capacity
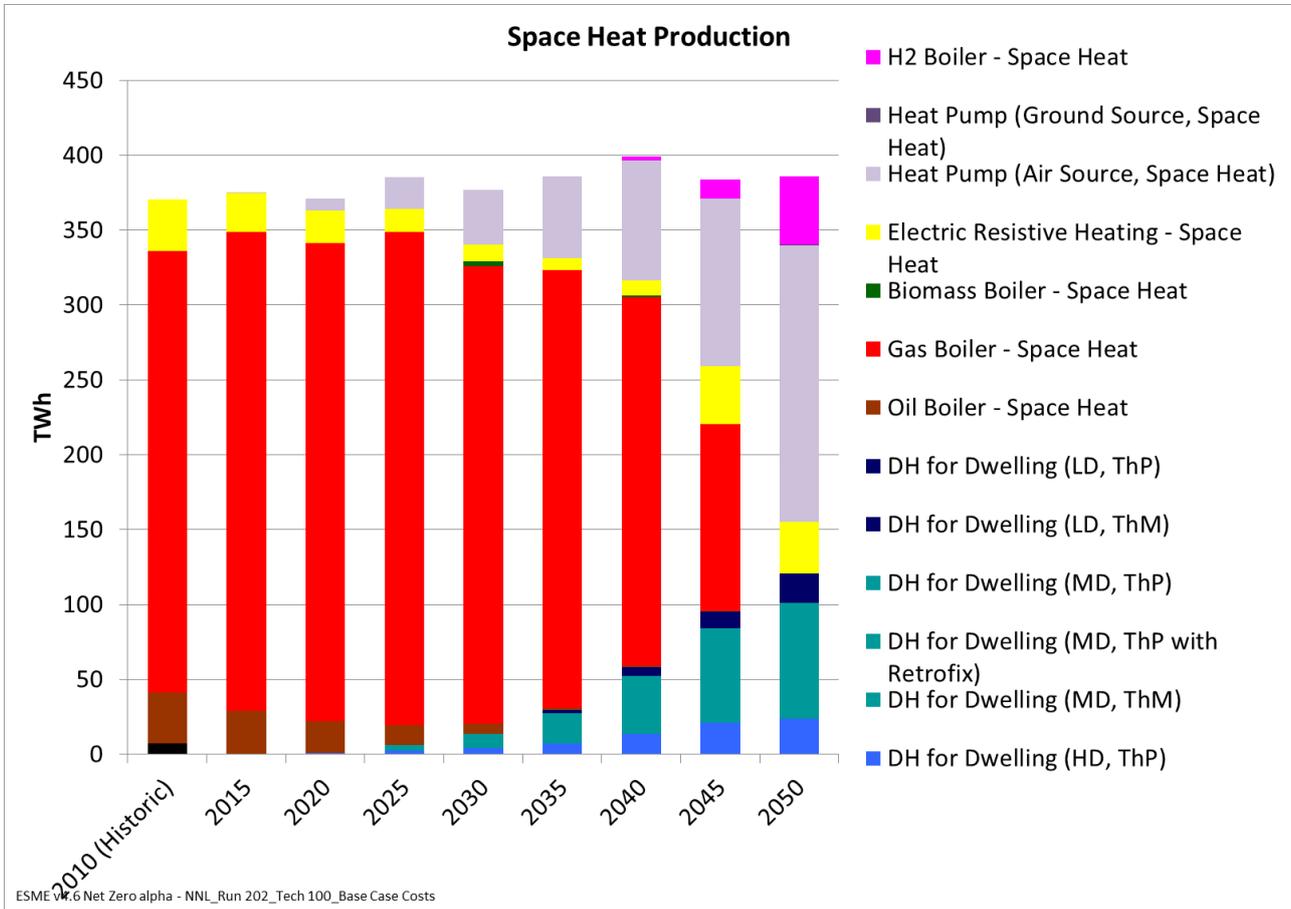
Figure A3-14 – Run 202 space heat production
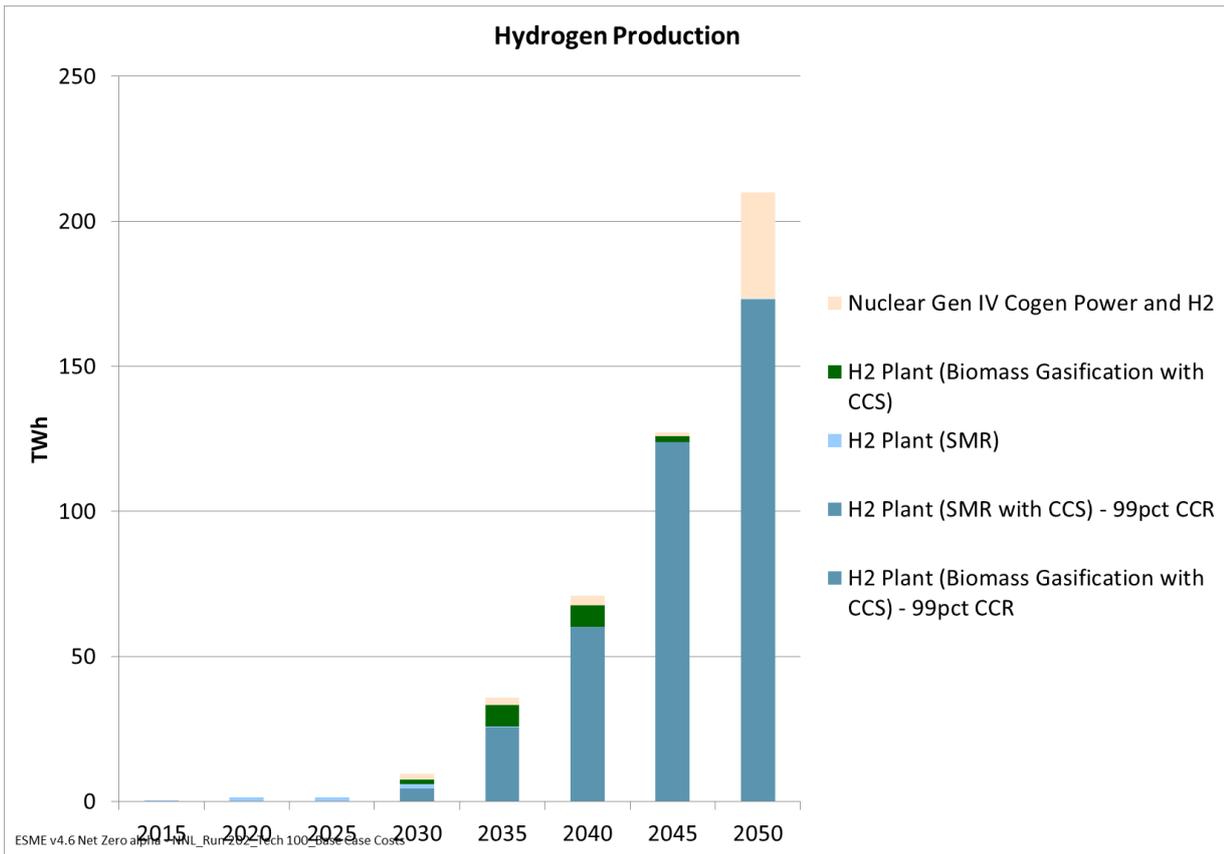
Figure A3-15 – Run 202 hydrogen production
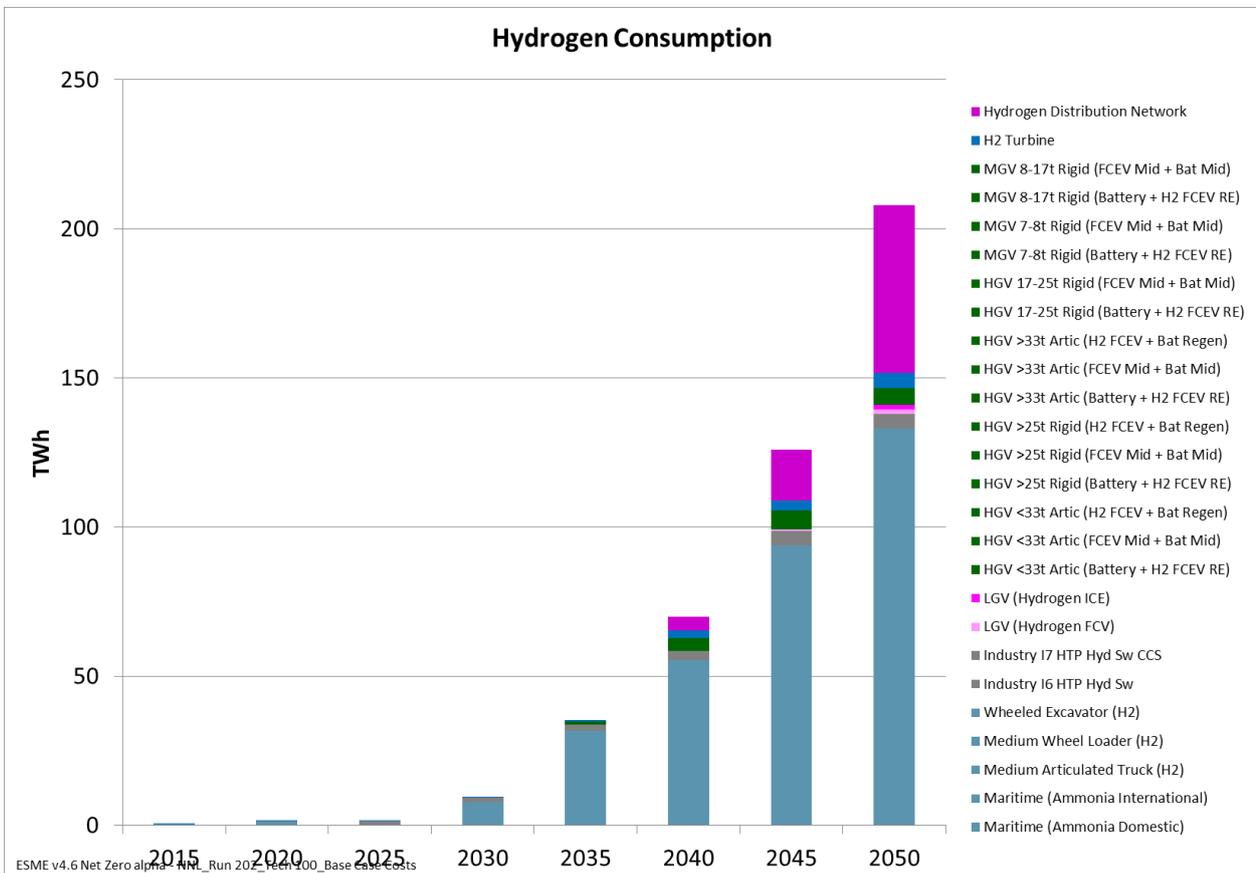
Figure A3-16 – Run 202 hydrogen consumption
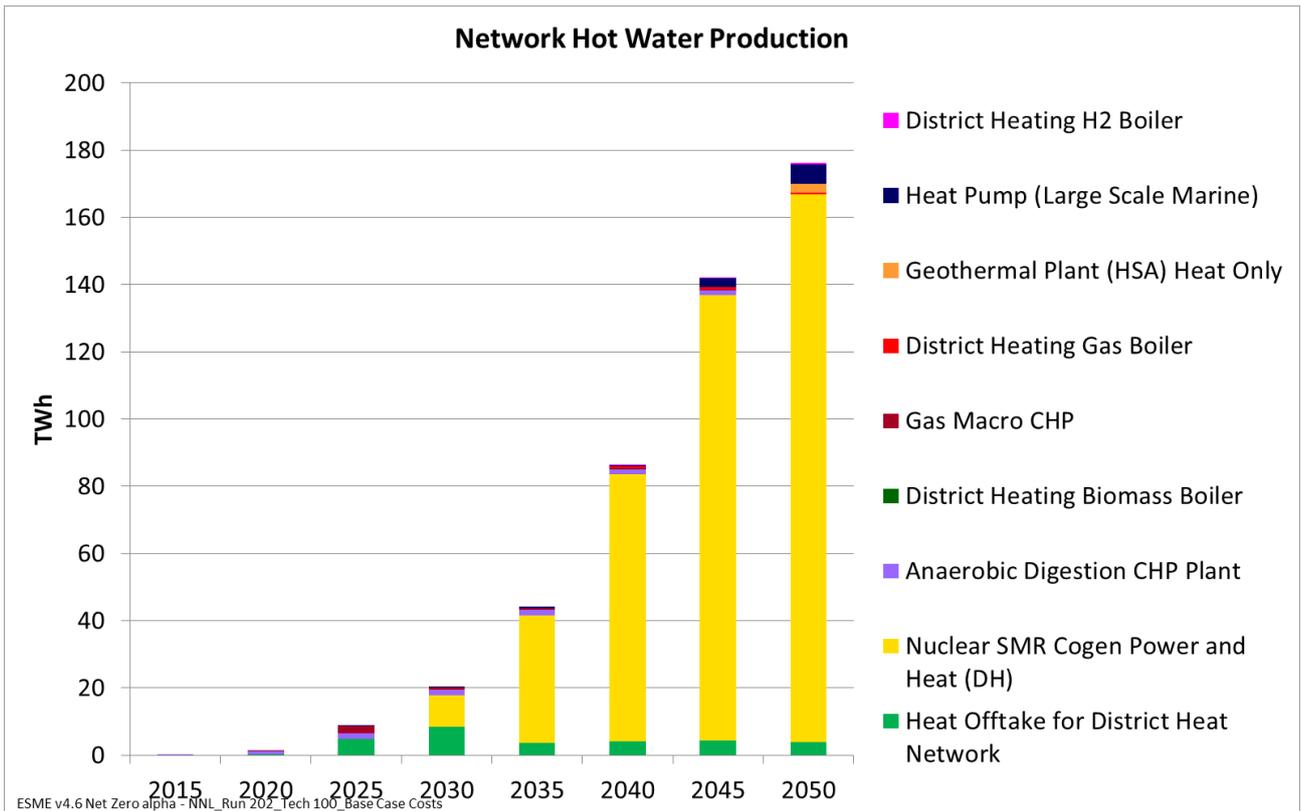
Figure A3-17 – Run 202 network hot water production
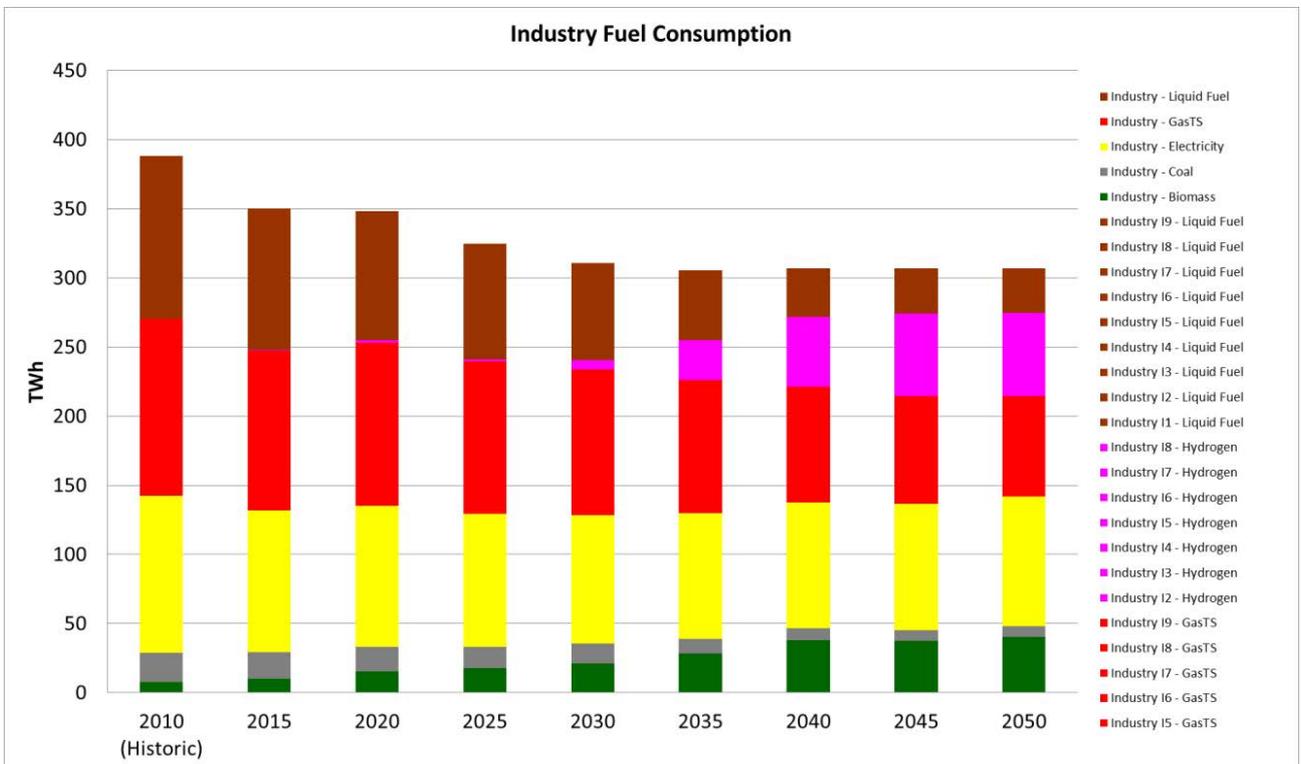
Figure A3-18 – Run 202 industry fuel consumption

Run 203 BOB100 – All nuclear technologies; base case data
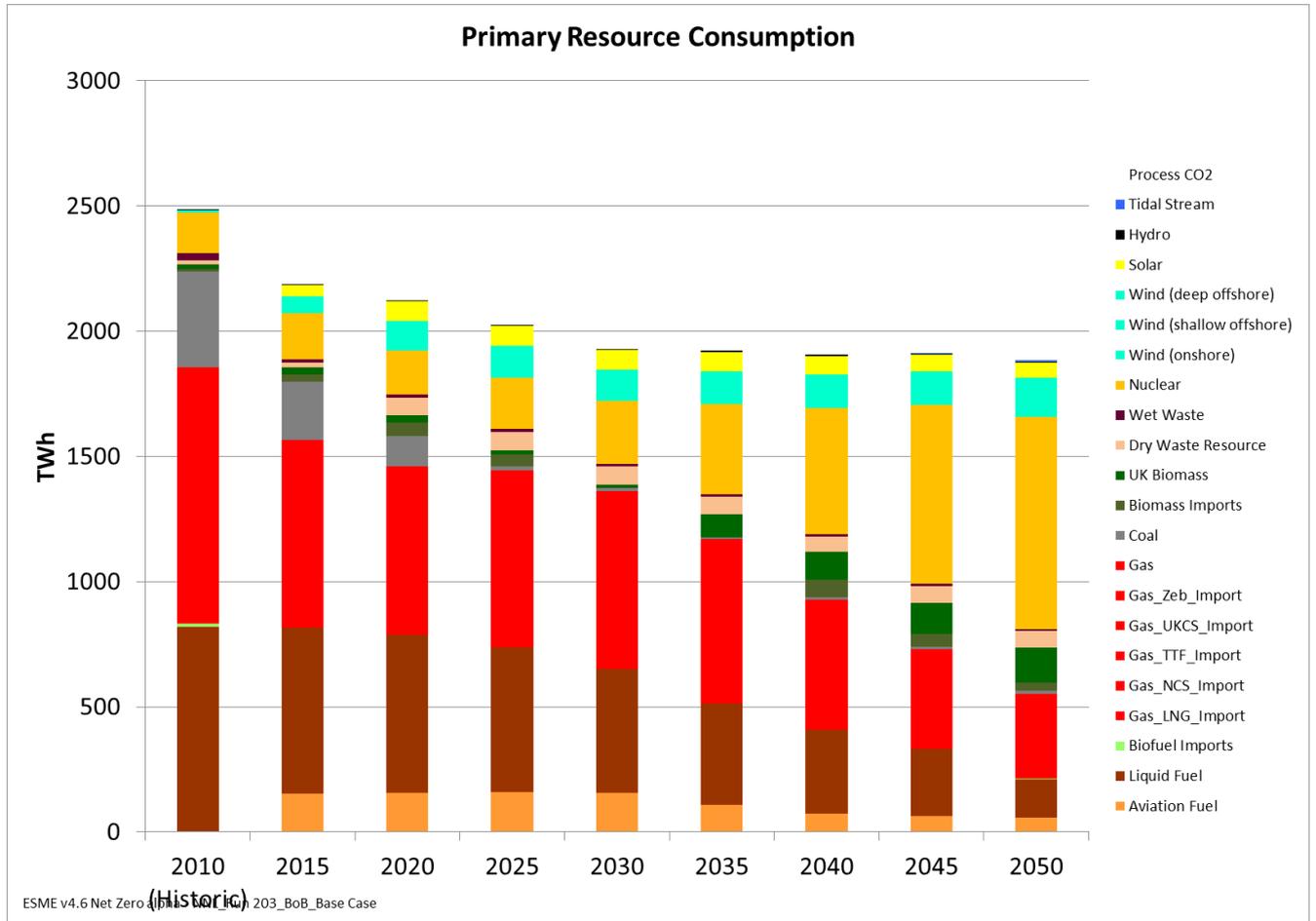
Figure A3-19 – Run 203 primary resource consumption
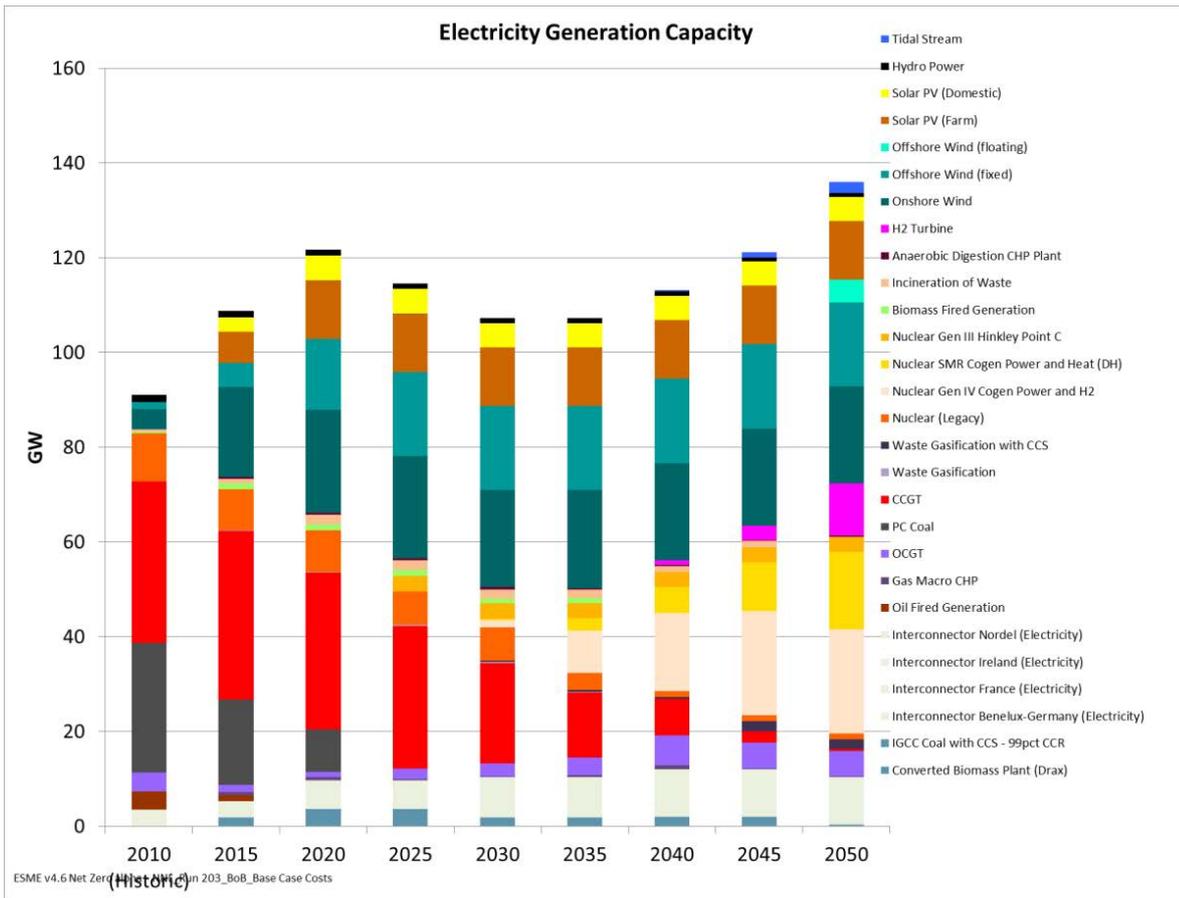
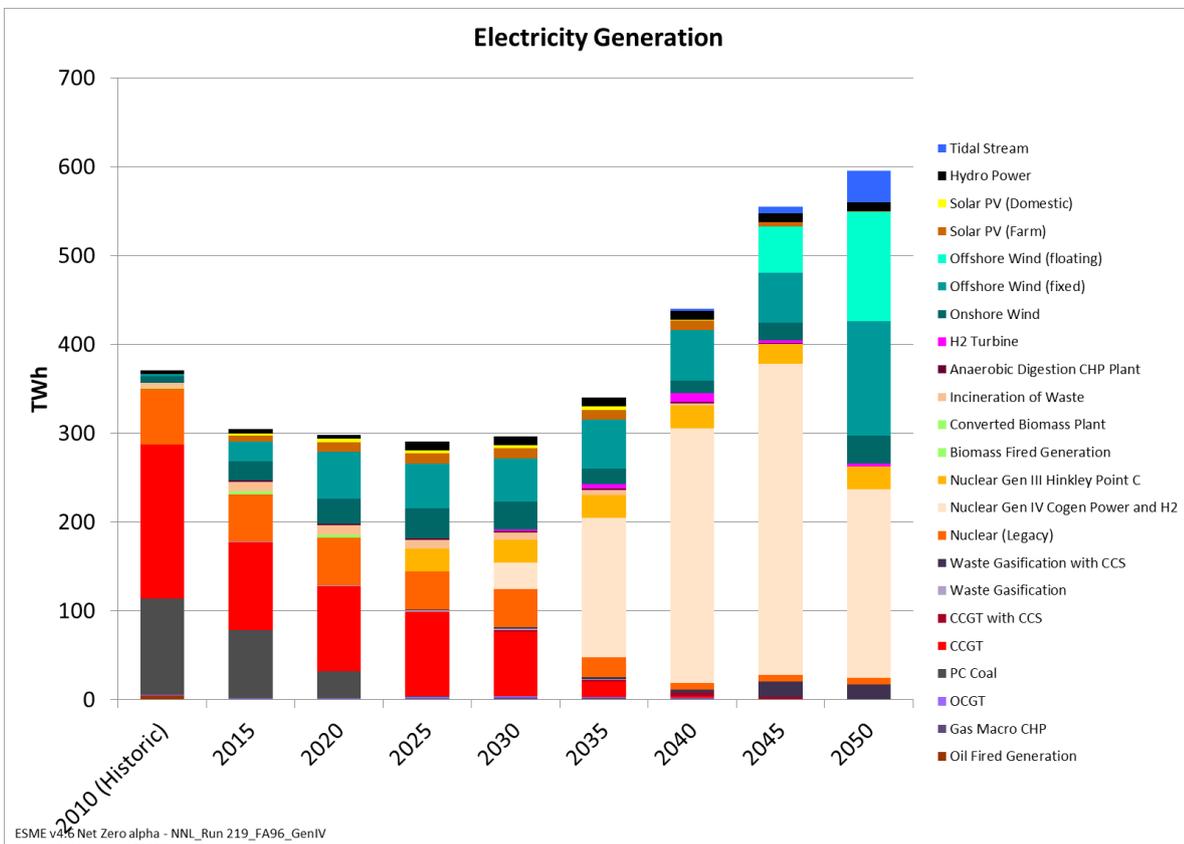Figure A3-20 – Run 203 electricity generation capacity
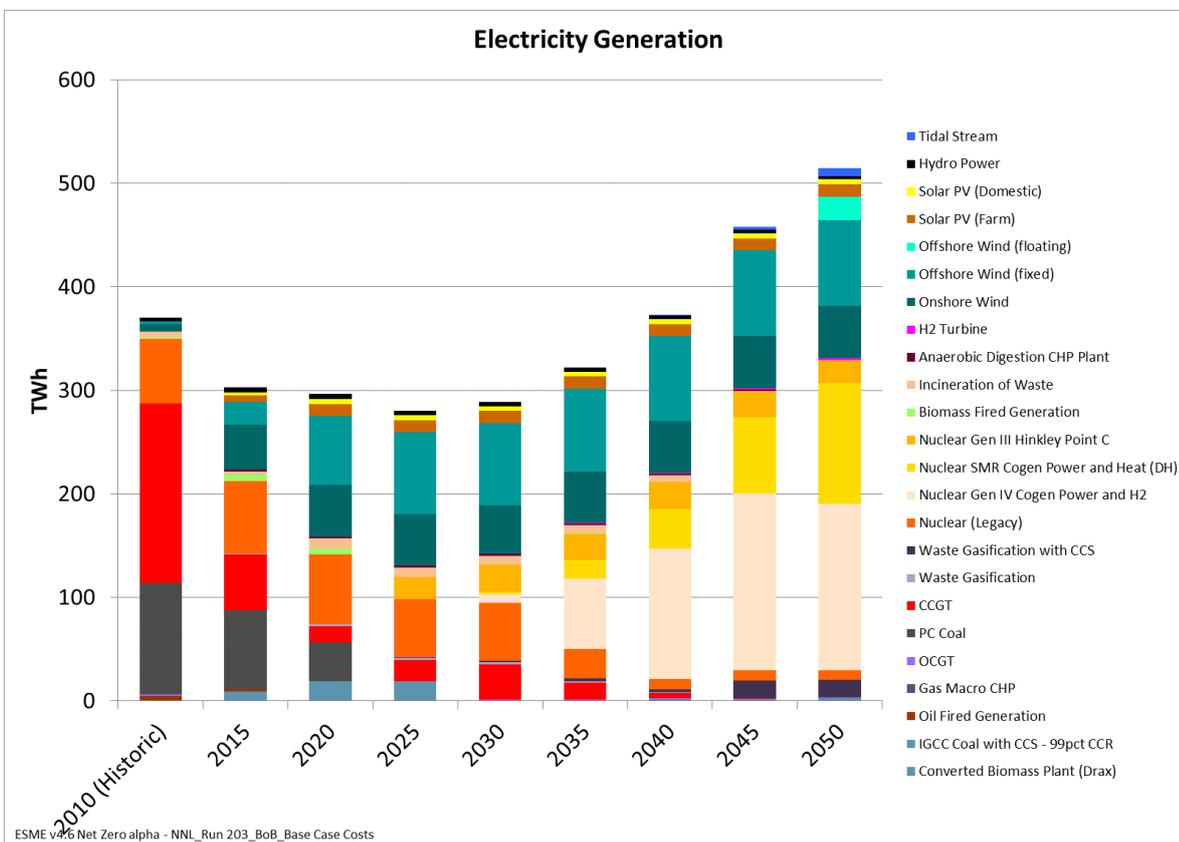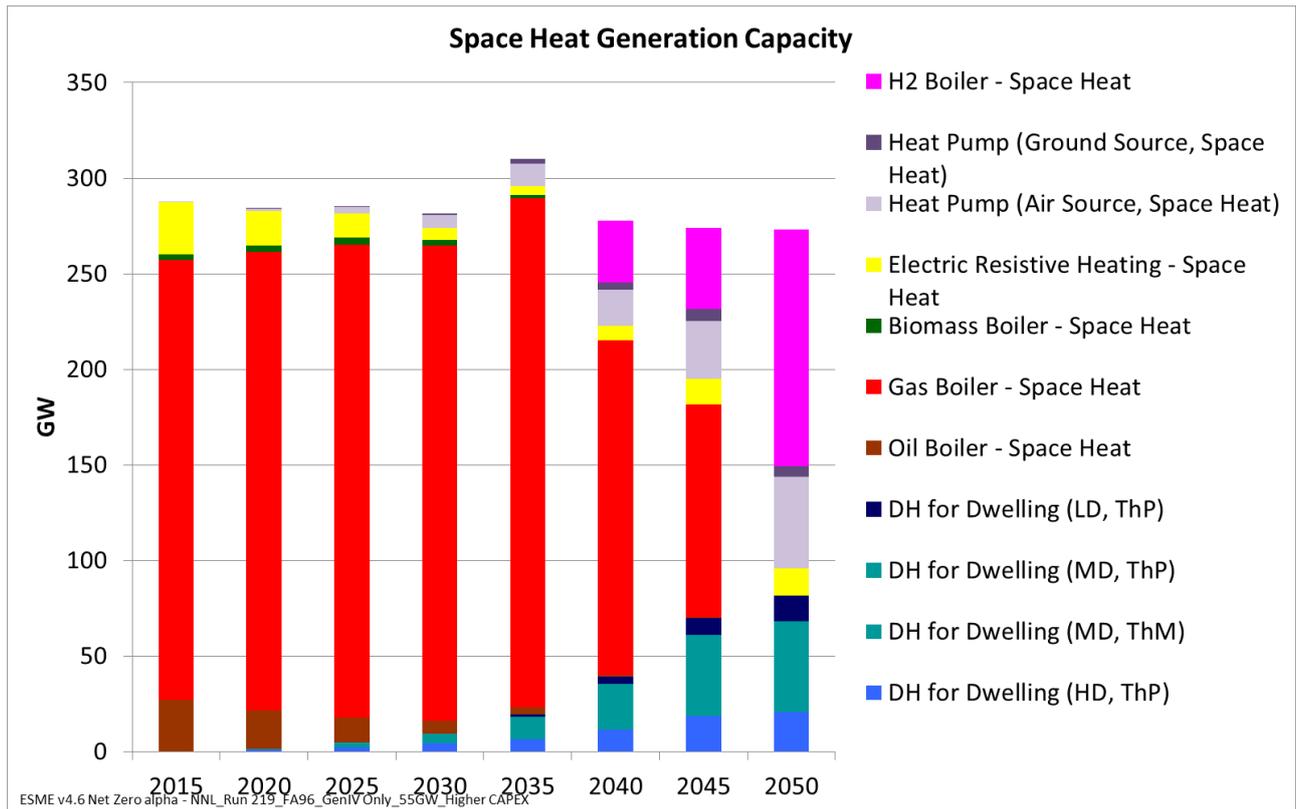

Figure A3-21 – Run 203 electricity generation
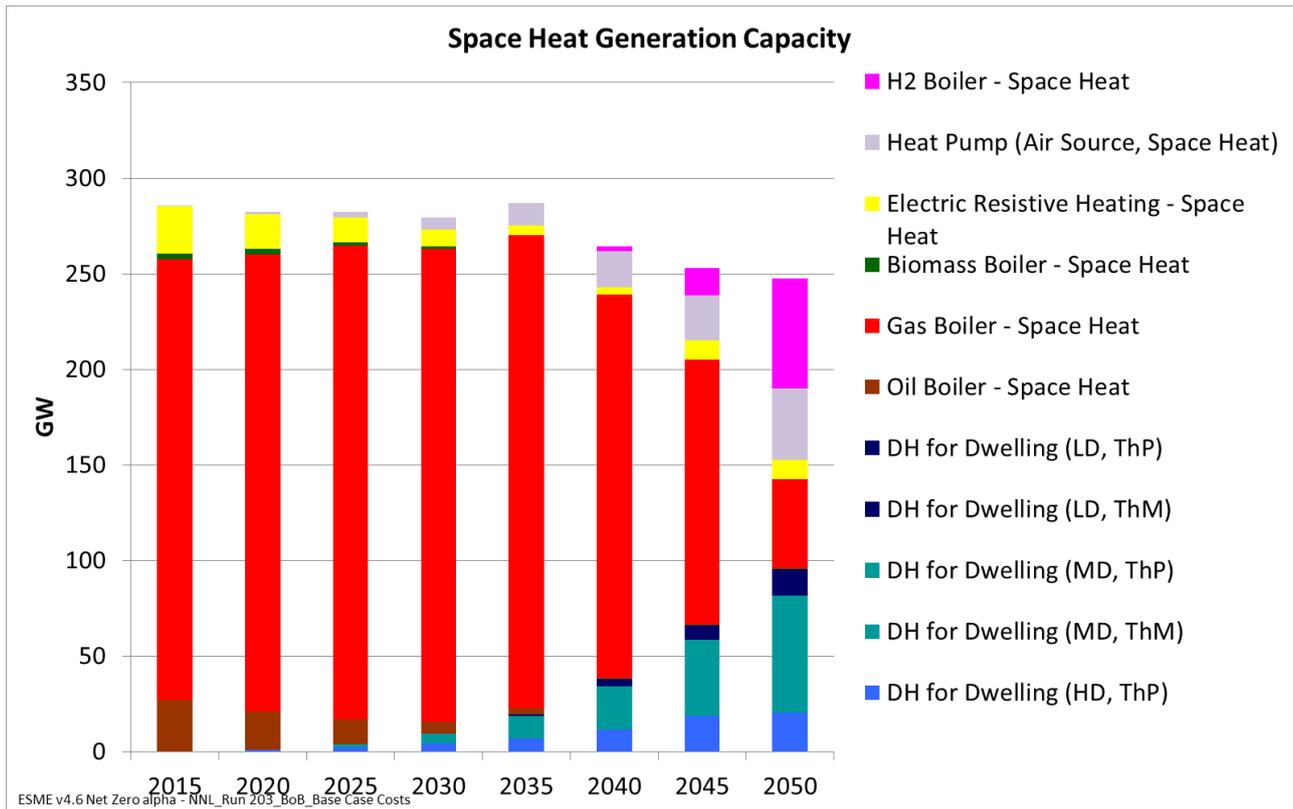
Figure A3-22 – Run 203 space heat generation capacity
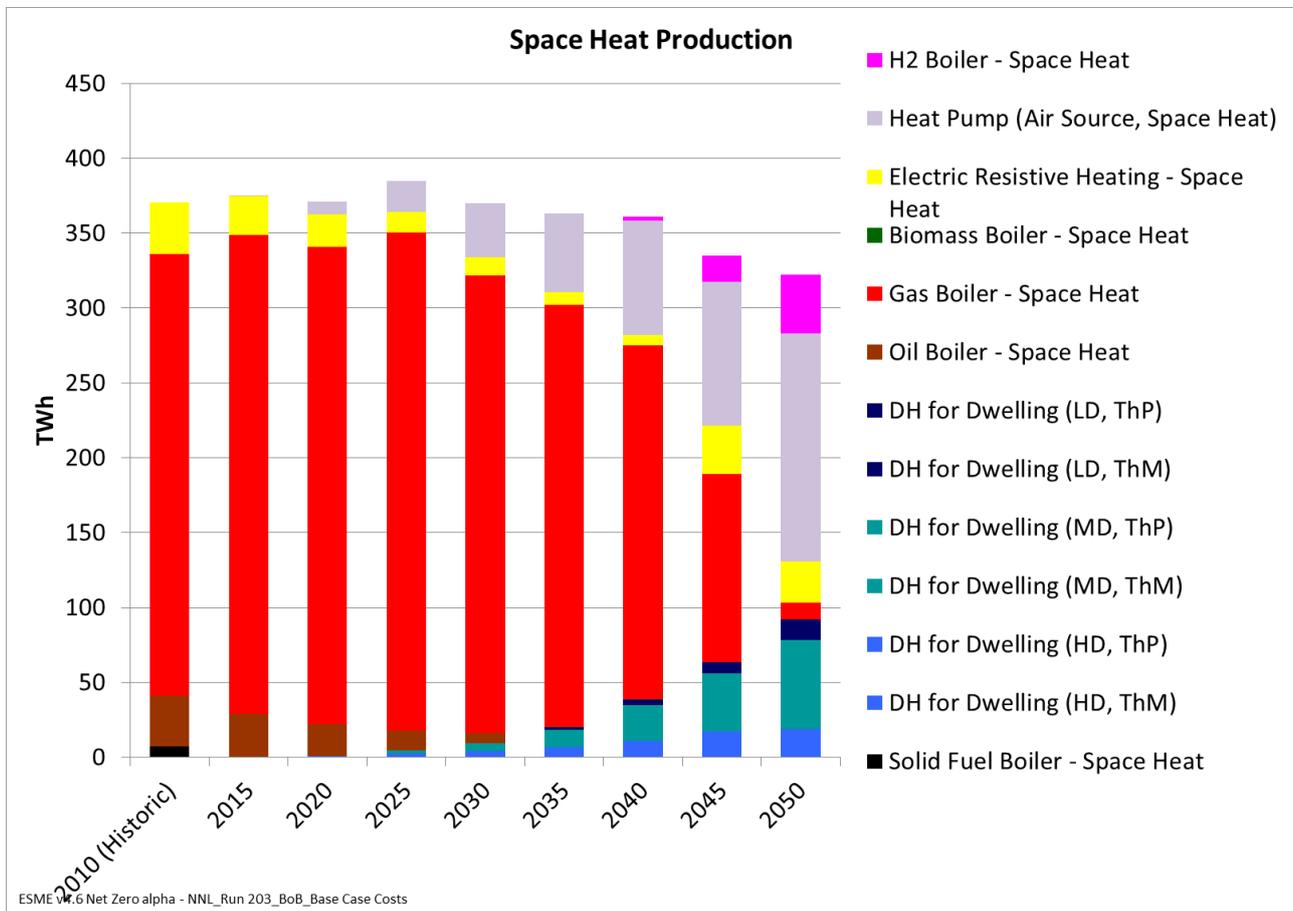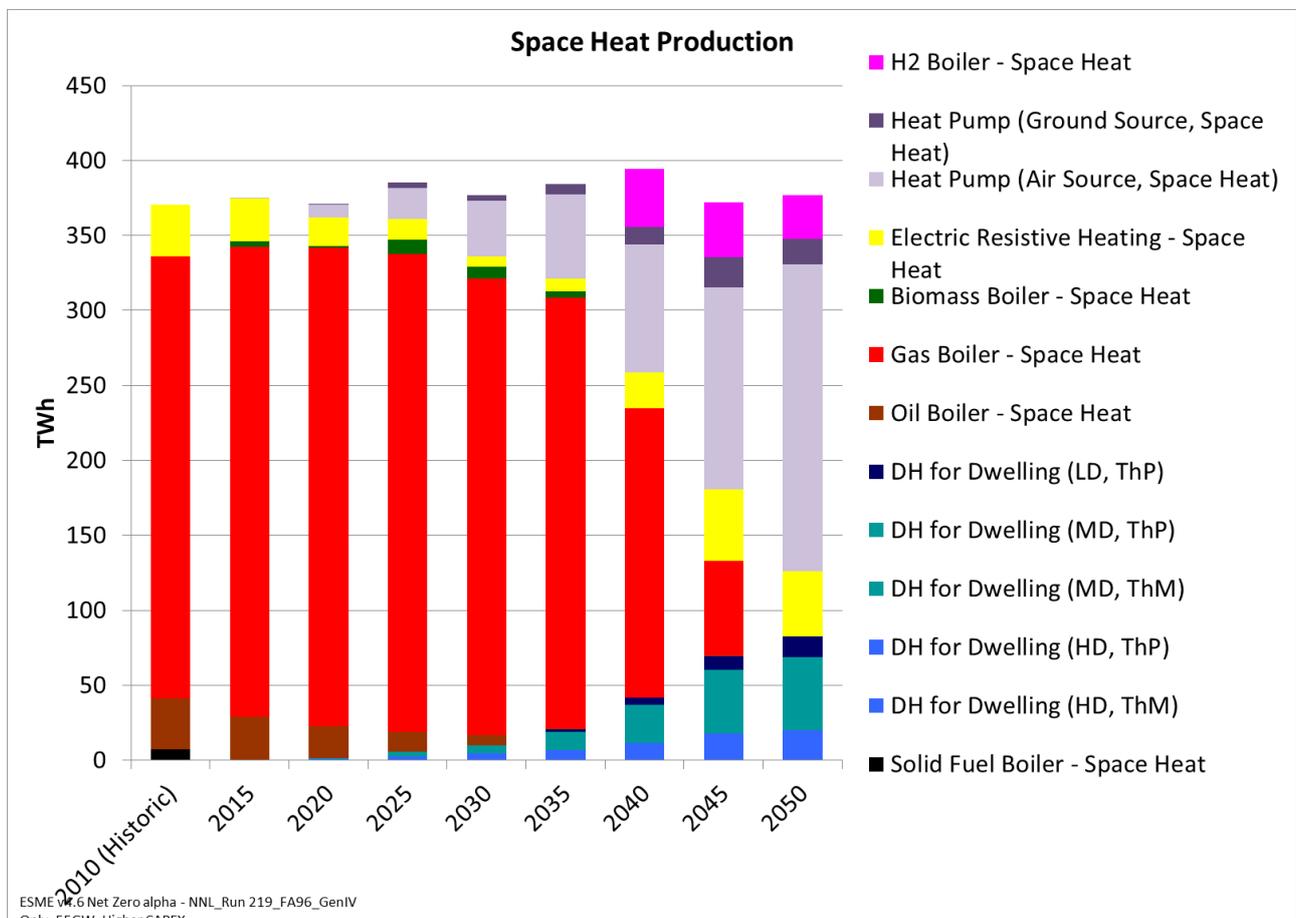

Figure A3-23 – Run 203 space heat production
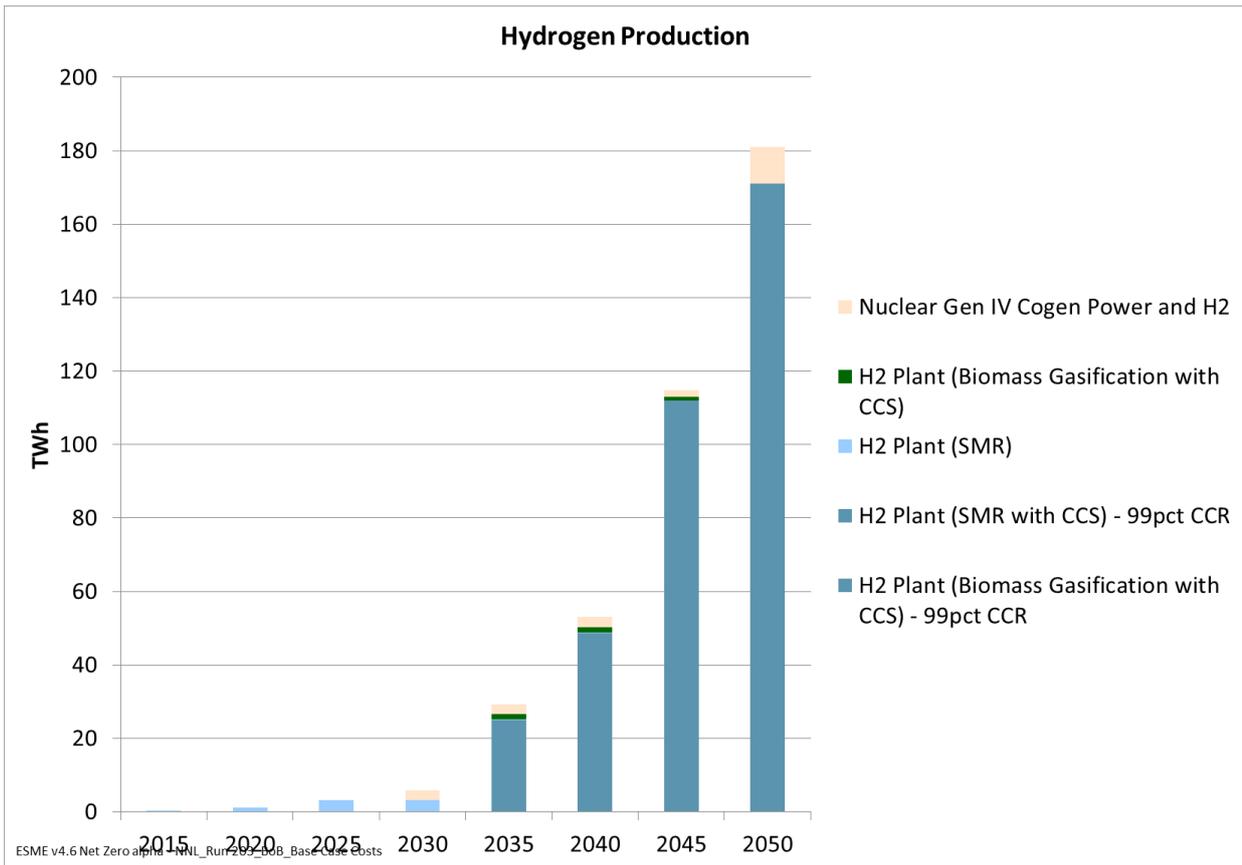
Figure A3-24 – Run 203 hydrogen production
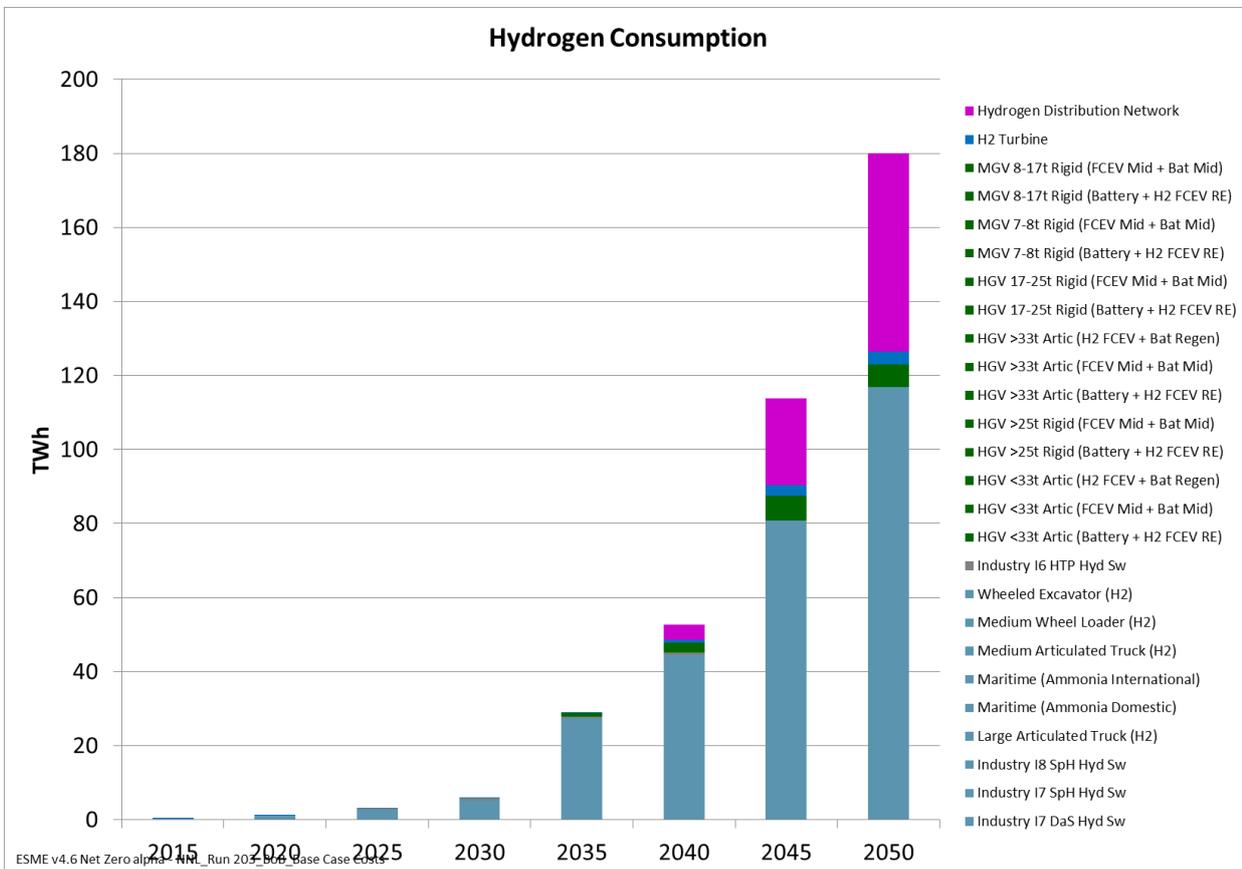
Figure A3-25 – Run 203 hydrogen consumption
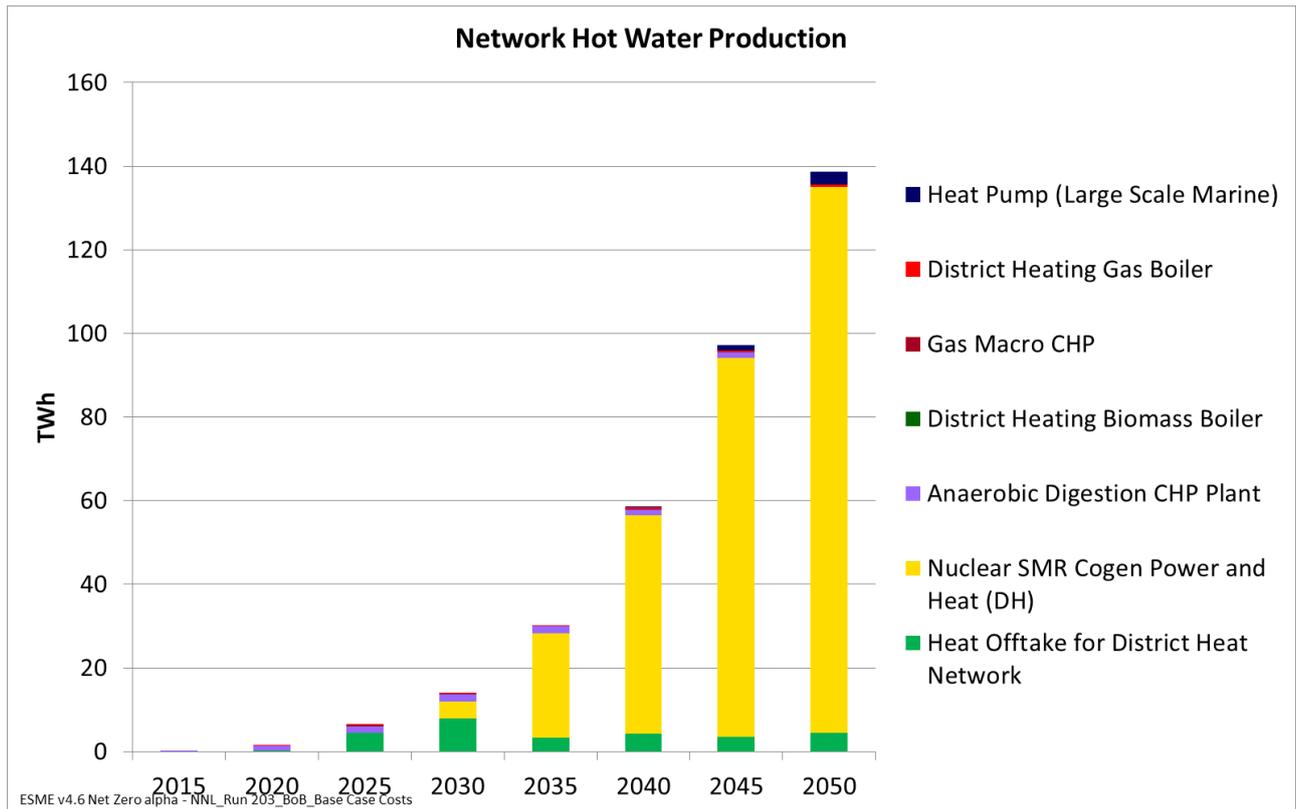
Figure A3-26 – Run 203 network hot water production
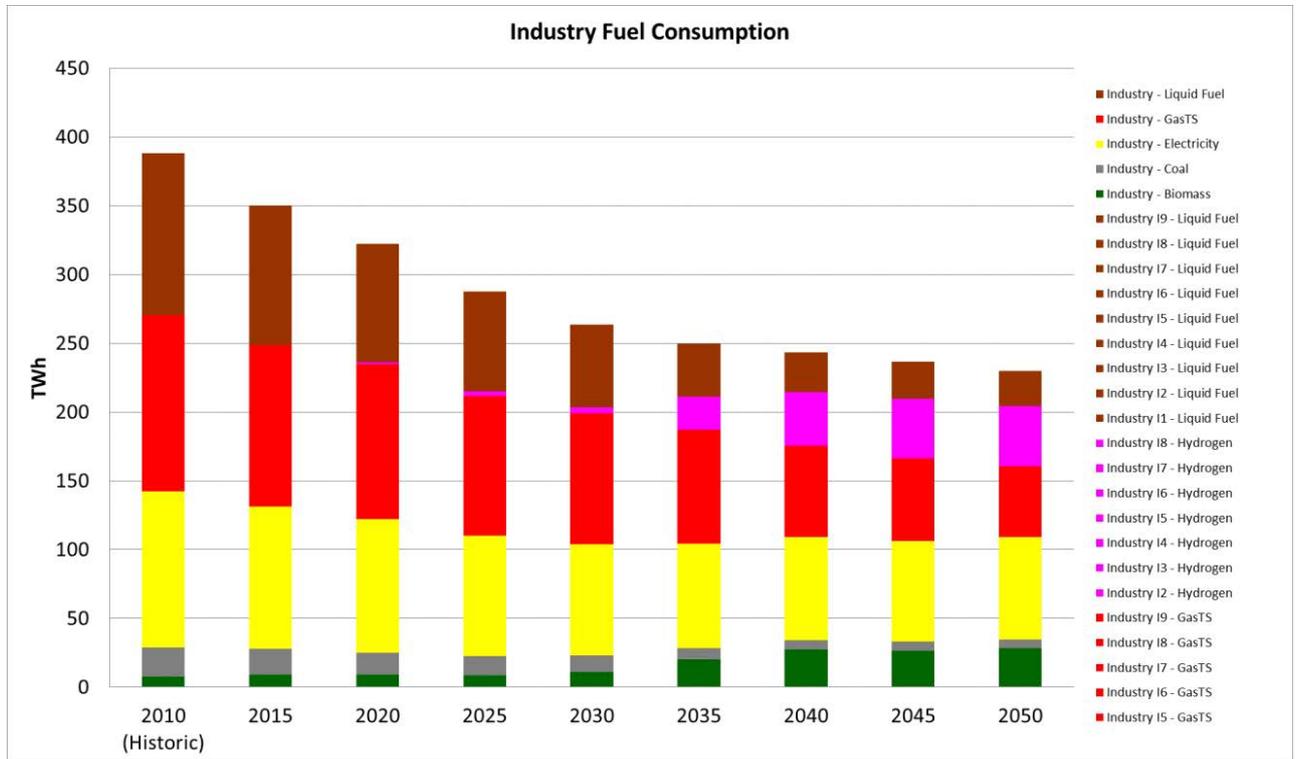
Figure A3-27 – Run 203 industry fuel consumption

Run 203 BOB100 – All nuclear technologies; base case data
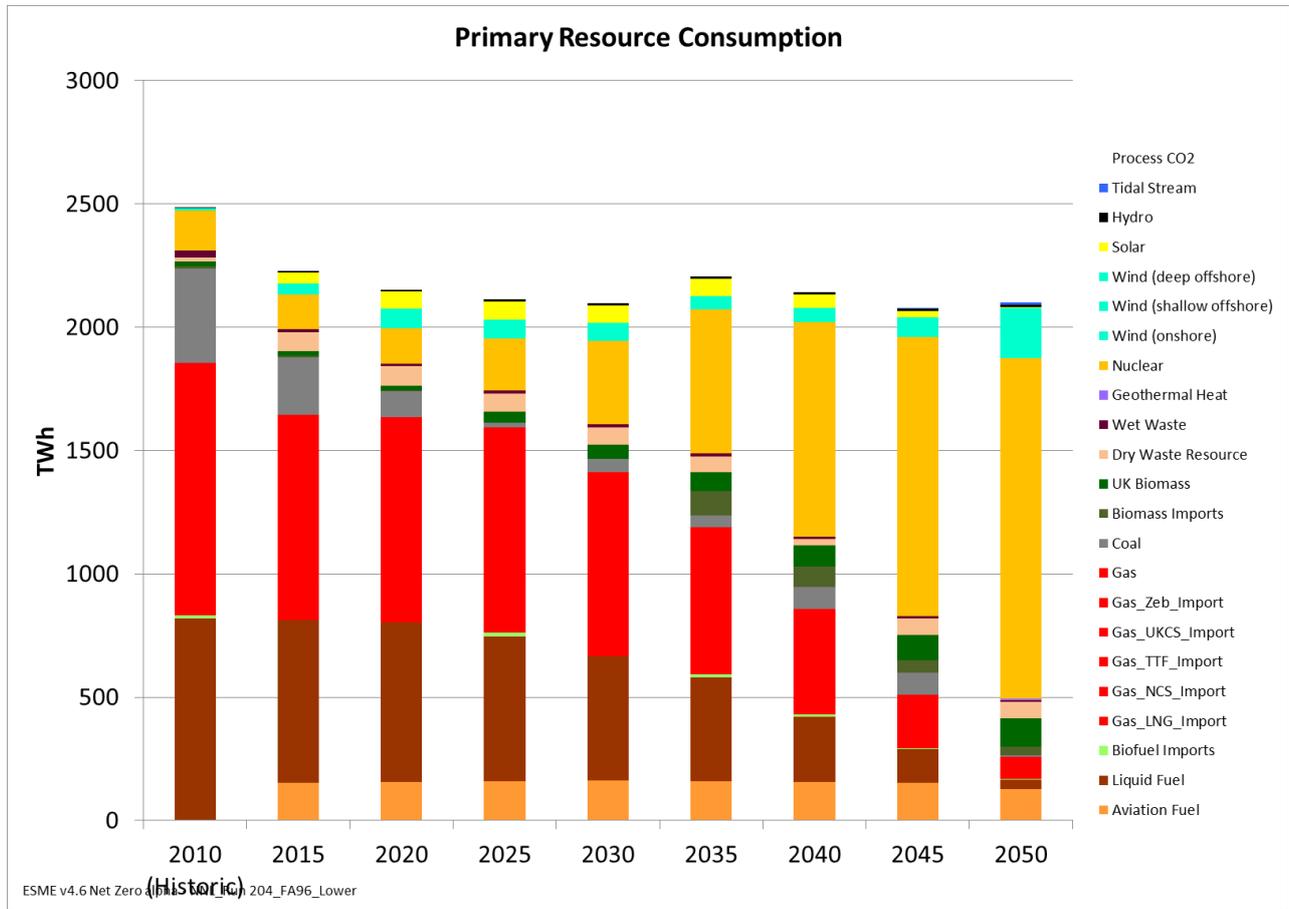
Figure A3-28 – Run 204 primary resource consumption
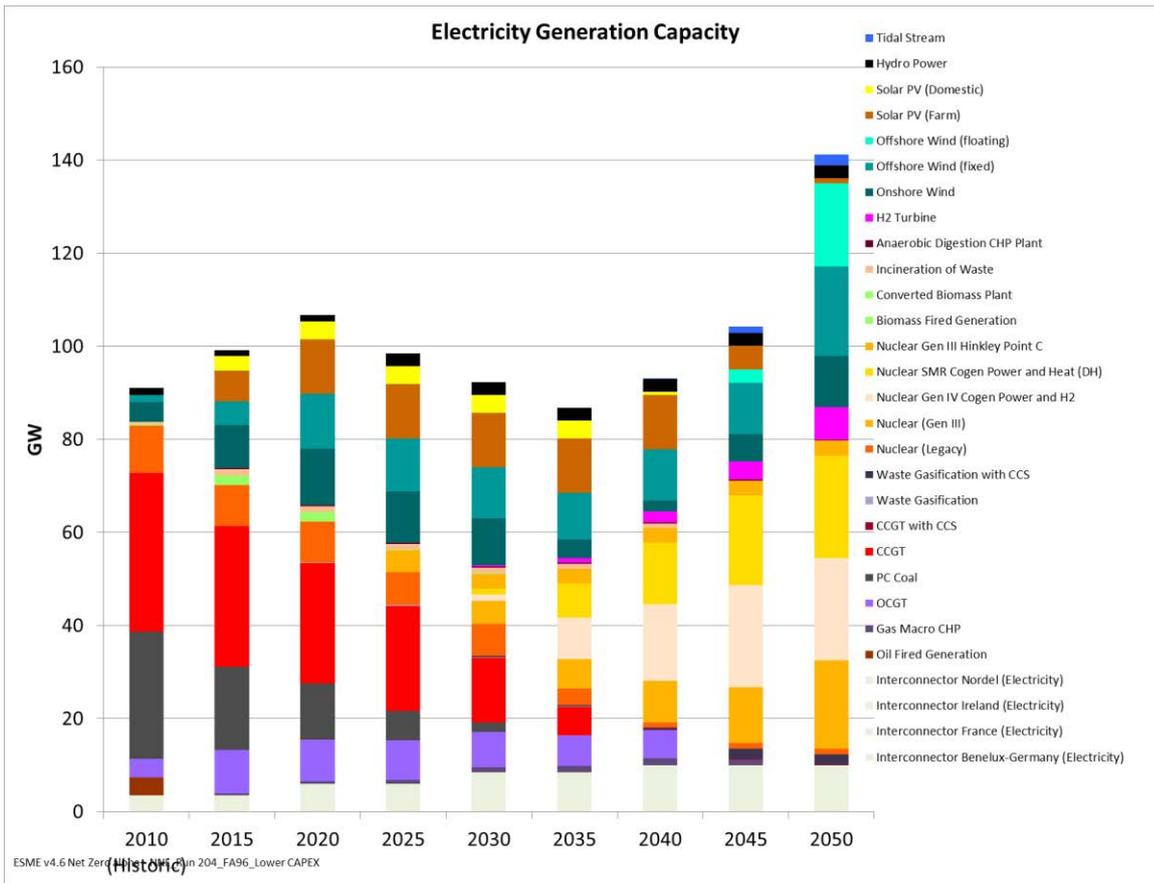
Figure A3-29 – Run 204 electricity generation capacity
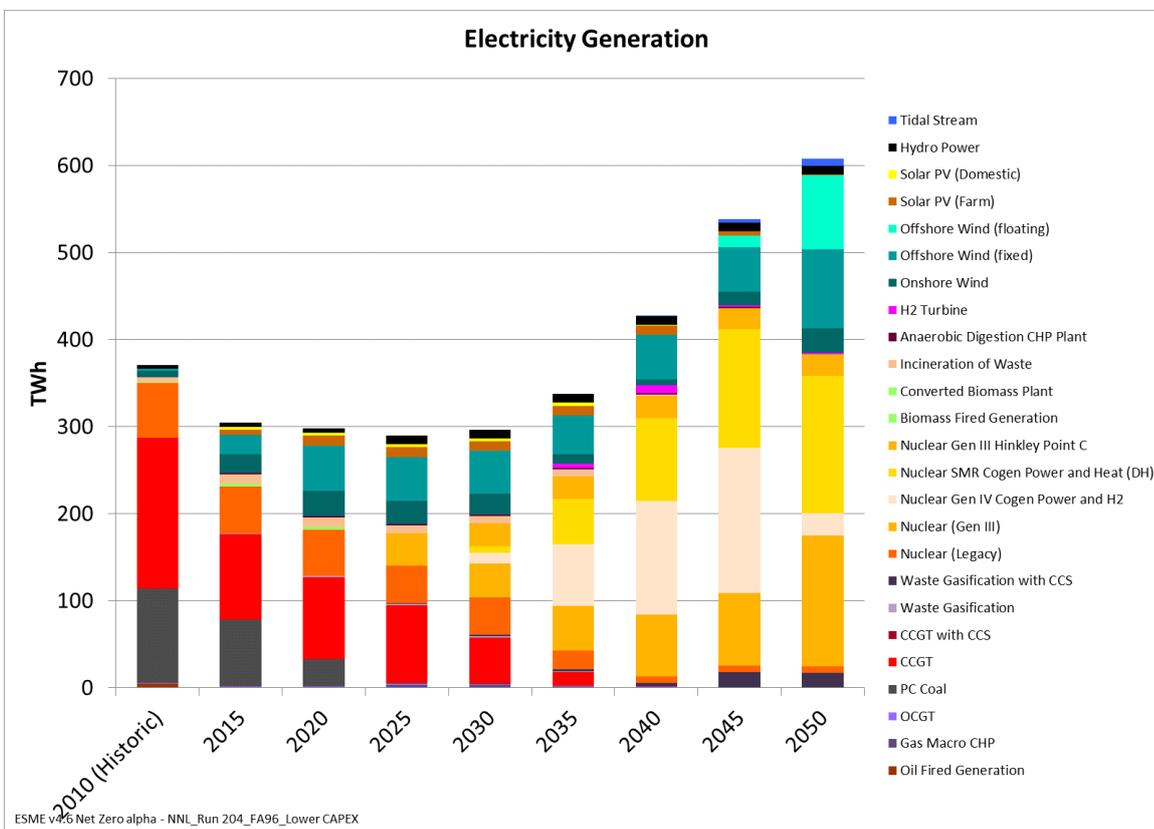
Figure A3-30 – Run 204 electricity generation
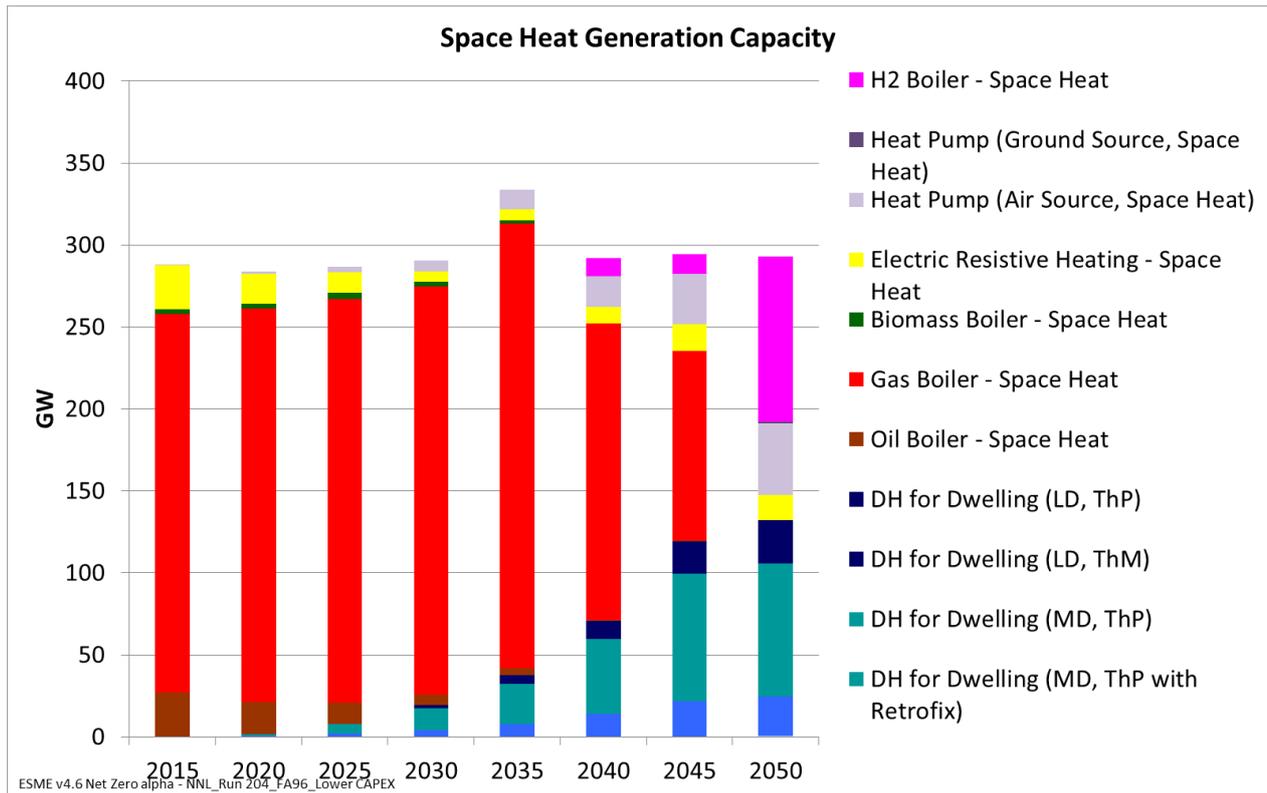
Figure A3-31 – Run 204 space heat generation capacity
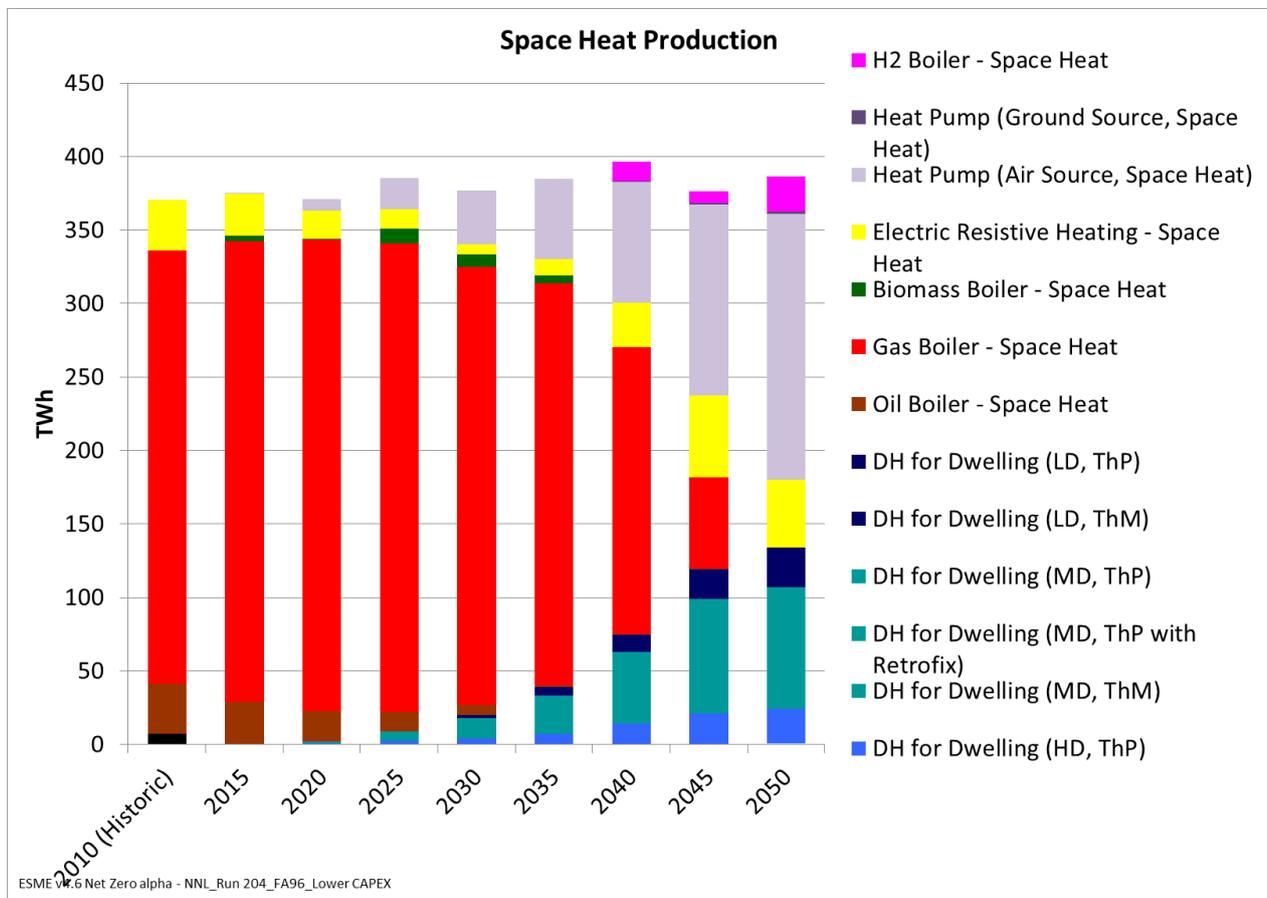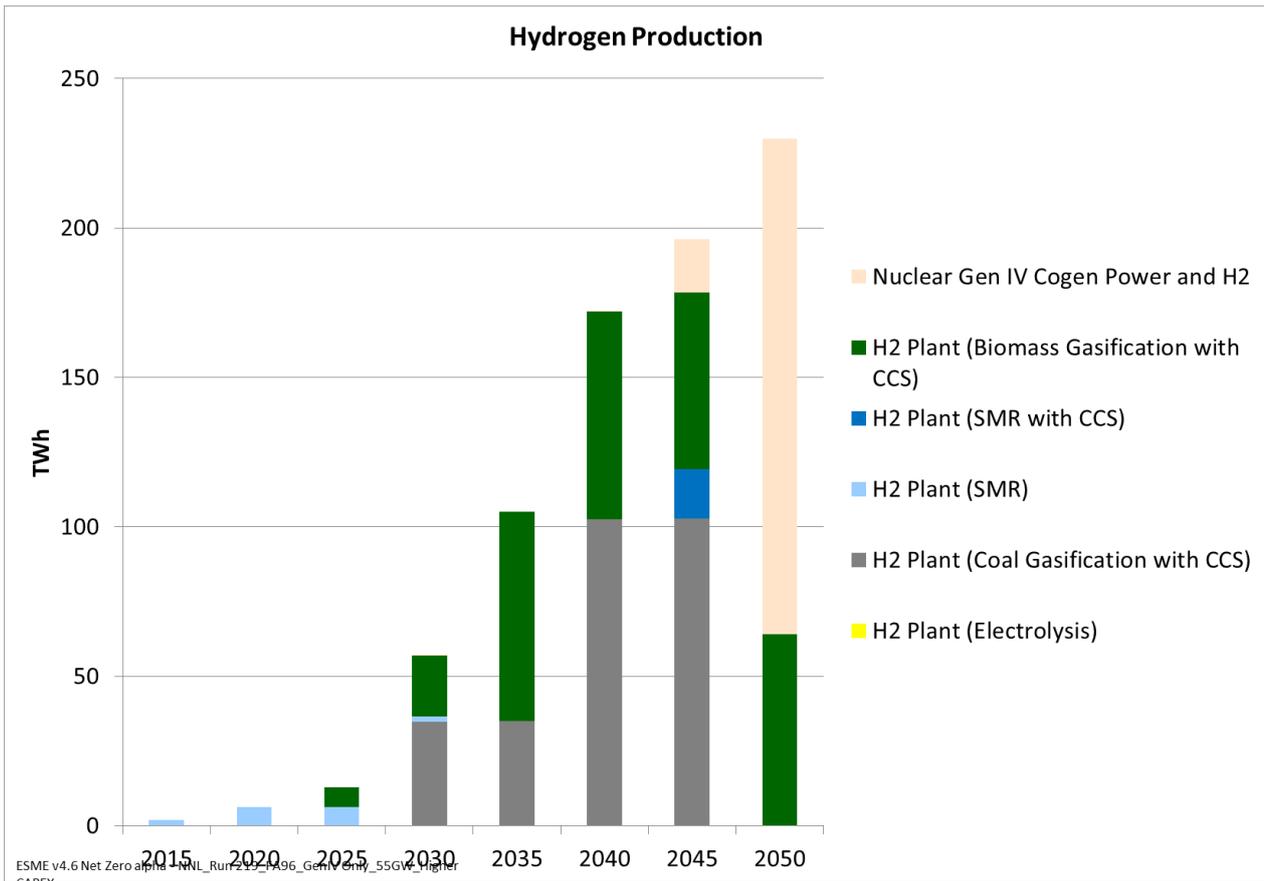

Figure A3-32 – Run 204 space heat production
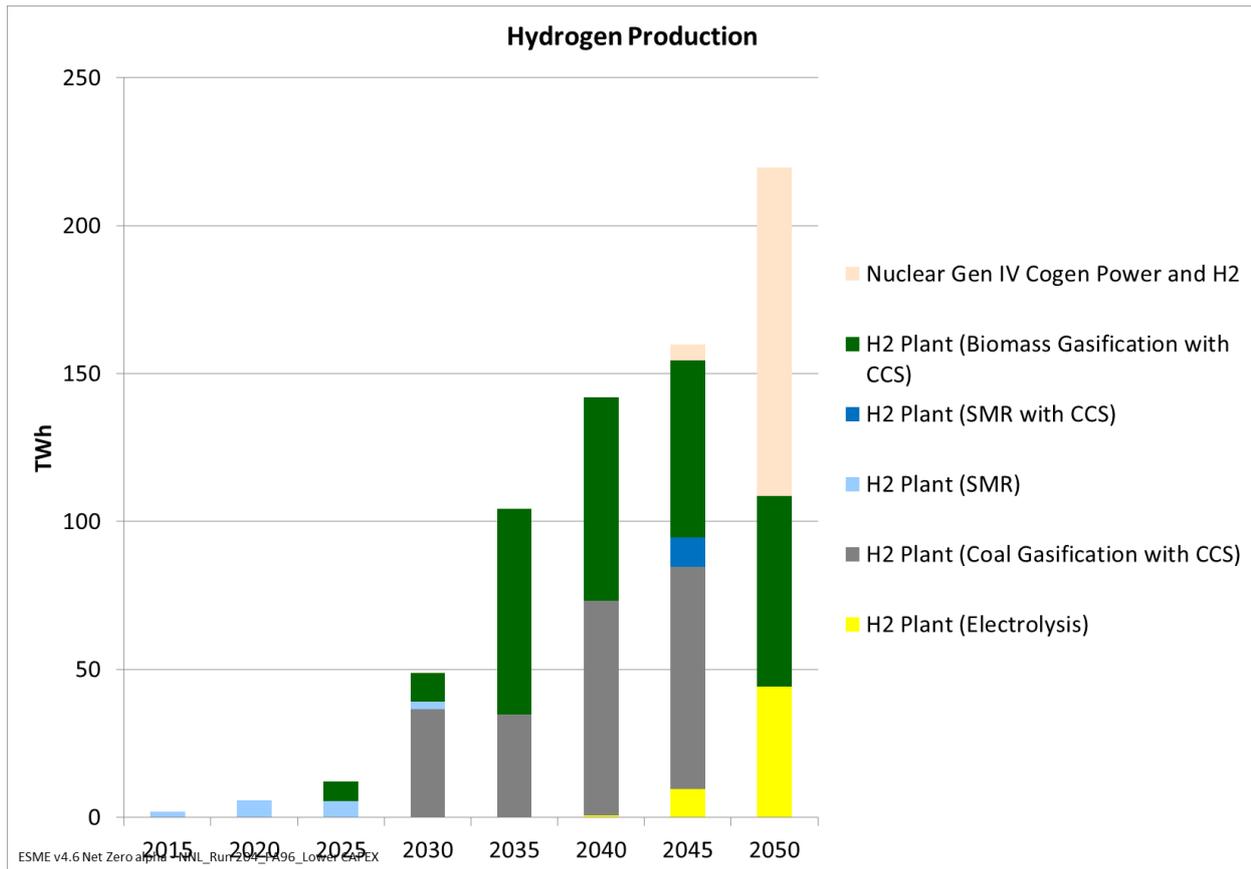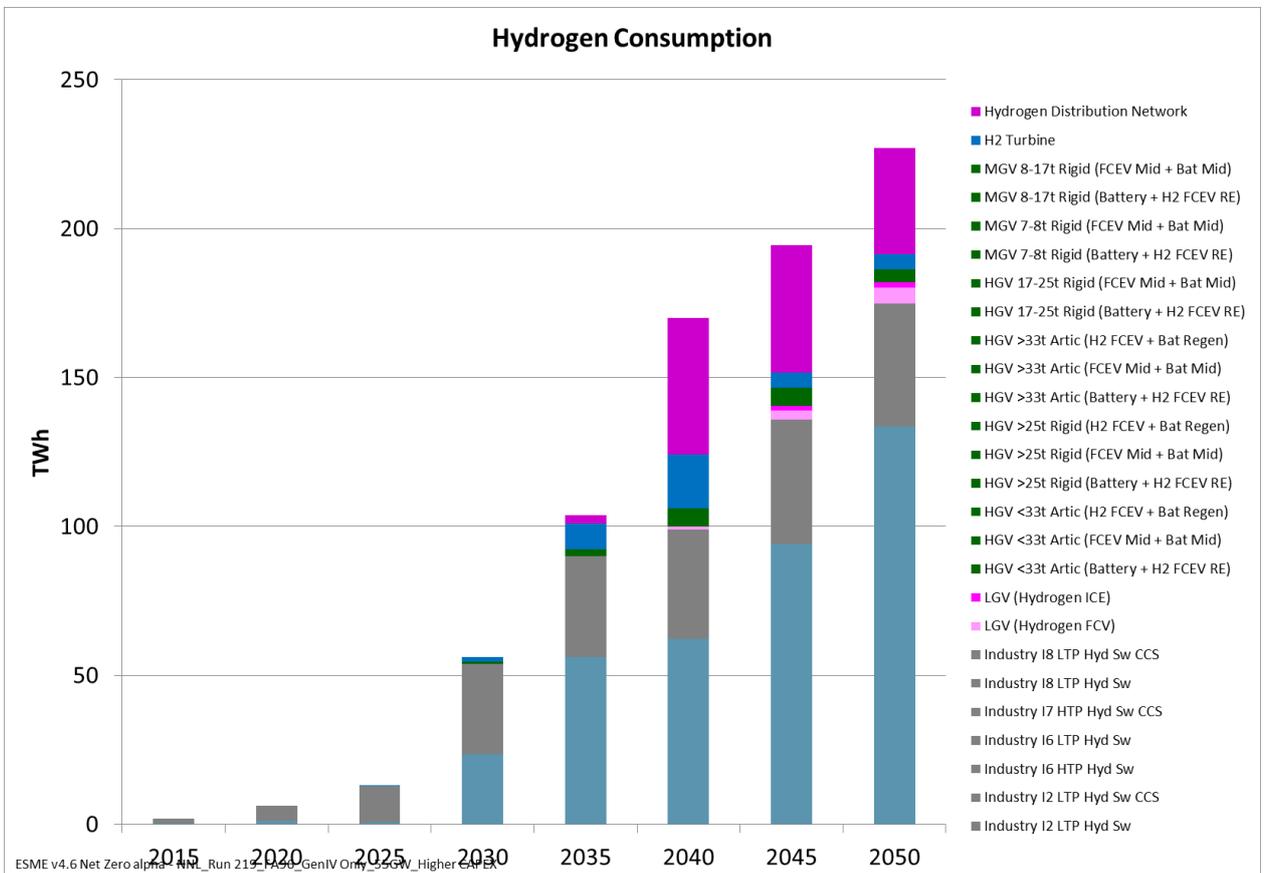
Figure A3-33 – Run 204 hydrogen production
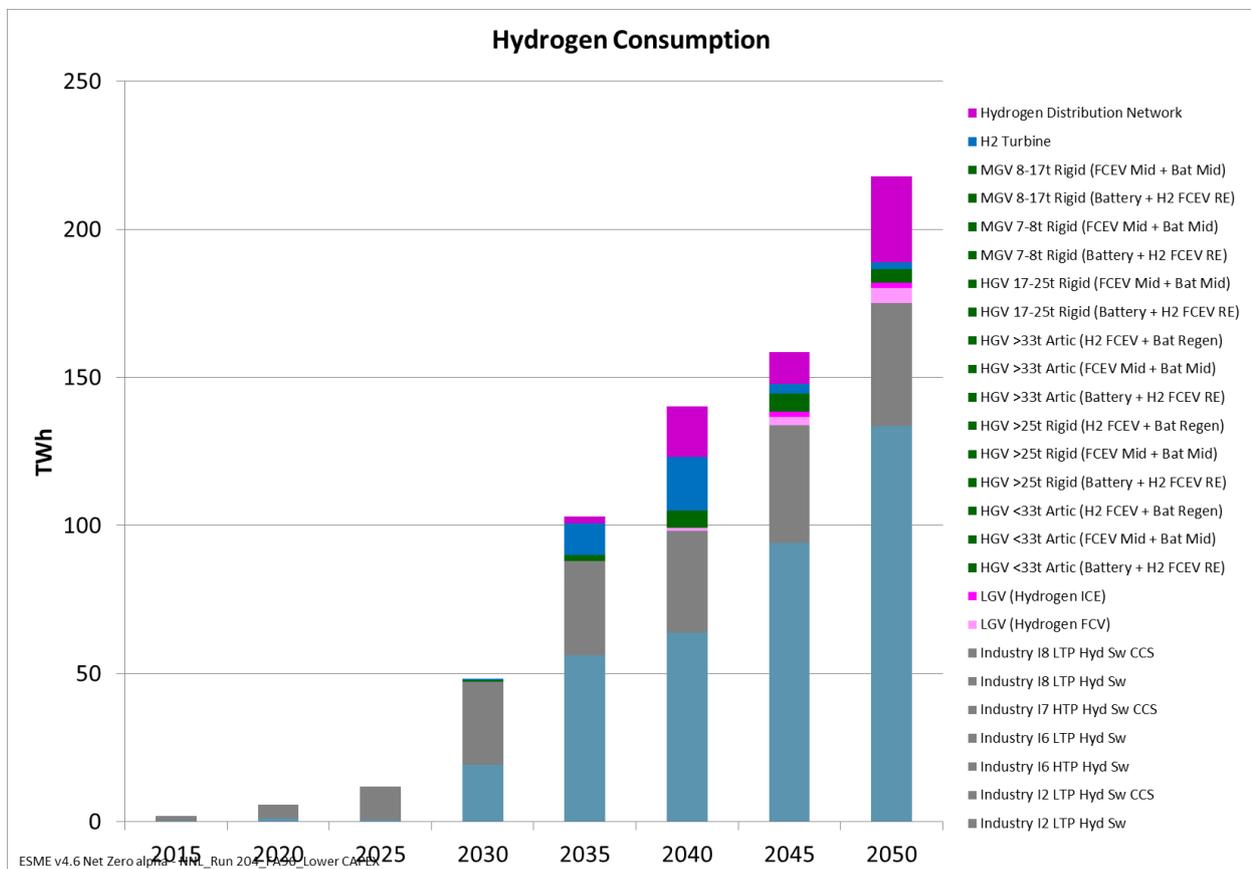
Figure A3-34 – Run 204 hydrogen consumption
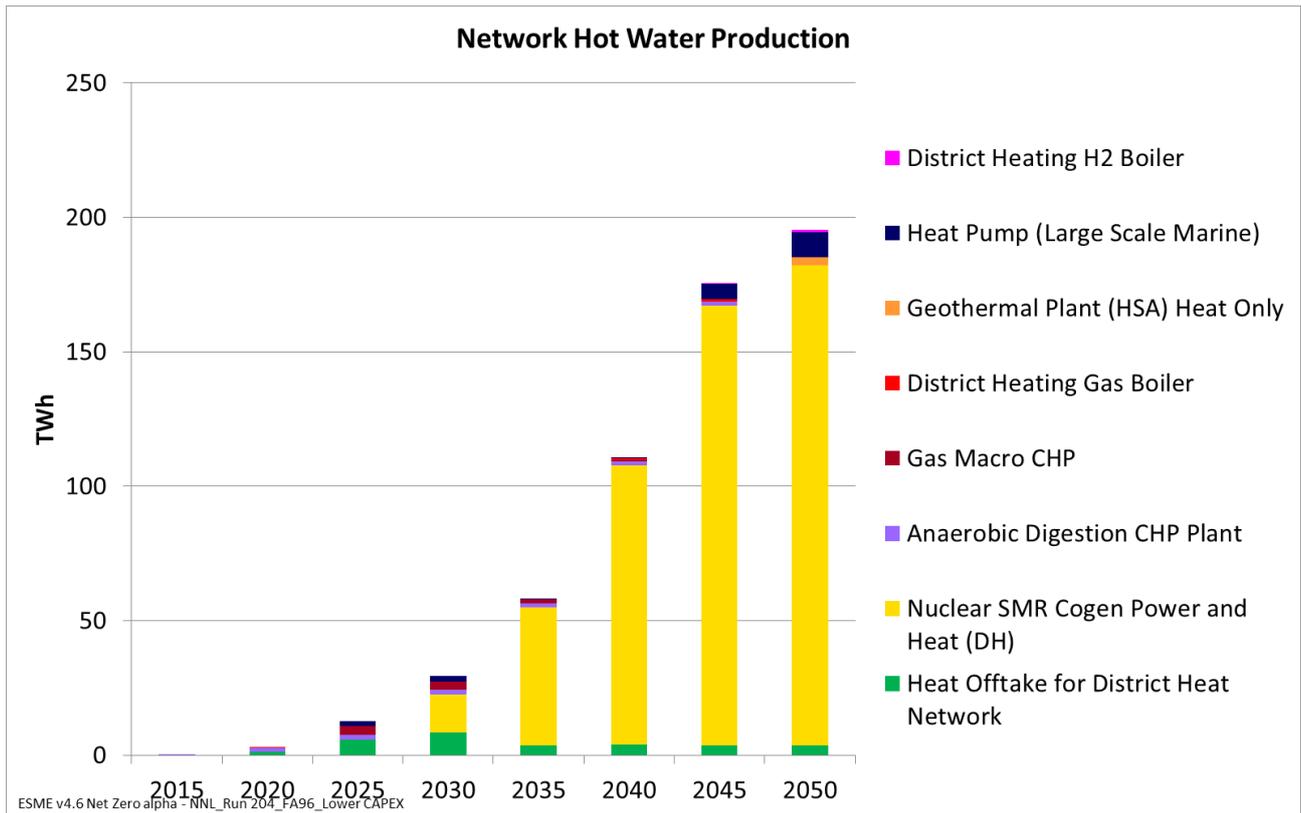
Figure A3-35 – Run 204 network hot water production
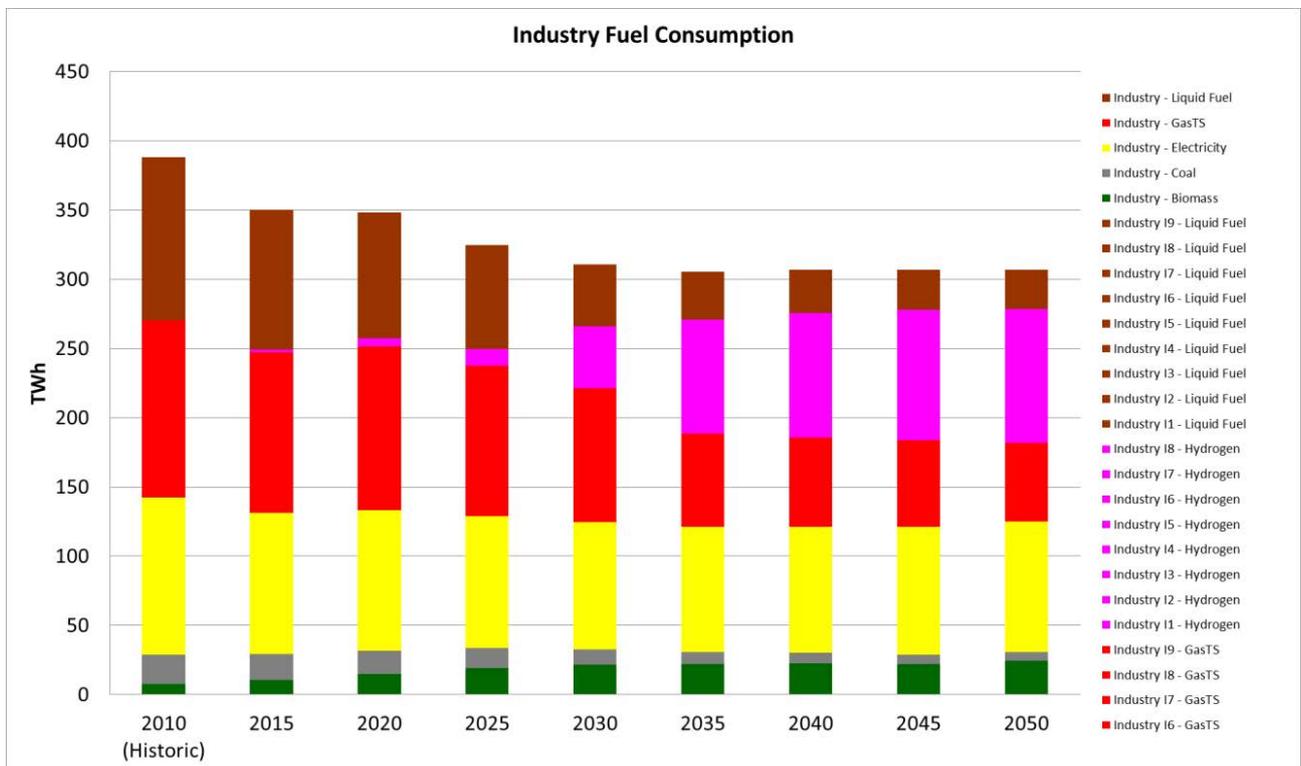
Figure A3-36 – Run 204 industry fuel consumption

Run 205 TECH100 – All nuclear technologies; base case data with lower capex values
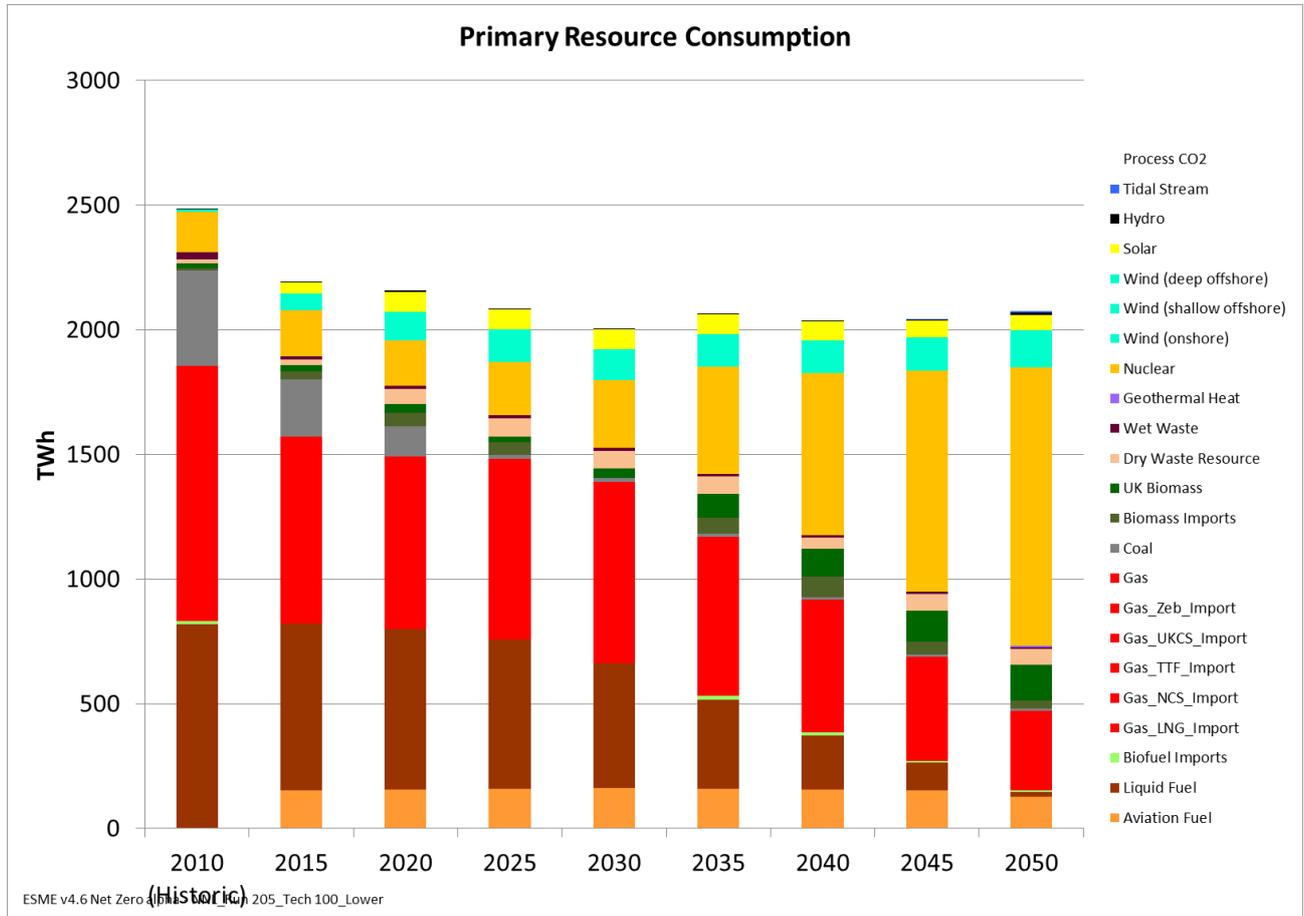
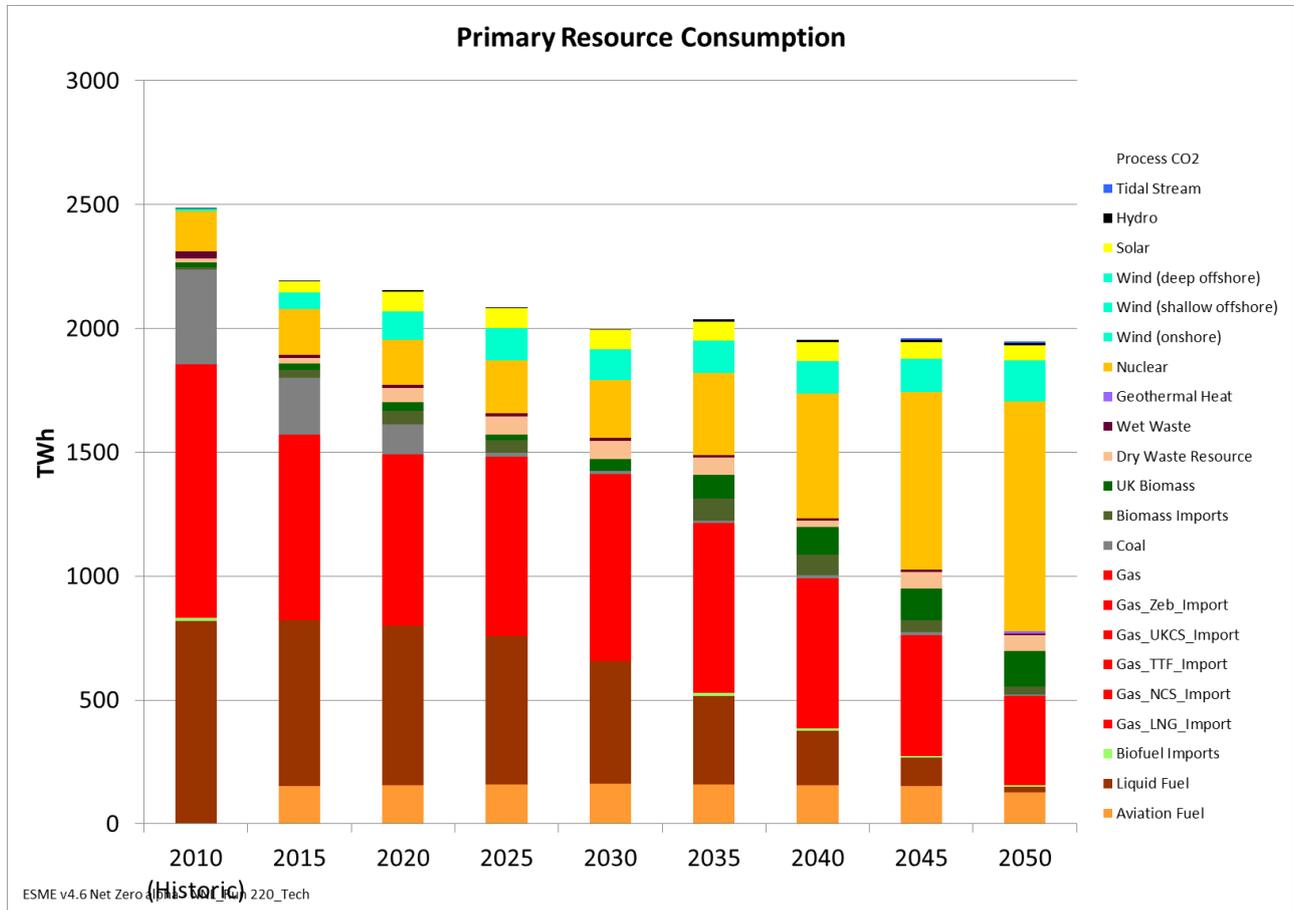**Figure A3-37 – Run 205 primary resource consumption**
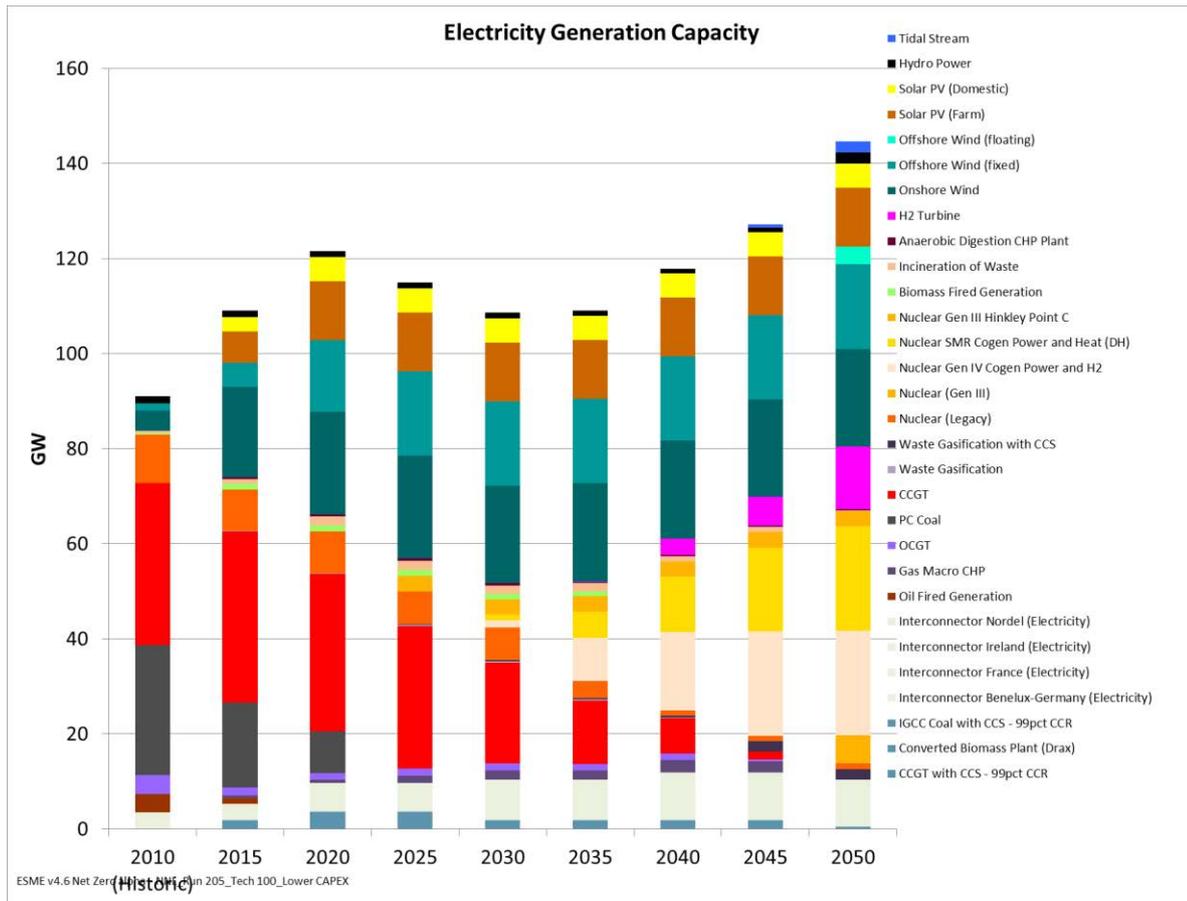
Figure A3-38 – Run 205 electricity generation capacity
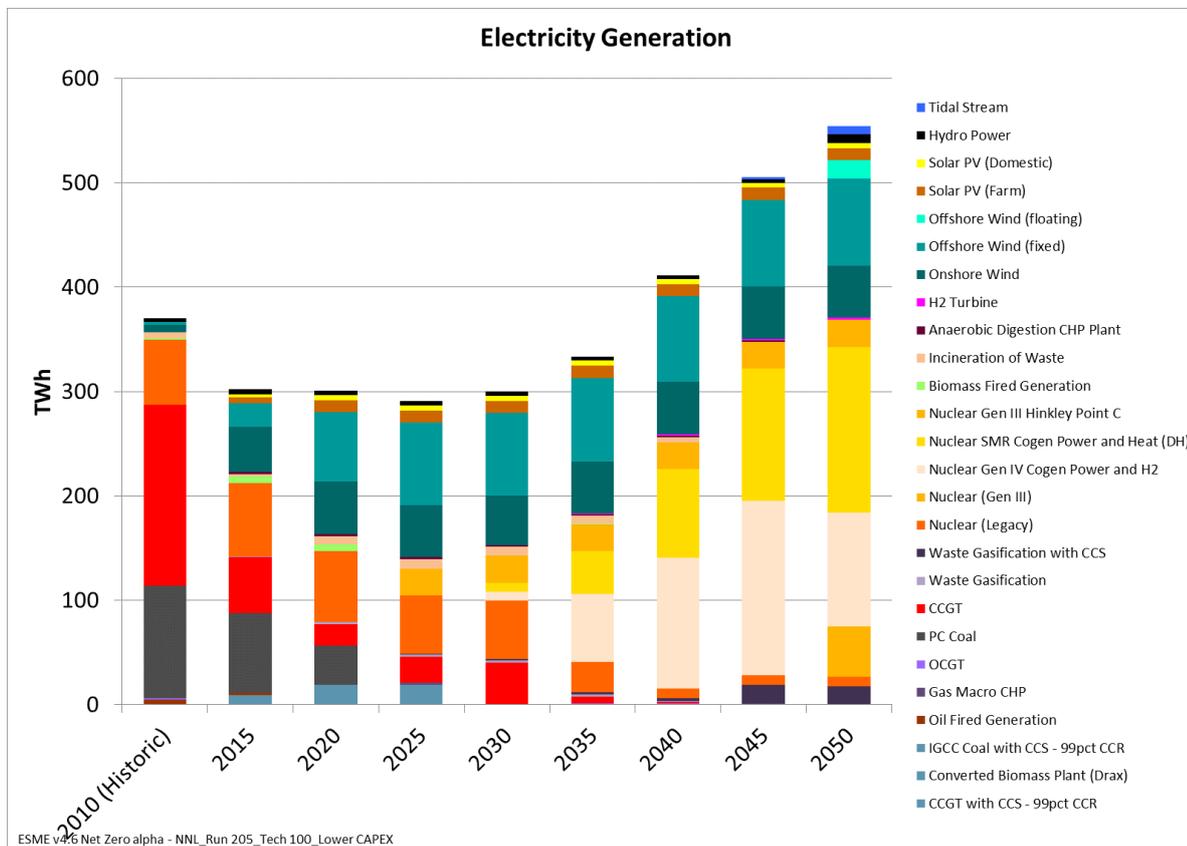
Figure A3-39 – Run 205 electricity generation
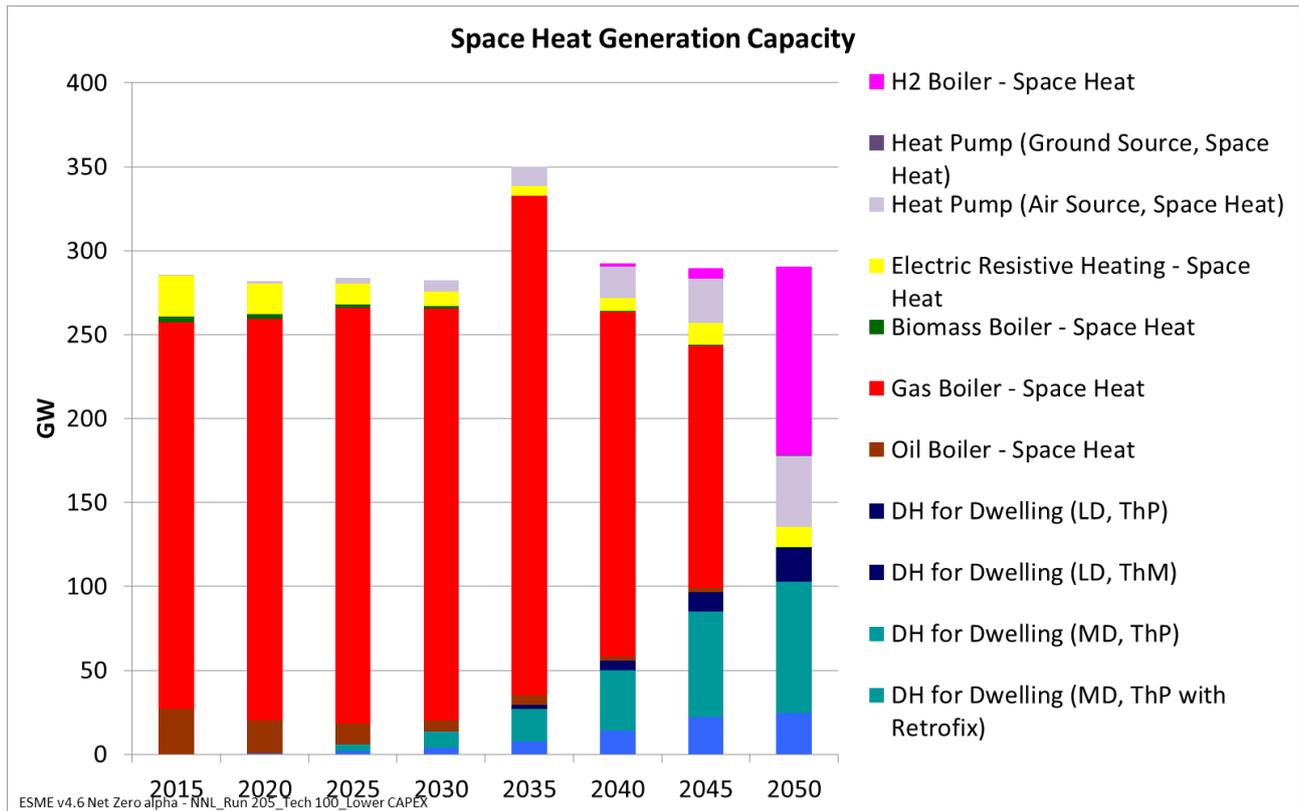
Figure A3-40 – Run 205 space heat generation capacity
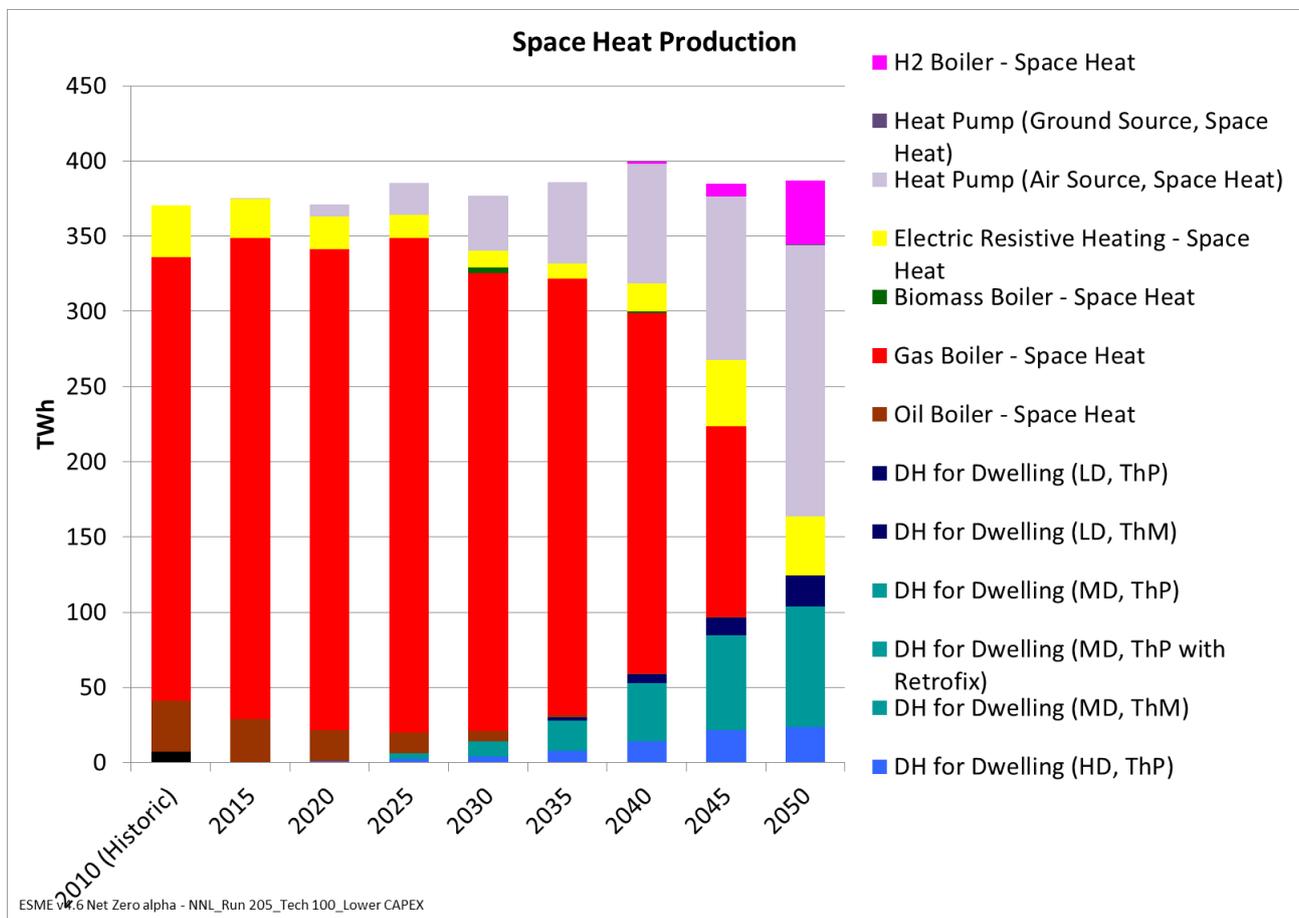
Figure A3-41 – Run 205 space heat production
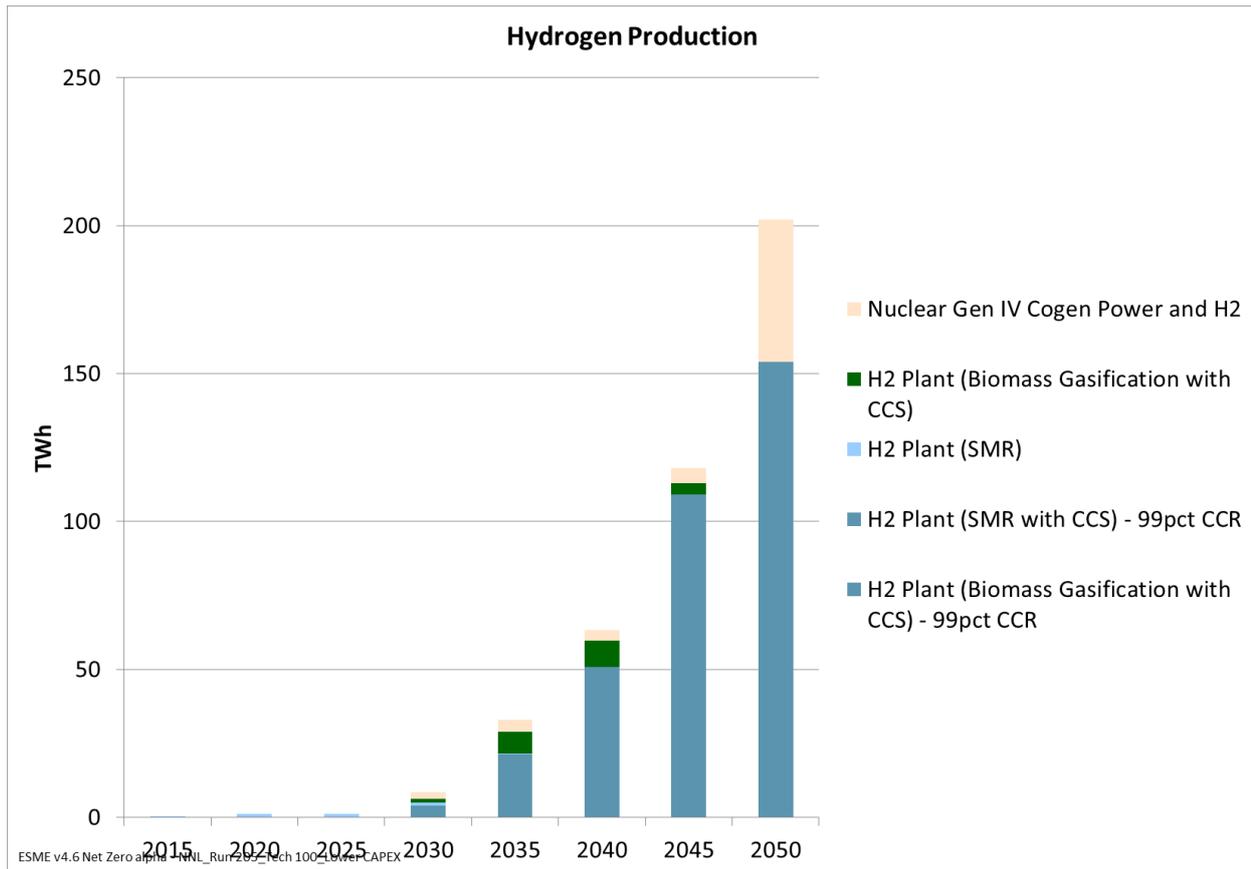
Figure A3-42 – Run 205 hydrogen production
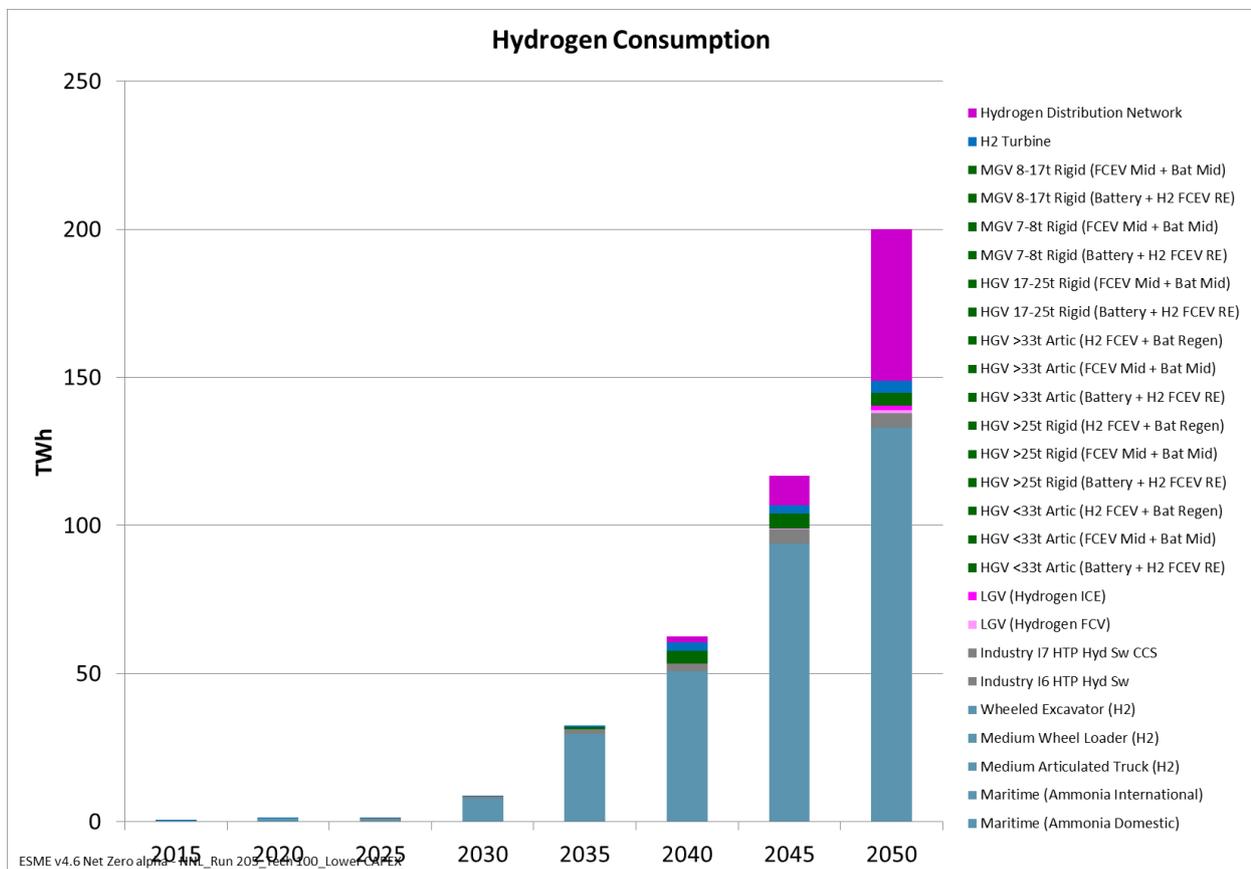
Figure A3-43 – Run 205 hydrogen consumption
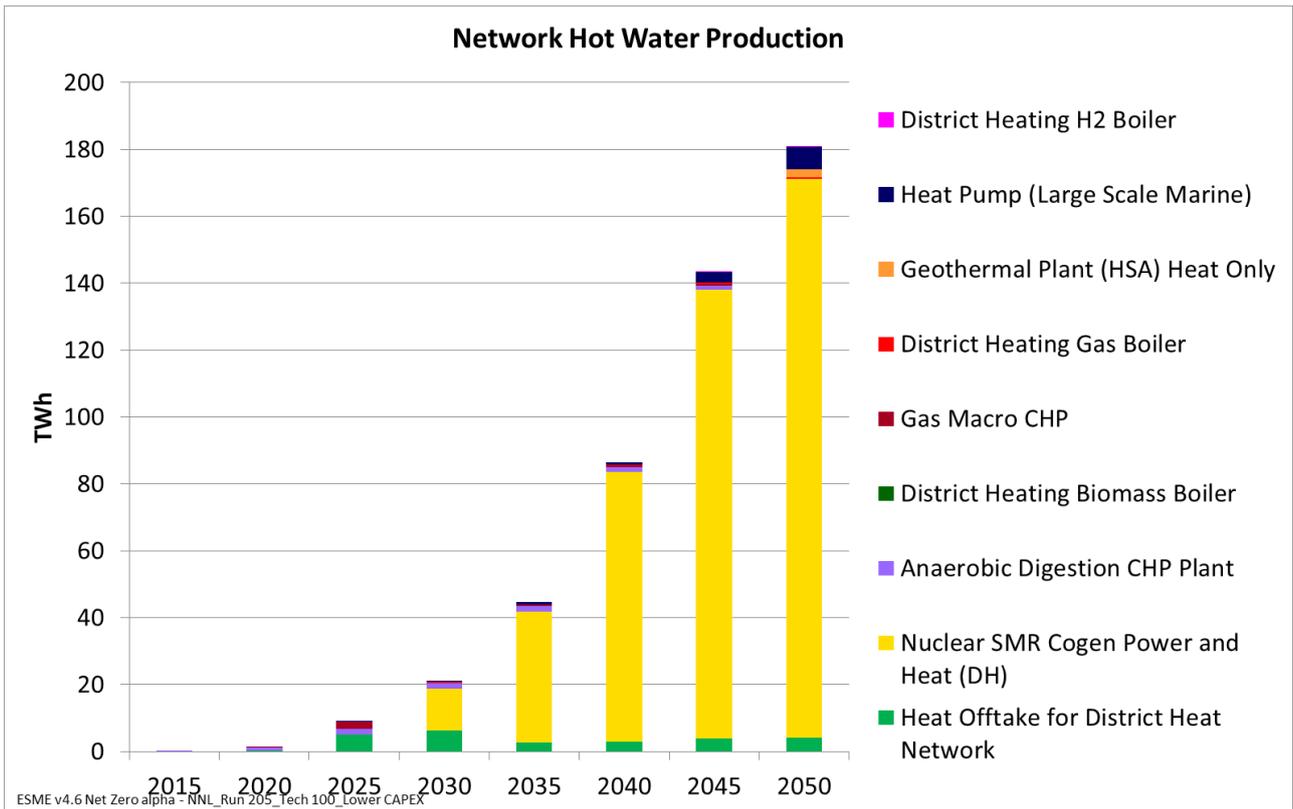
Figure A3-44 – Run 205 network hot water production
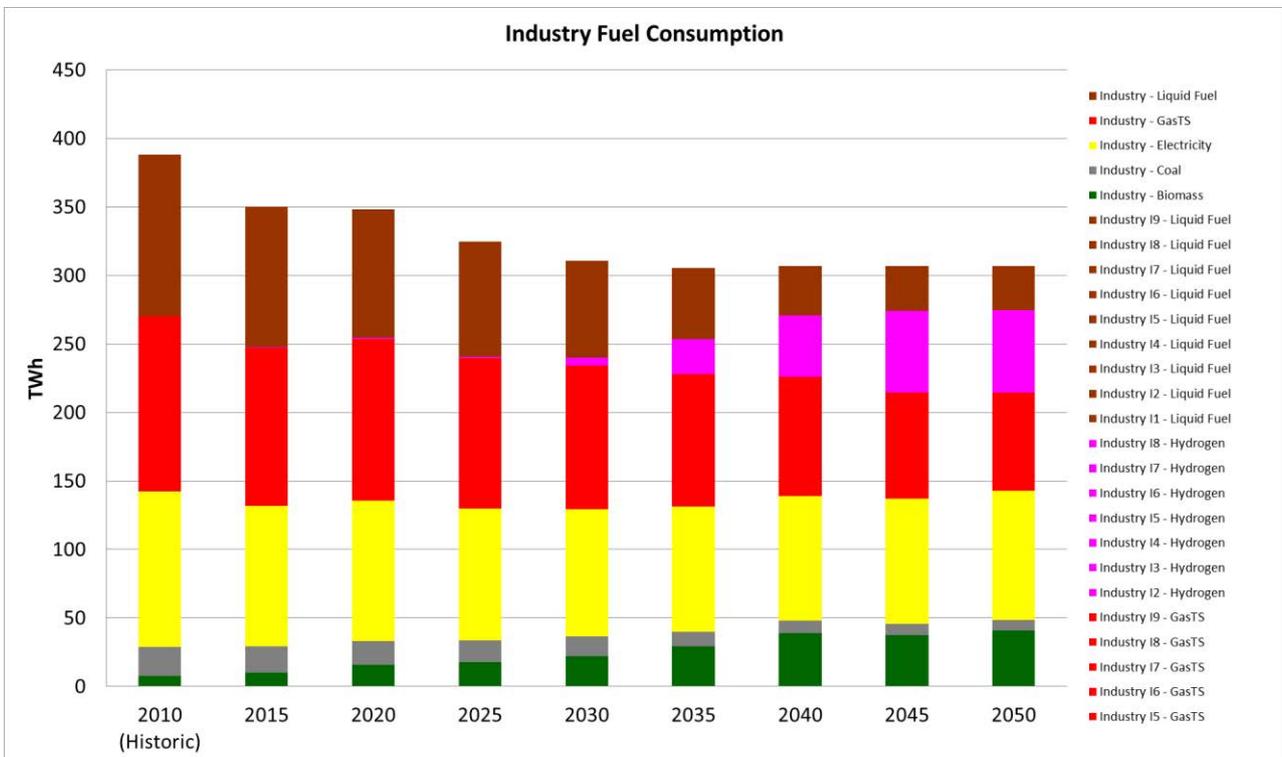
Figure A3-45 – Run 205 industry fuel consumption

Run 206 FA96 – All nuclear technologies; base case data with higher capex values
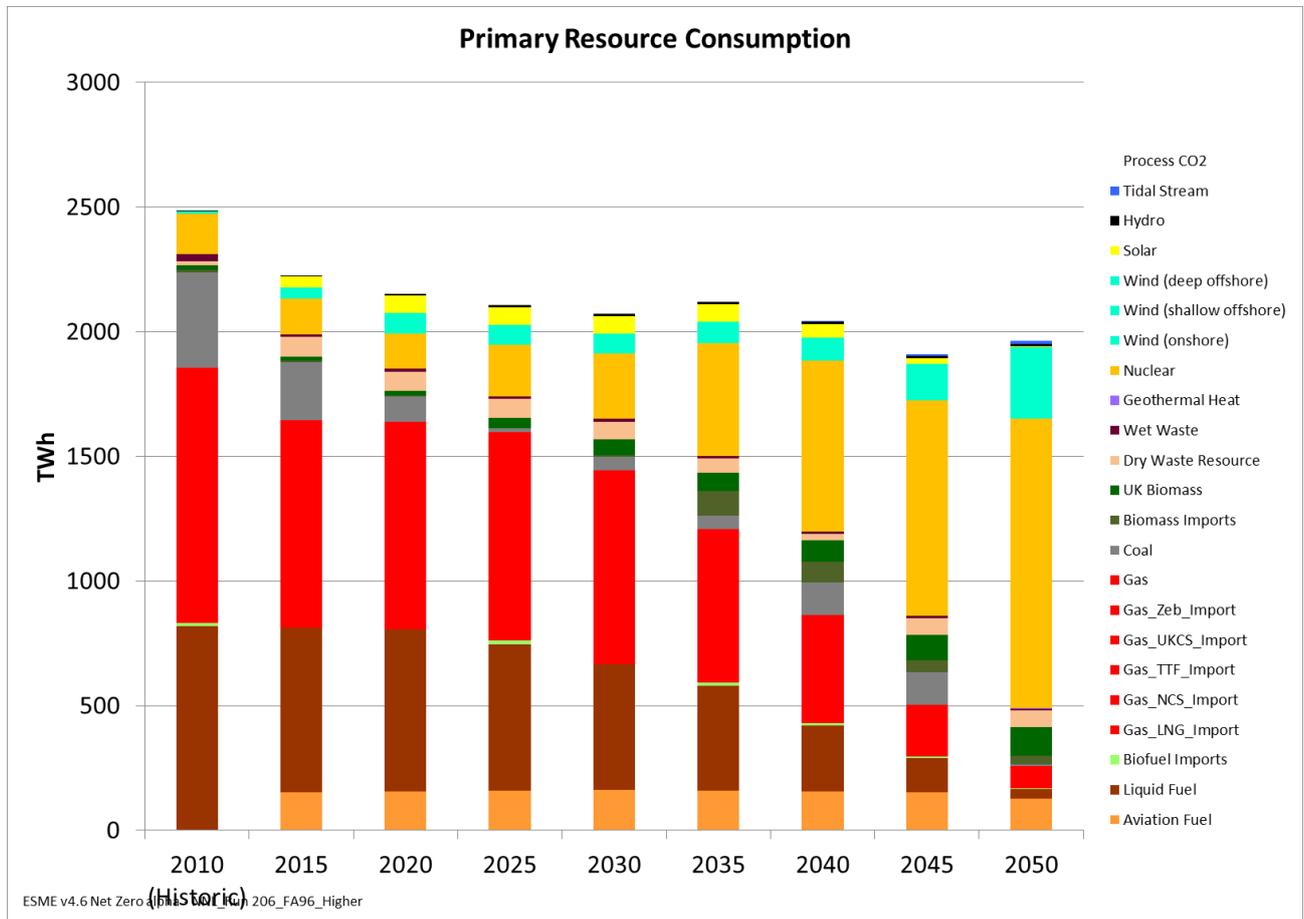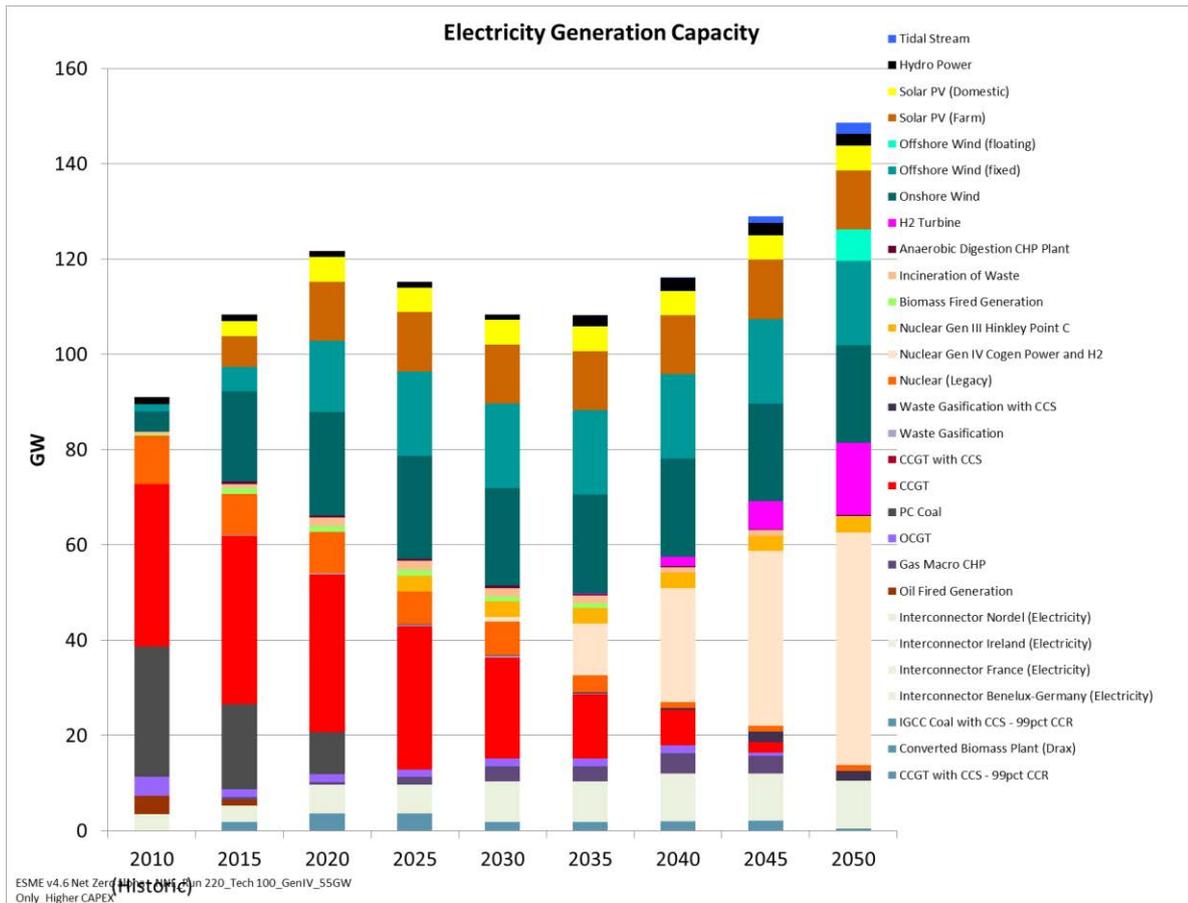

Figure A3-46 – Run 206 primary resource consumption
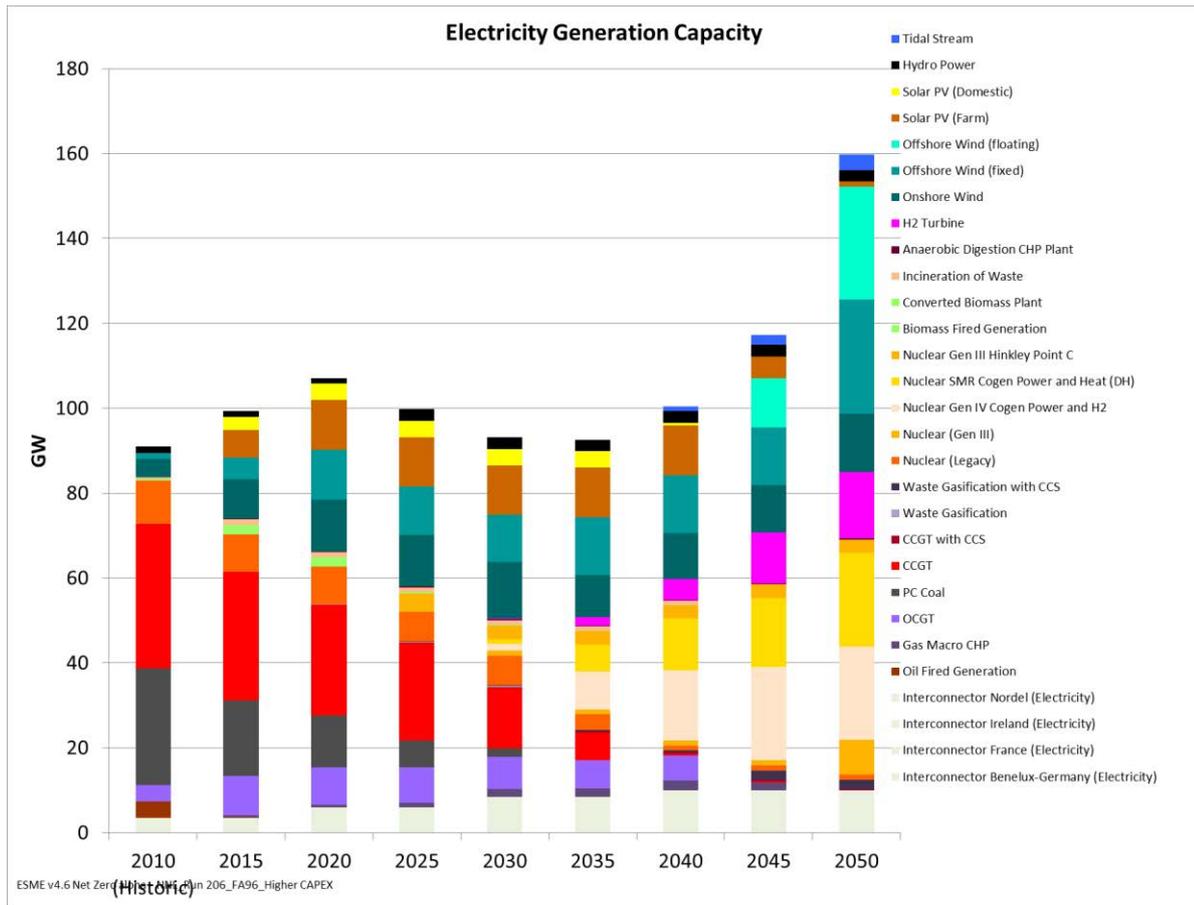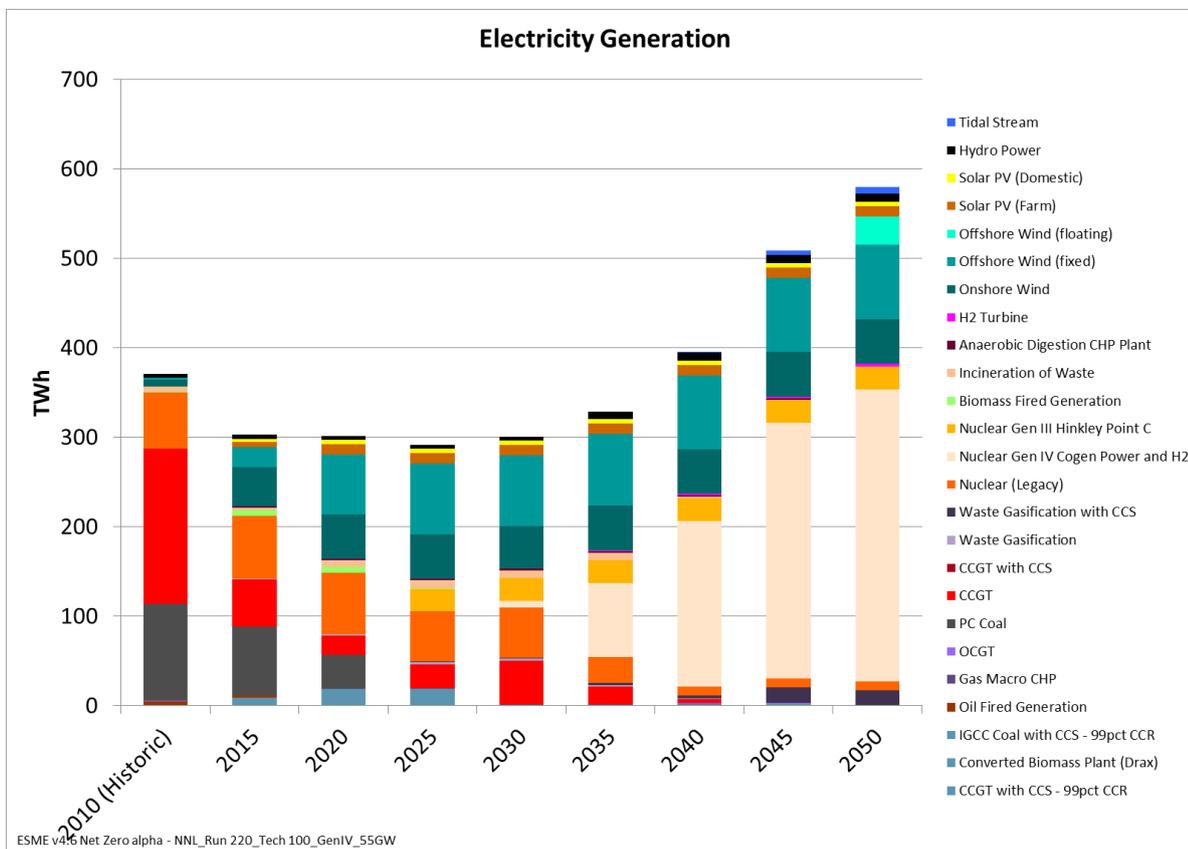
Figure A3-47 – Run 206 electricity generation capacity
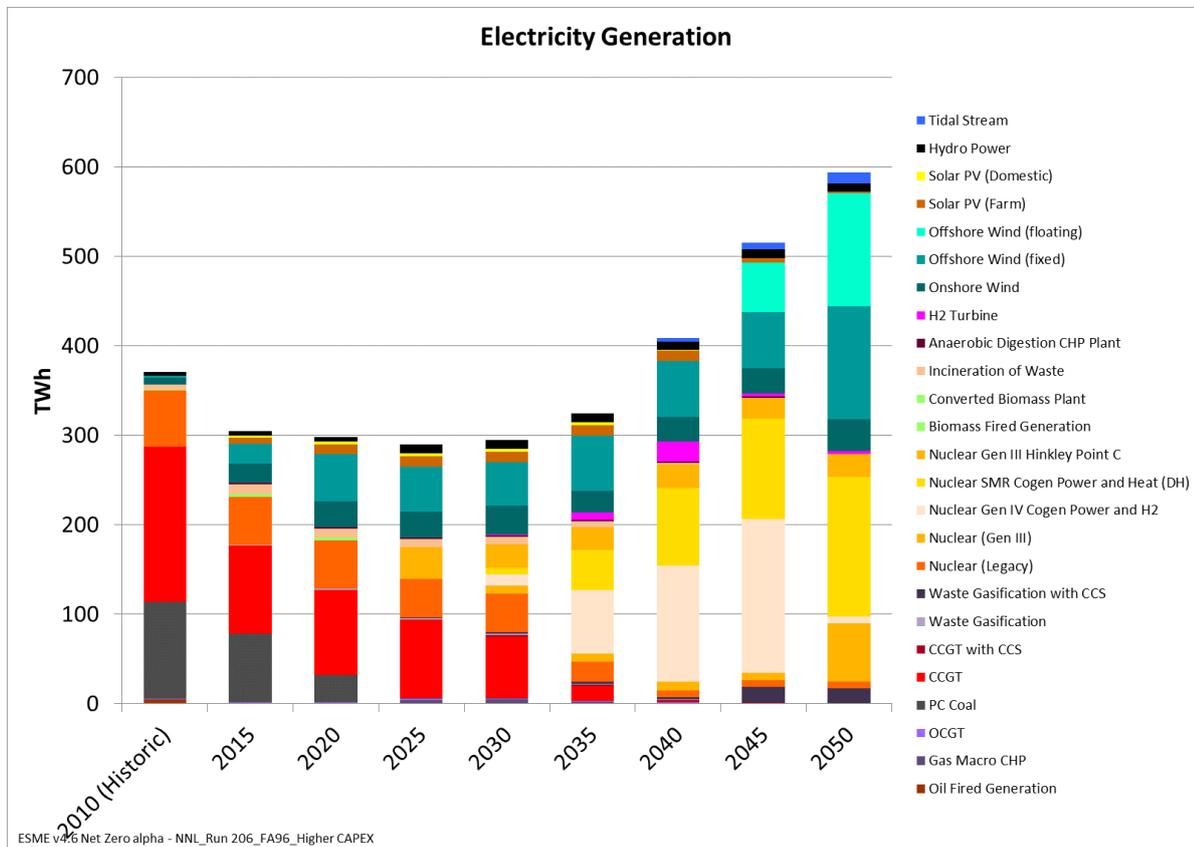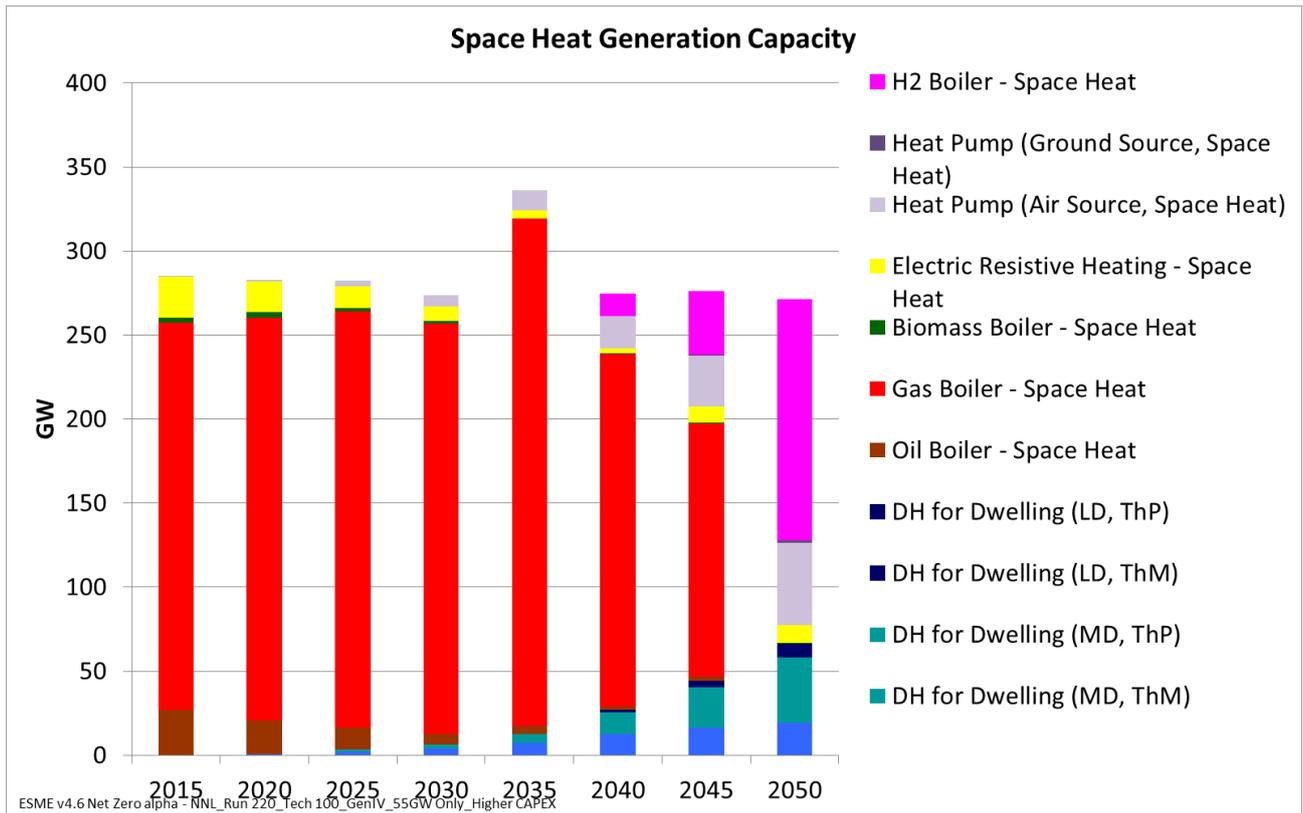

Figure A3-48 – Run 206 electricity generation
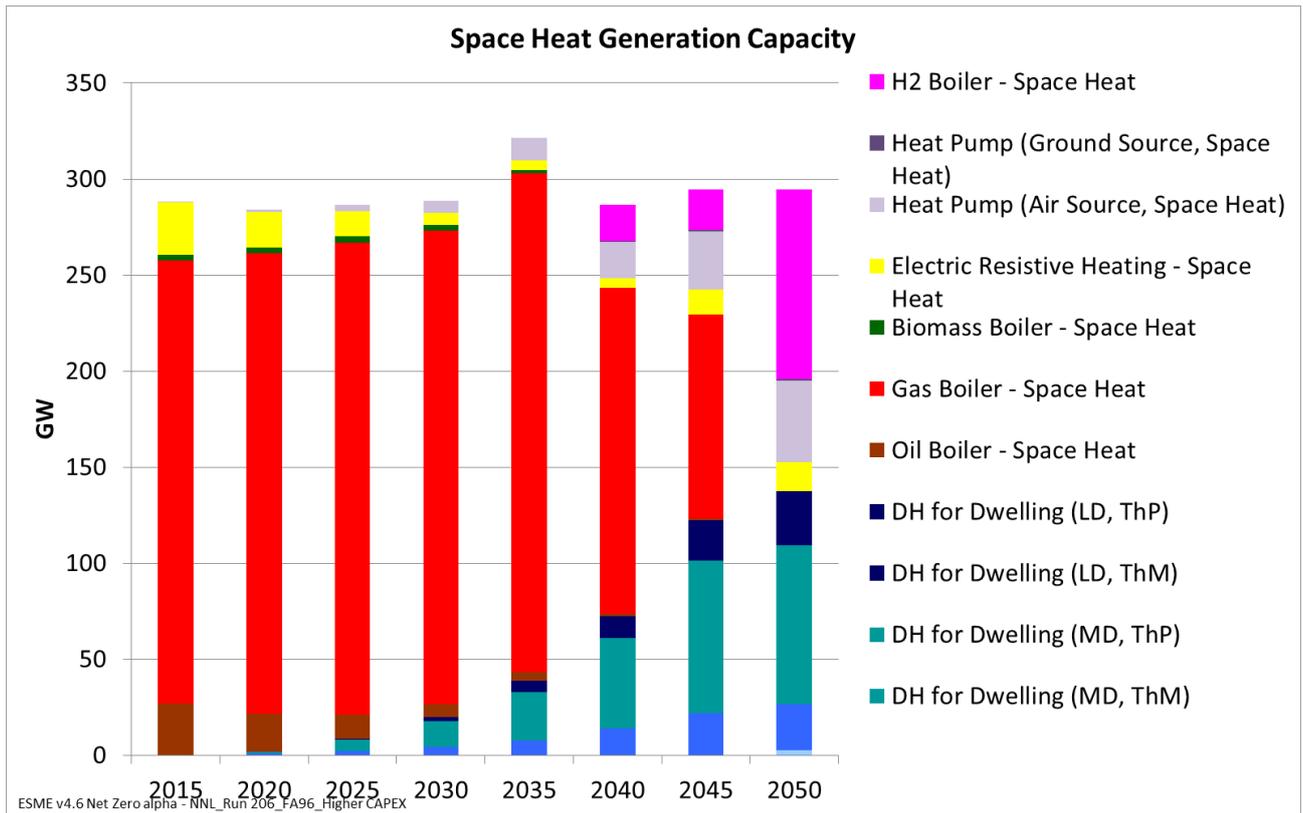
Figure A3-49 – Run 206 space heat generation capacity
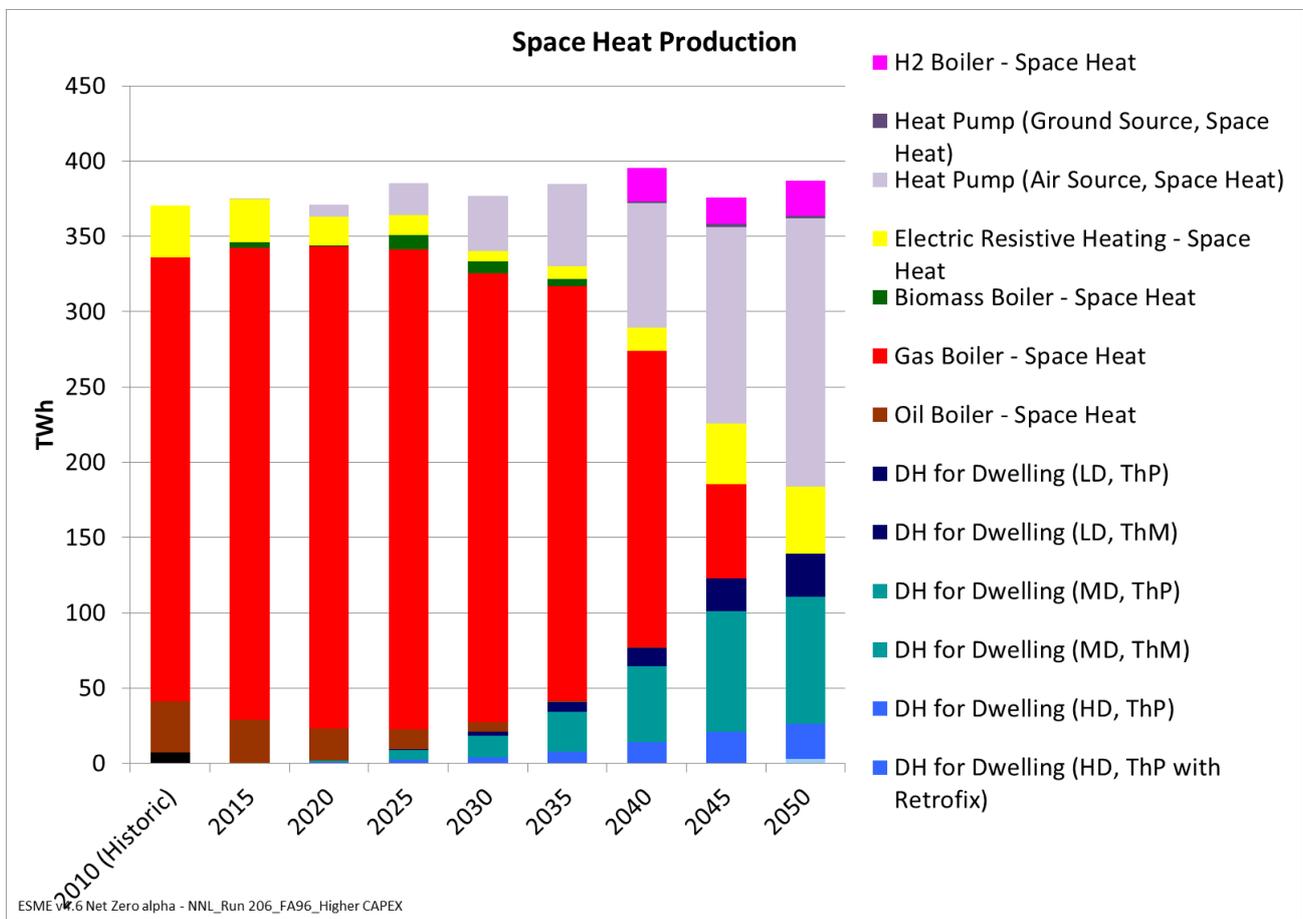
Figure A3-50 – Run 206 space heat production
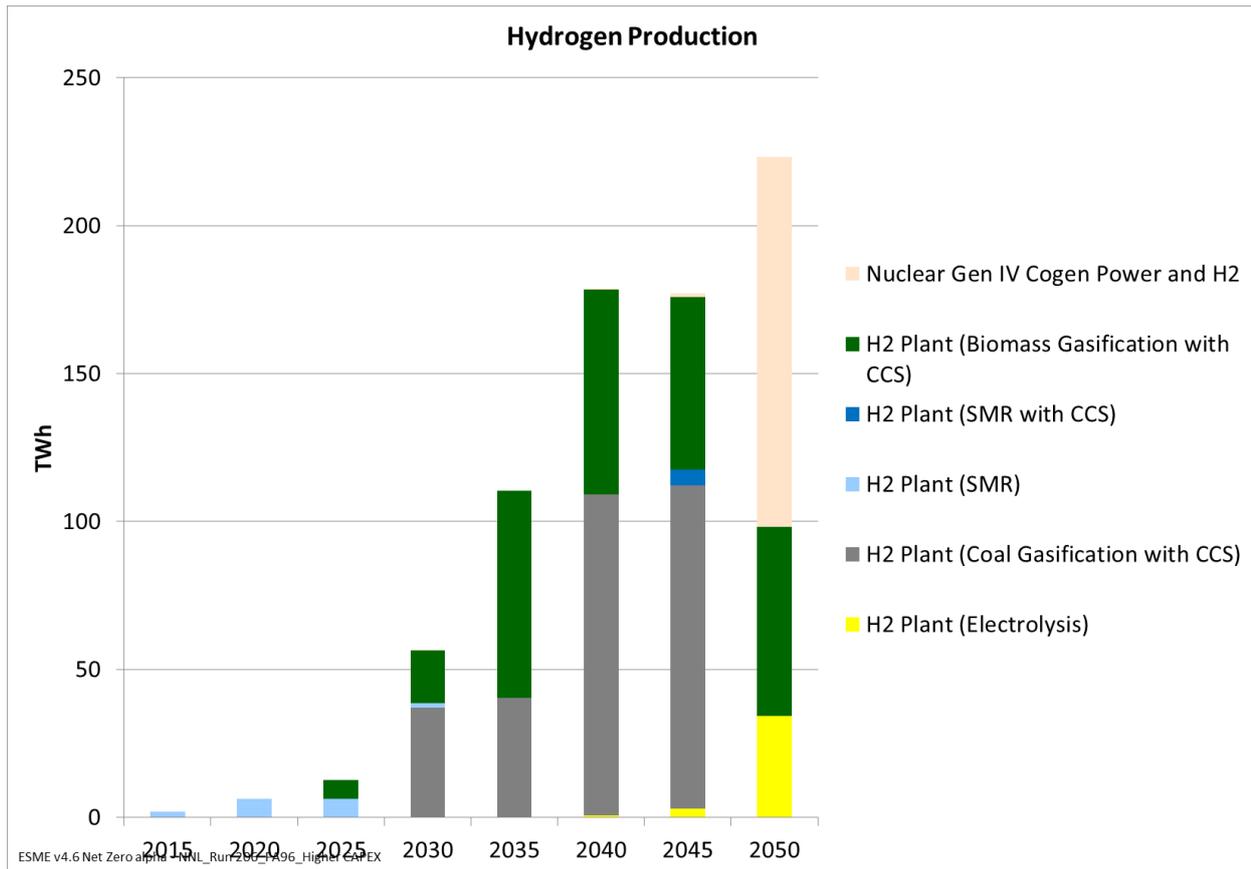
Figure A3-51 – Run 206 hydrogen production
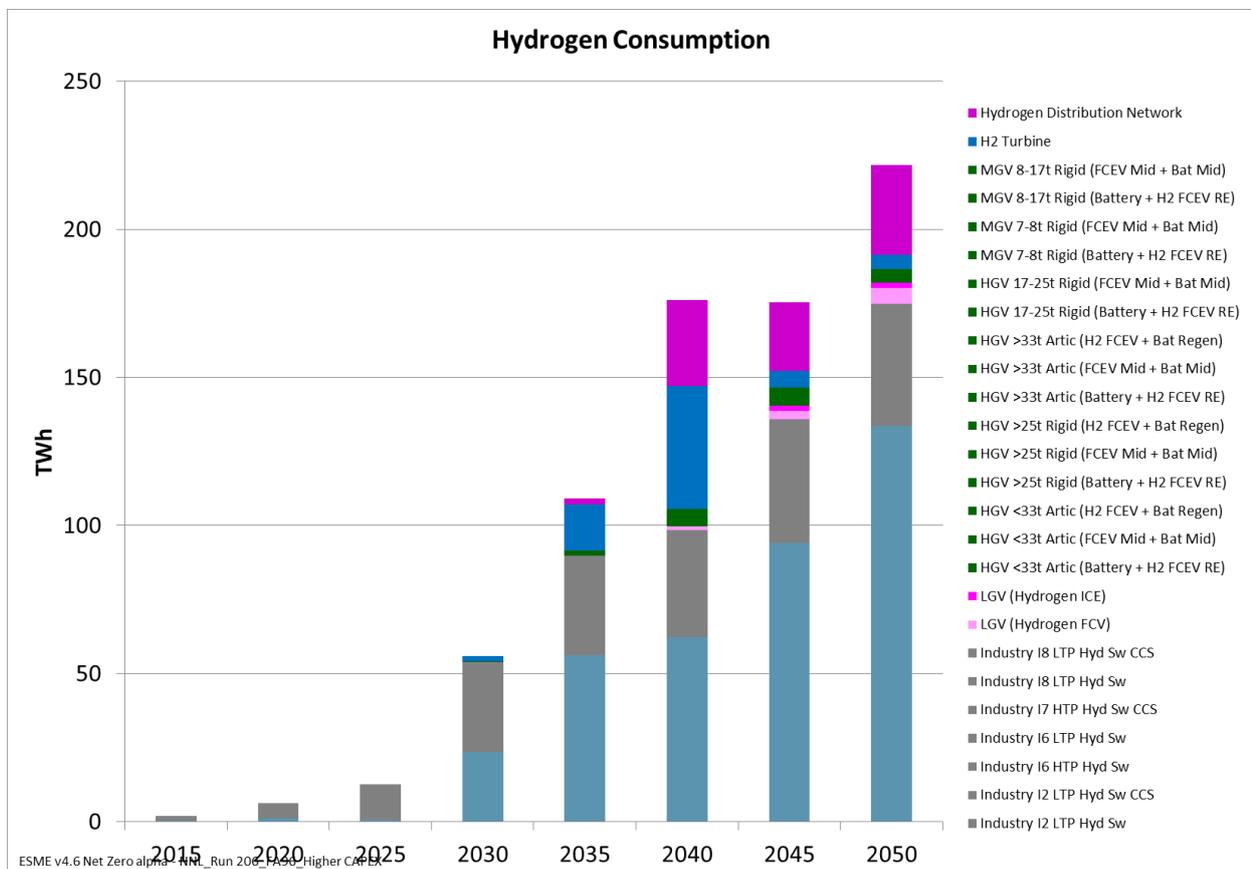
Figure A3-52 – Run 206 hydrogen consumption
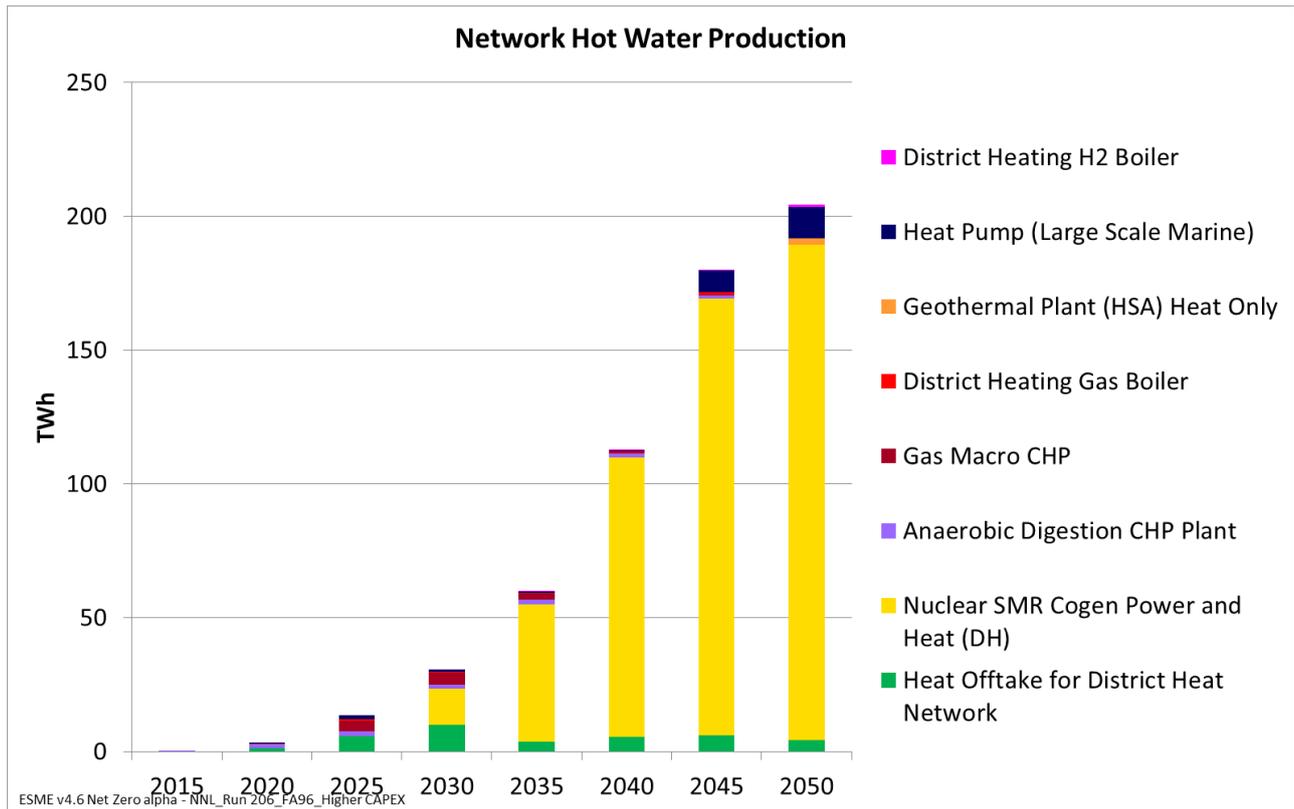
Figure A3-53 – Run 206 network hot water production
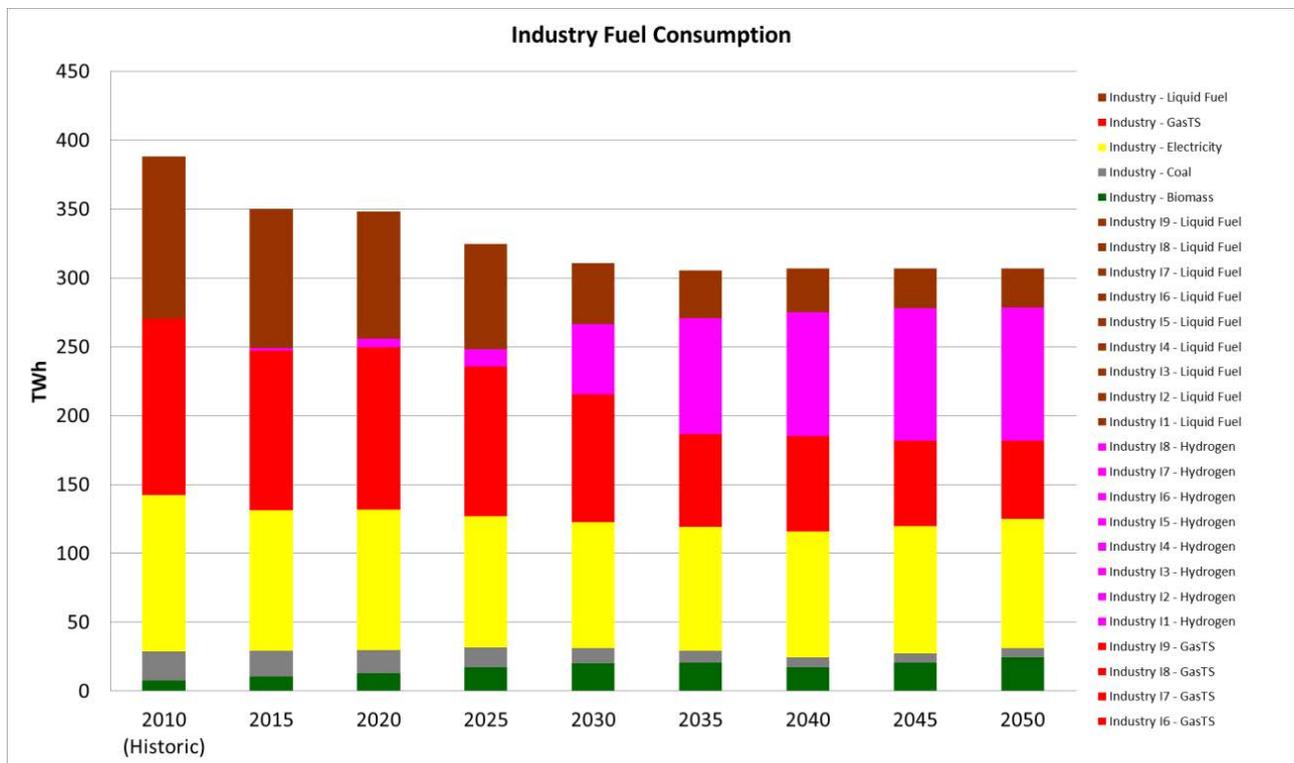
Figure A3-54 – Run 206 industry fuel consumption

Run 207 TECH100 – All nuclear technologies; base case data with higher capex values
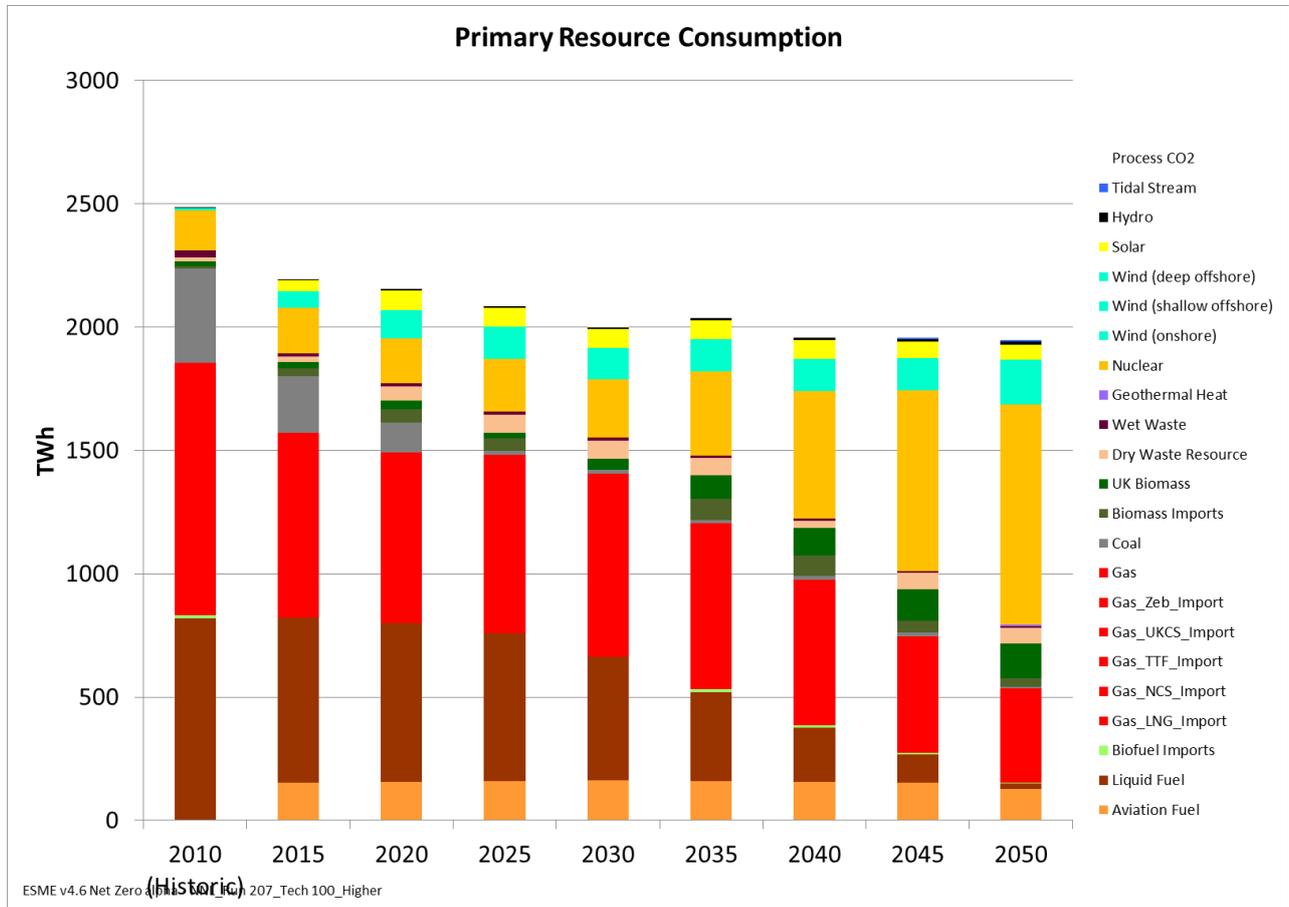
Figure A3-55 – Run 207 primary resource consumption
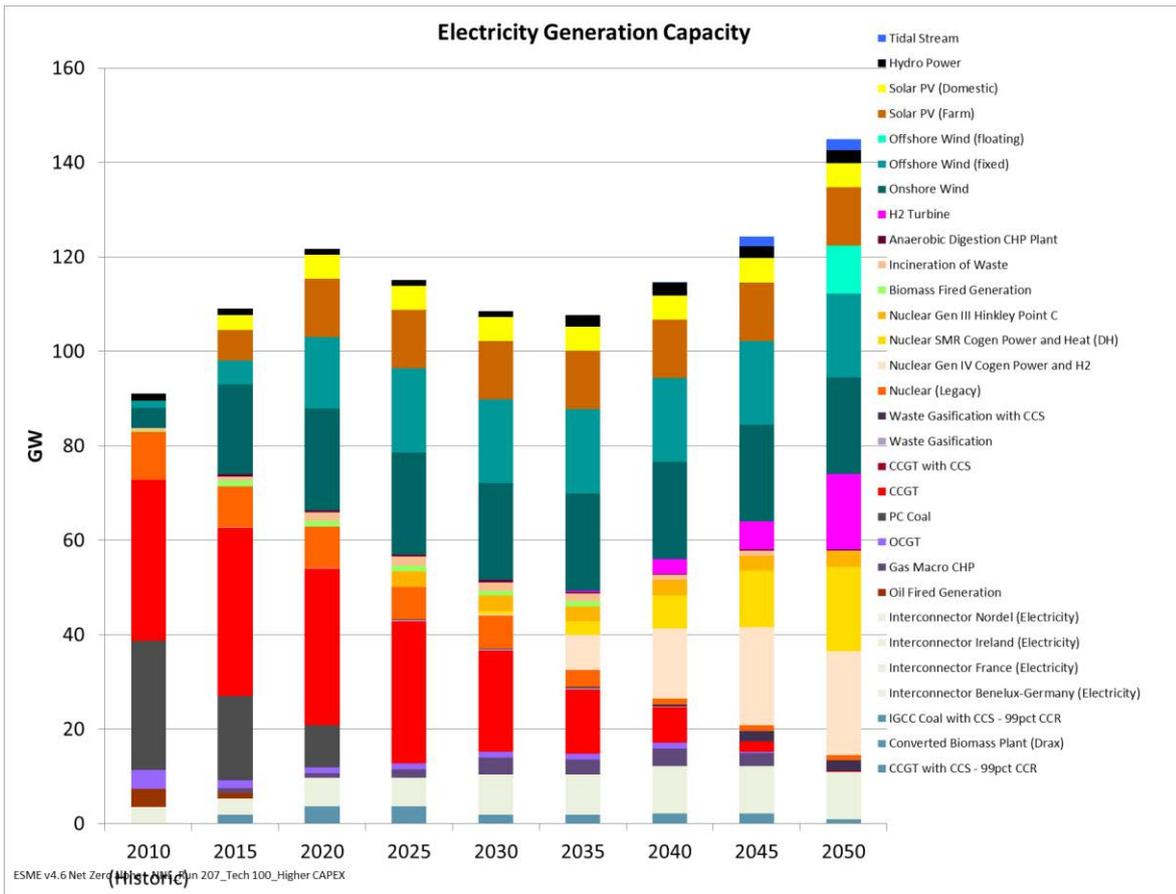
Figure A3-56 – Run 207 electricity generation capacity
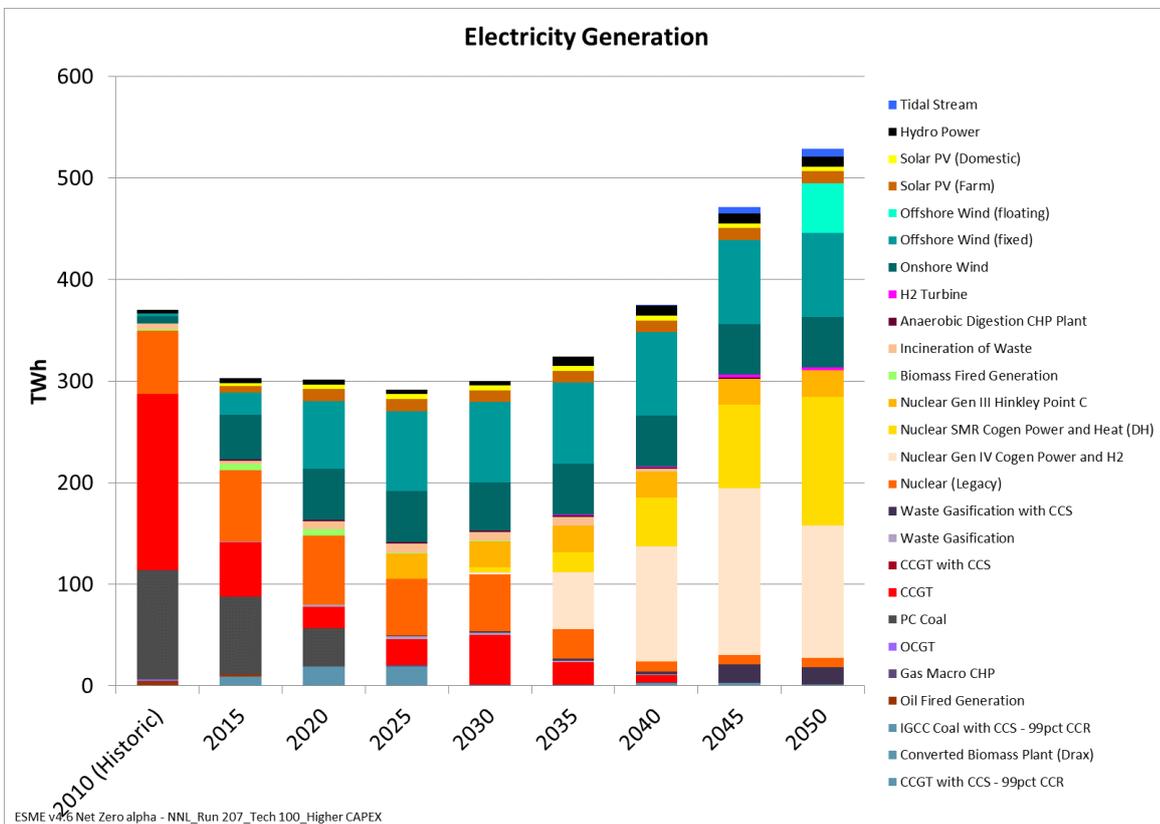
Figure A3-57 – Run 207 electricity generation
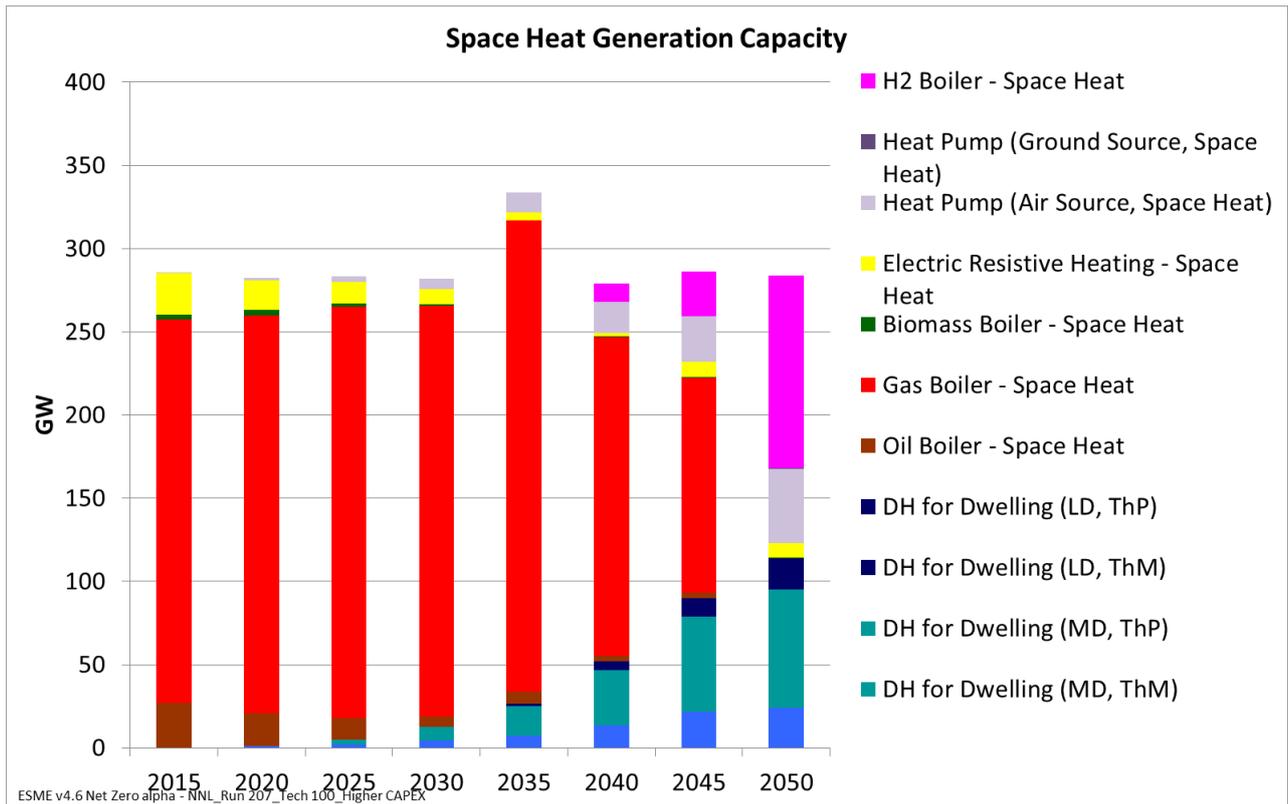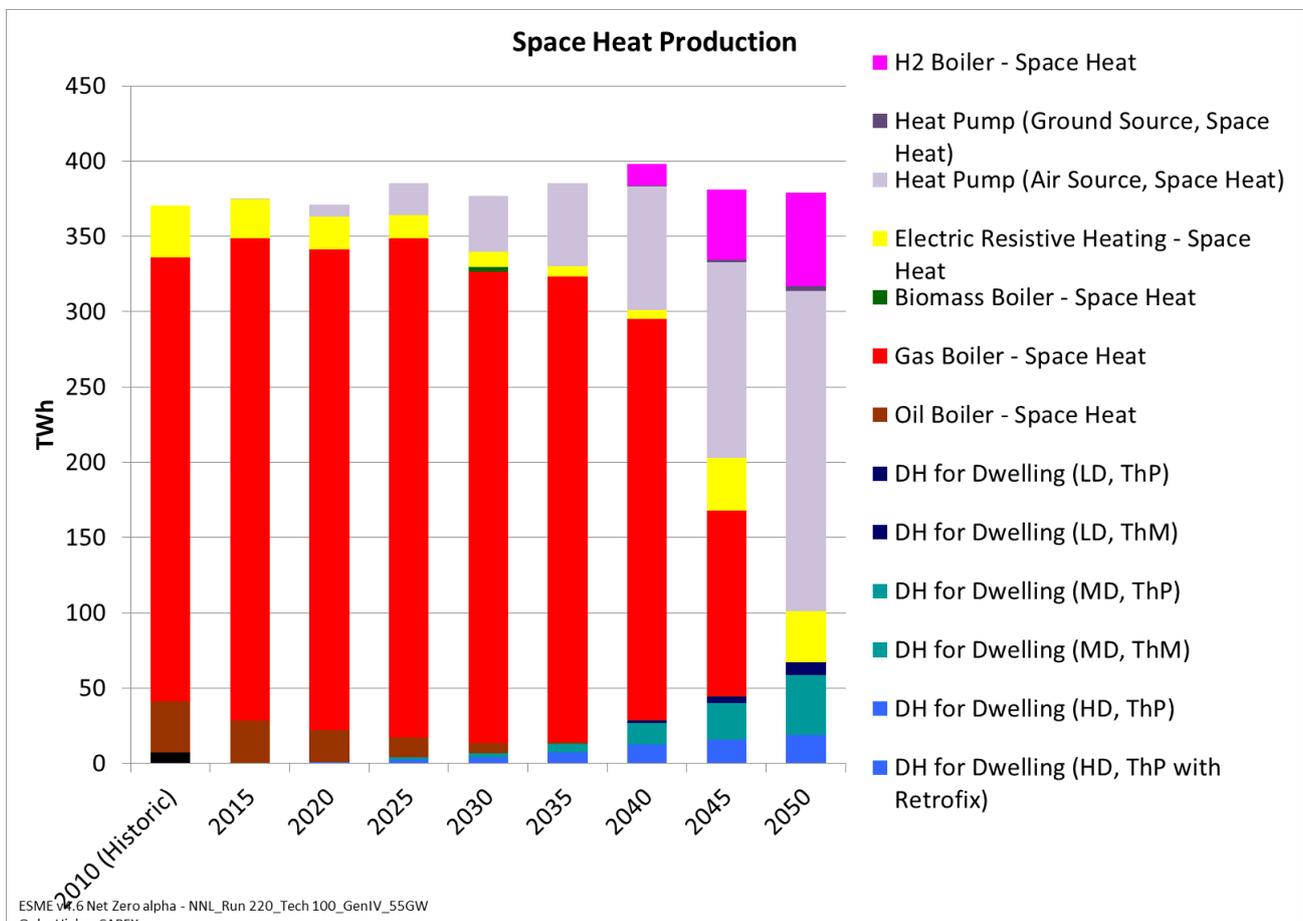
Figure A3-58 – Run 207 space heat generation capacity
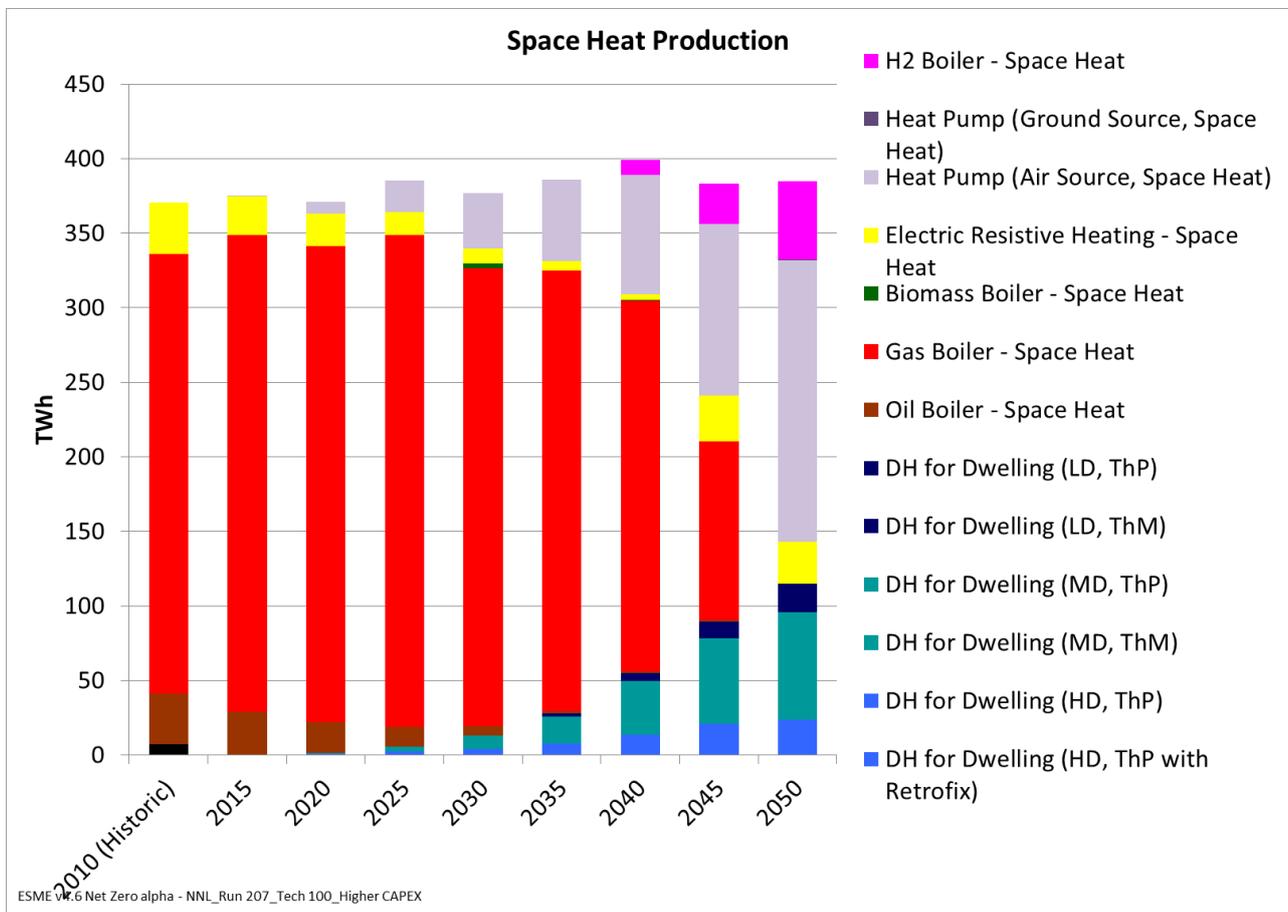
Figure A3-59 – Run 207 space heat production
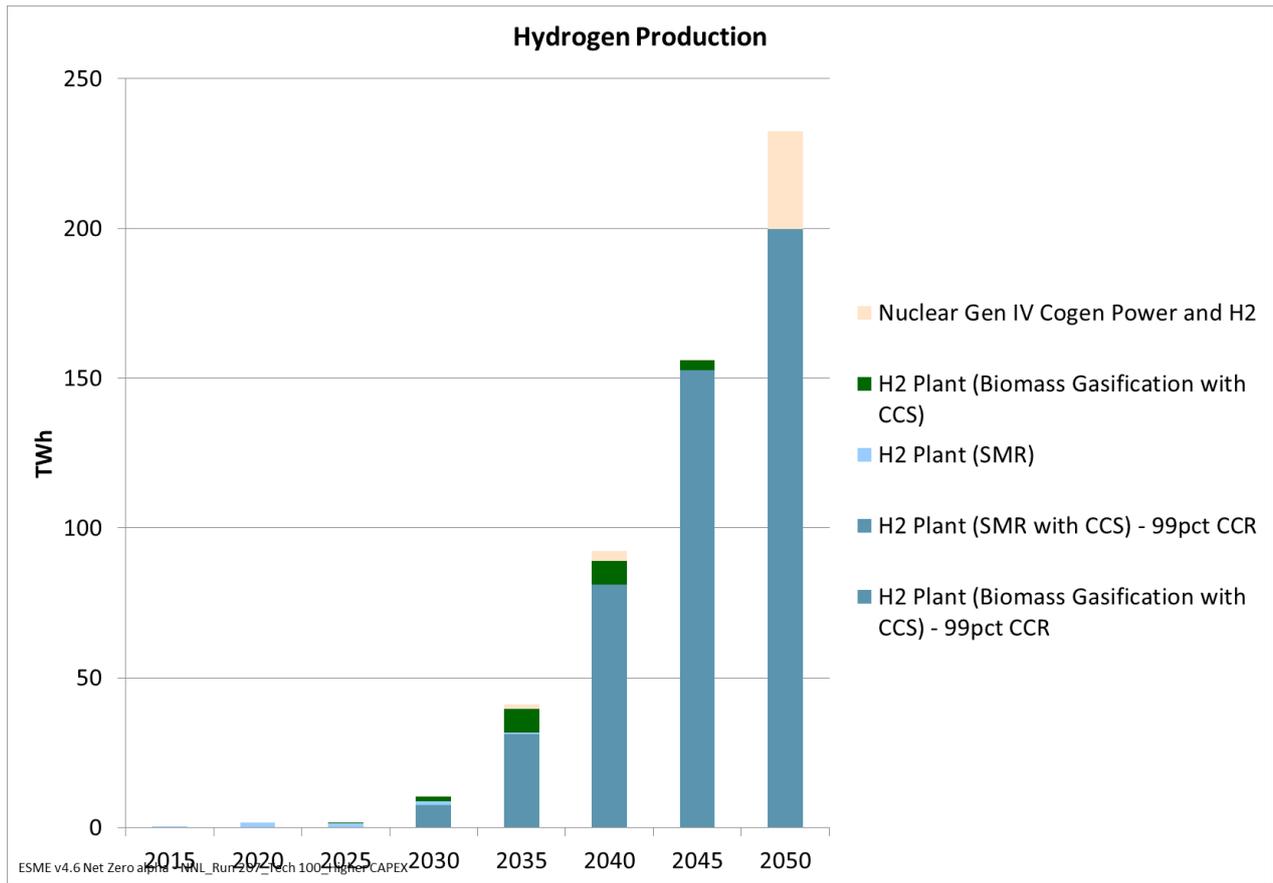
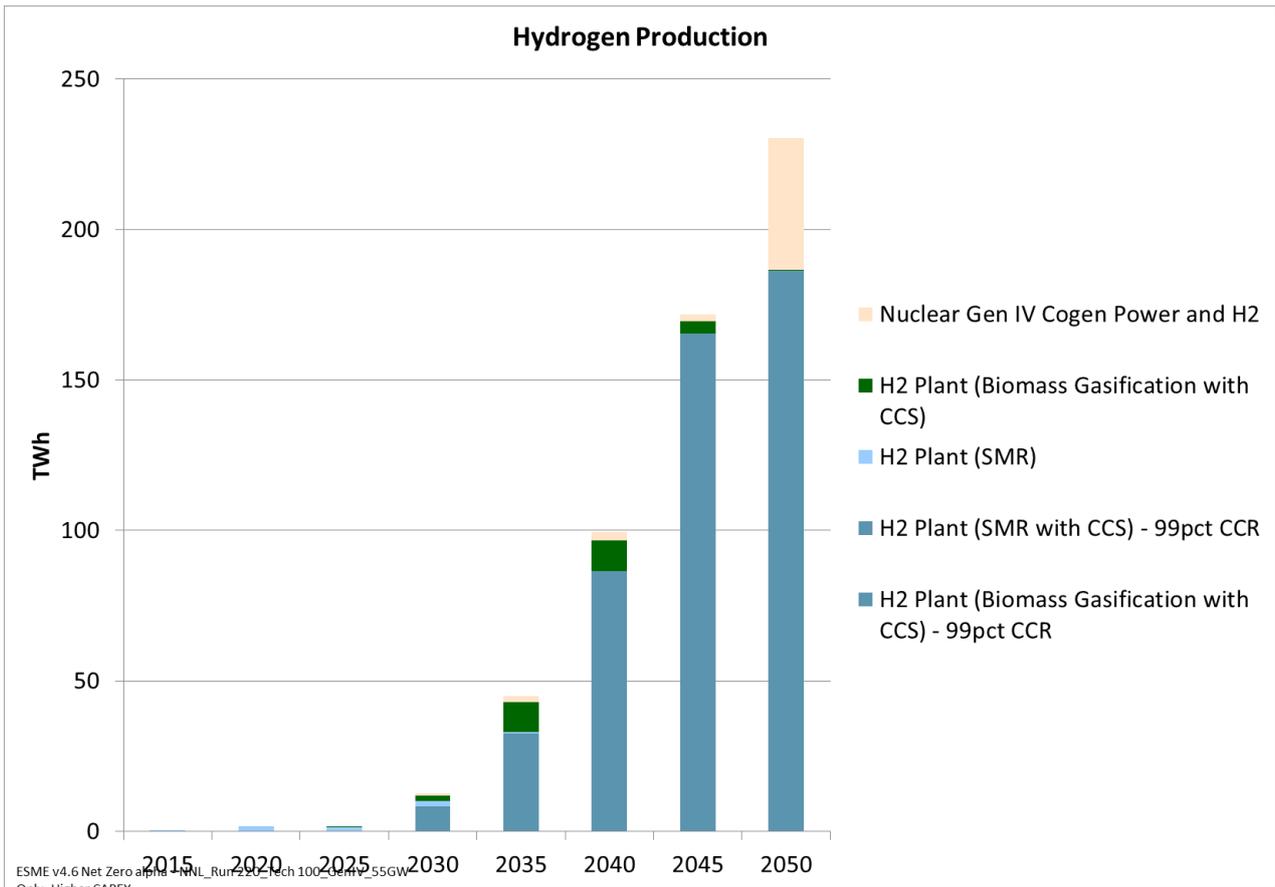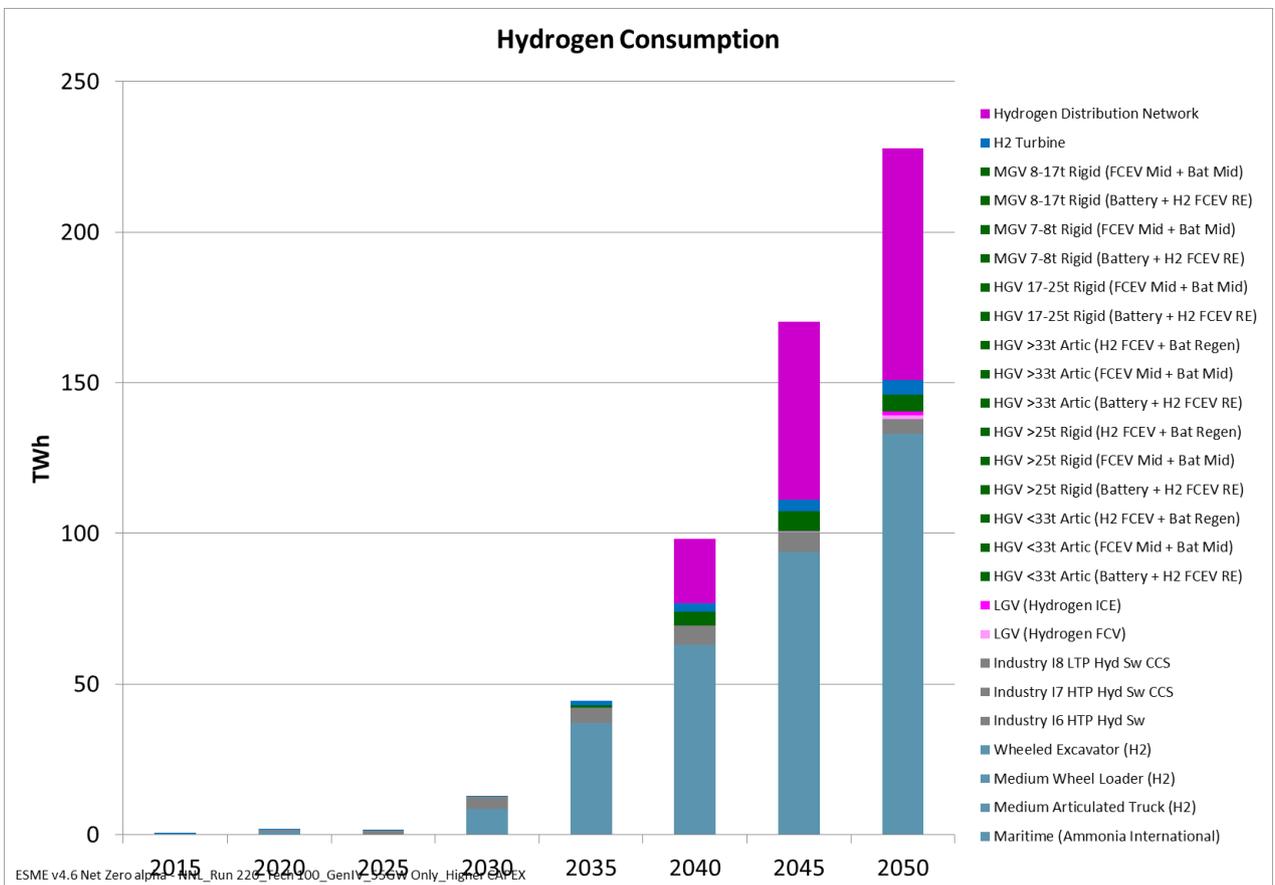Figure A3-60 – Run 207 hydrogen production
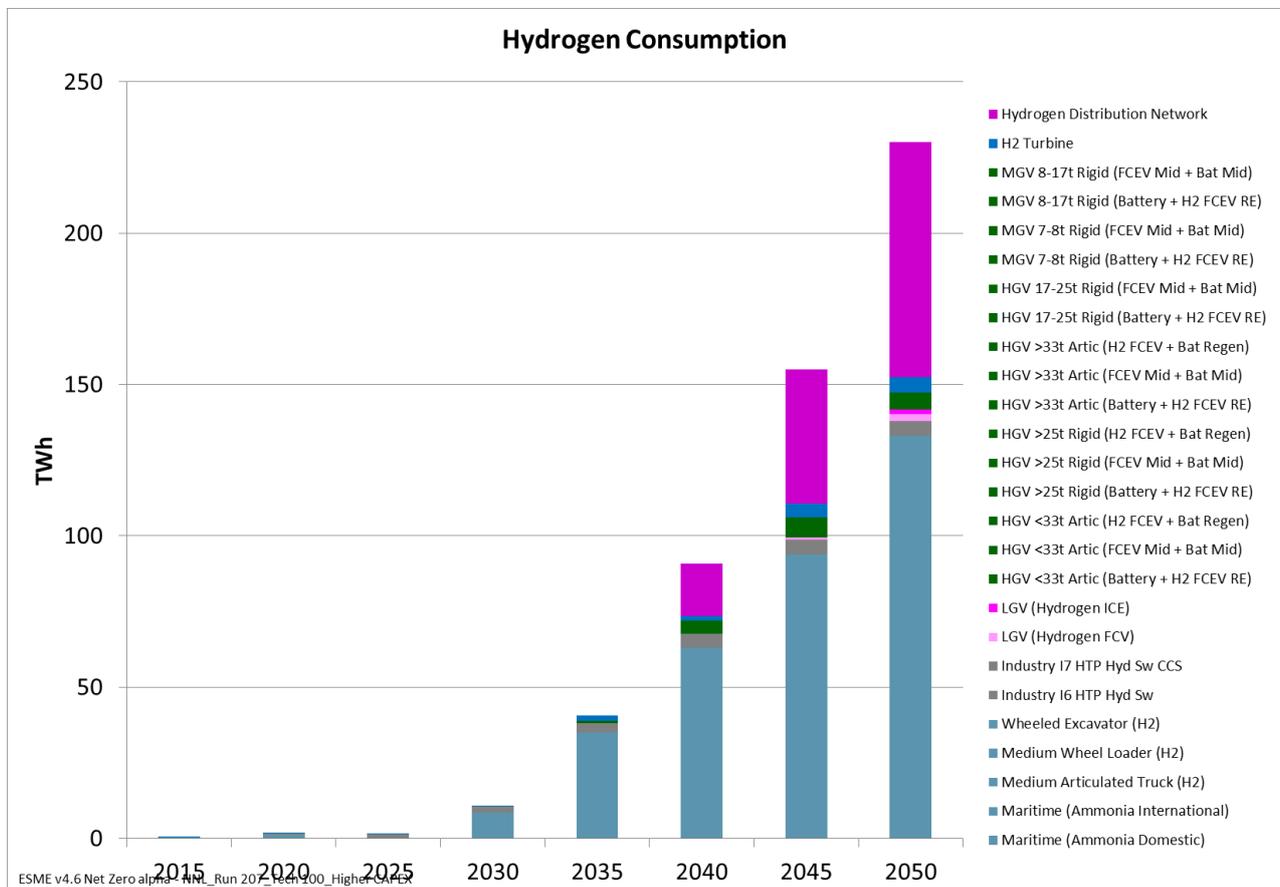

Figure A3-61 – Run 207 hydrogen consumption
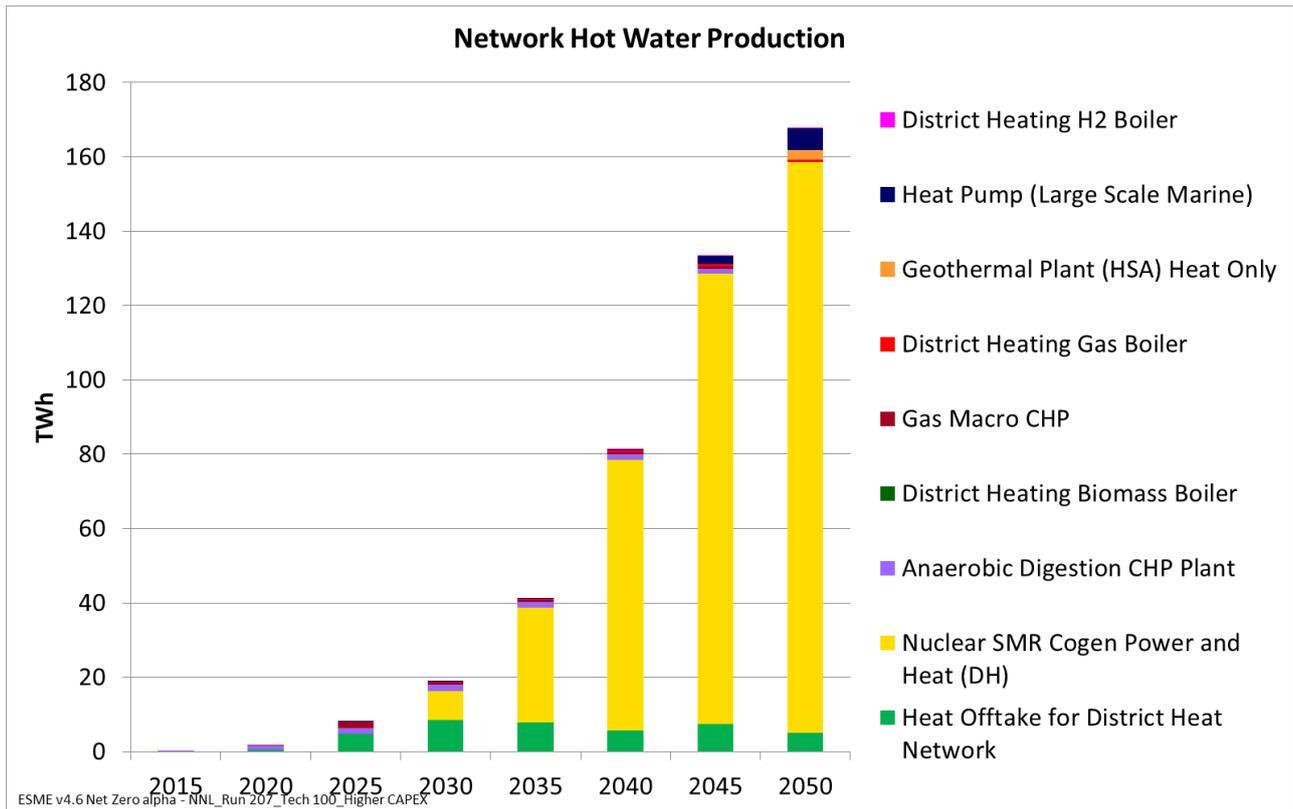
Figure A3-62 – Run 207 network hot water production
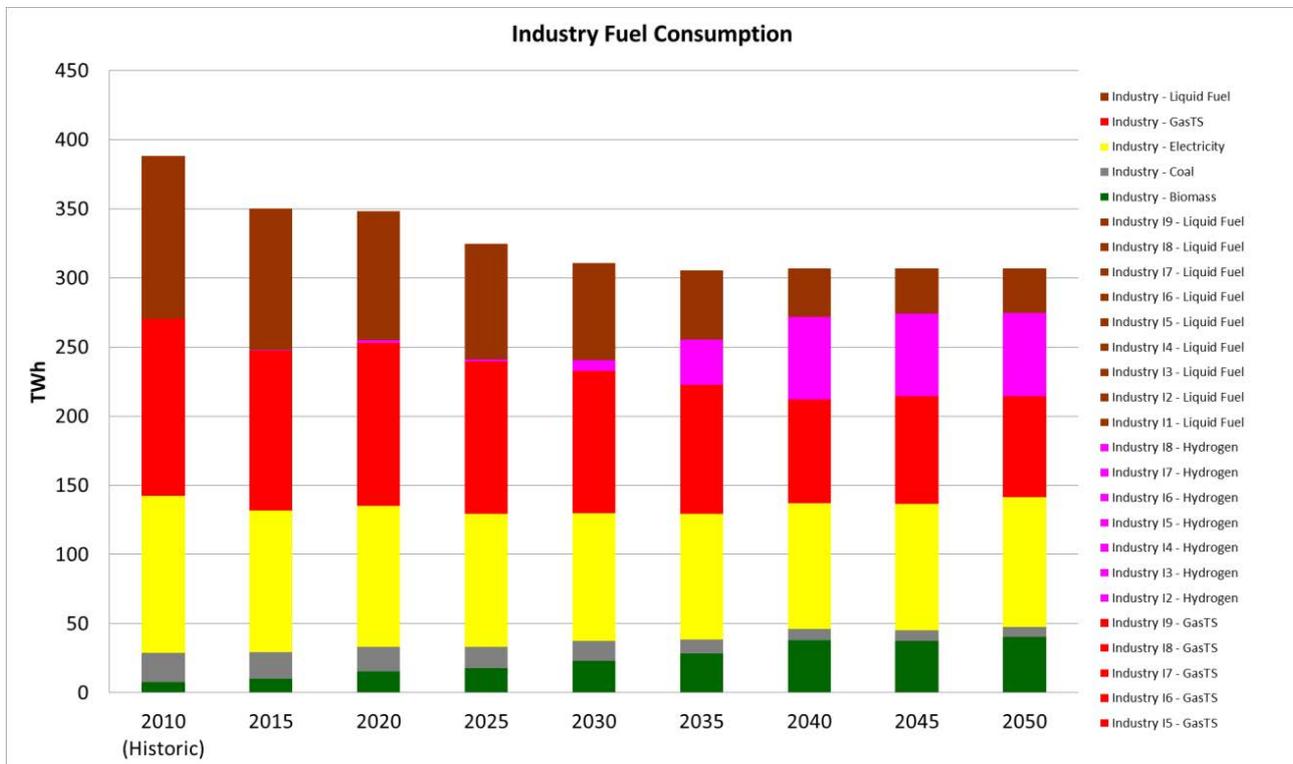
Figure A3-63 – Run 207 industry fuel consumption

Run 208 FA96 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data
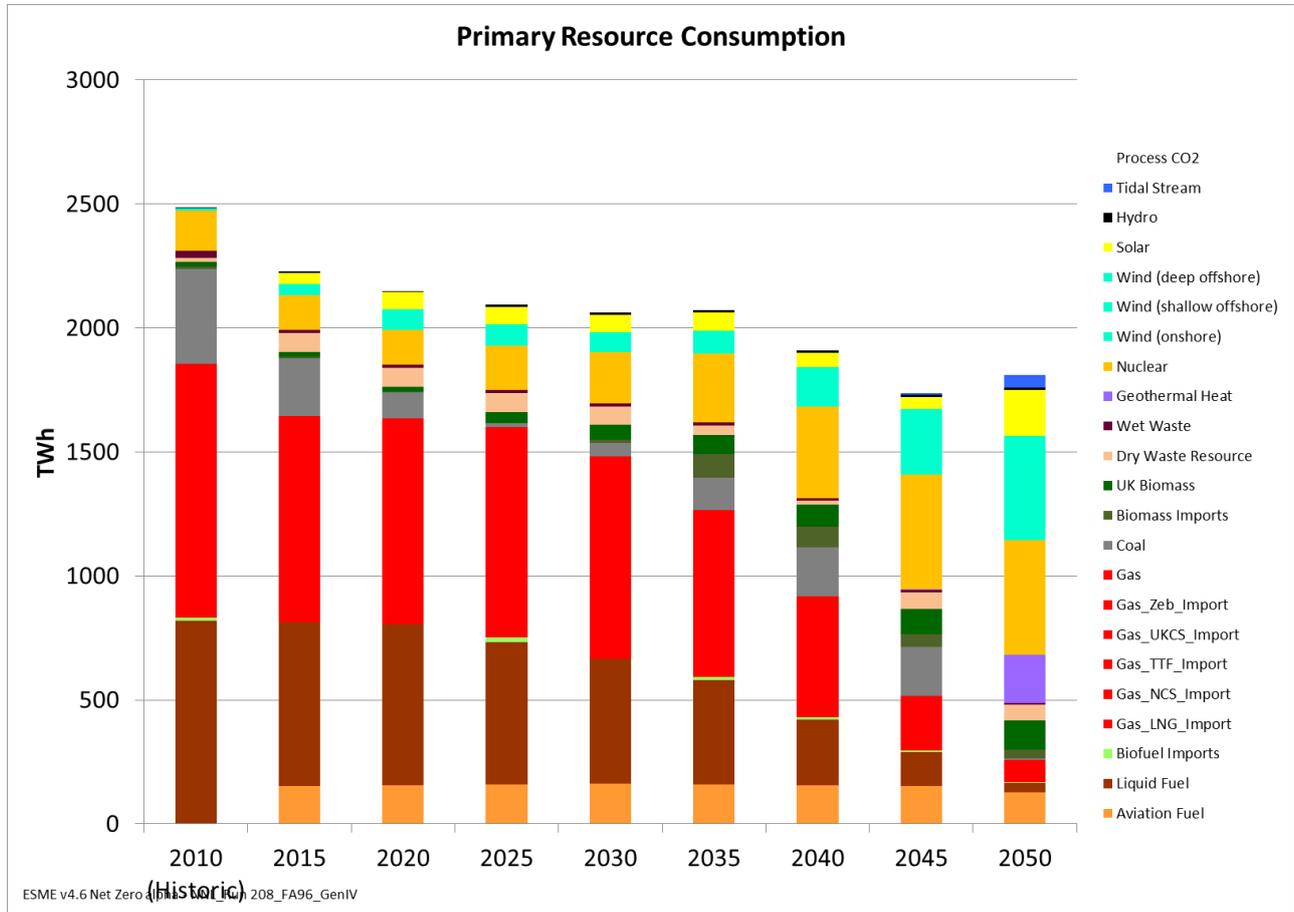
Figure A3-64 – Run 208 primary resource consumption
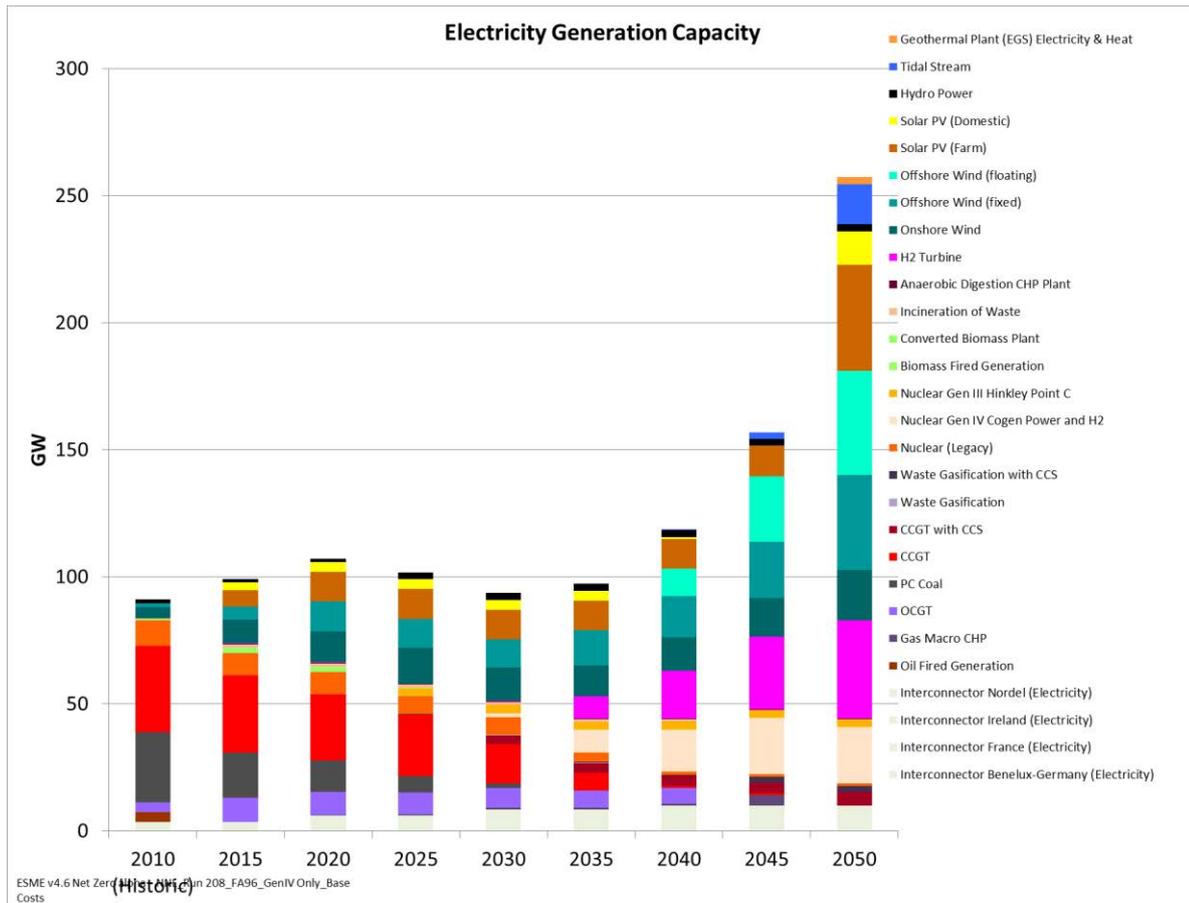
Figure A3-65 – Run 208 electricity generation capacity
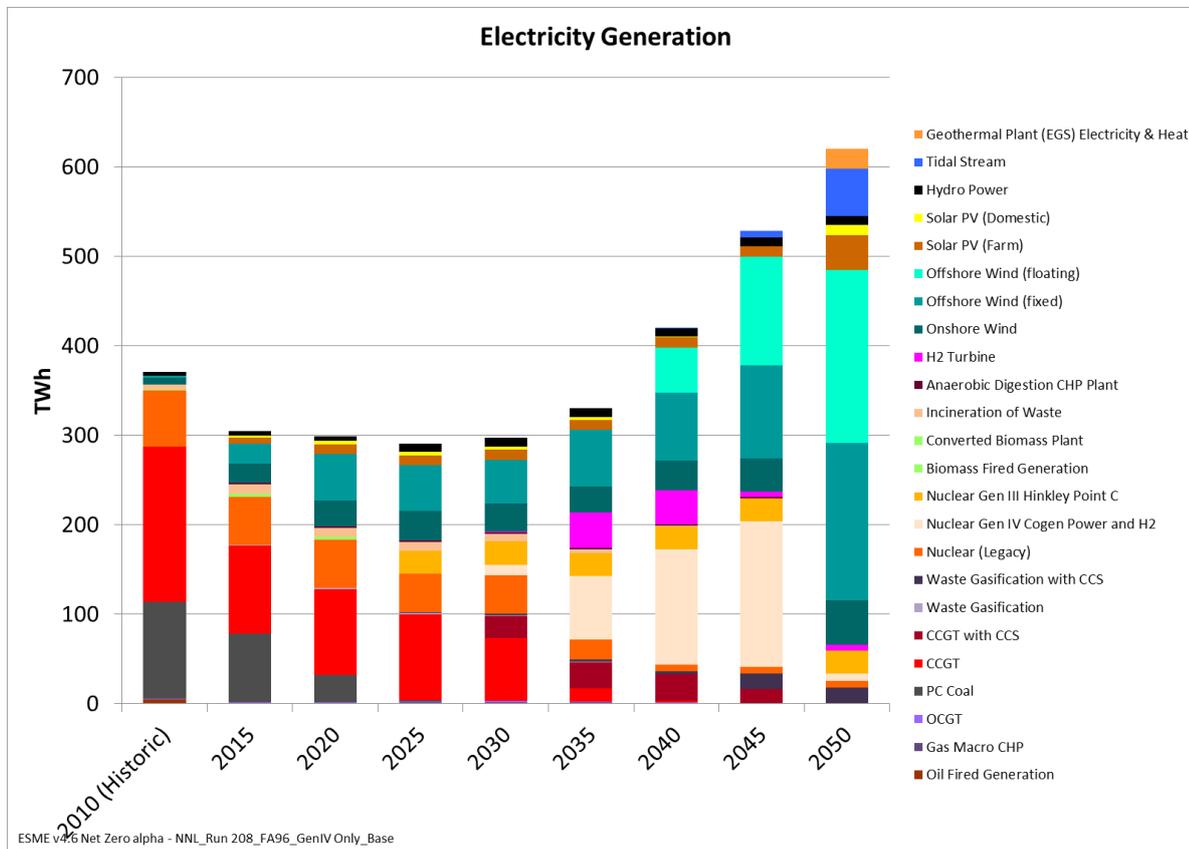
Figure A3-66 – Run 208 electricity generation
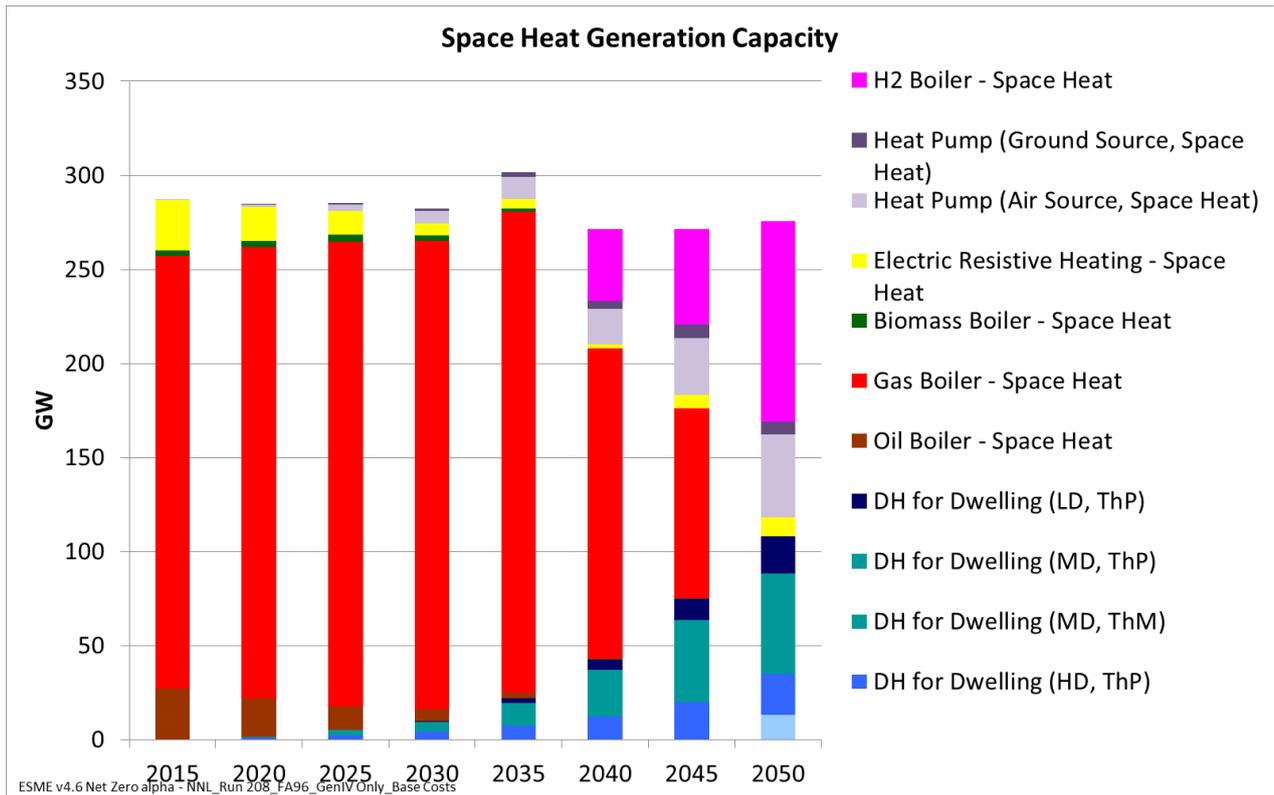
Figure A3-67 – Run 208 space heat generation capacity
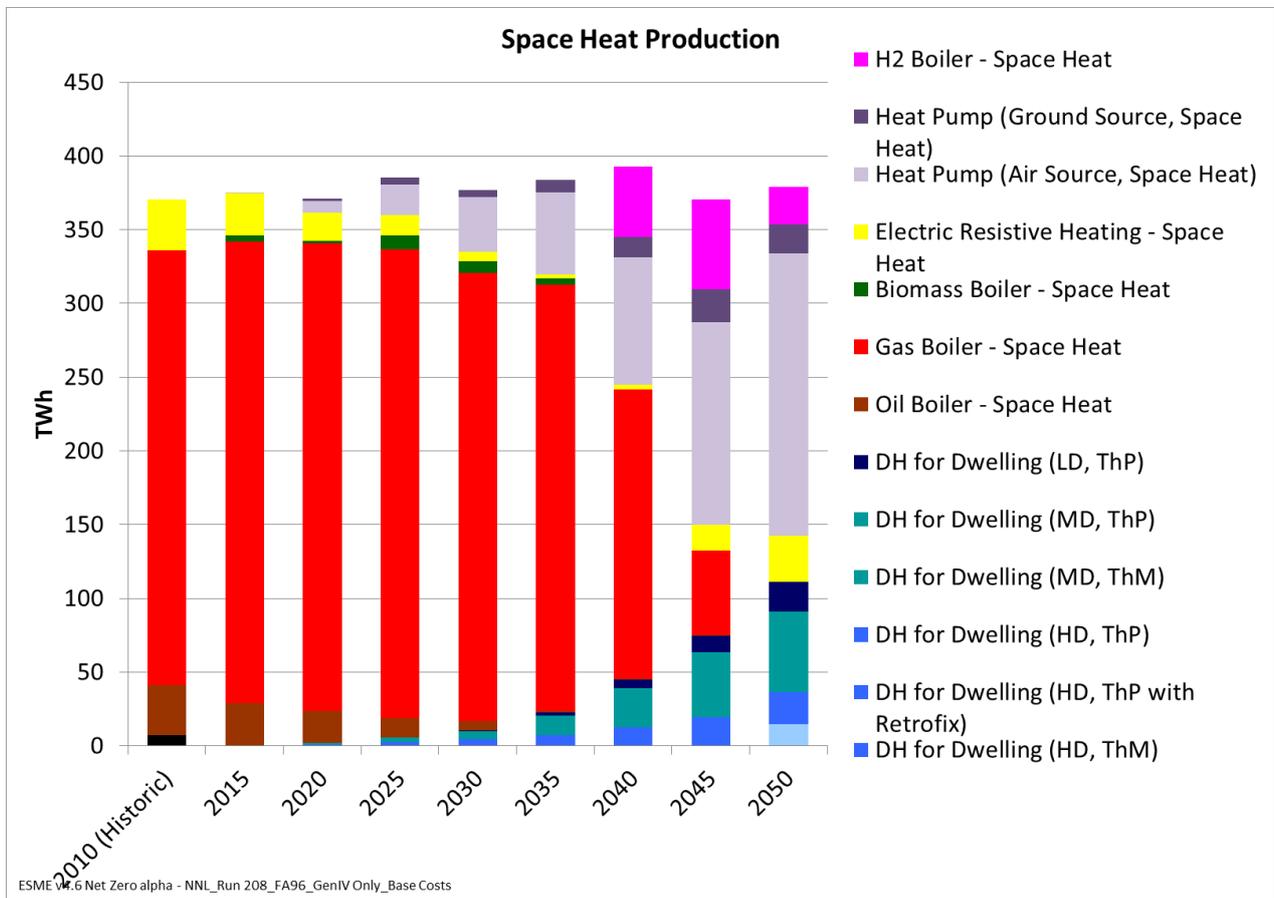
Figure A3-68 – Run 208 space heat production
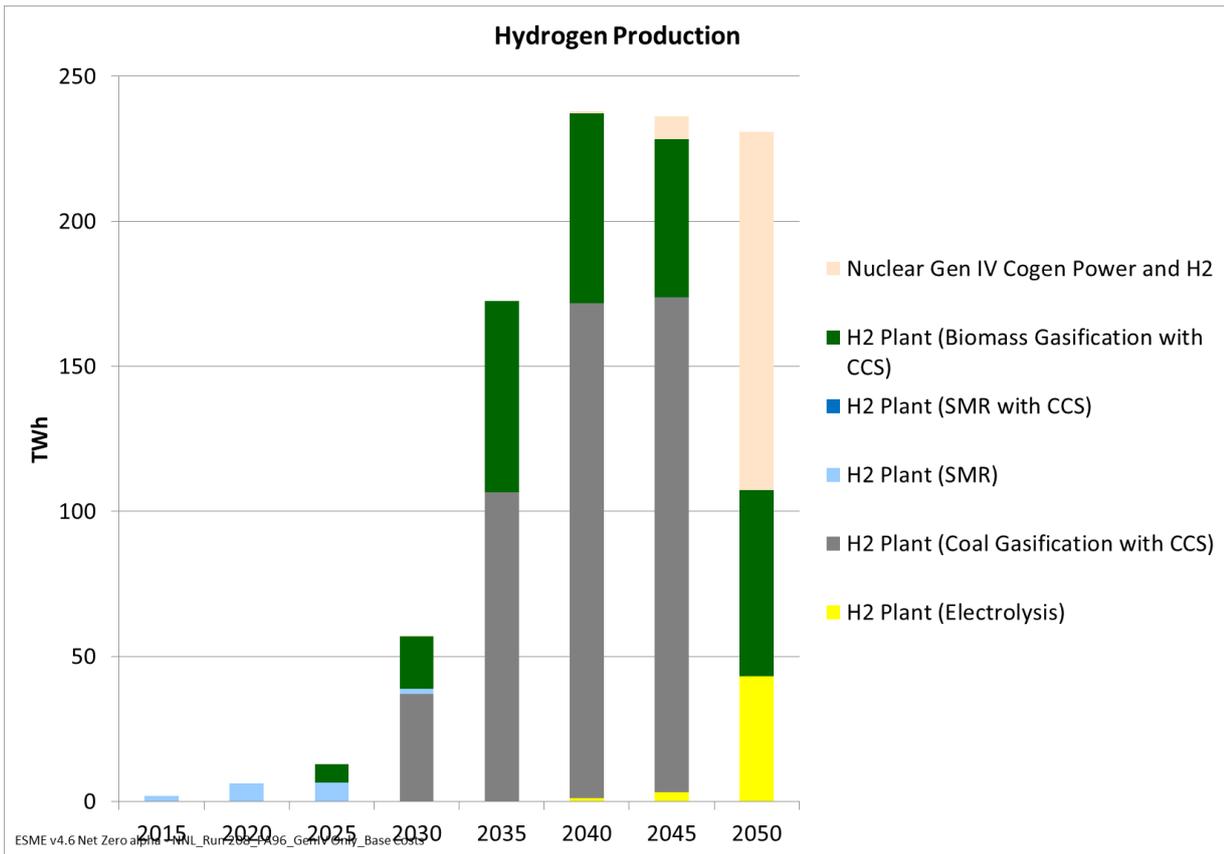
Figure A3-69 – Run 208 hydrogen production
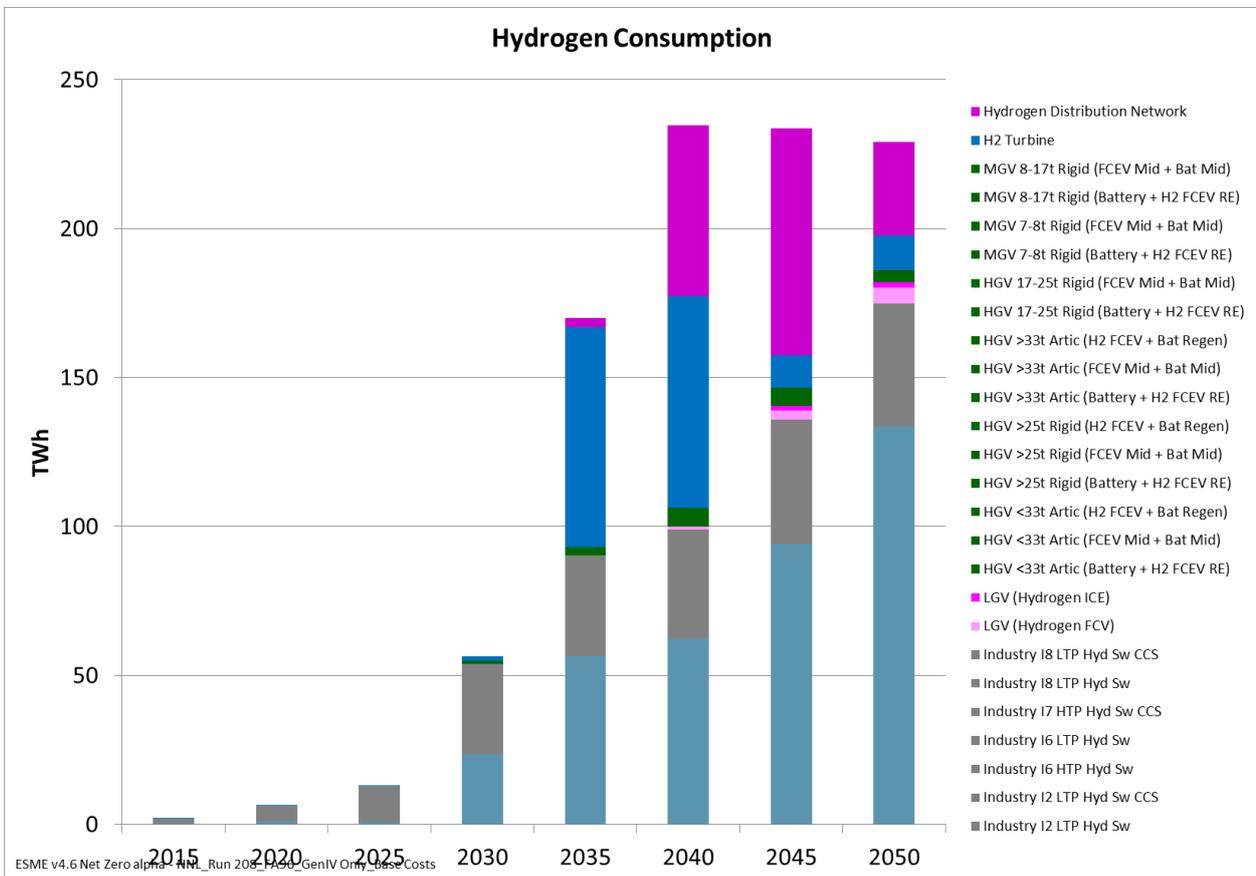
Figure A3-70 – Run 208 hydrogen consumption
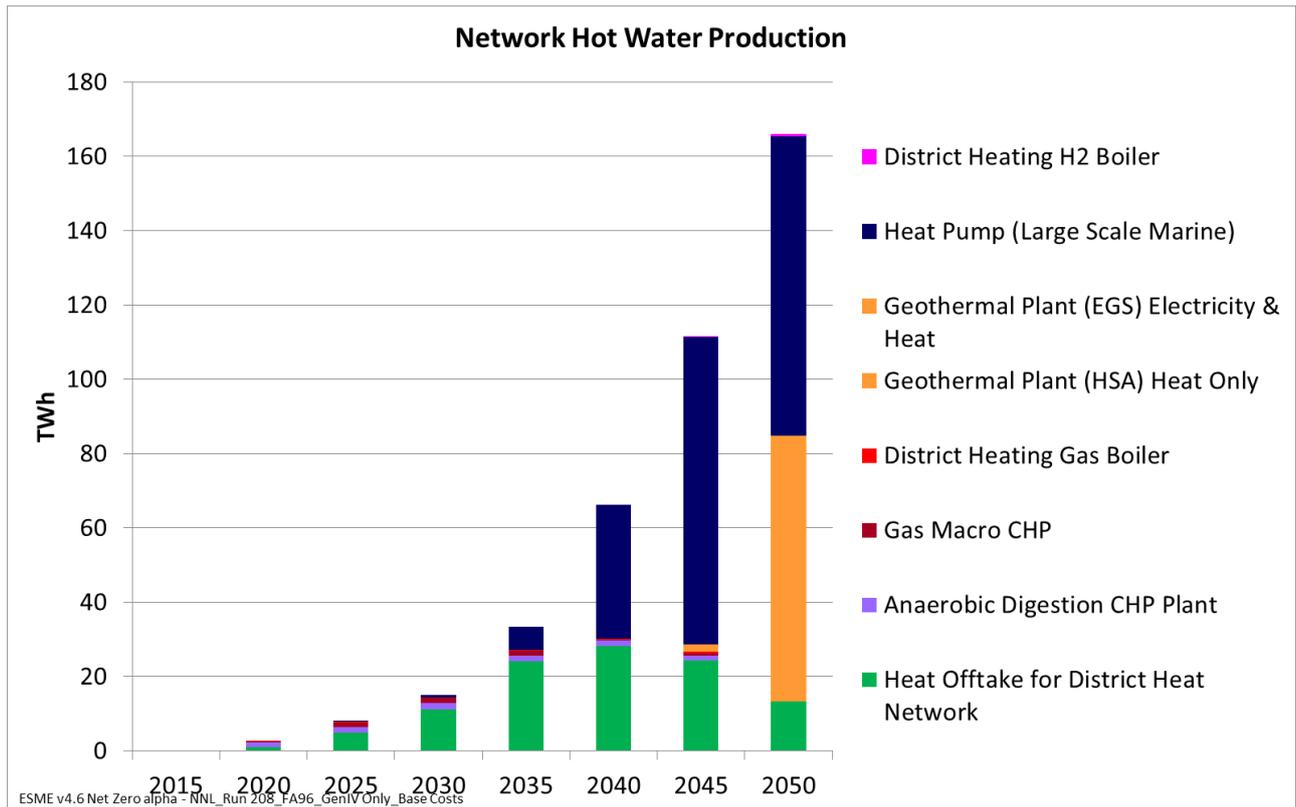
Figure A3-71 – Run 208 network hot water production
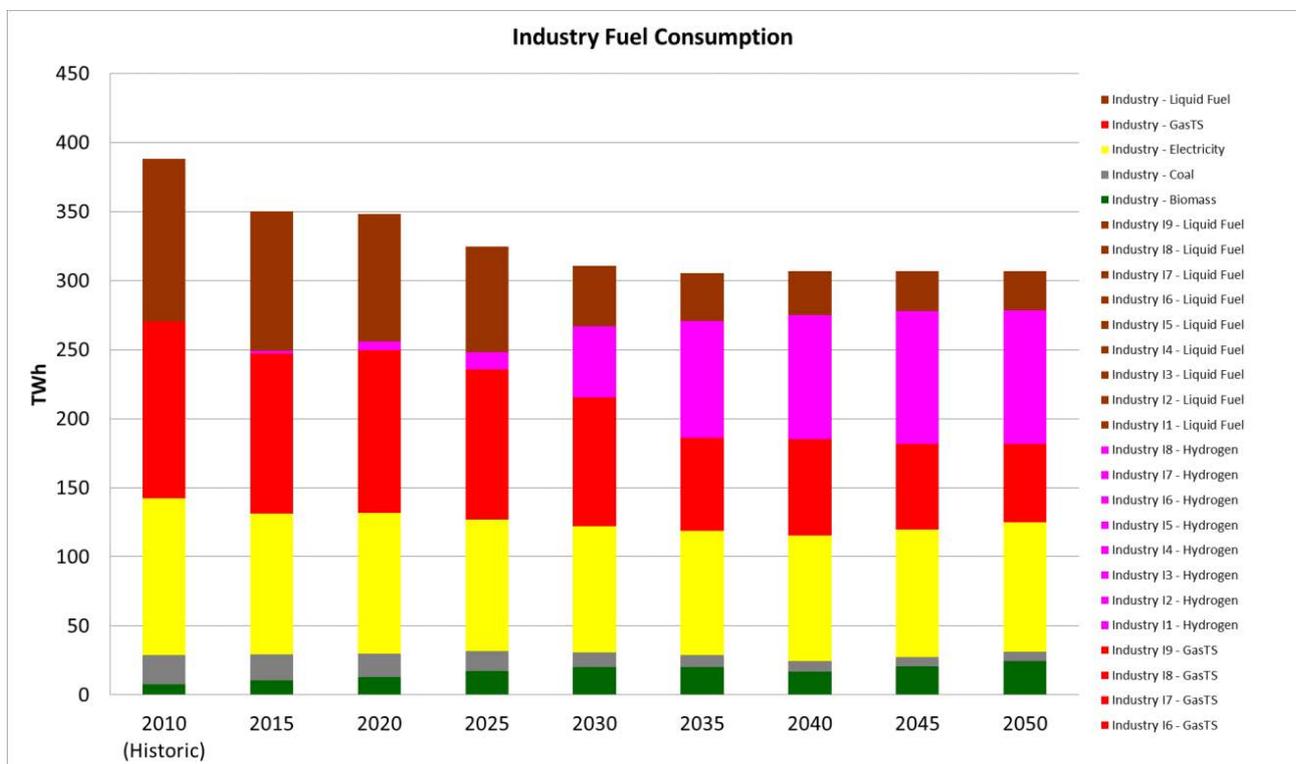
Figure A3-72 – Run 208 industry fuel consumption

Run 209 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data
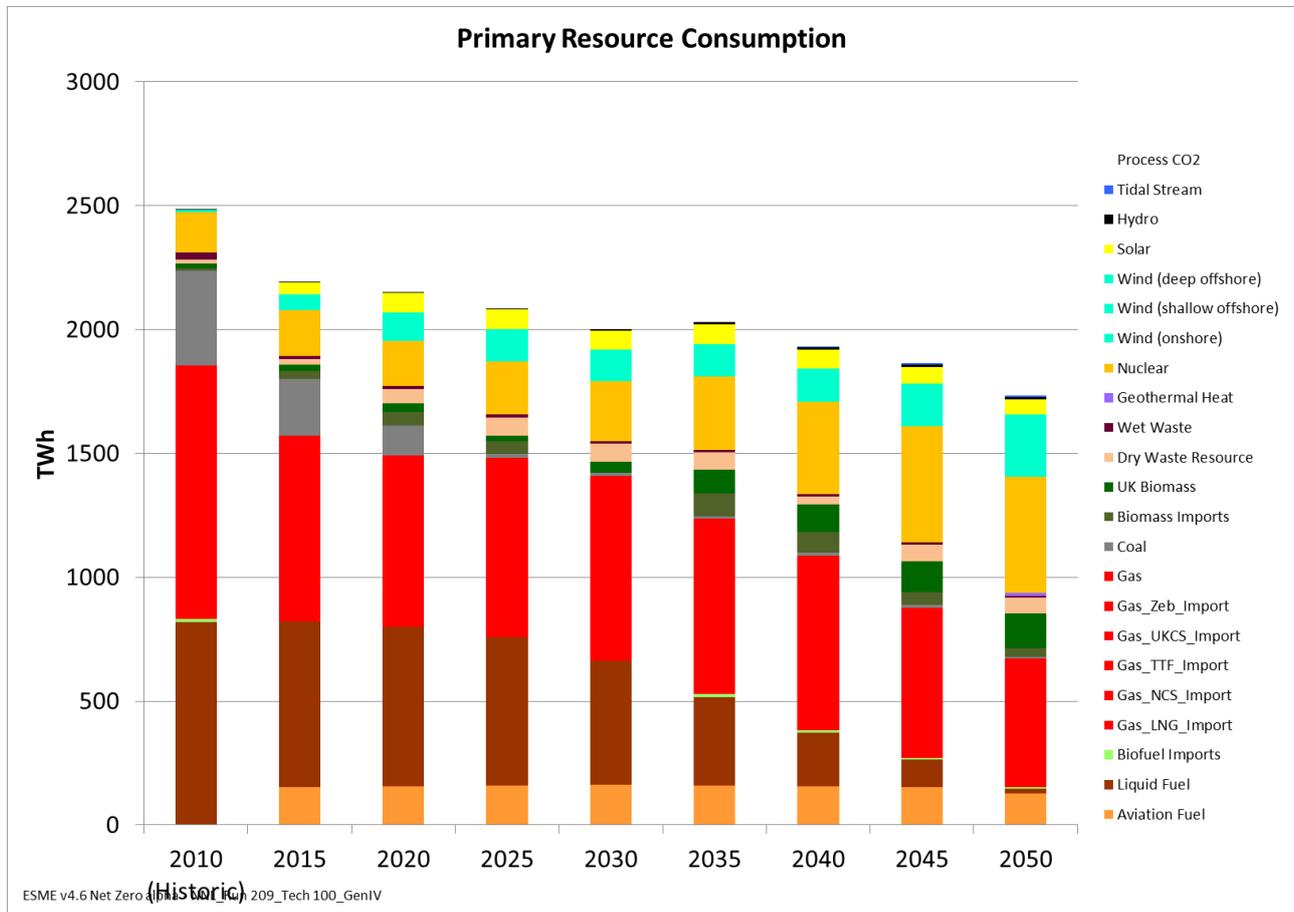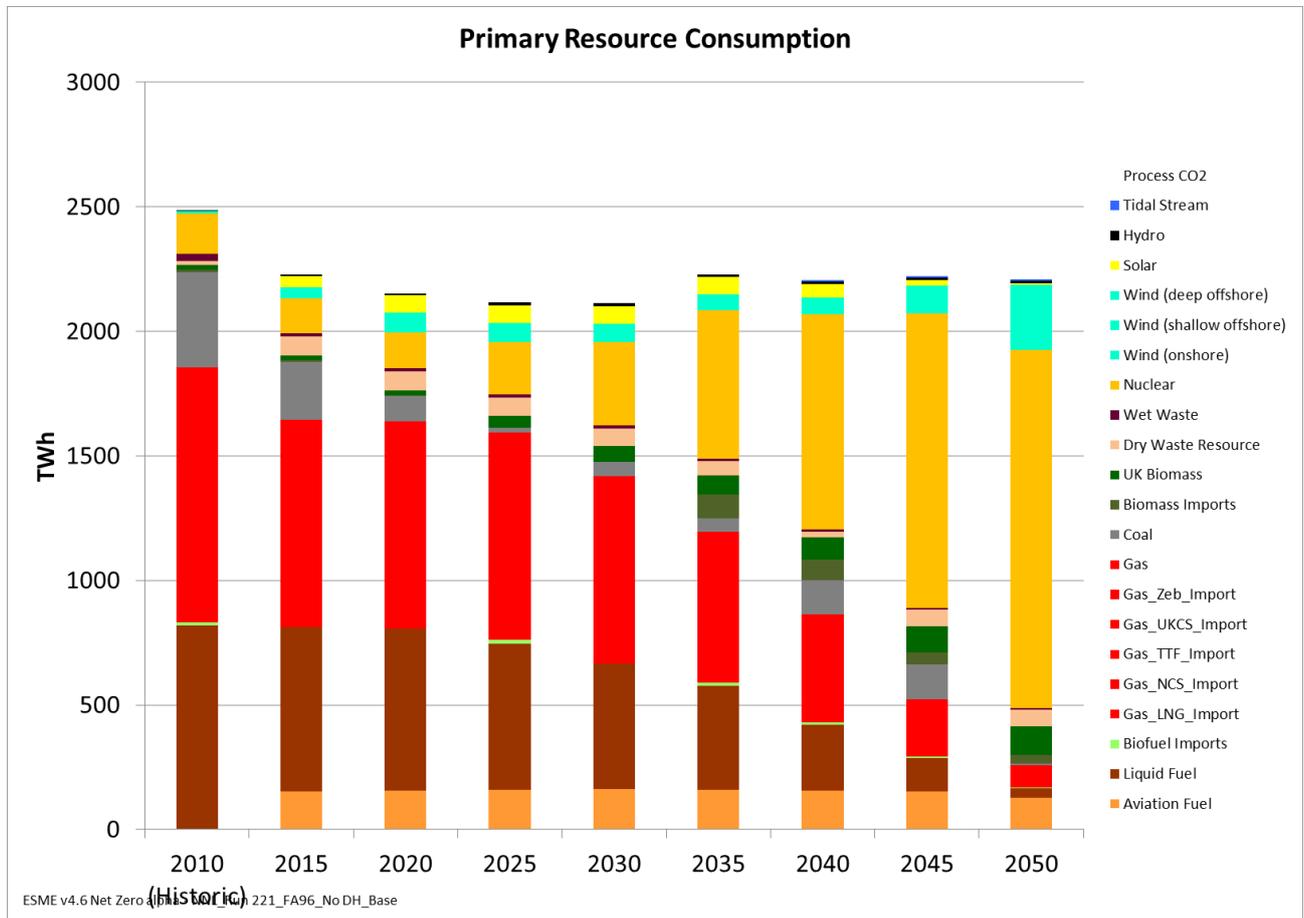

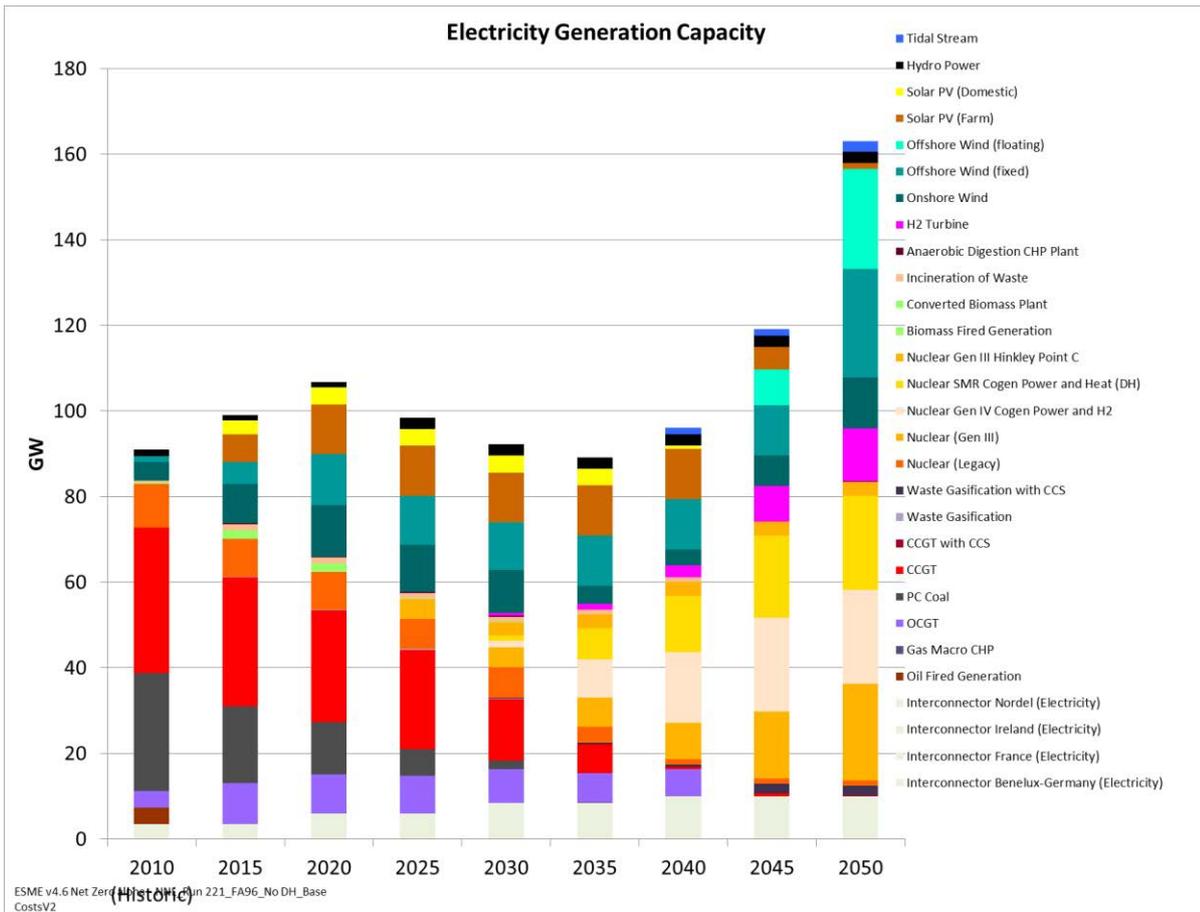
Figure A3-73 – Run 209 primary resource consumption
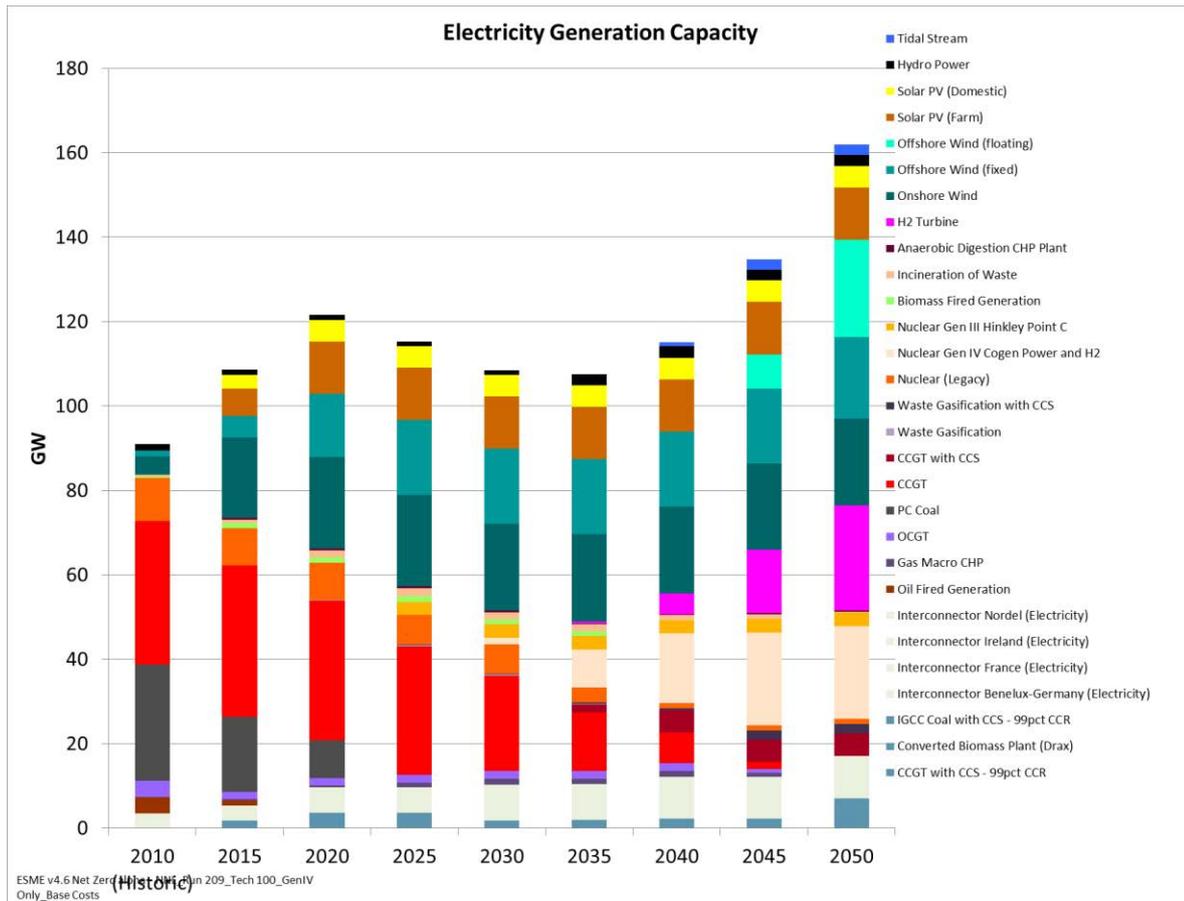
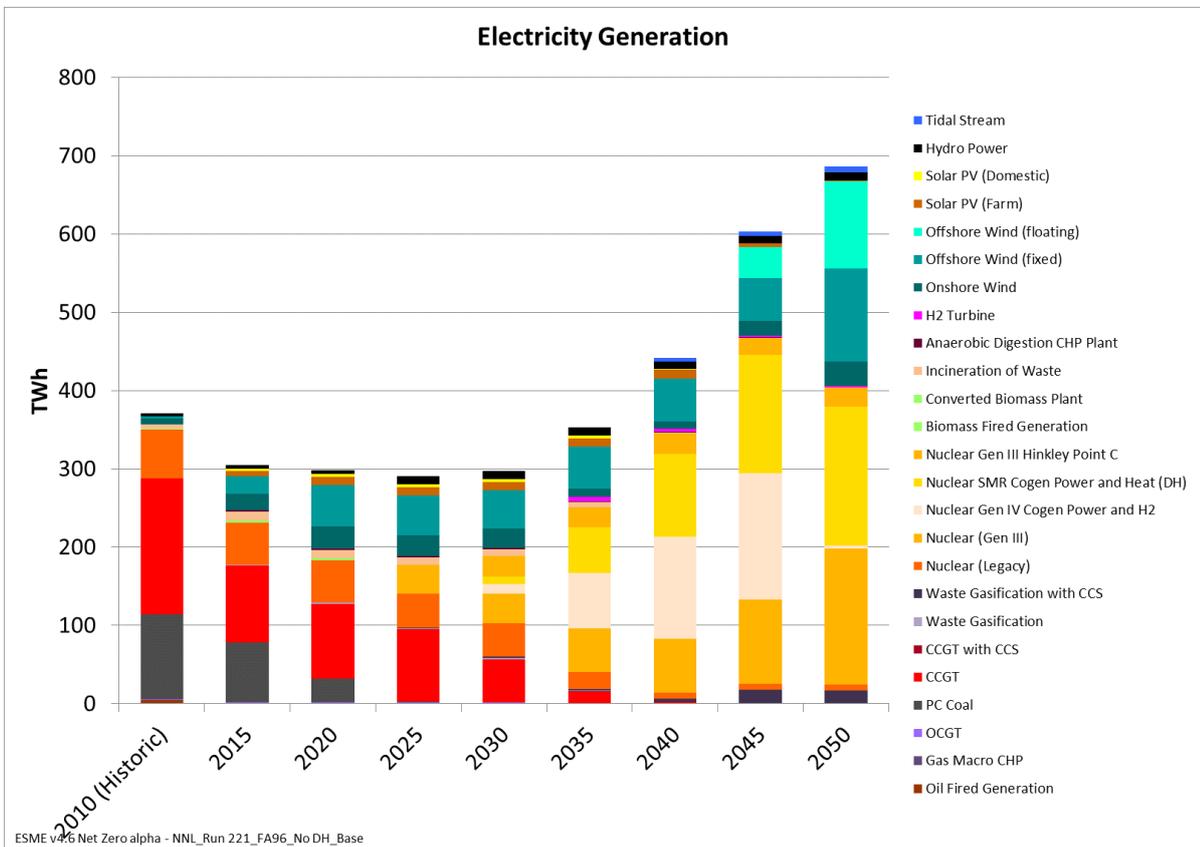Figure A3-74 – Run 209 electricity generation capacity
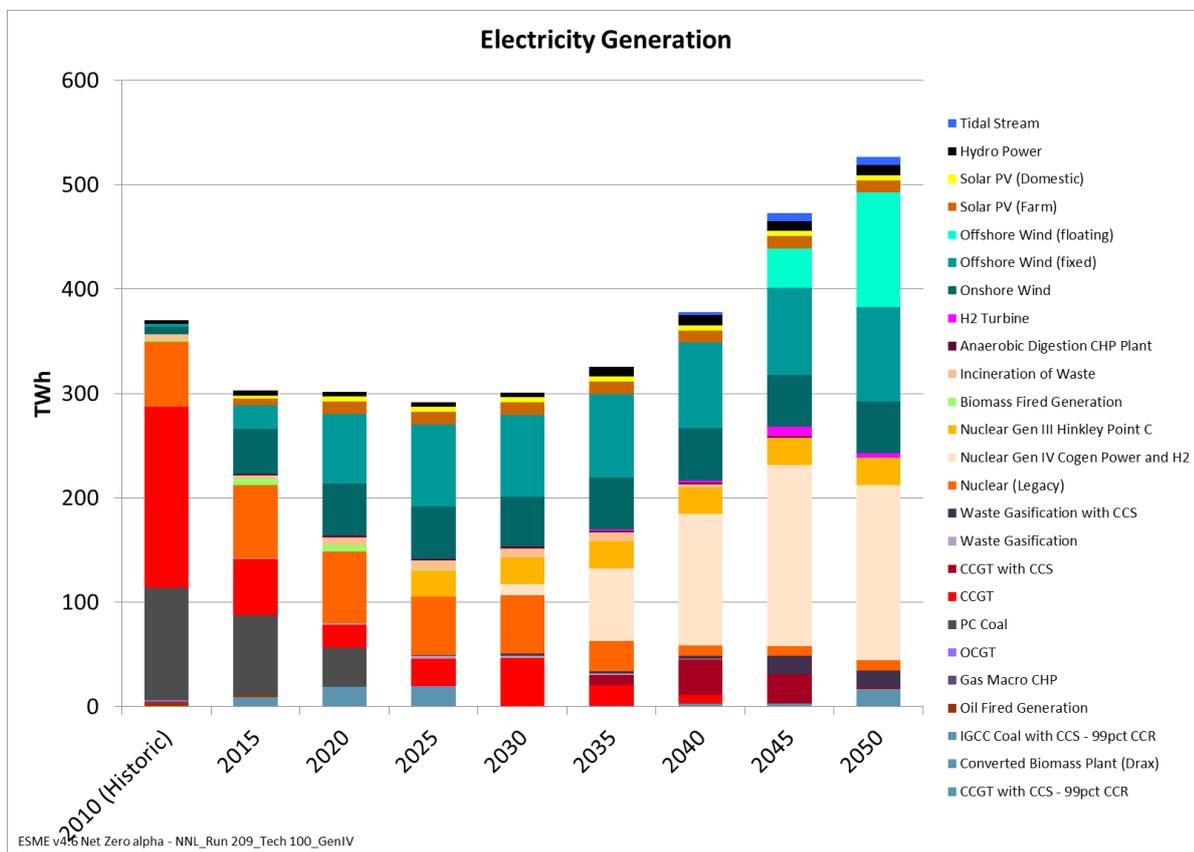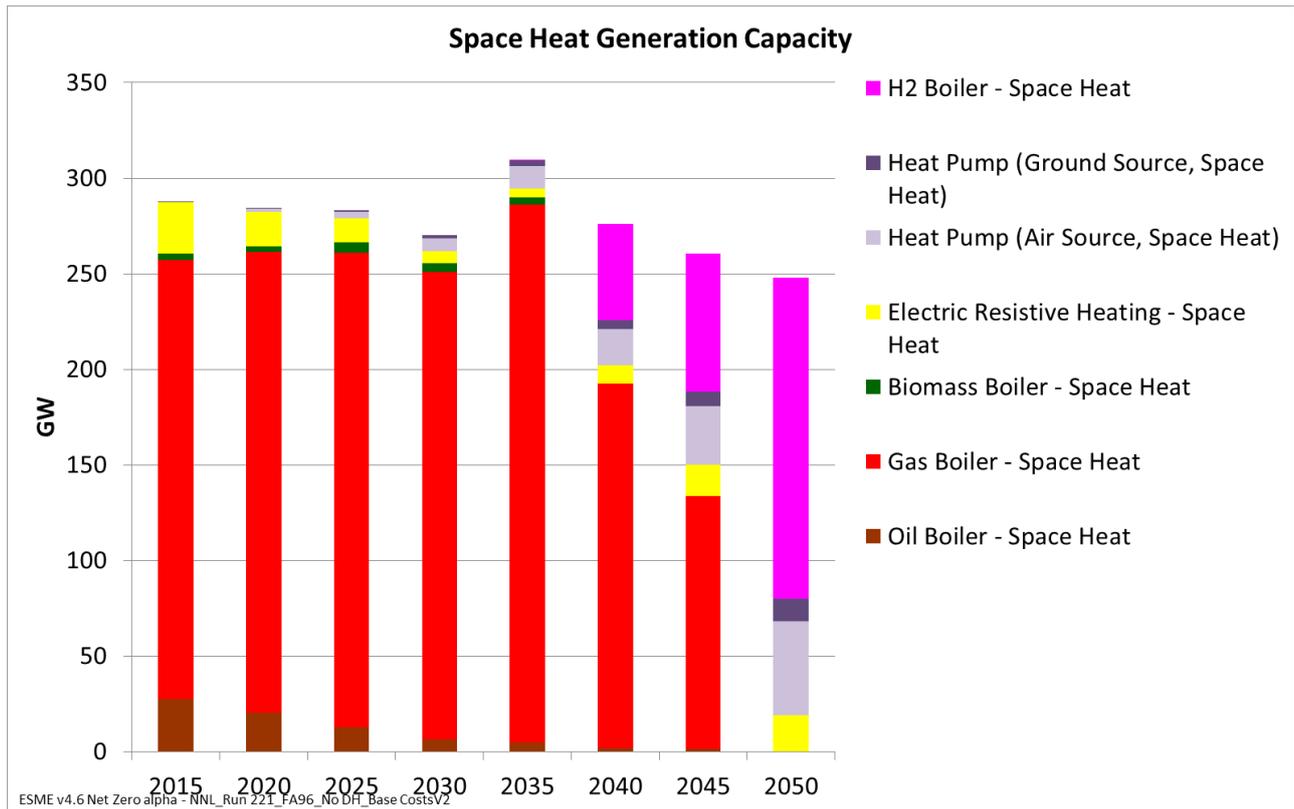

Figure A3-75 – Run 209 electricity generation
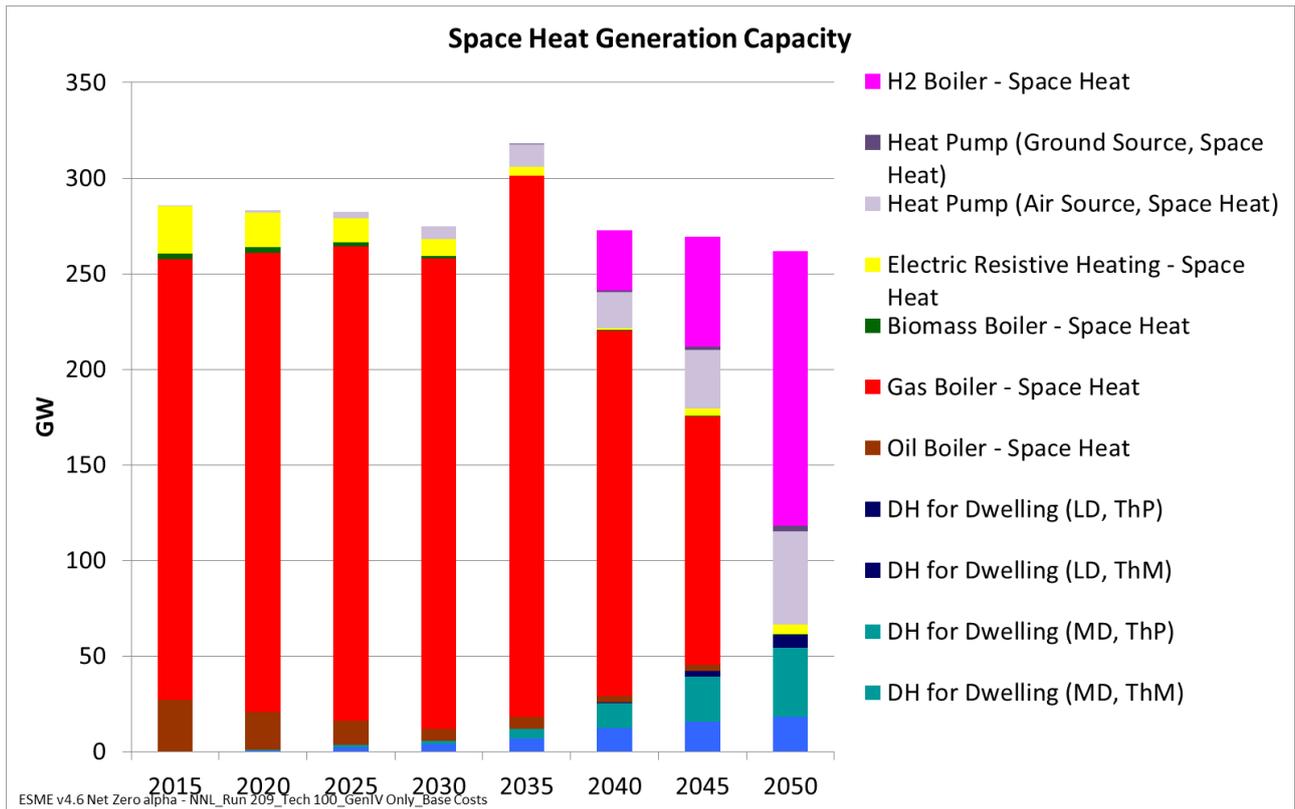
Figure A3-76 – Run 209 space heat generation capacity
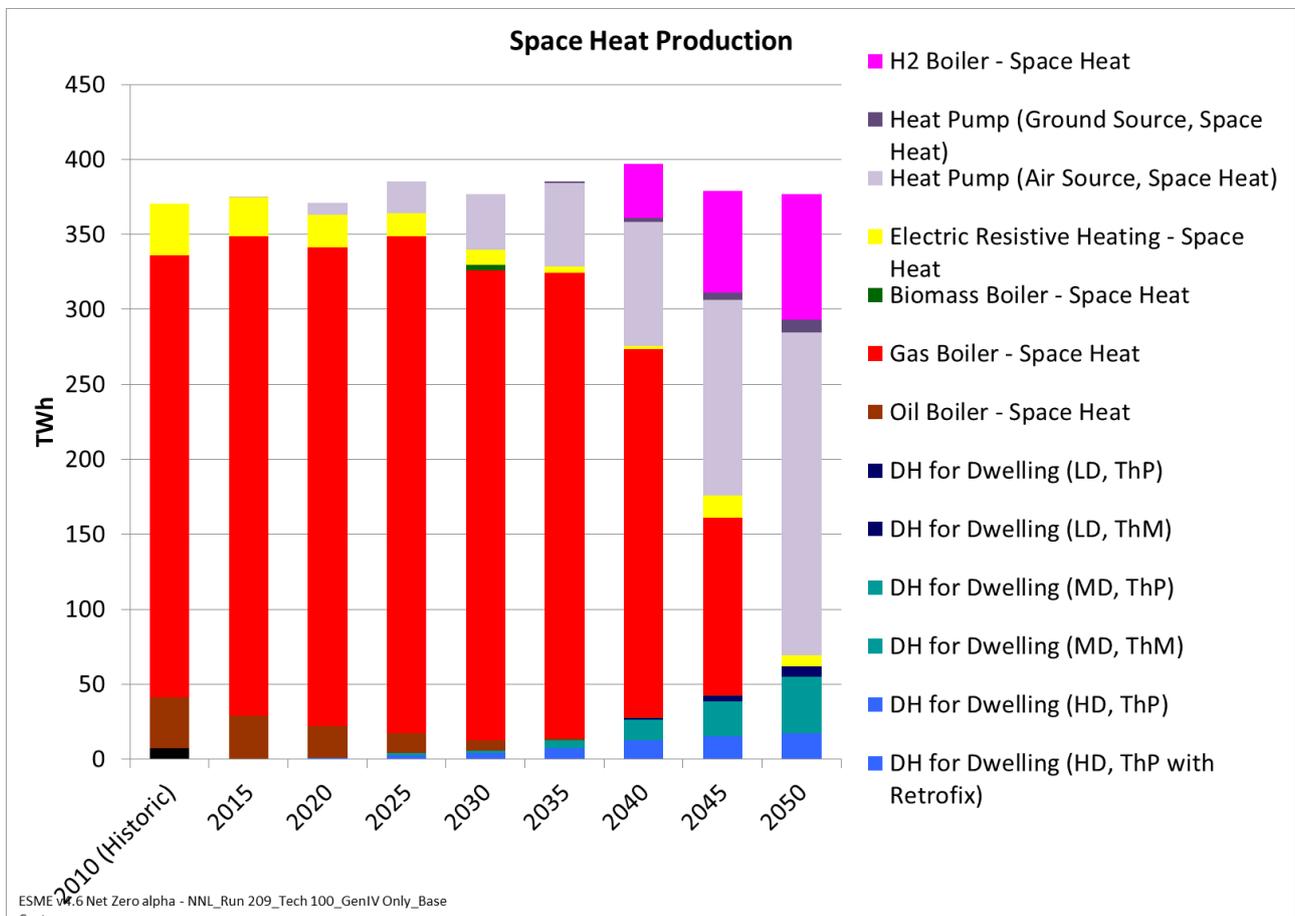
Figure A3-77 – Run 209 space heat production
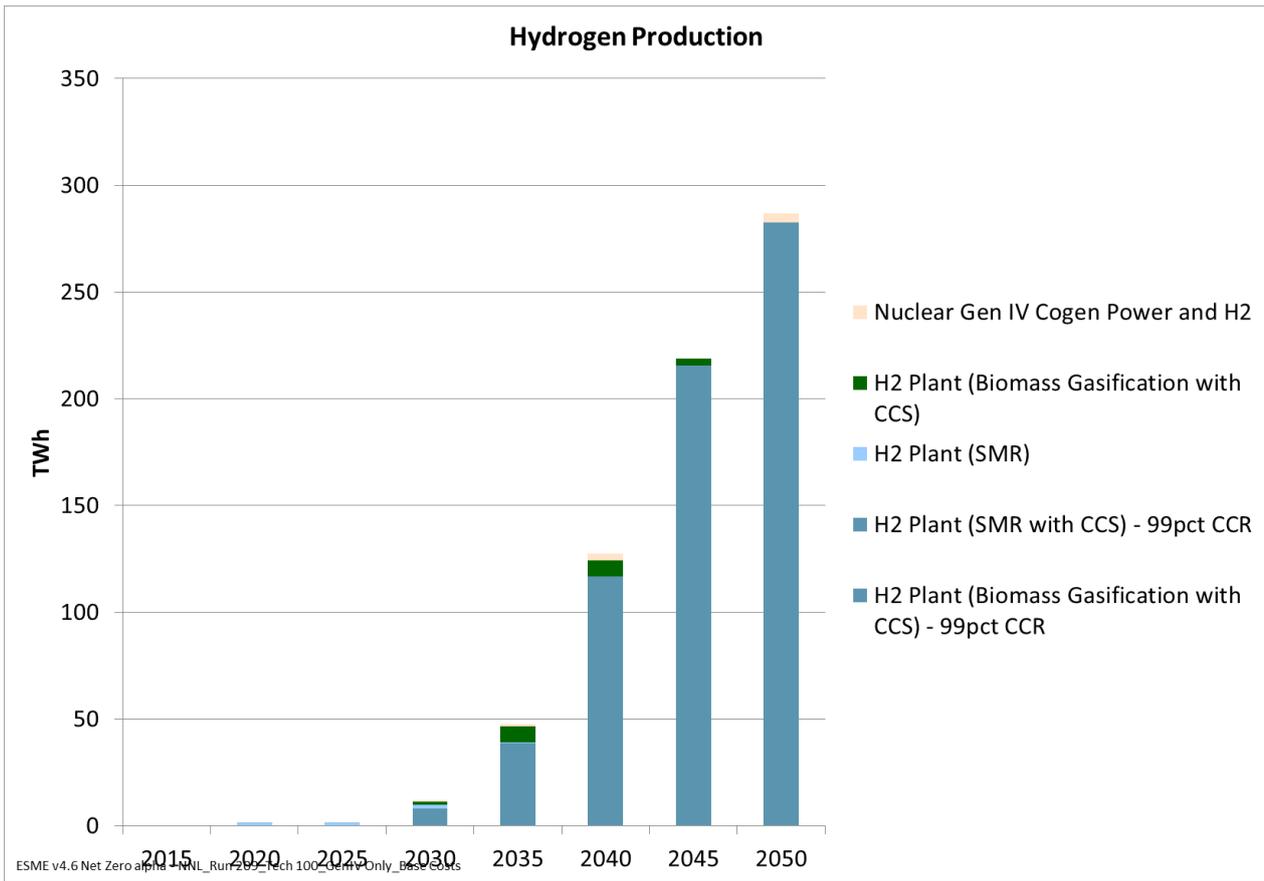
Figure A3-78 – Run 209 hydrogen production
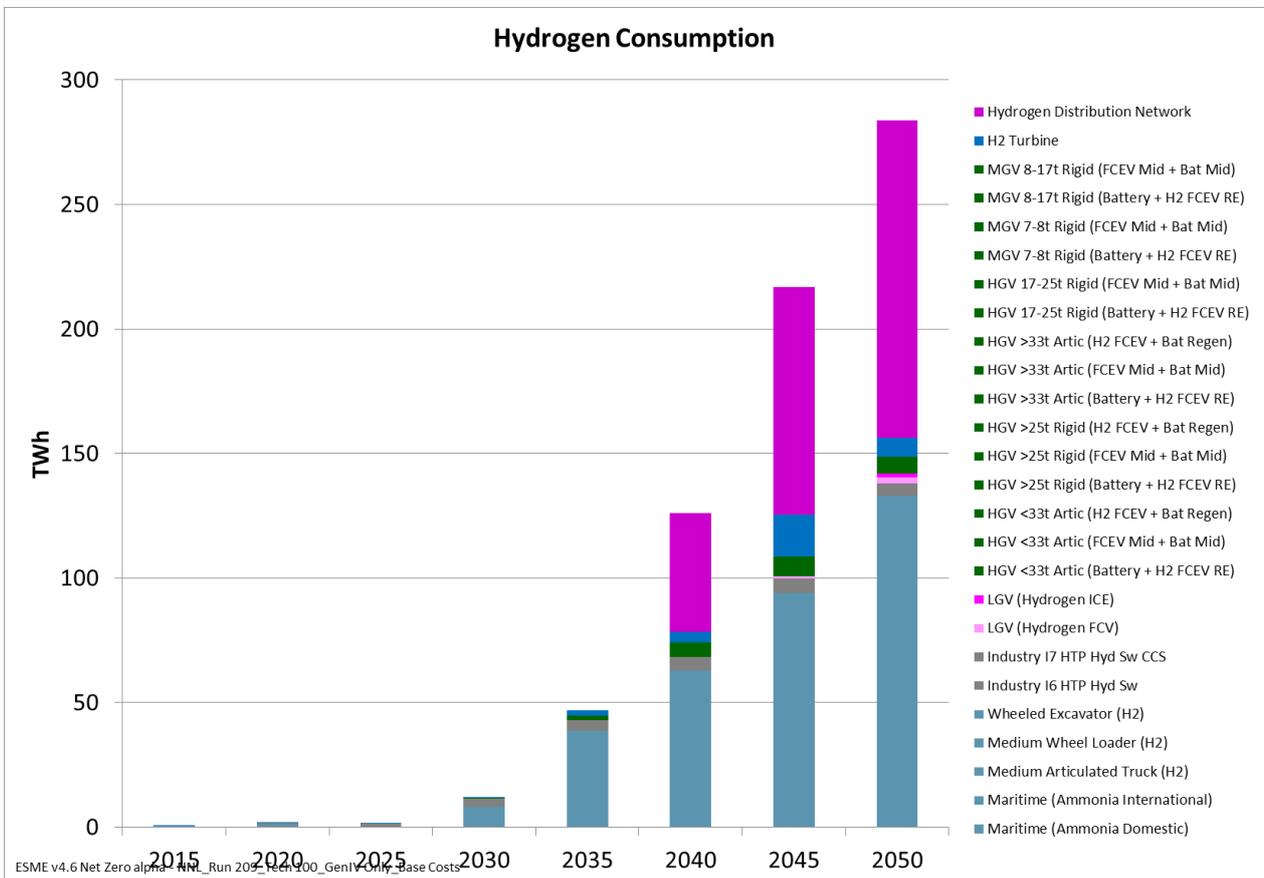
Figure A3-79 – Run 209 hydrogen consumption
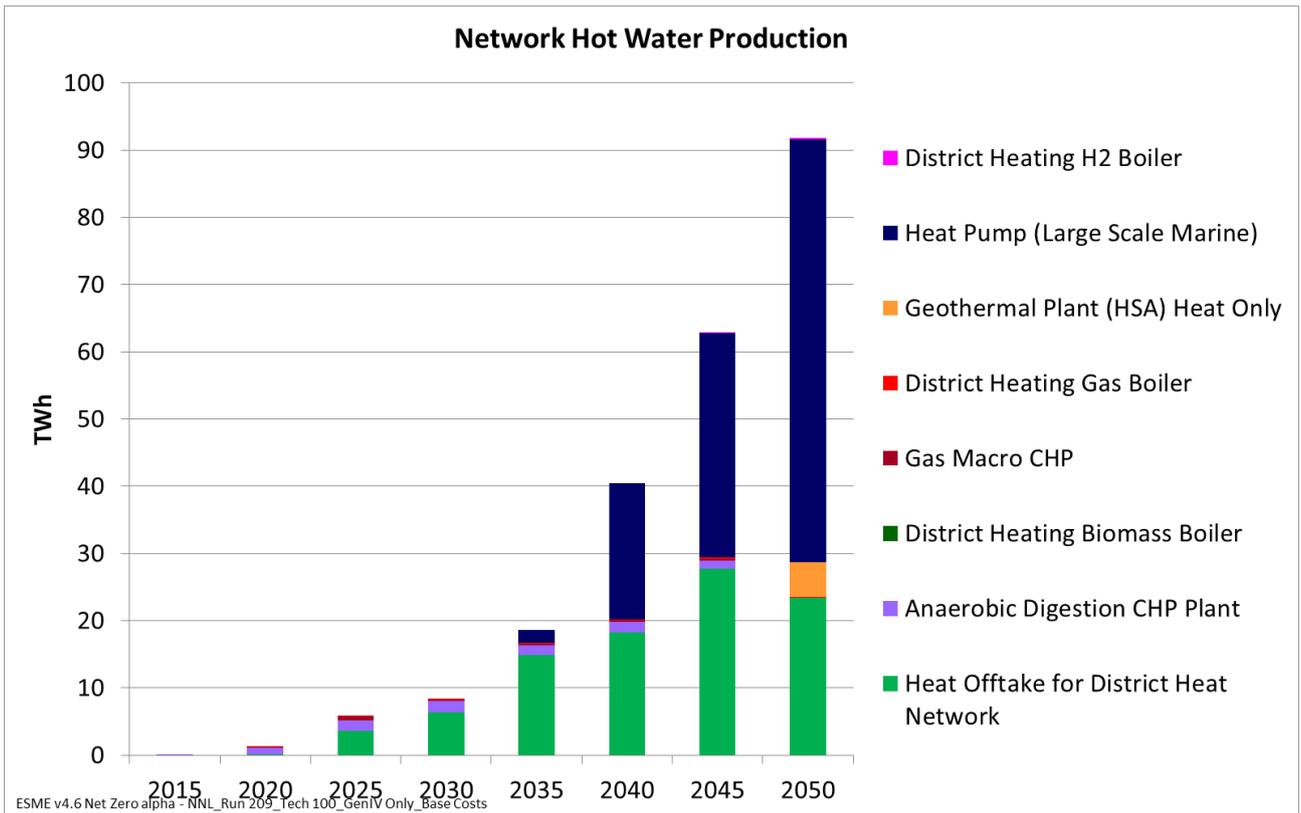
Figure A3-80 – Run 209 network hot water production
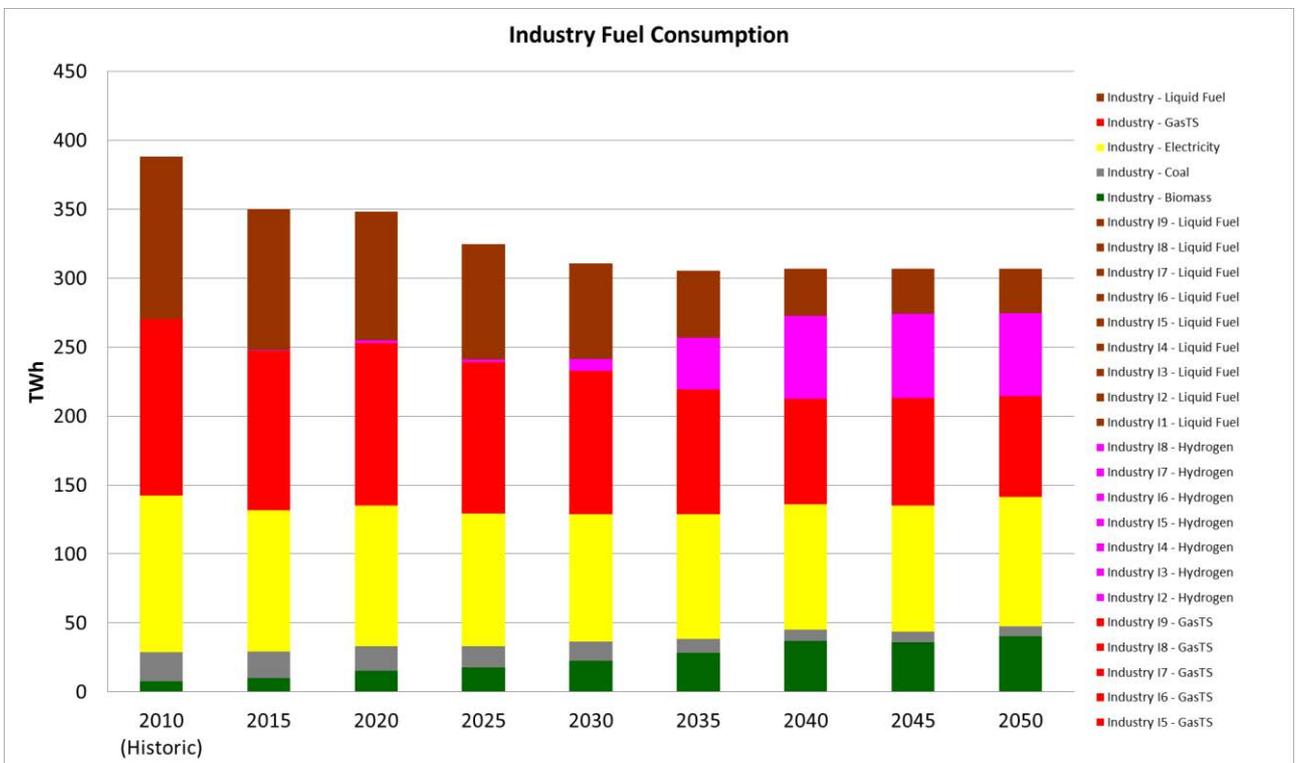
Figure A3-82 – Run 210 primary resource consumption

Run 210 BOB100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data
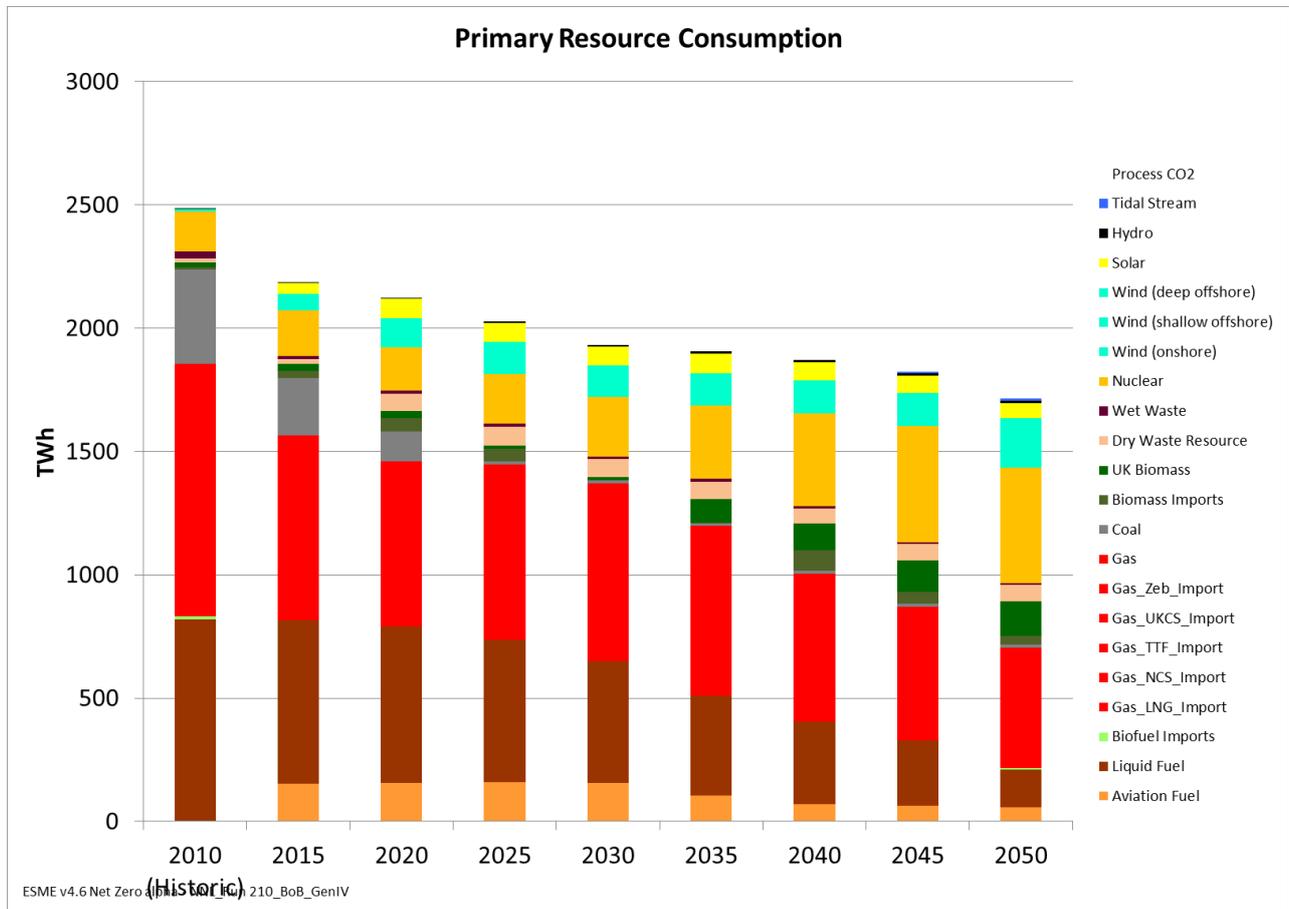
Figure A3-81 – Run 209 industry fuel consumption
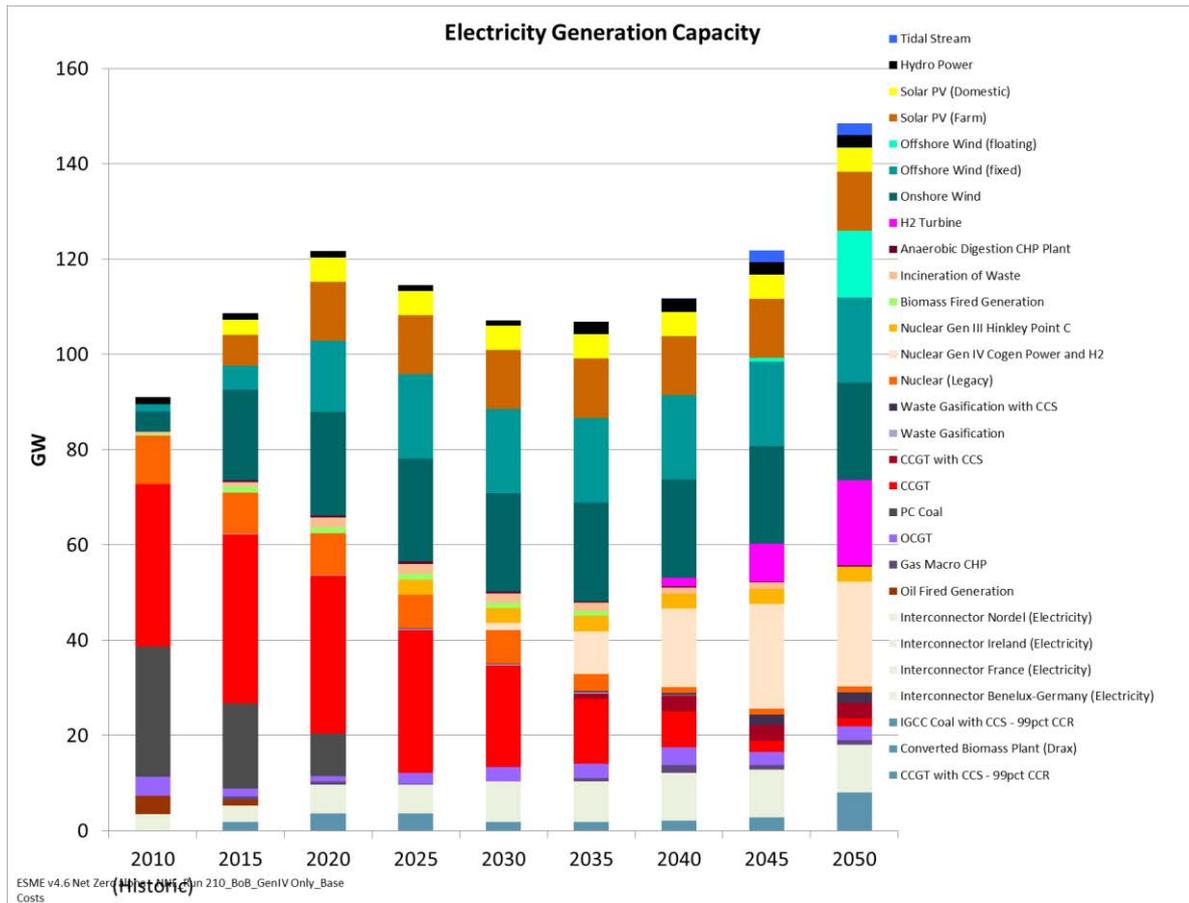
Figure A3-83 – Run 210 electricity generation capacity
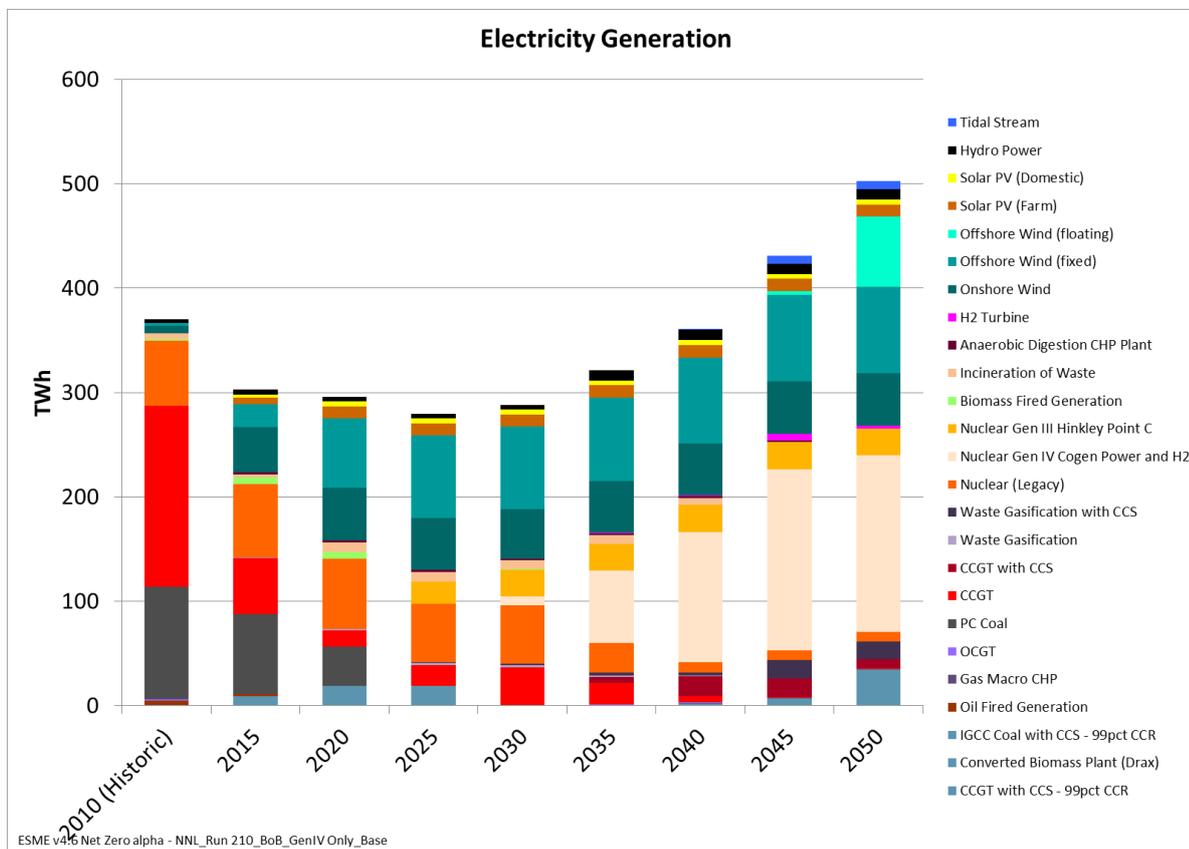
Figure A3-84 – Run 210 electricity generation
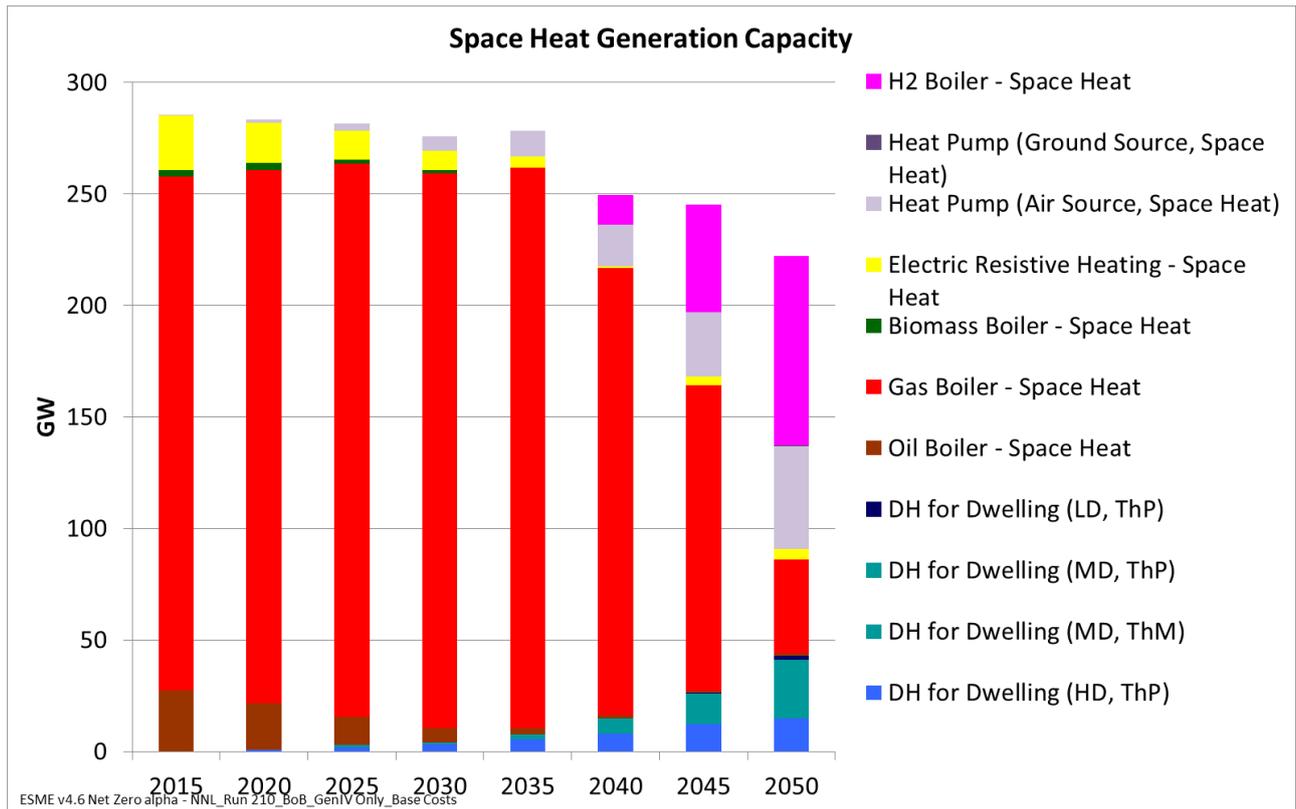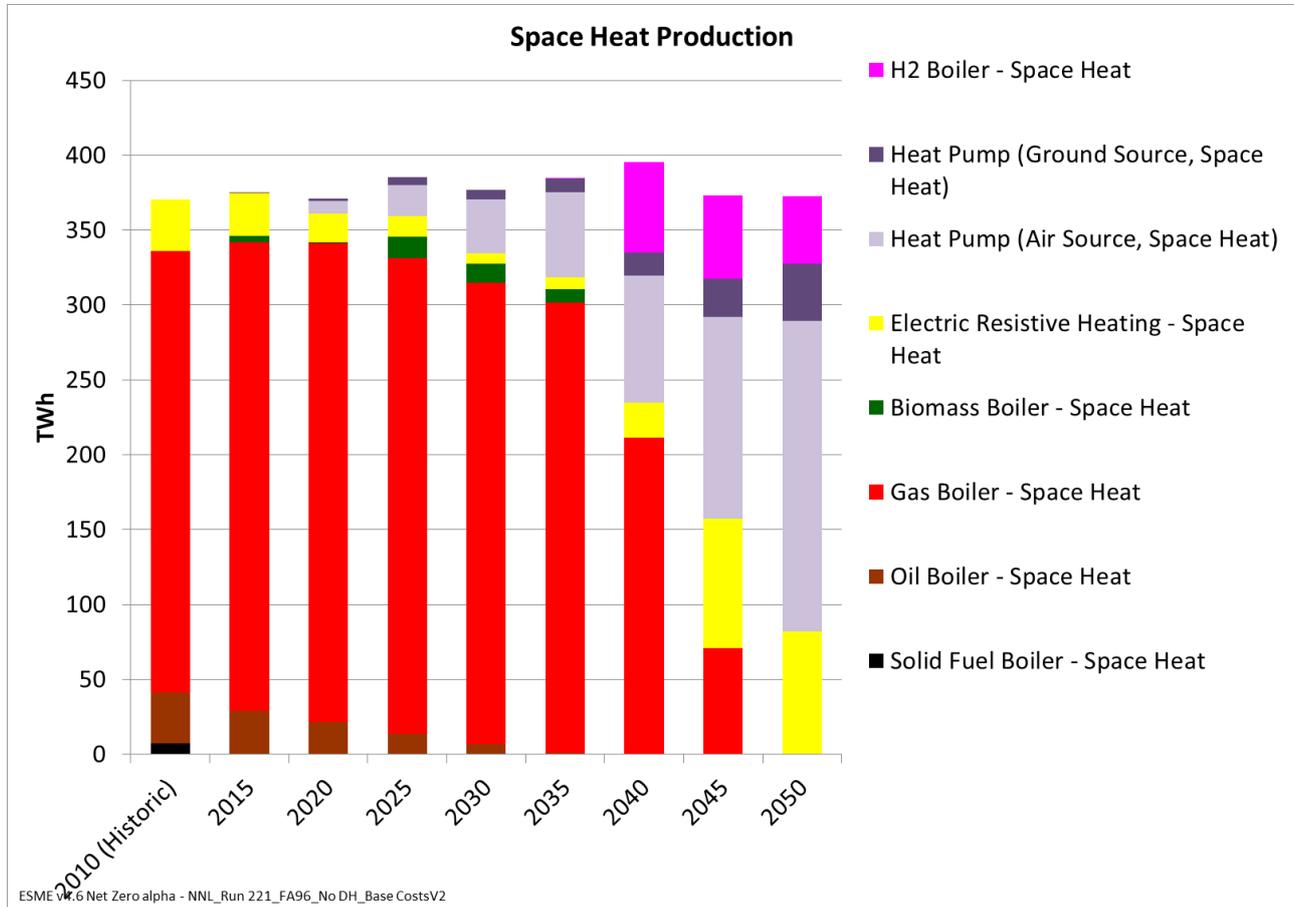
Figure A3-85 – Run 210 space heat generation capacity
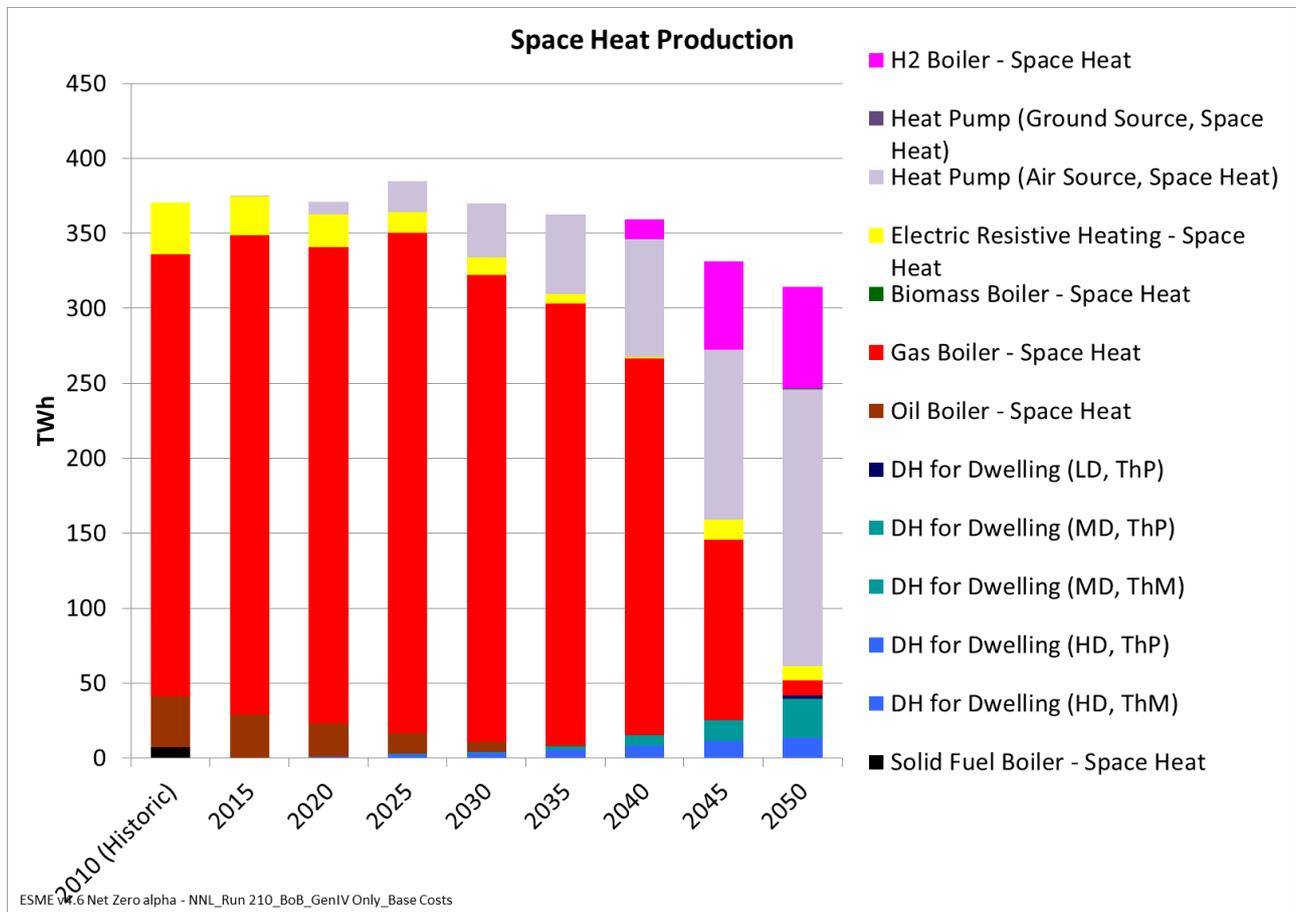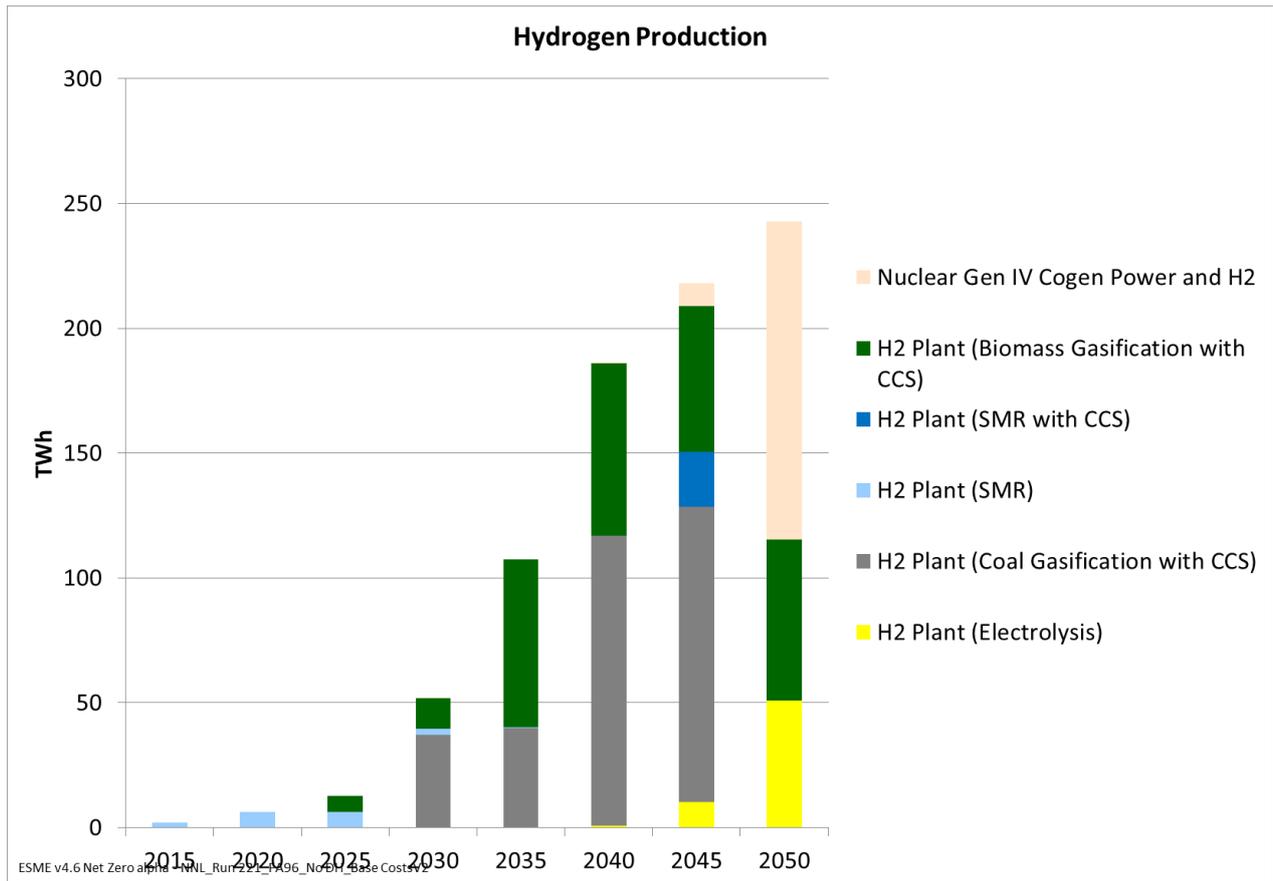

Figure A3-86 – Run 210 space heat production
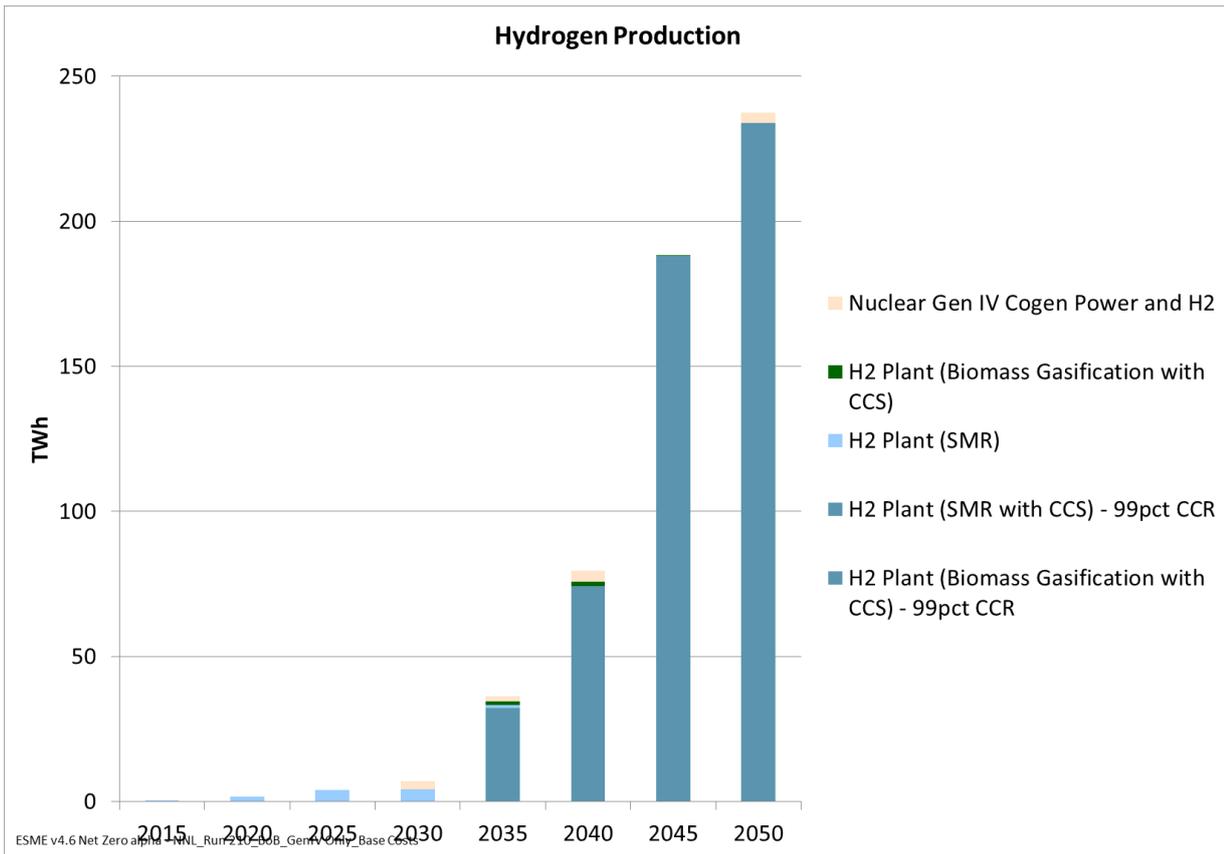
Figure A3-87 – Run 210 hydrogen production
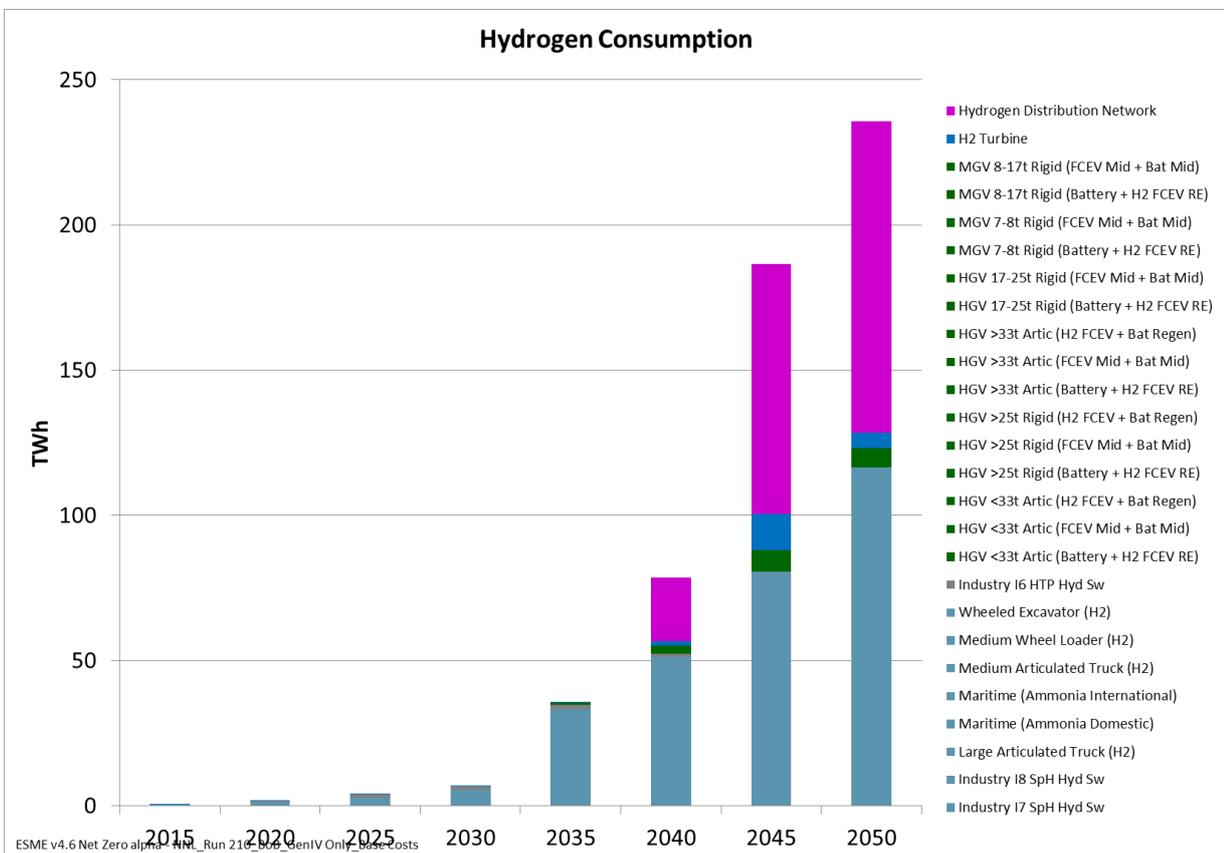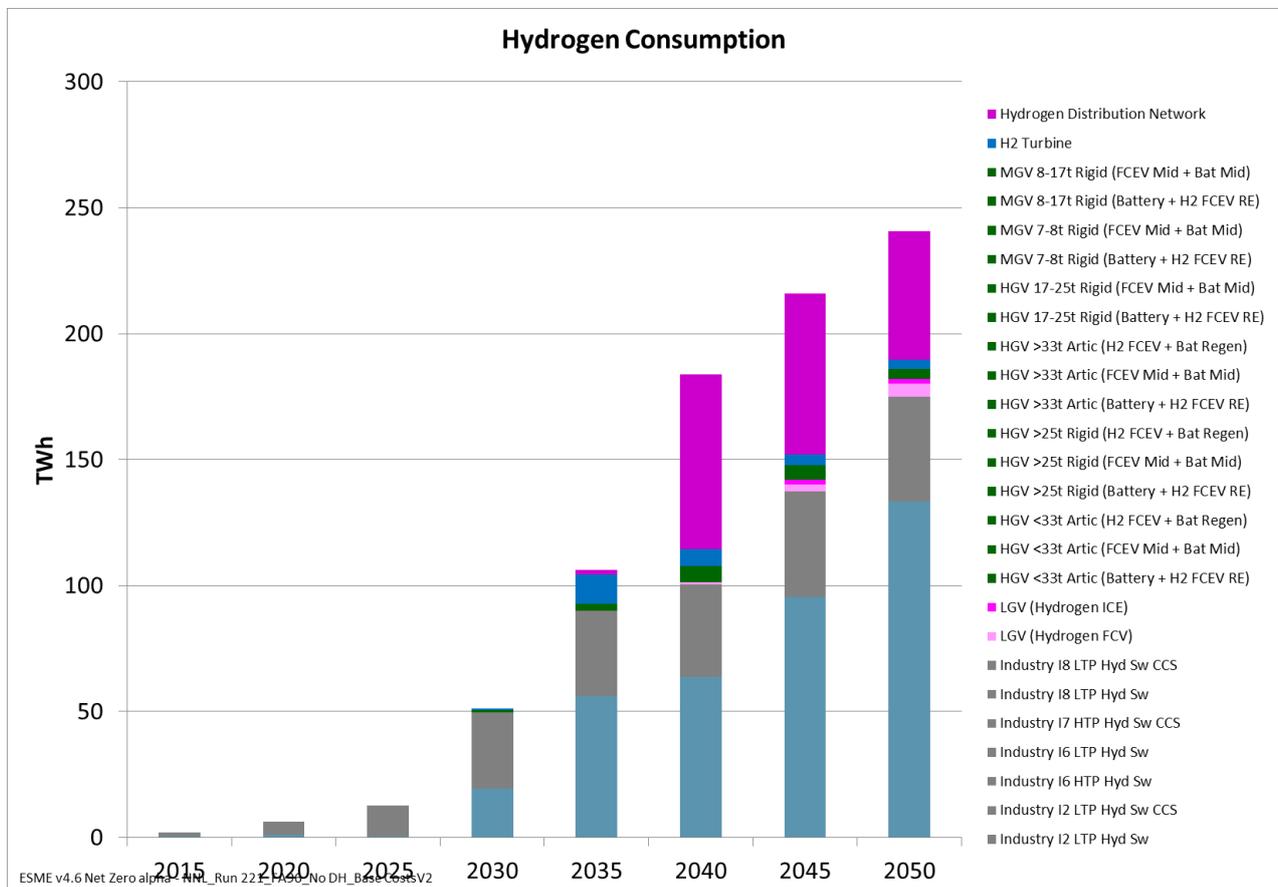

Figure A3-88 – Run 210 hydrogen consumption
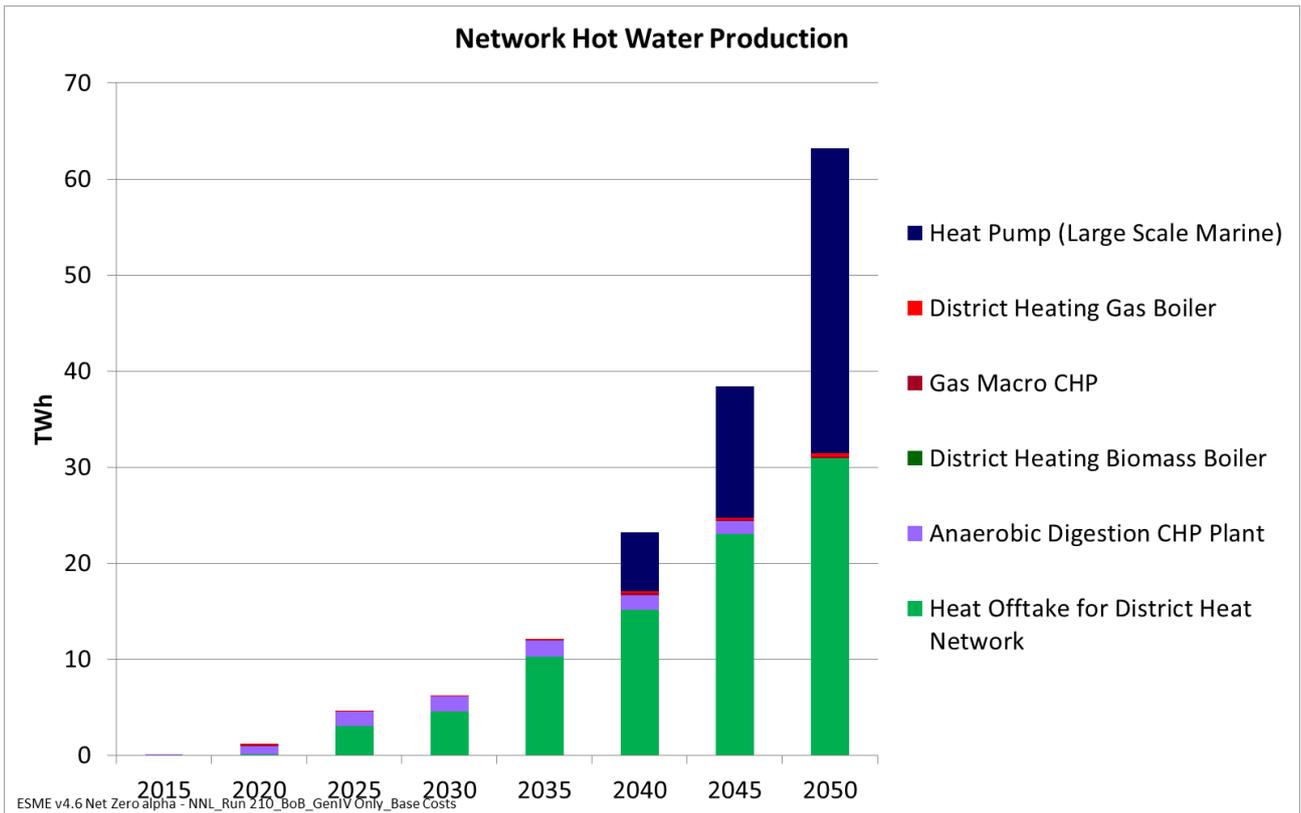
Figure A3-89 – Run 210 network hot water production
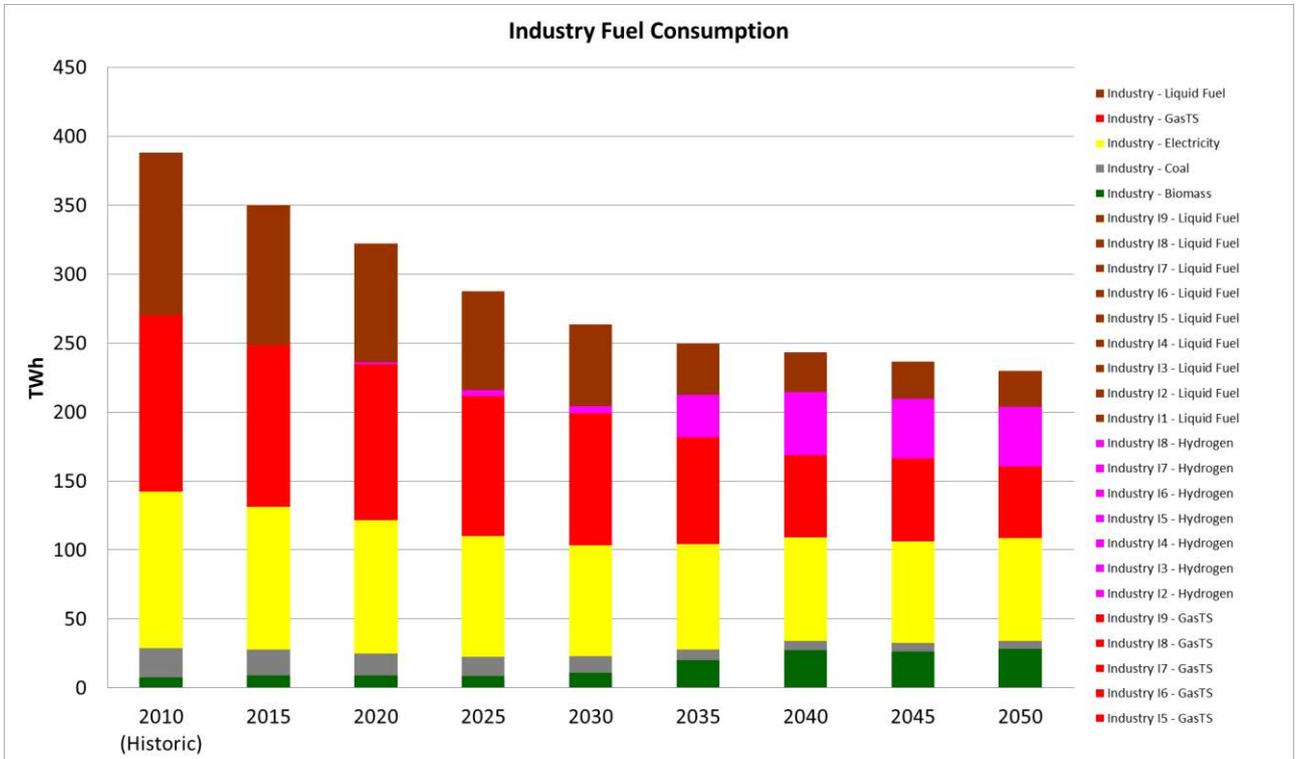
Figure A3-90 – Run 210 industry fuel consumption

Run 211 FA96 – Gen IV Cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data with lower capex
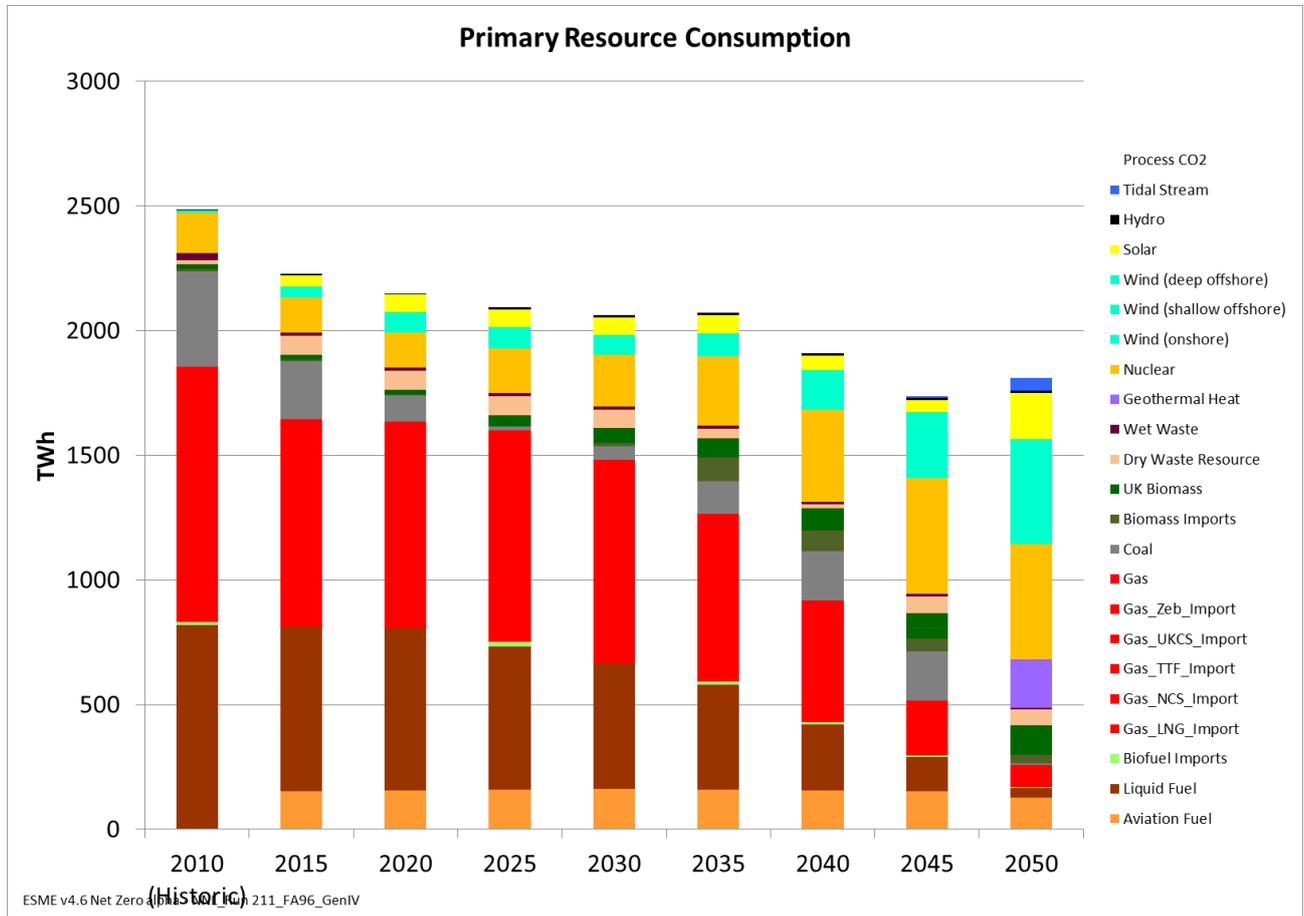
Figure A3-91 – Run 211 primary resource consumption
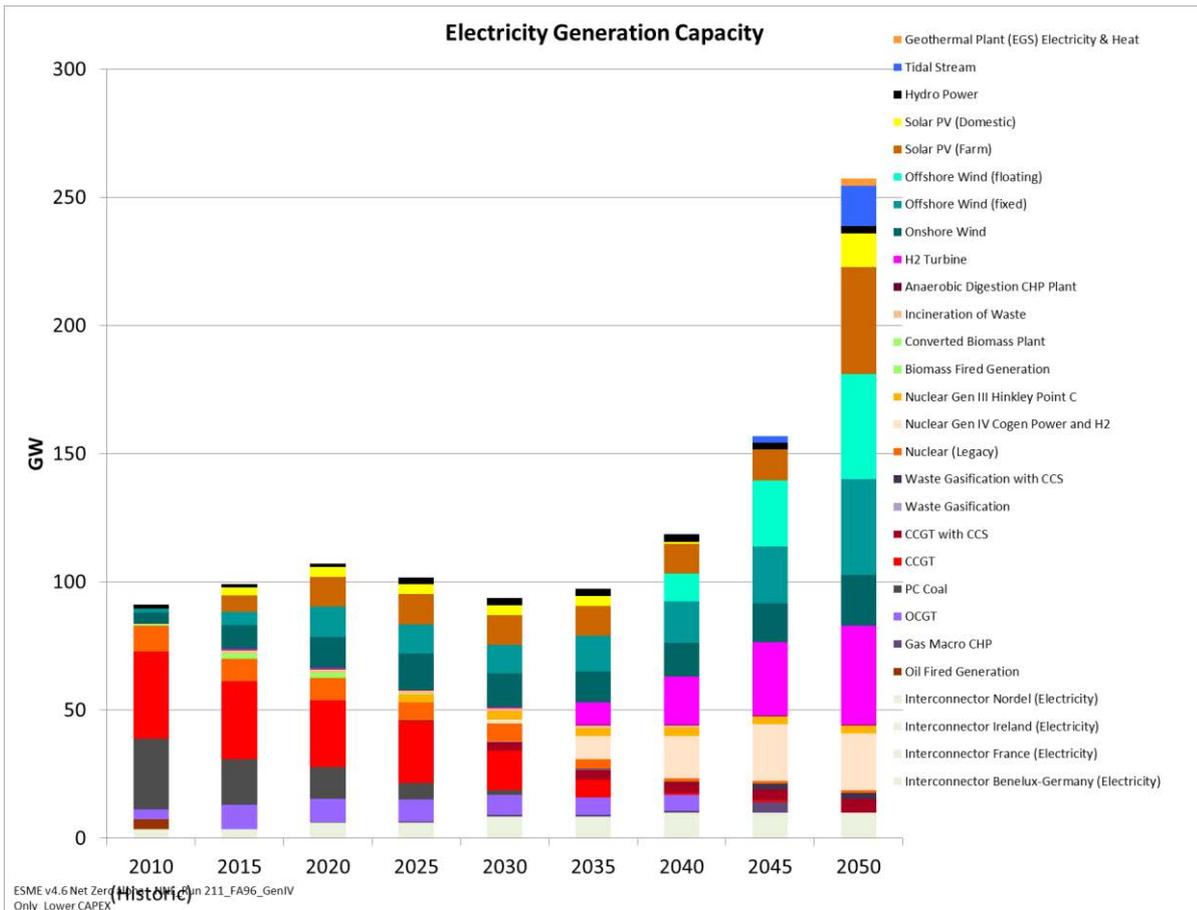
Figure A3-92 – Run 211 electricity generation capacity
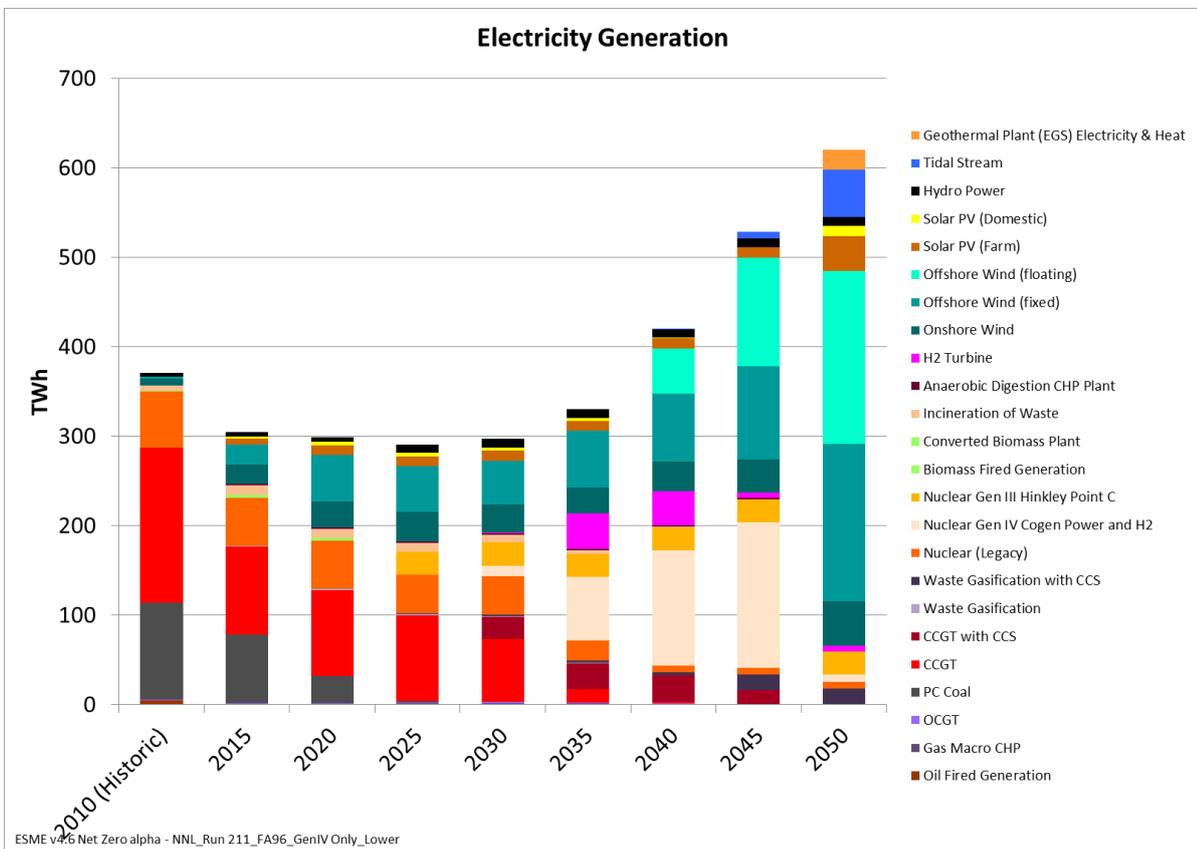
Figure A3-93 – Run 211 electricity generation
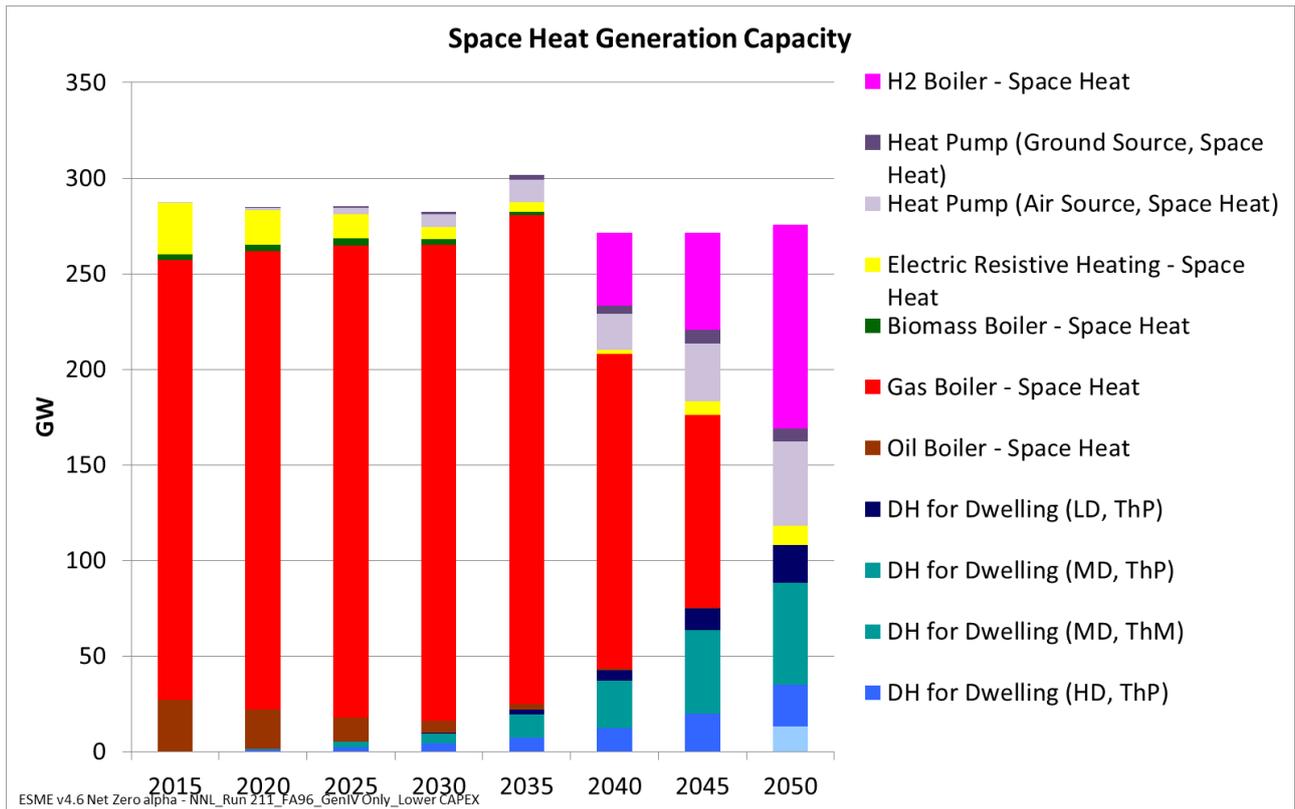
Figure A3-94 – Run 211 space heat generation capacity
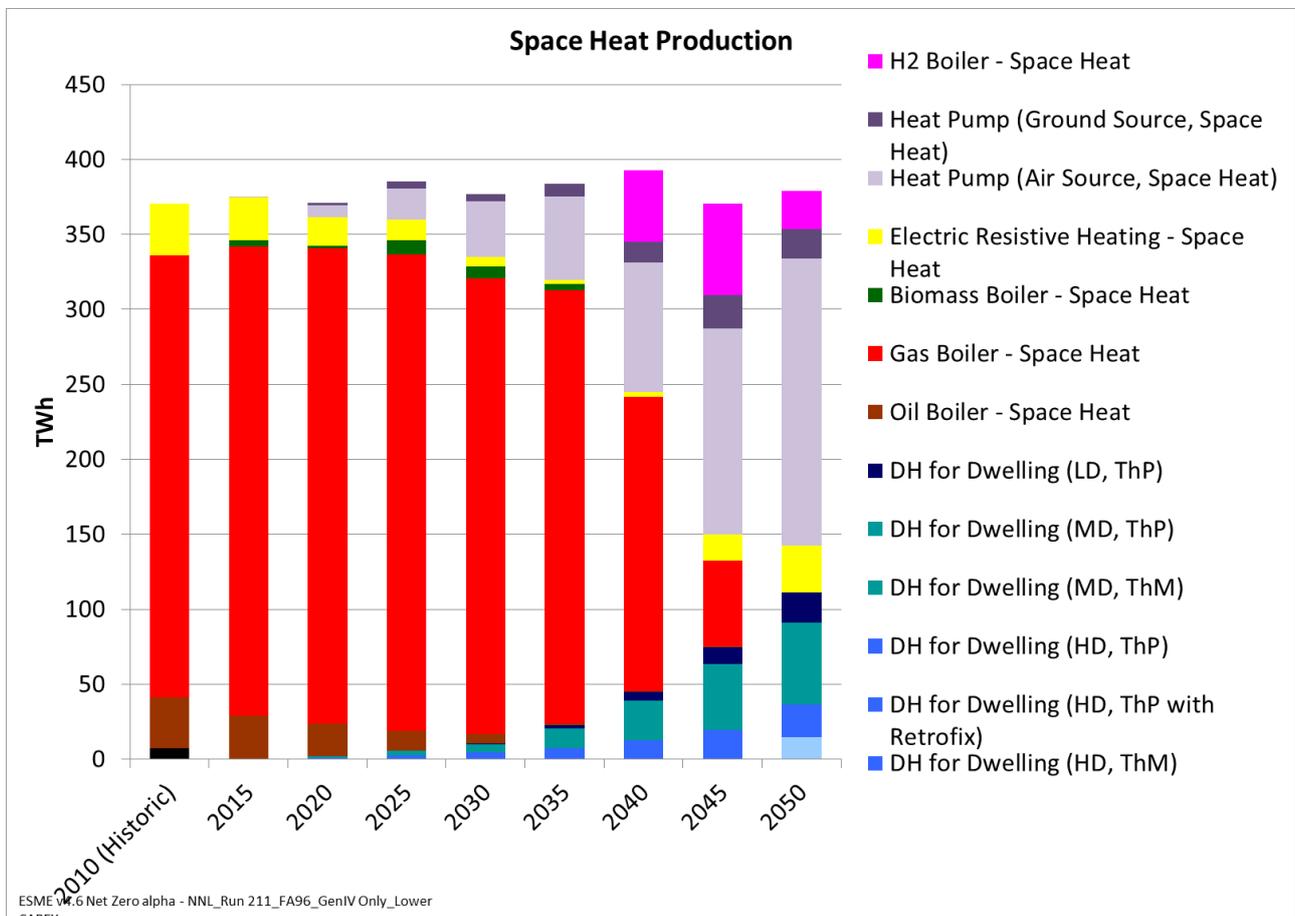
Figure A3-95 – Run 211 space heat production
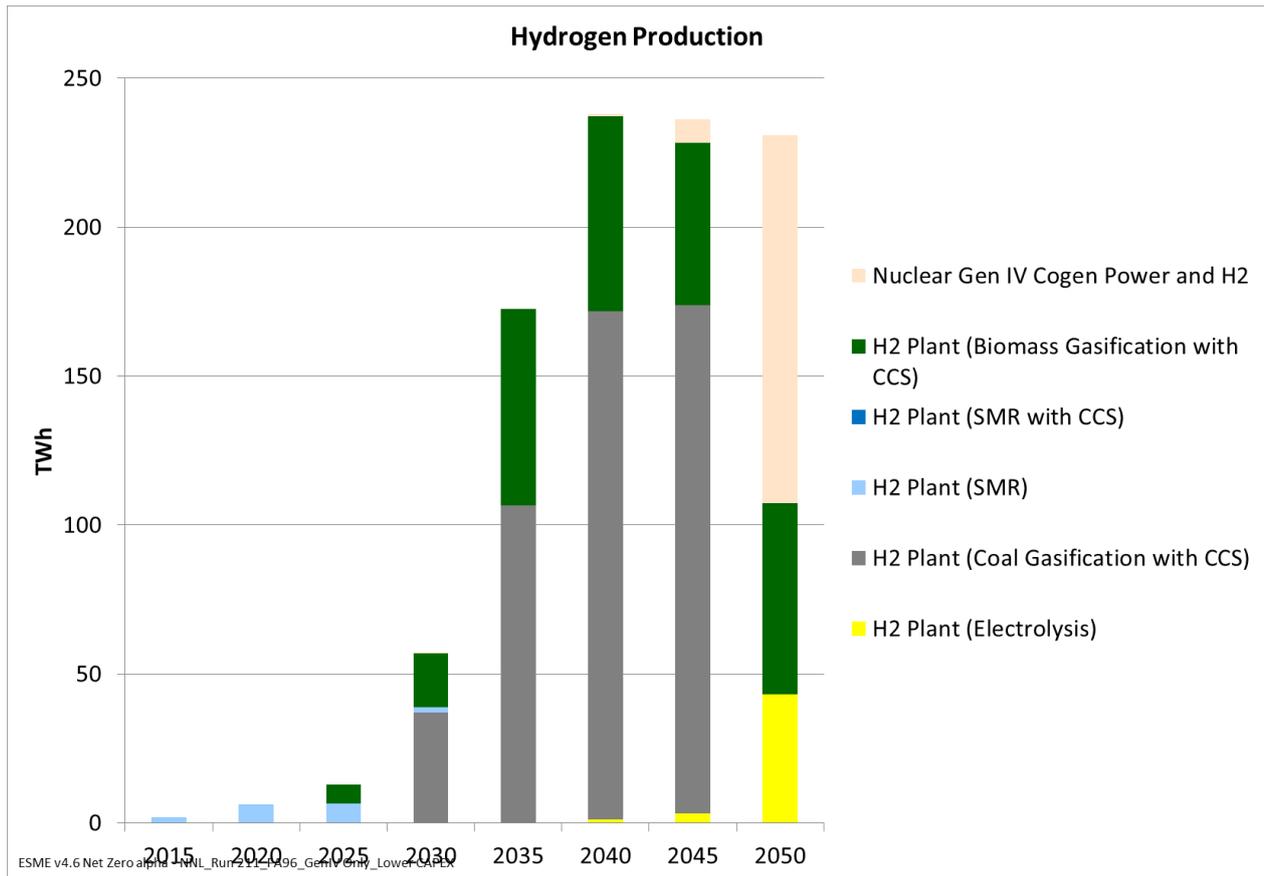
Figure A3-96 – Run 211 hydrogen production
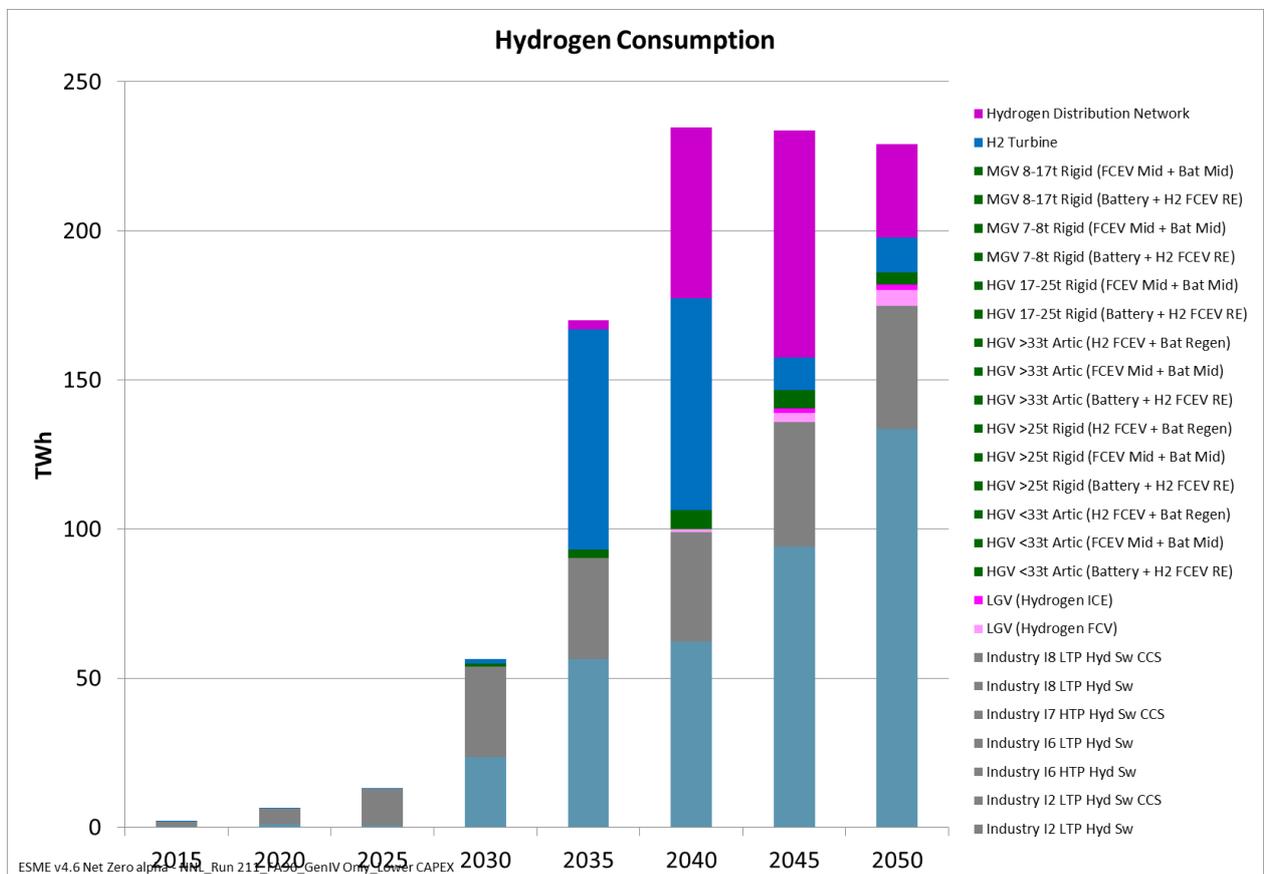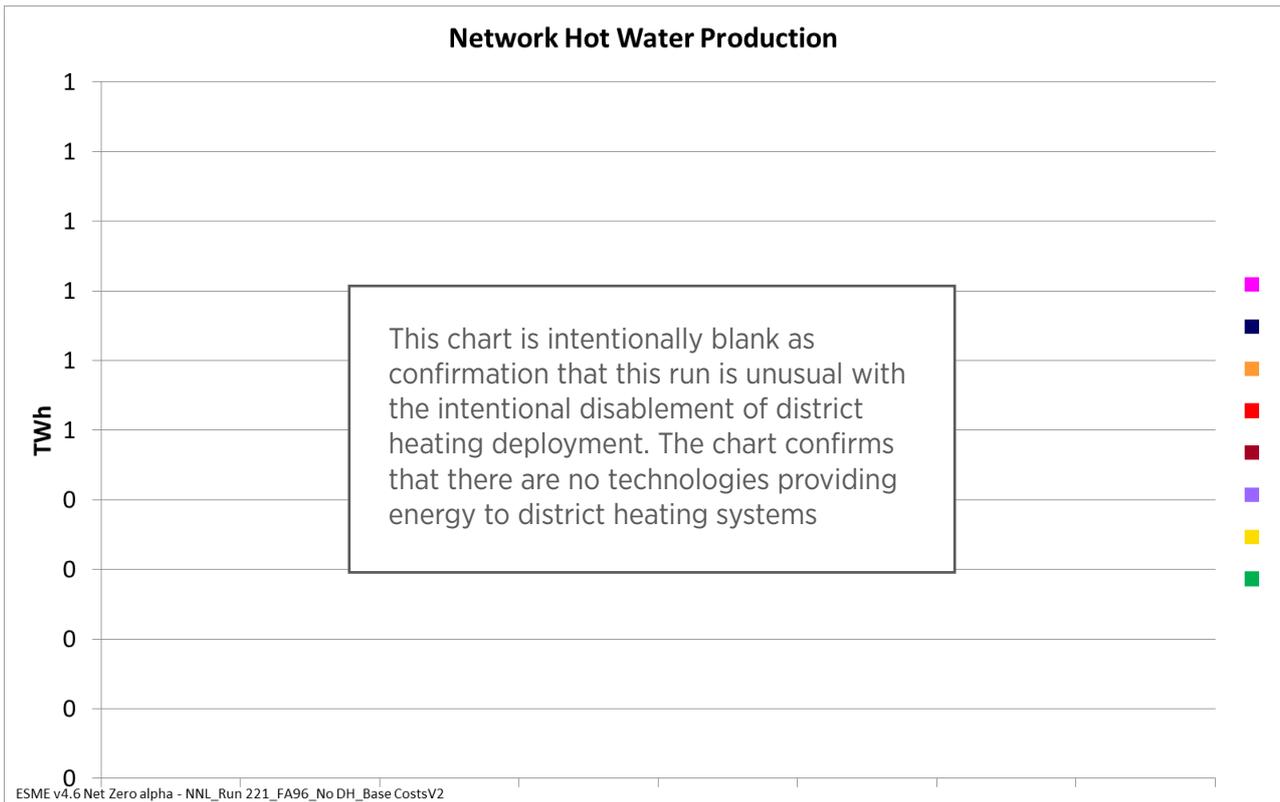

Figure A3-97 – Run 211 hydrogen consumption
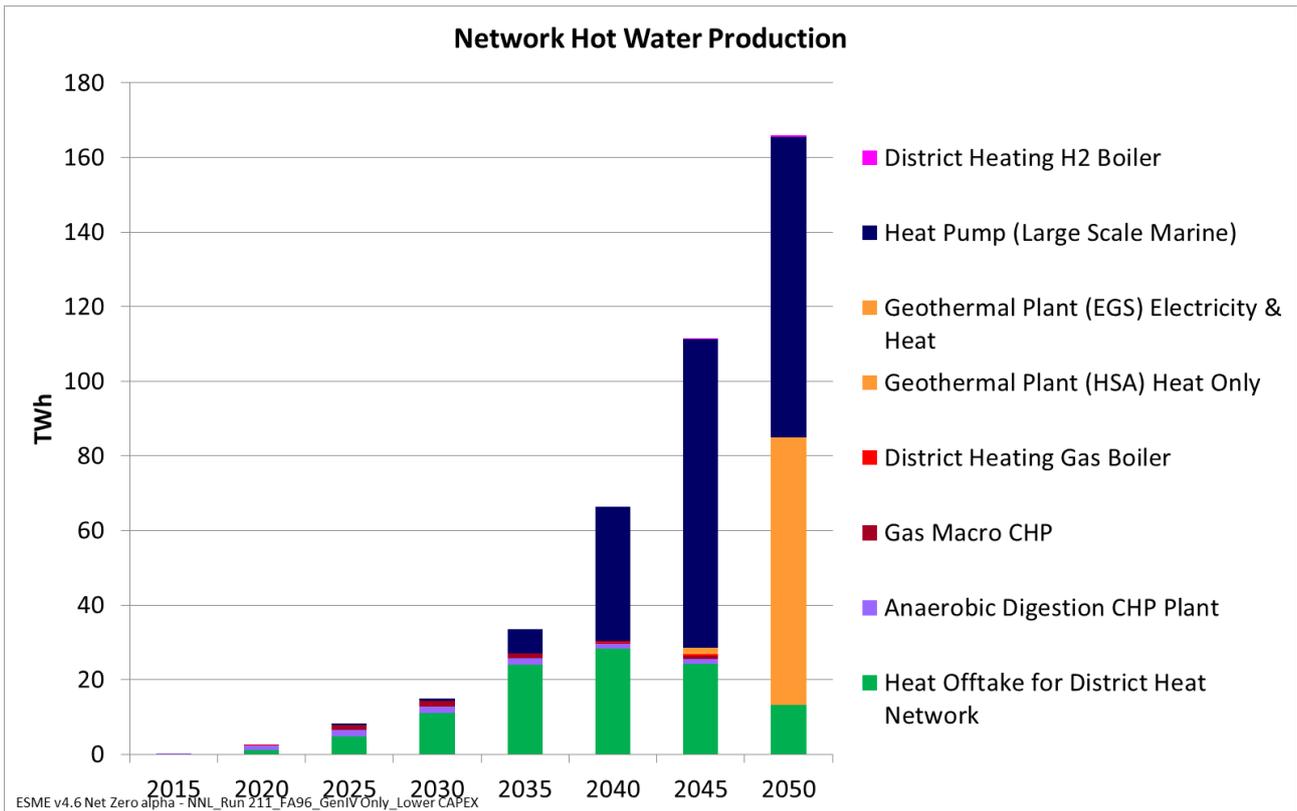
Figure A3-98 – Run 211 network hot water production
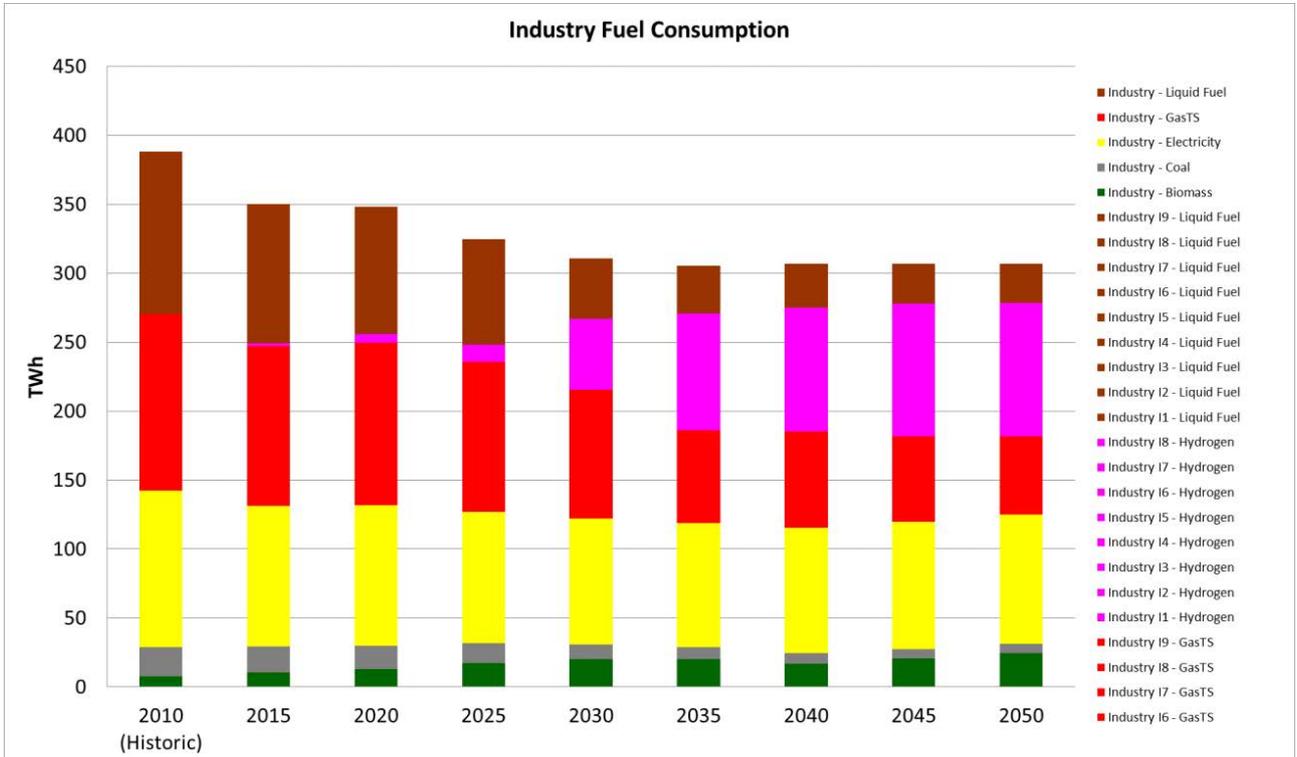
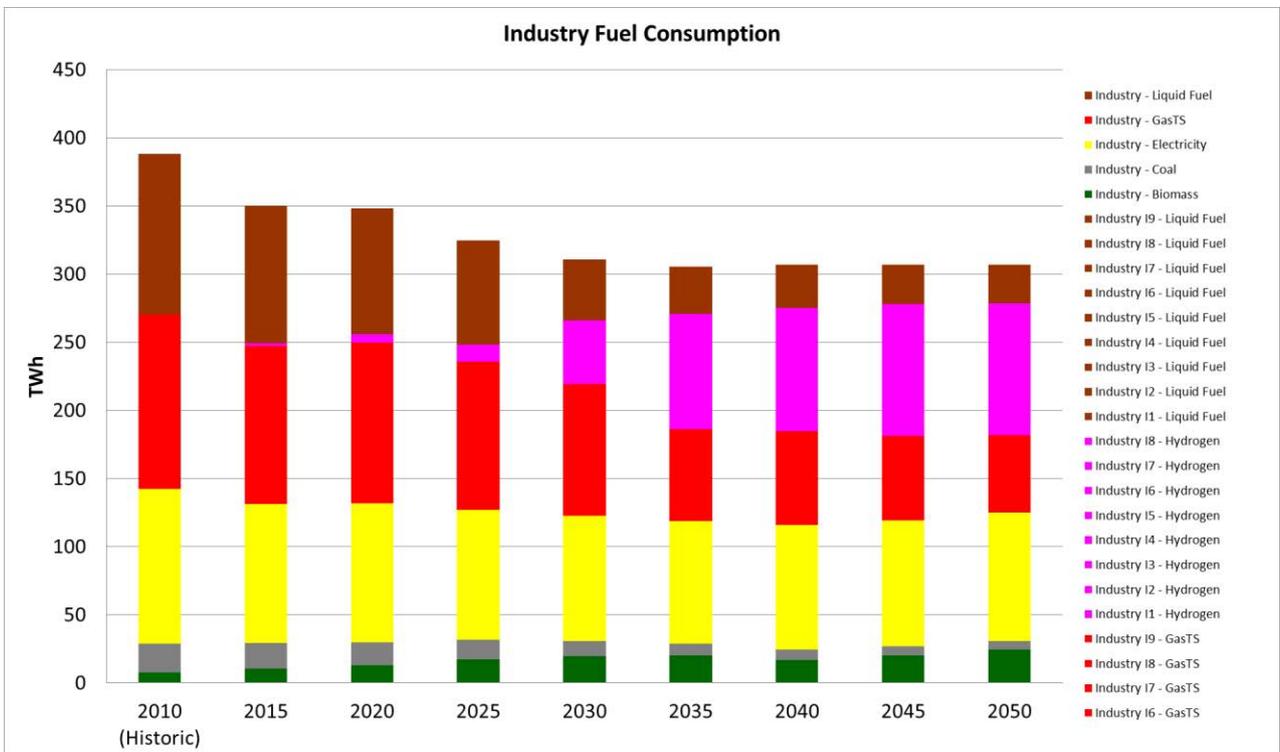Figure A3-99 – Run 211 industry fuel consumption

Run 212 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data with lower capex values
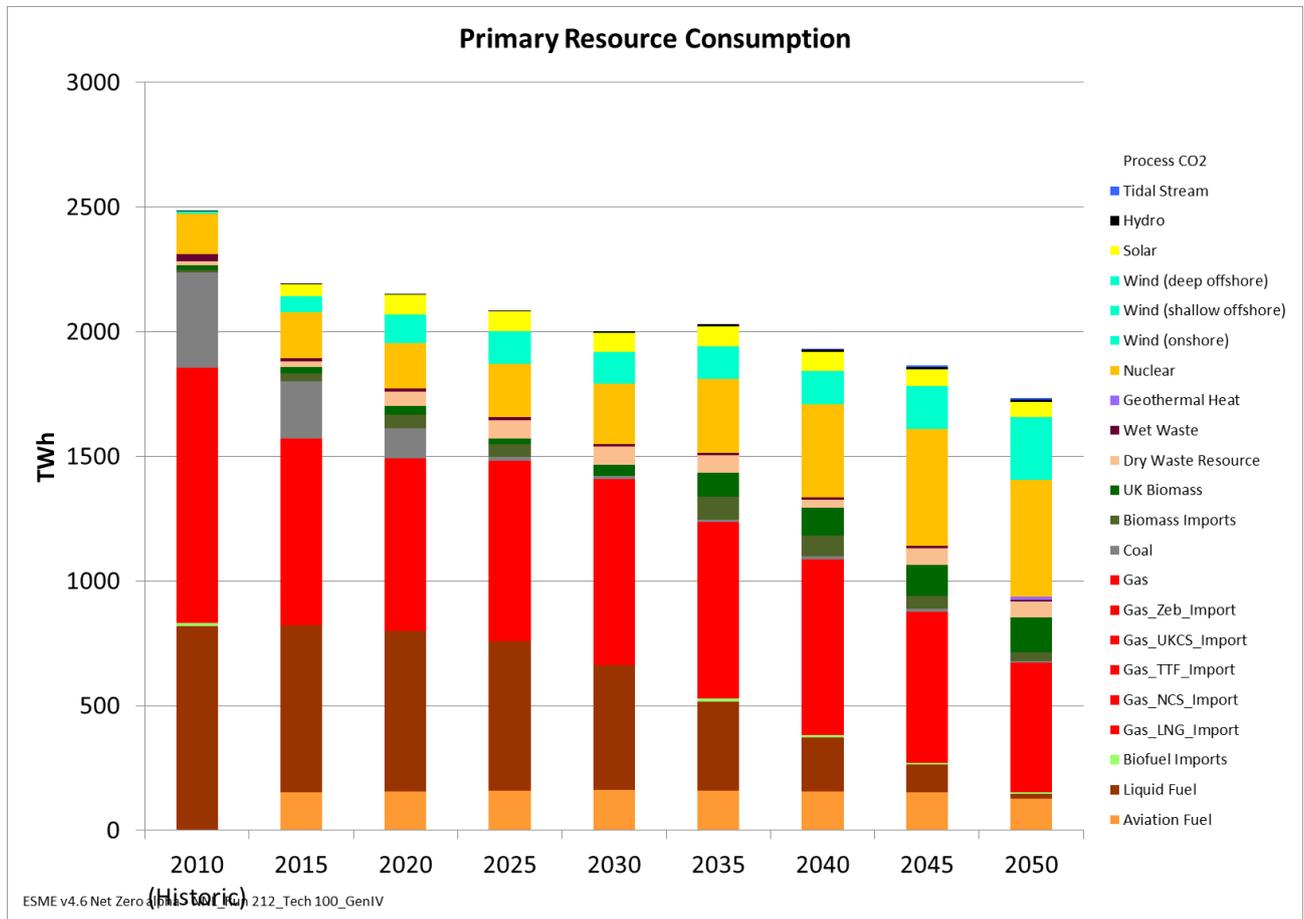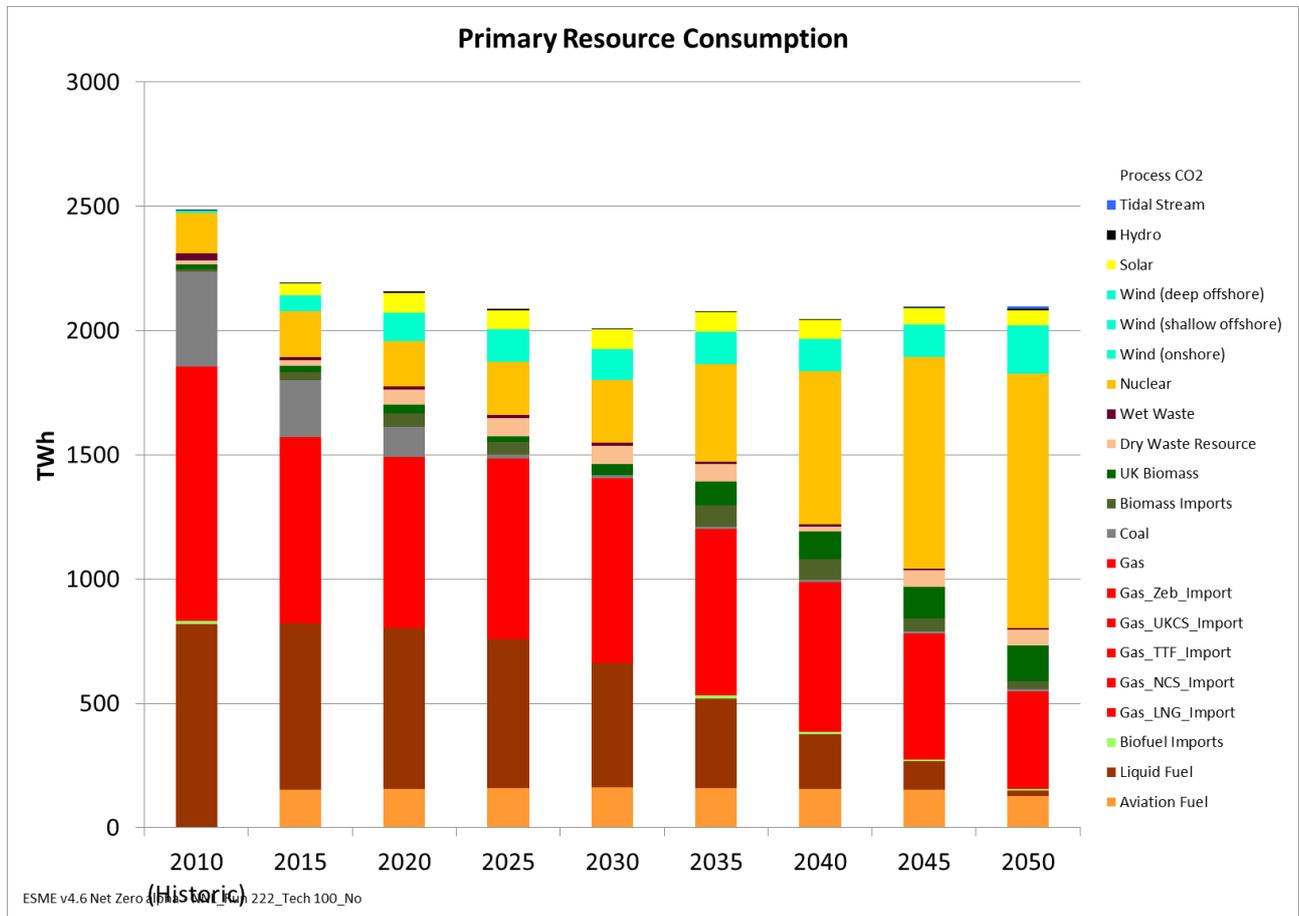

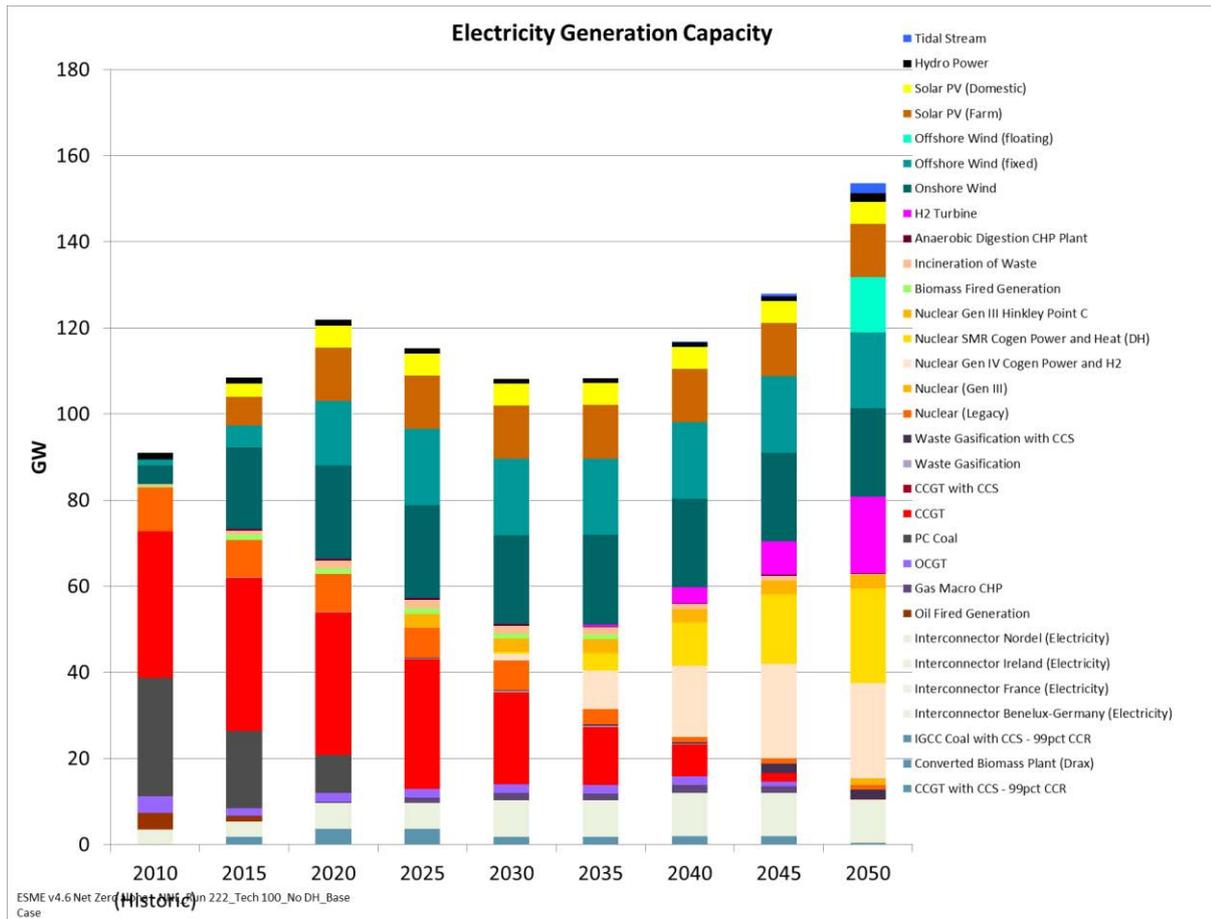Figure A3-100 – Run 212 primary resource consumption
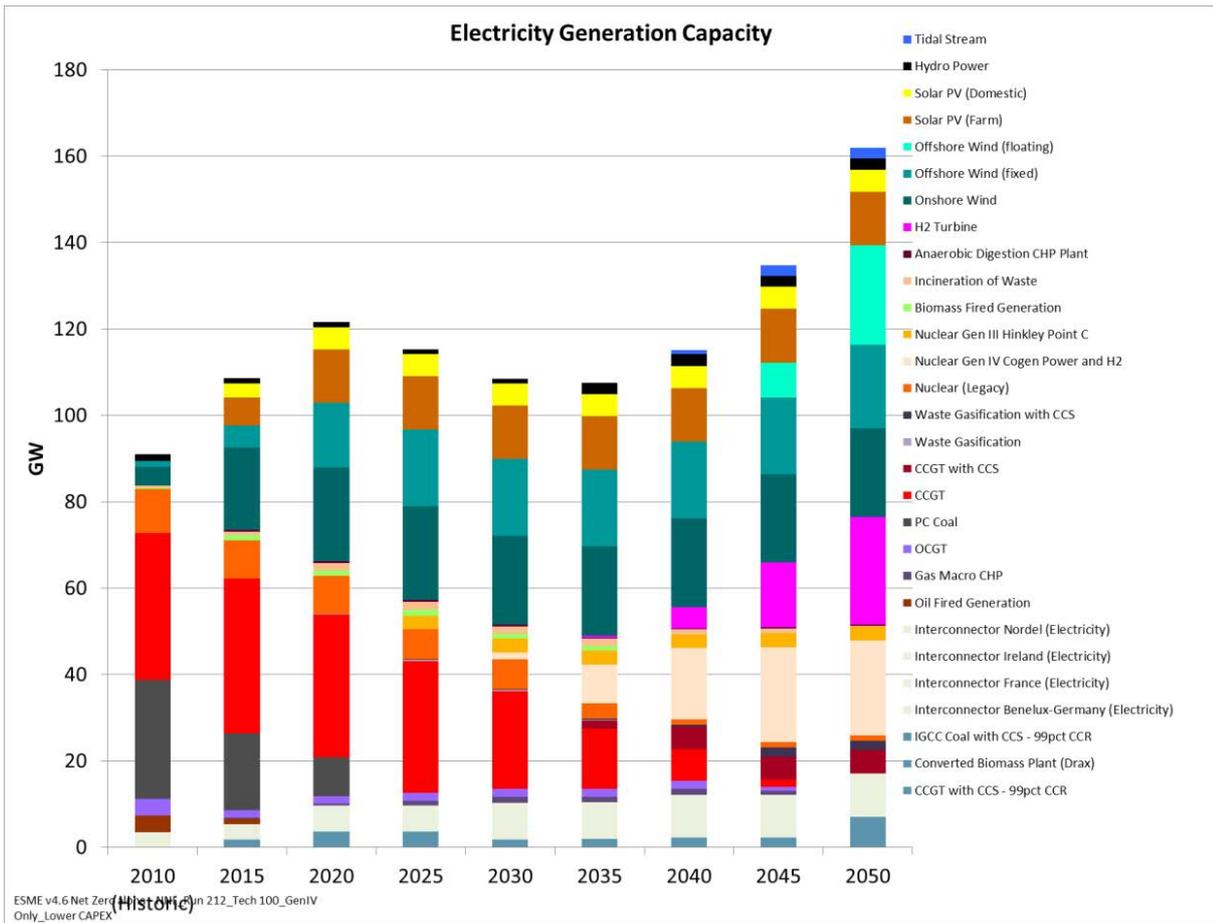
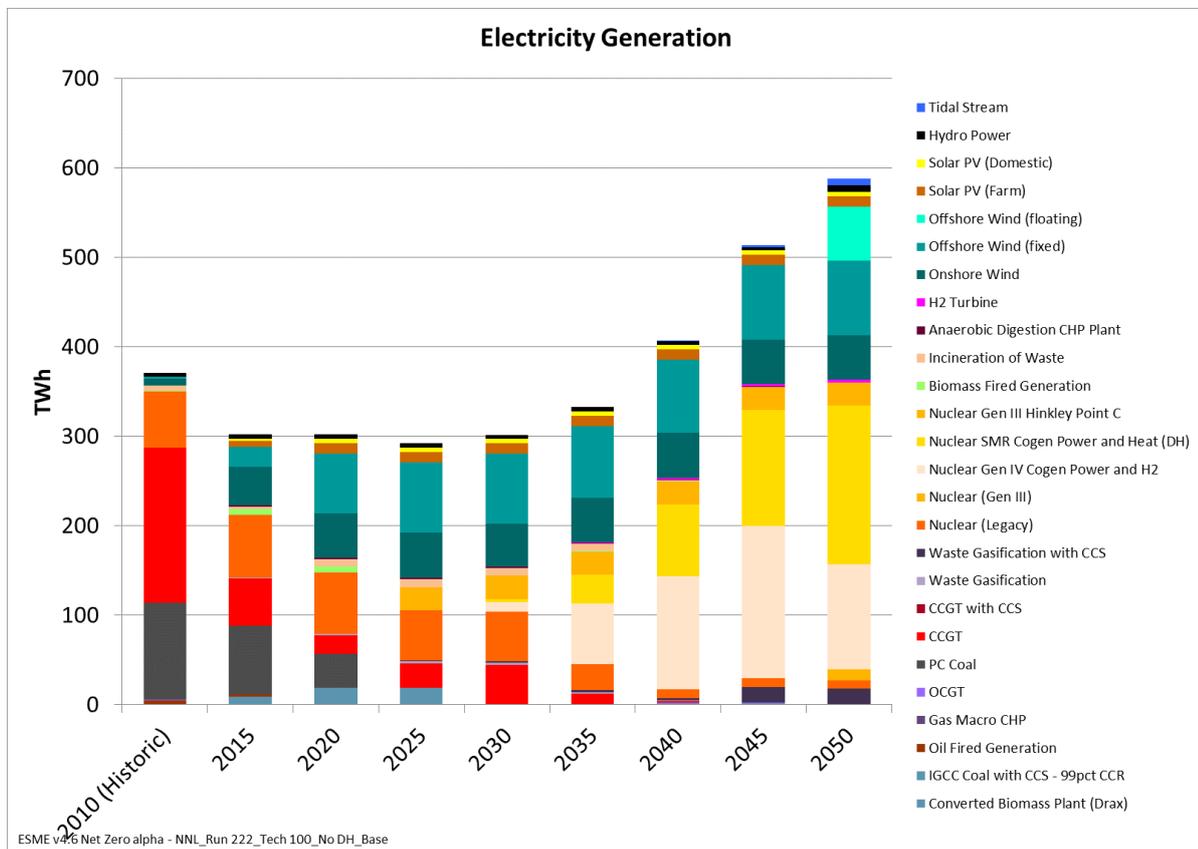Figure A3-101 – Run 212 electricity generation capacity
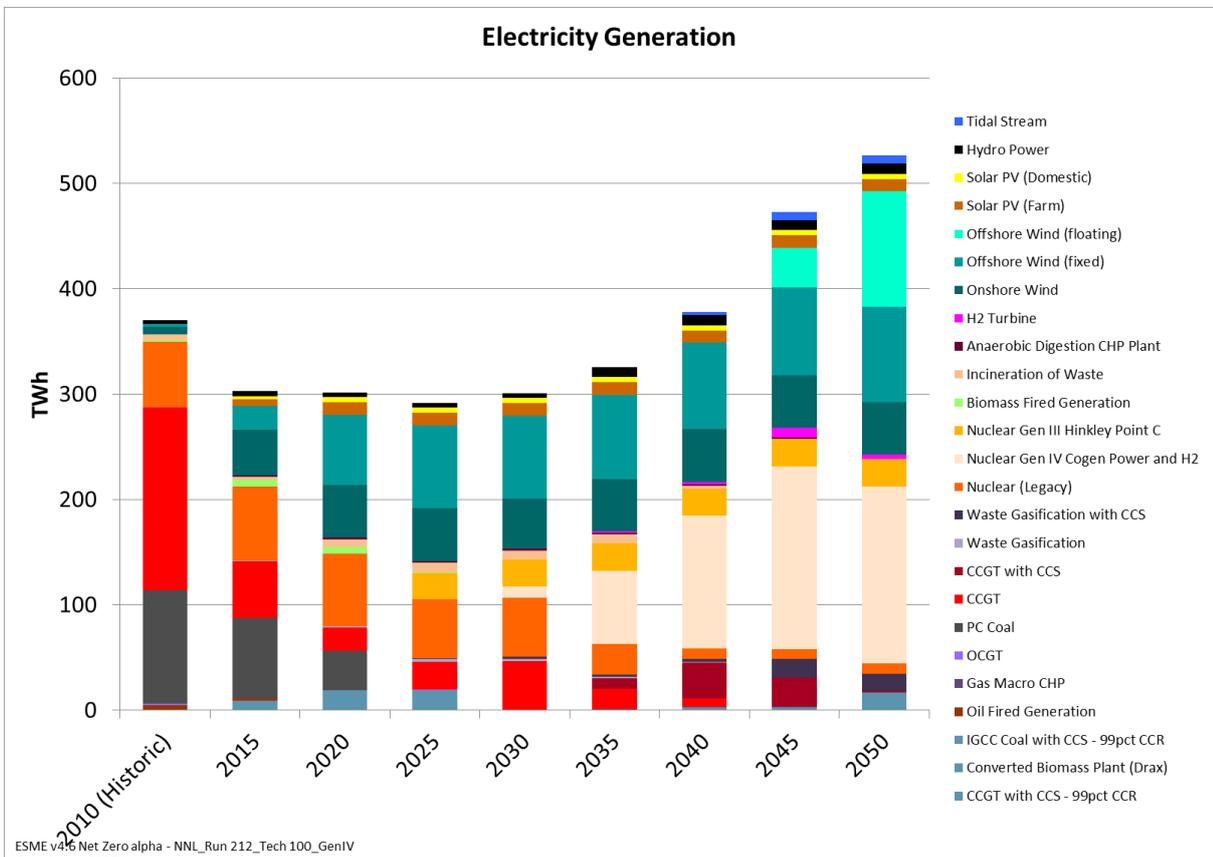
Figure A3-102 – Run 212 electricity generation
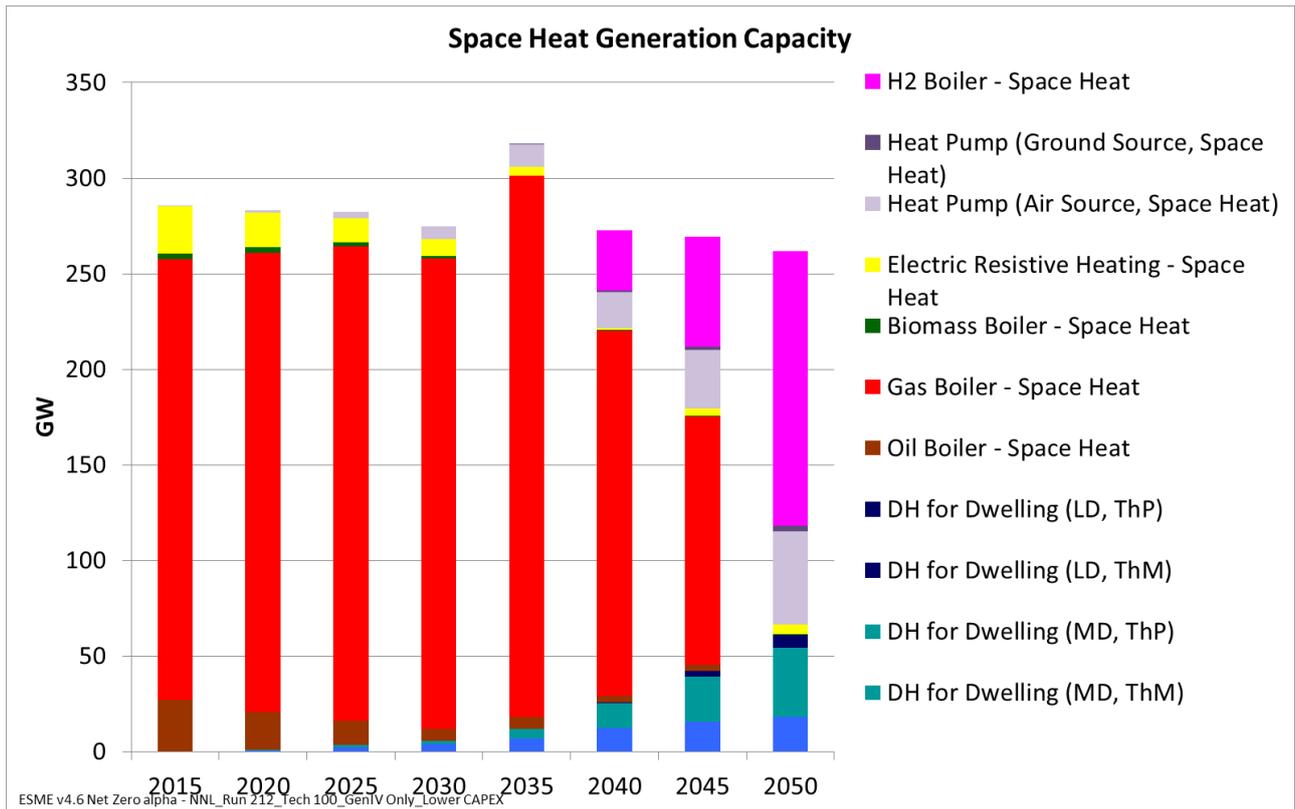
Figure A3-103 – Run 212 space heat generation capacity
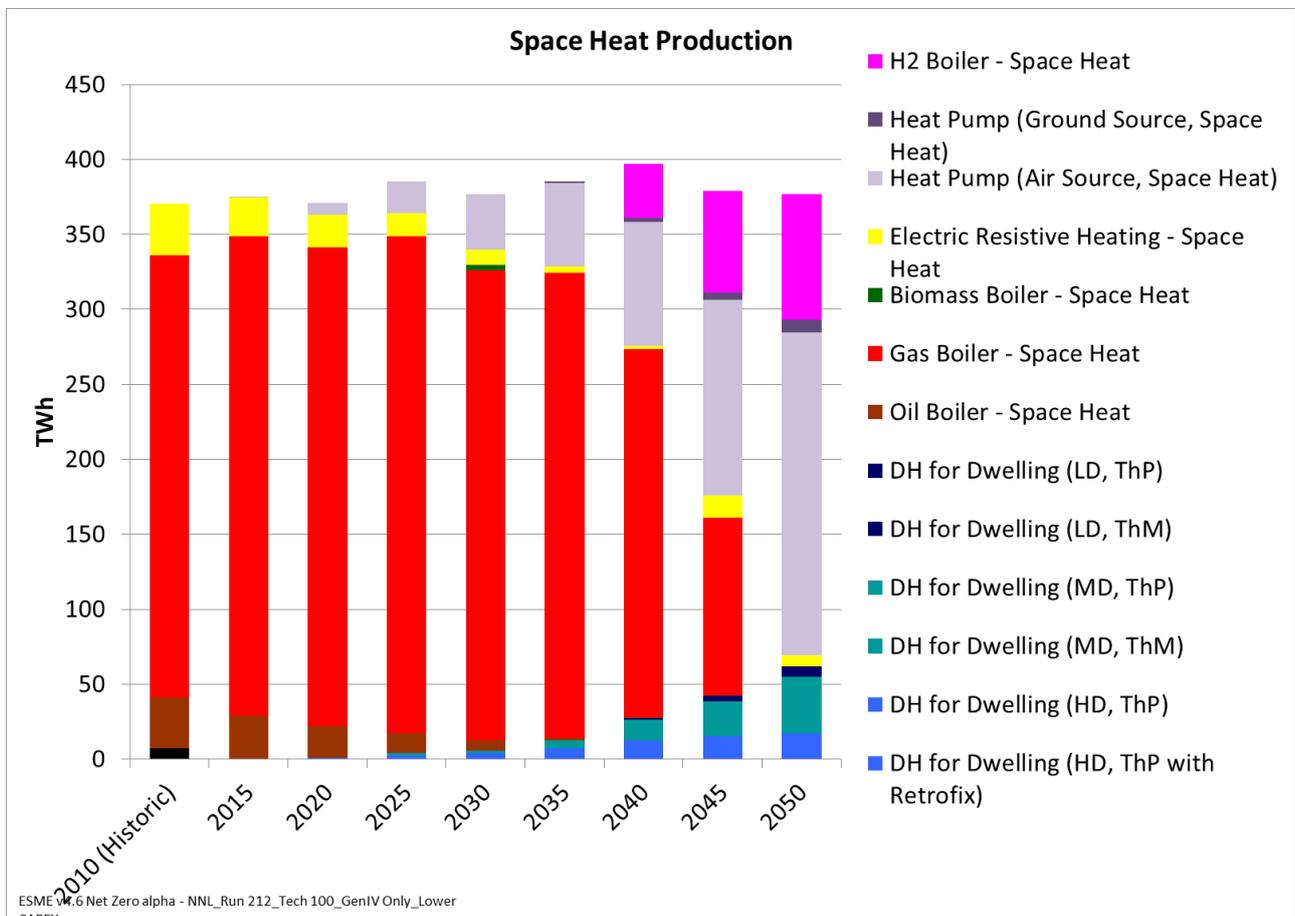
Figure A3-104 – Run 212 space heat production
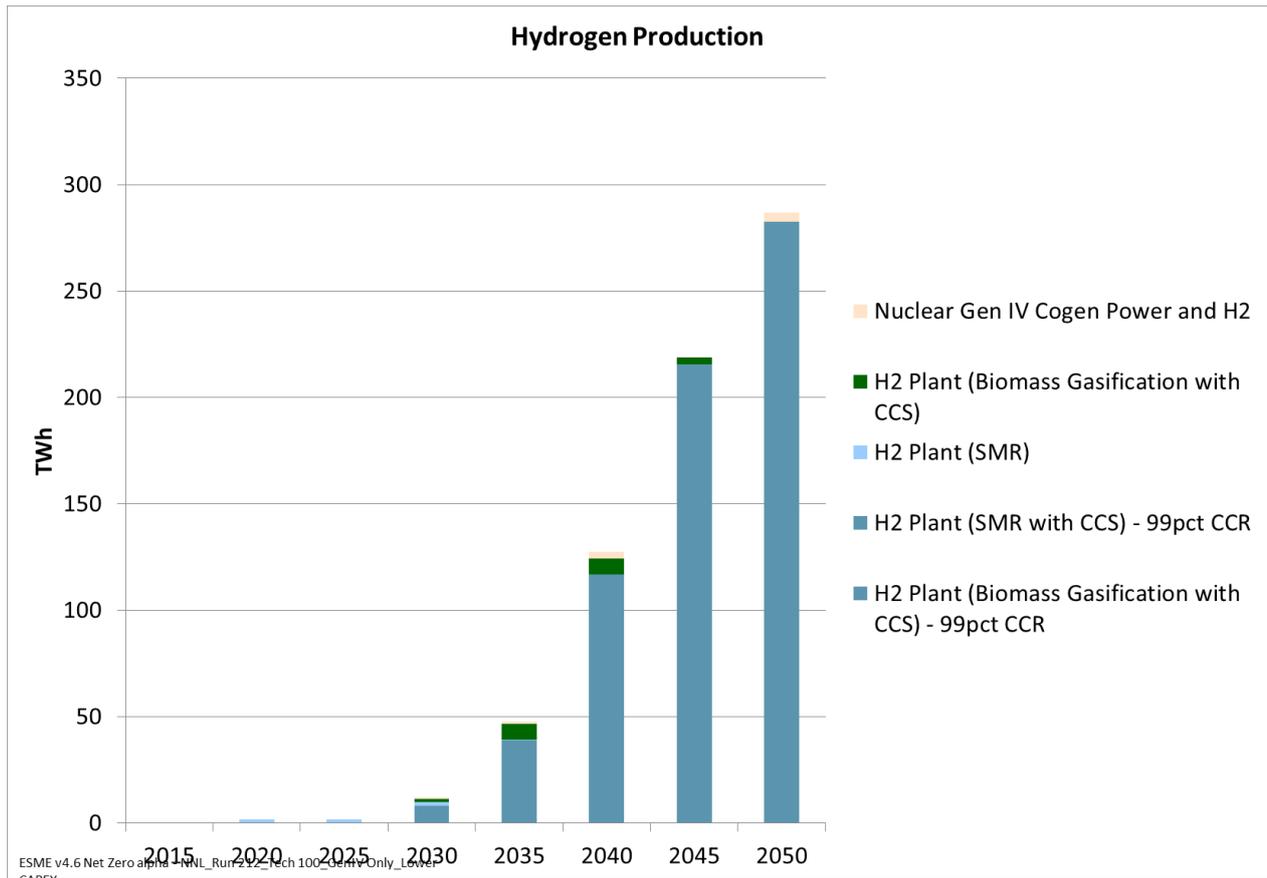
Figure A3-105 – Run 212 hydrogen production
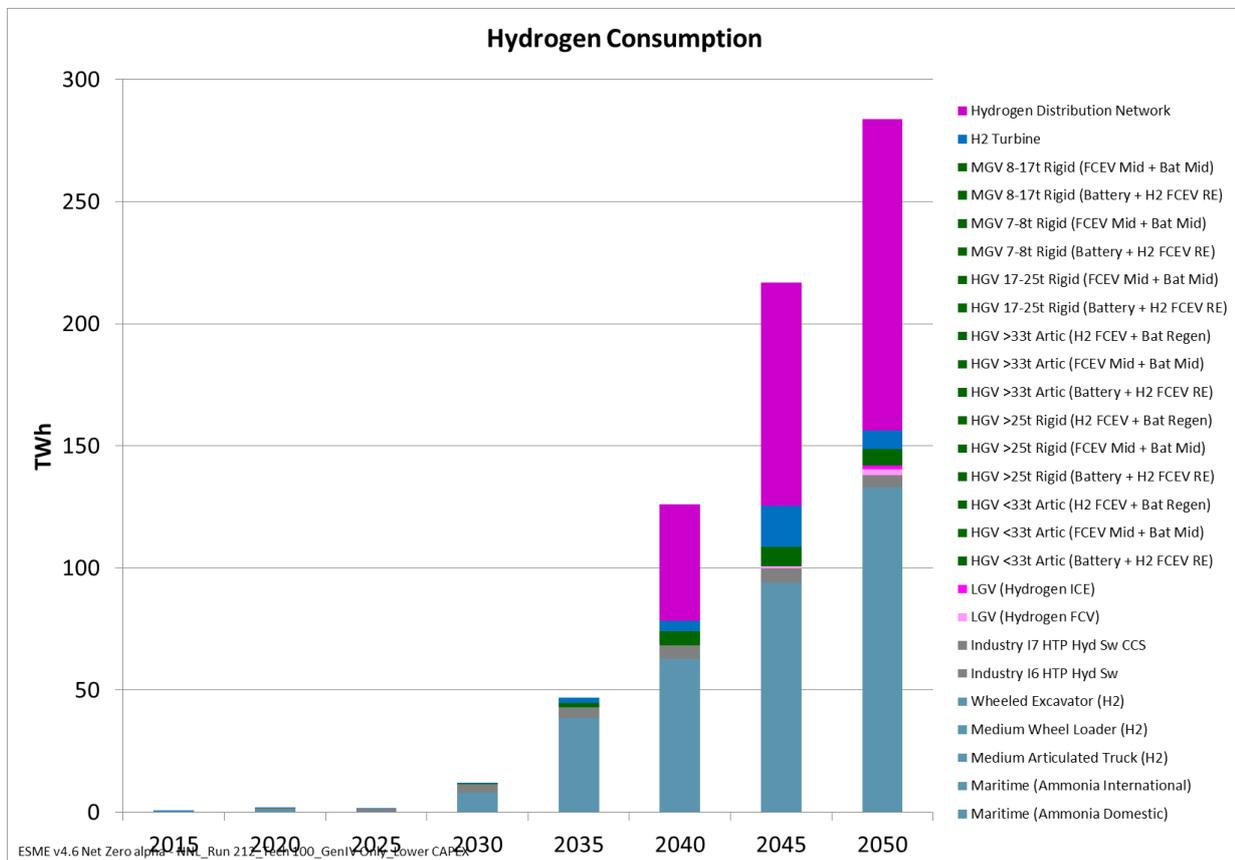
Figure A3-106 – Run 212 hydrogen consumption
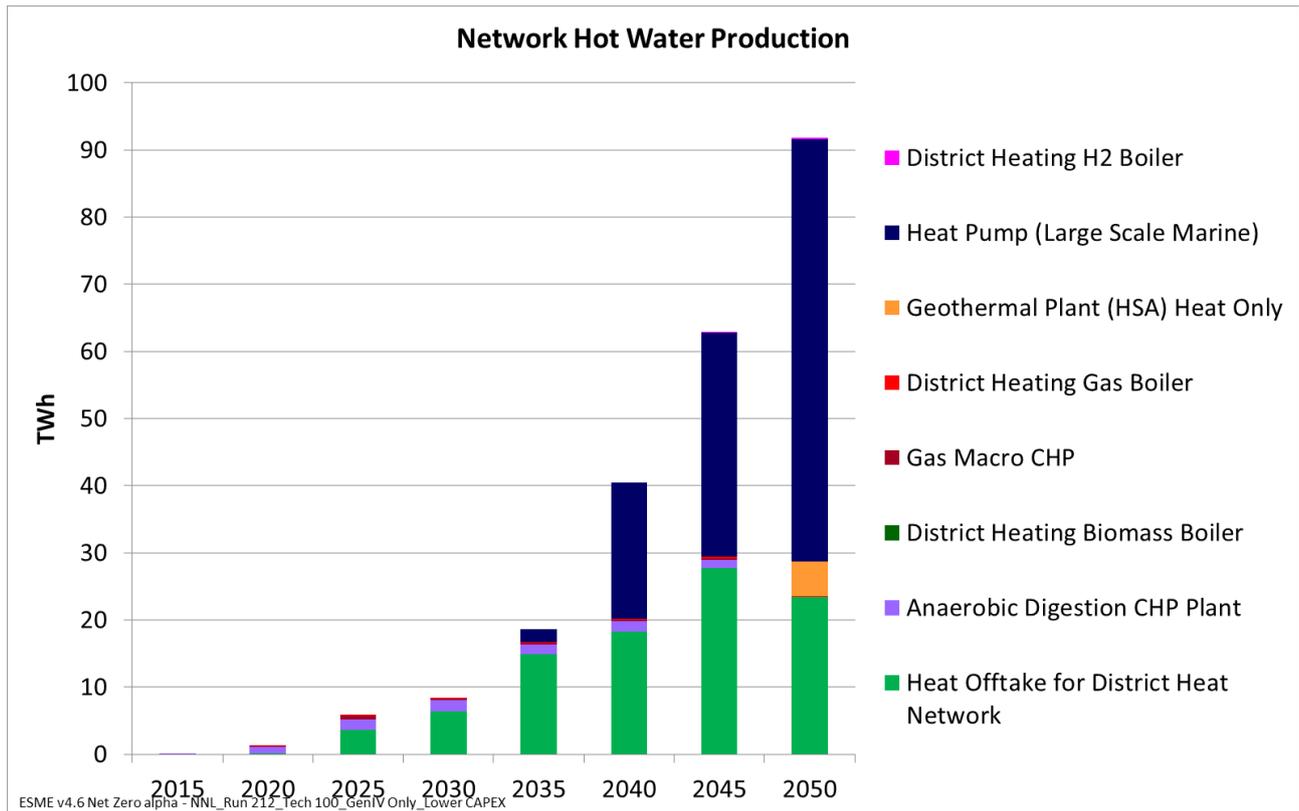
Figure A3-107 – Run 212 network hot water production
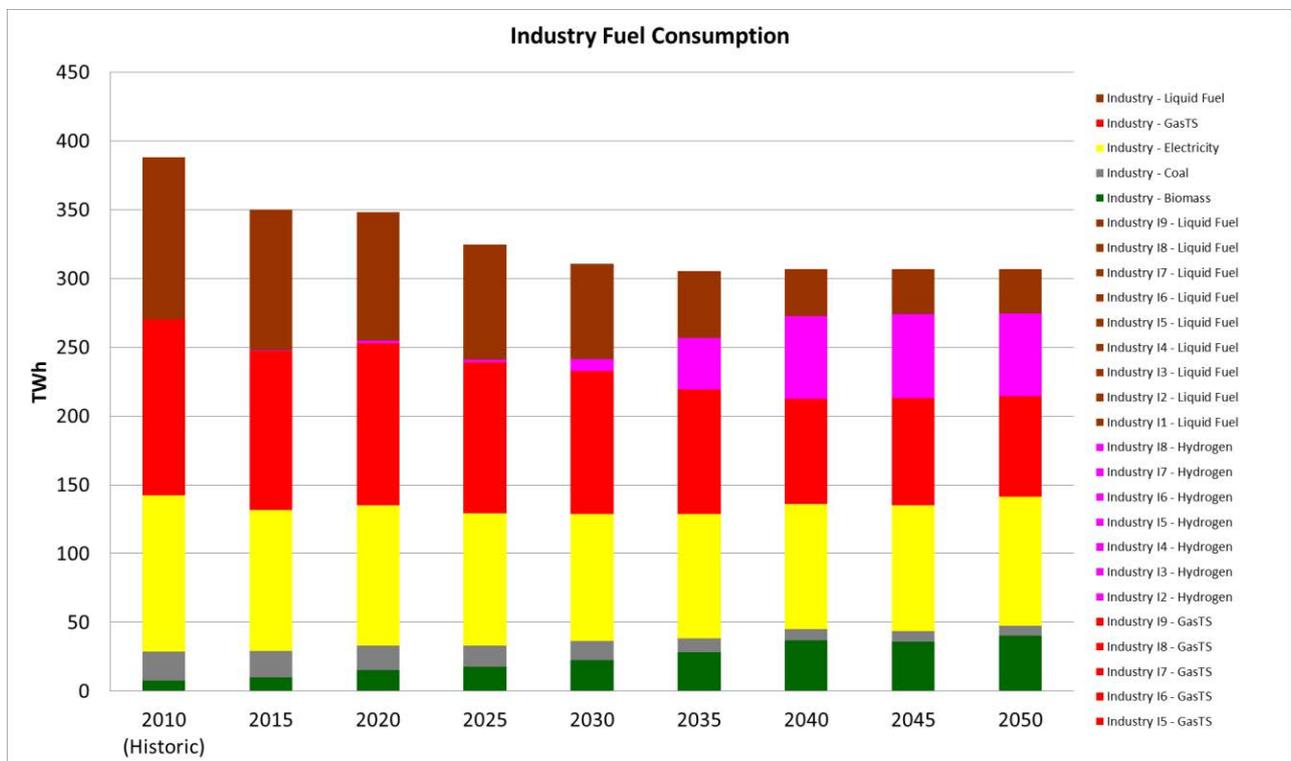
Figure A3-108 – Run 212 industry fuel consumption

Run 213 FA96 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data with higher capex values
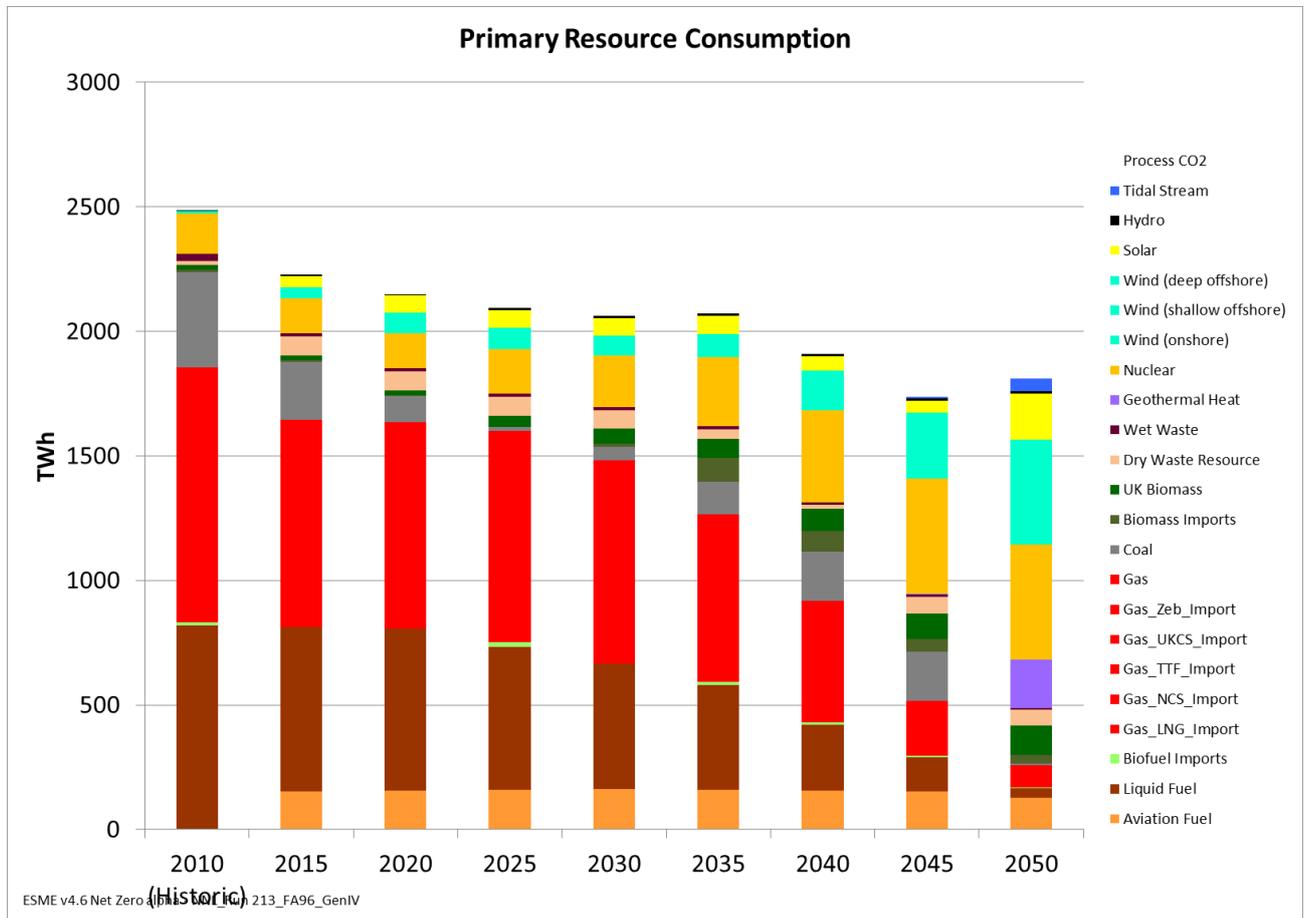
Figure A3-109 – Run 213 primary resource consumption
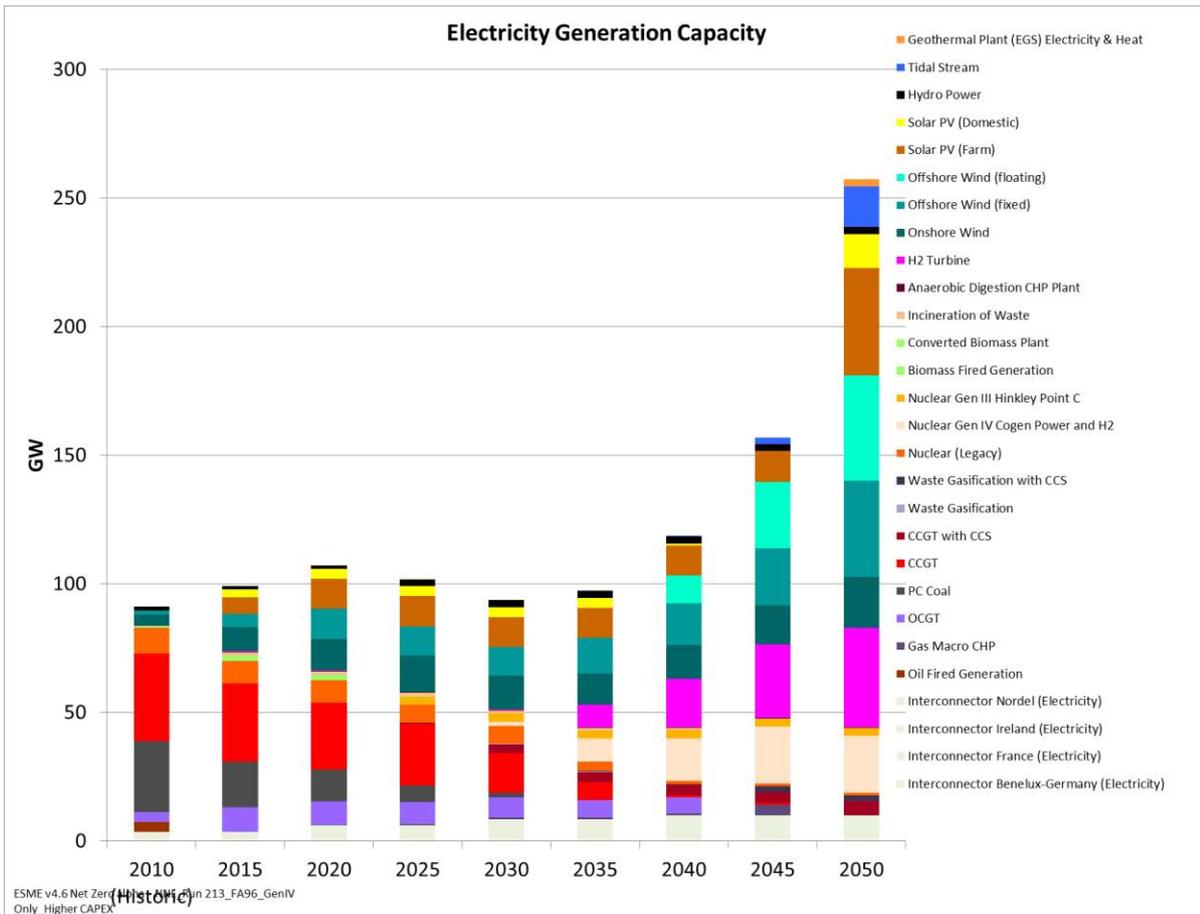
Figure A3-110 – Run 213 electricity generation capacity
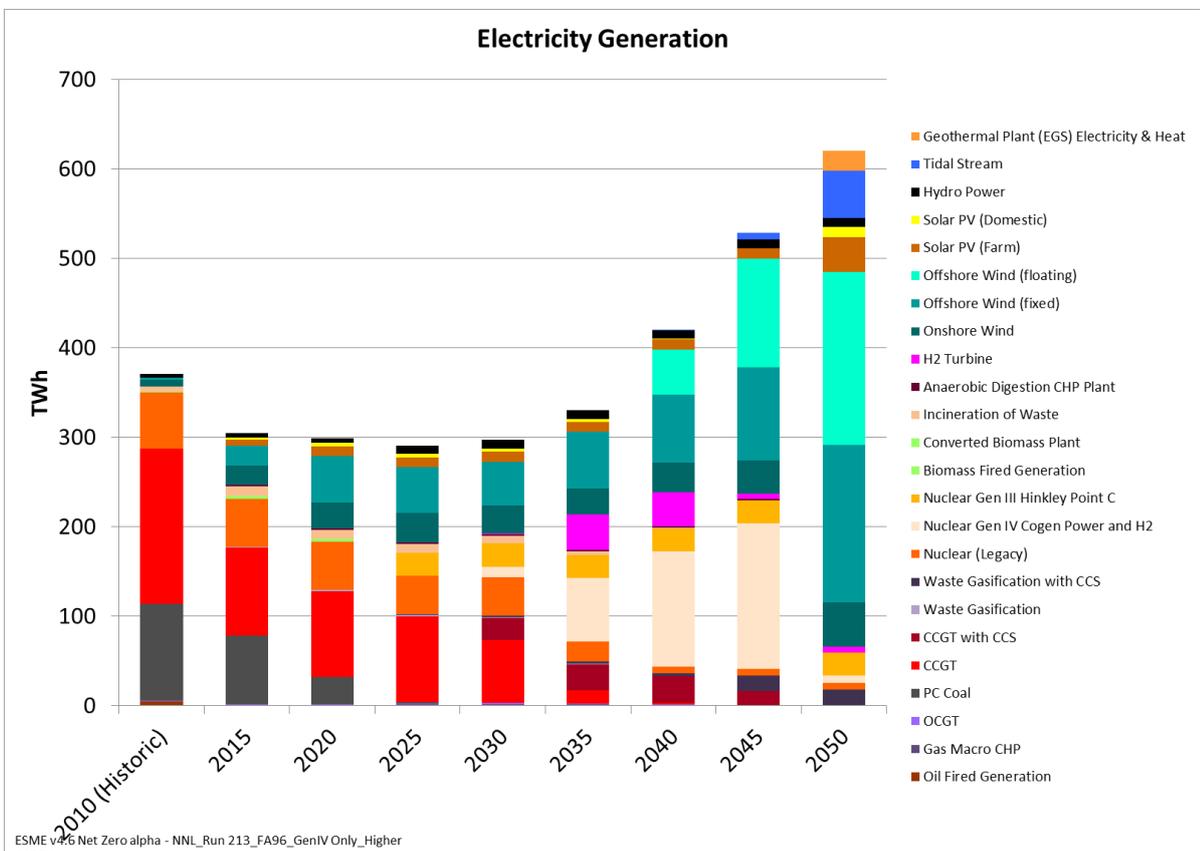
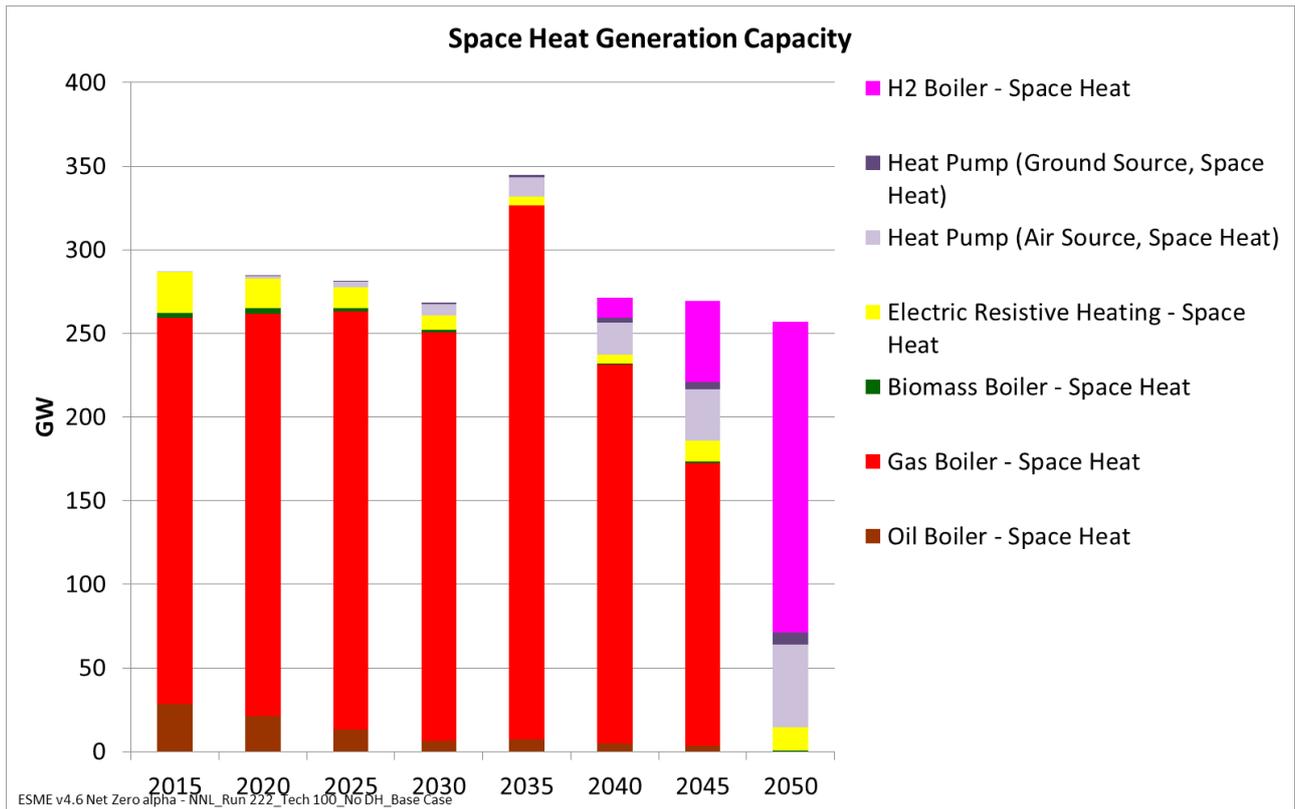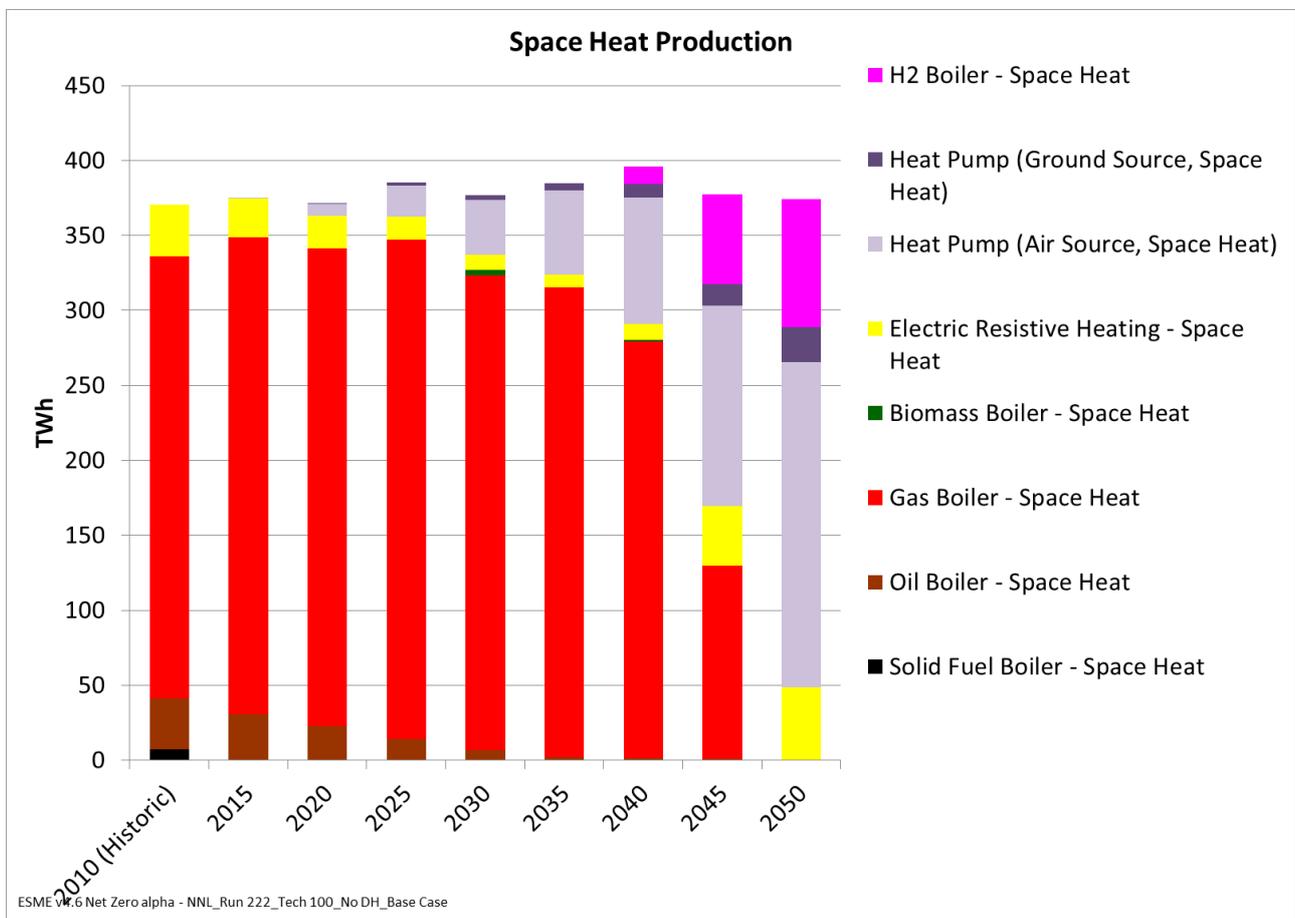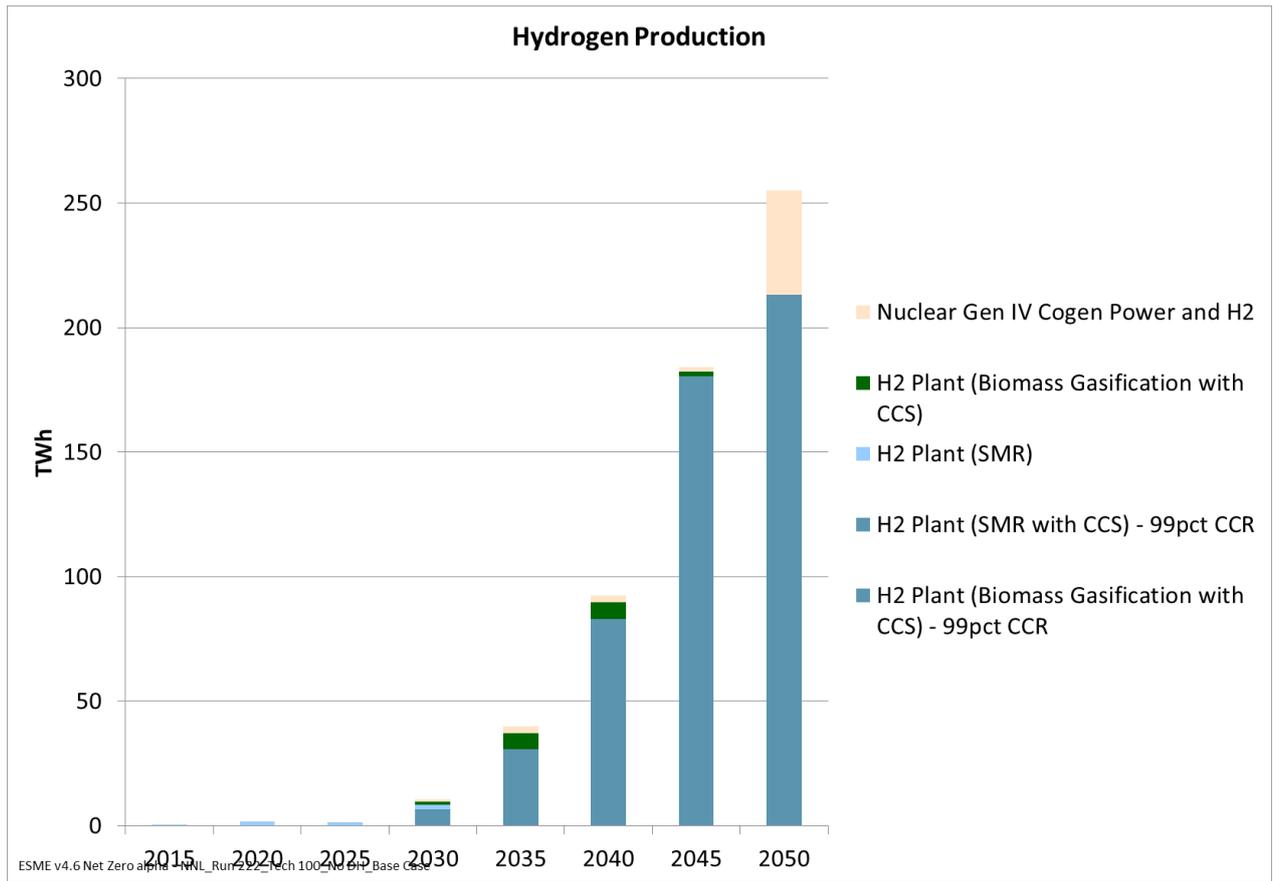Figure A3-111 – Run 213 electricity generation

Electricity Generation
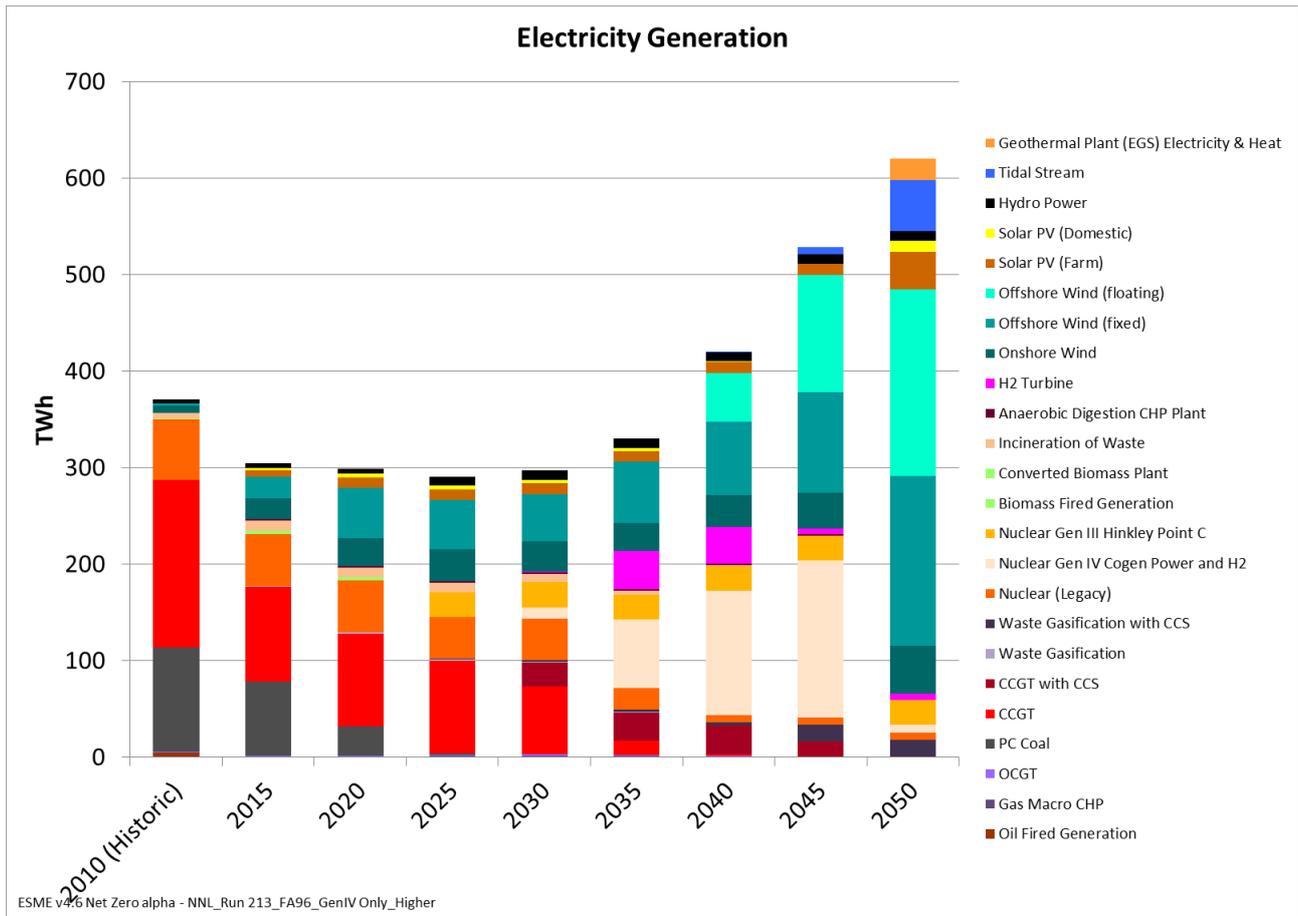
Figure A3-112 – Run 213 space heat generation capacity

Space Heat Generation Capacity
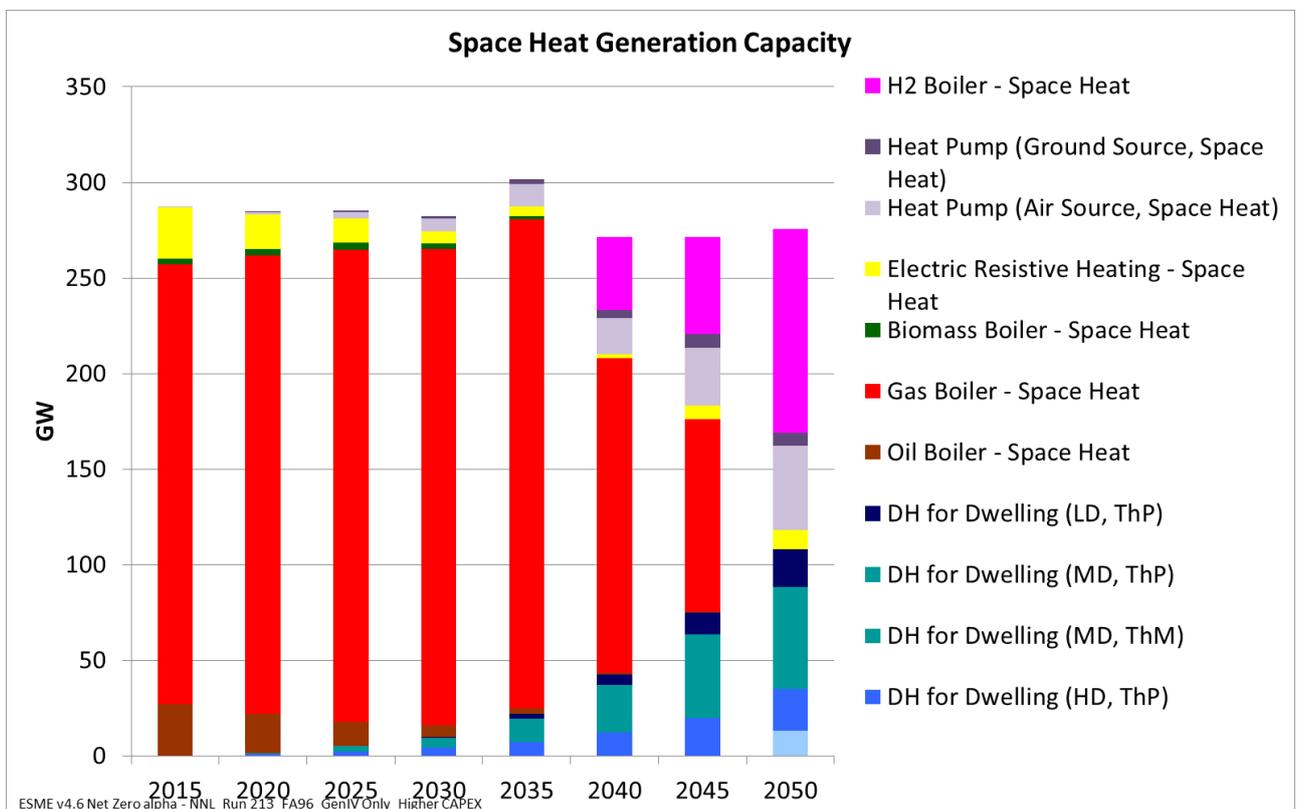
Figure A3-113 – Run 213 space heat production
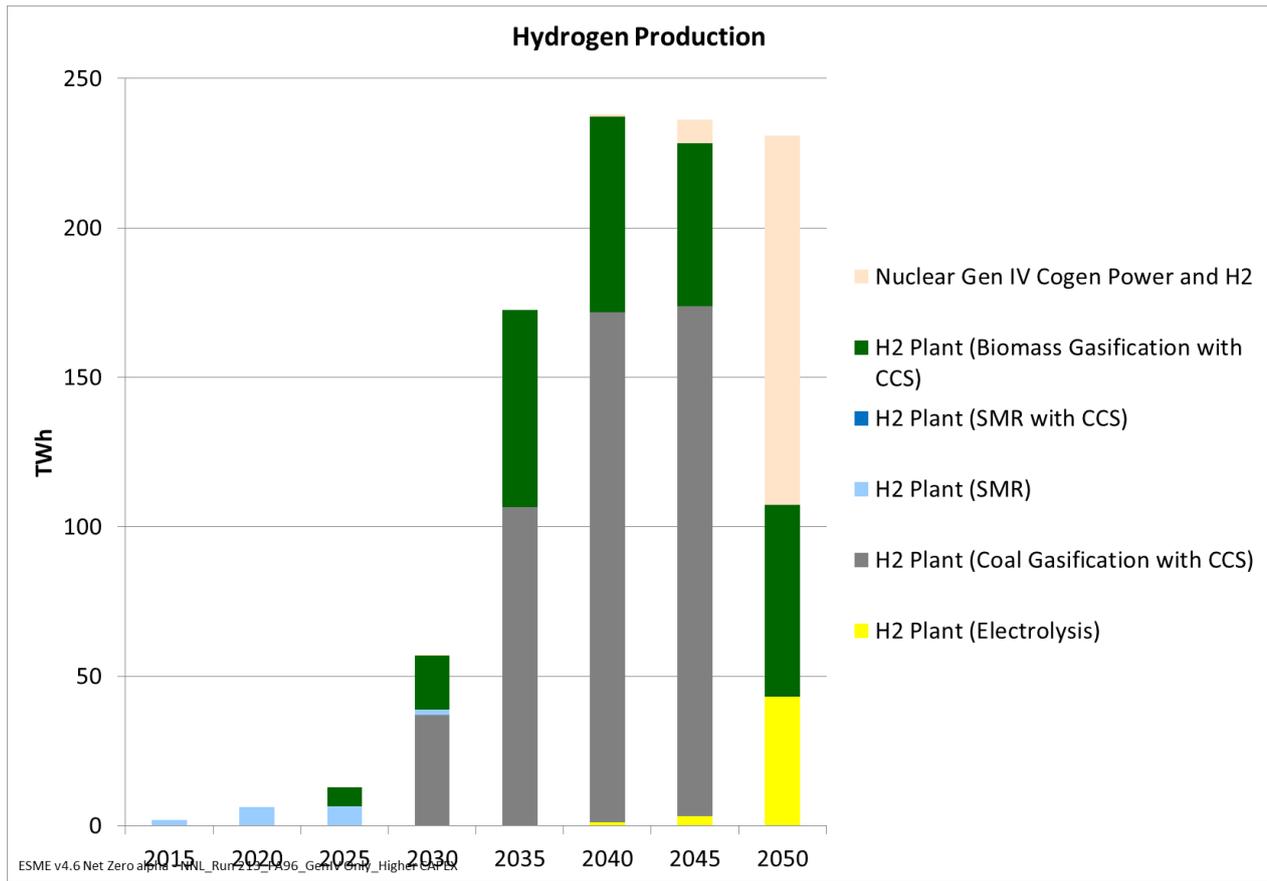
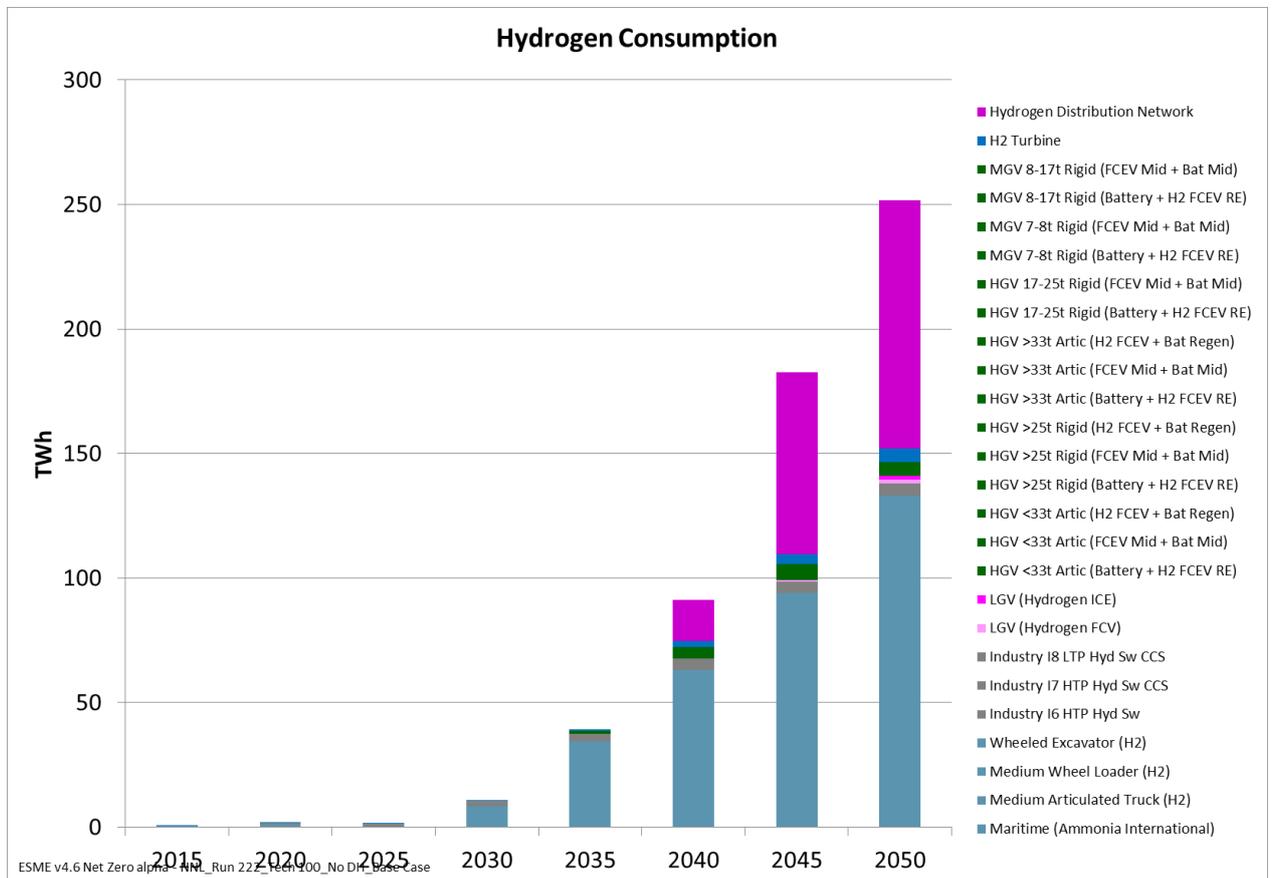Figure A3-114 – Run 213 hydrogen production
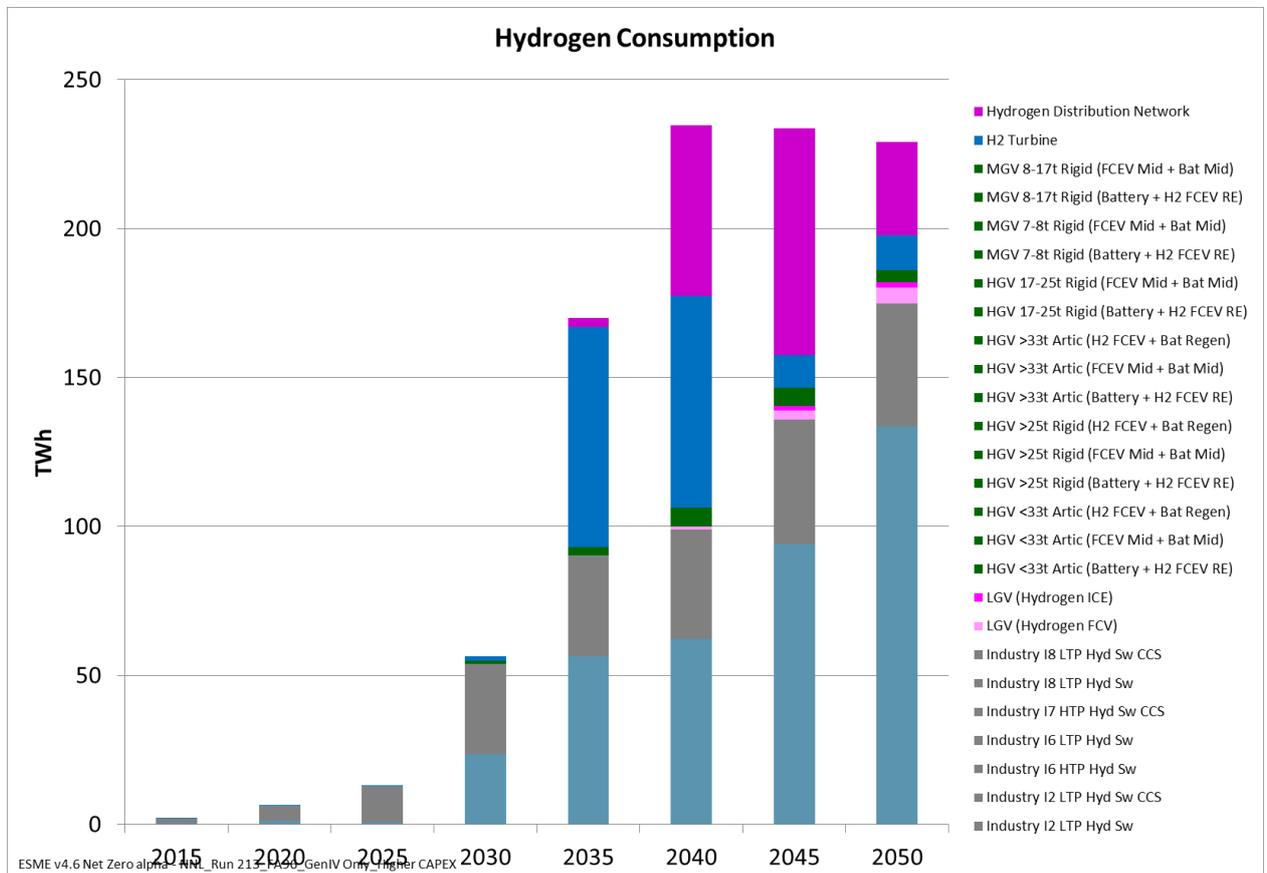
Figure A3-115 – Run 213 hydrogen consumption
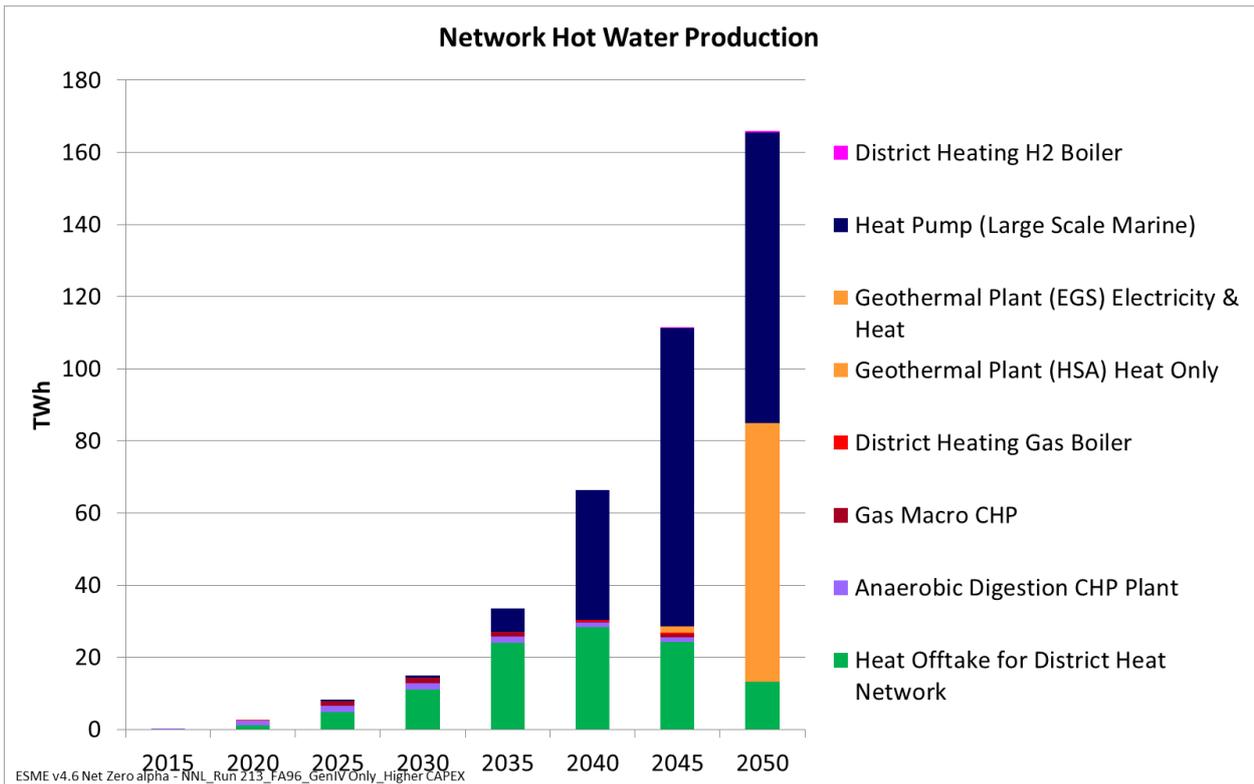
Figure A3-116 – Run 213 network hot water production
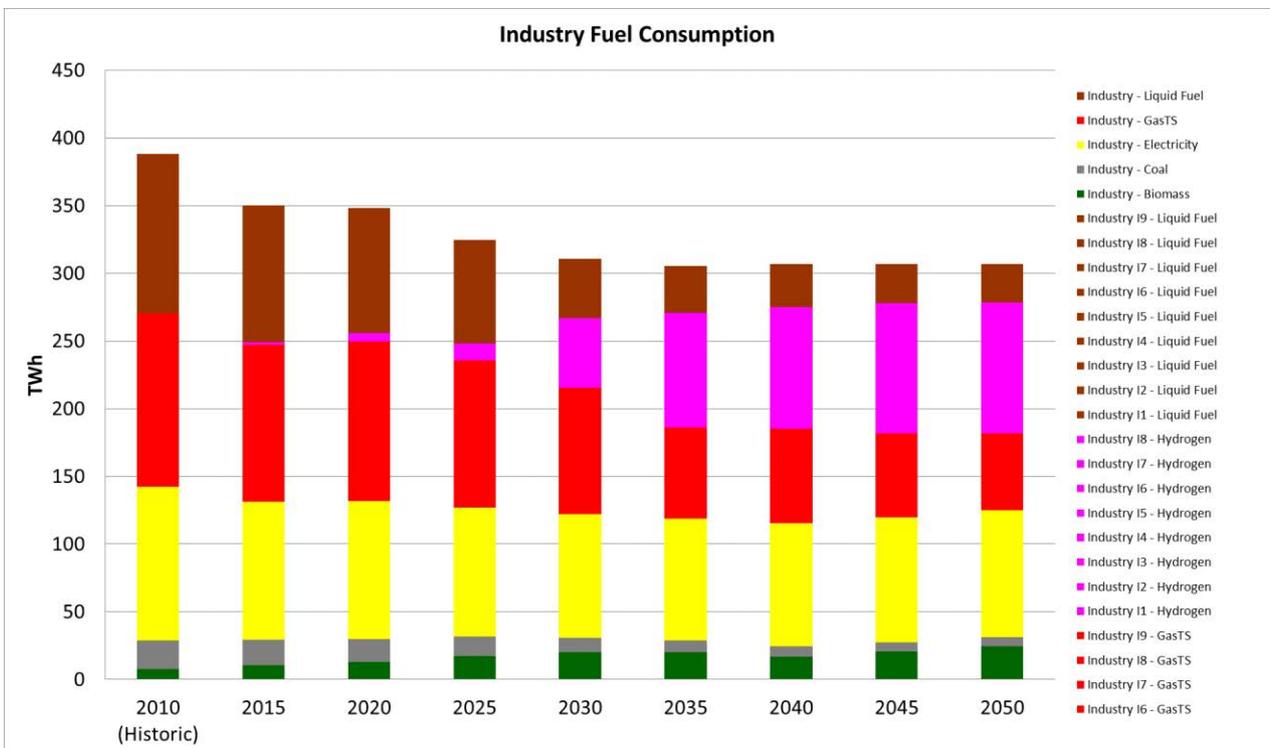
Figure A3-117 – Run 213 industry fuel consumption

Run 214 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; base case data with higher capex values
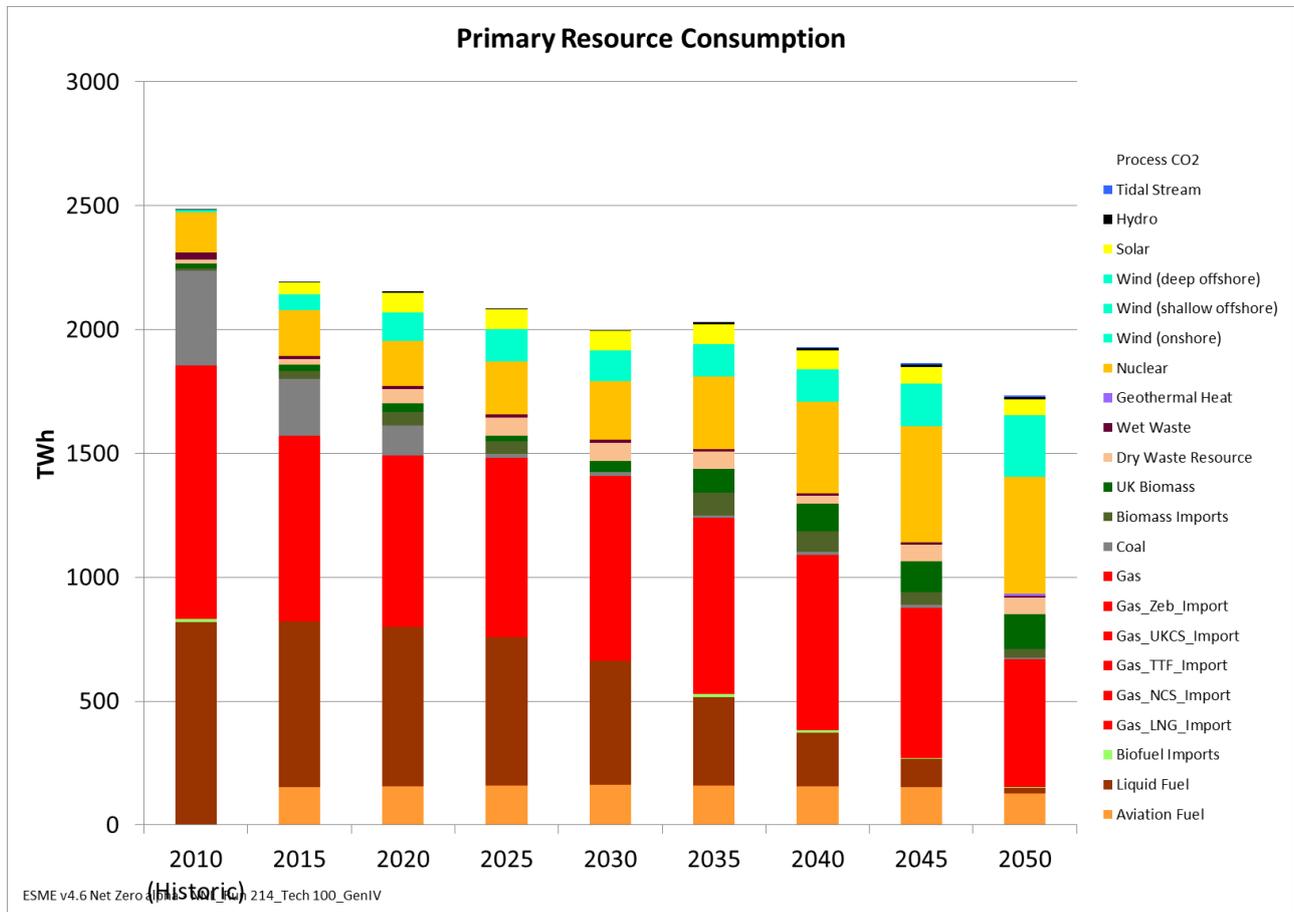
Figure A3-118 – Run 214 primary resource consumption
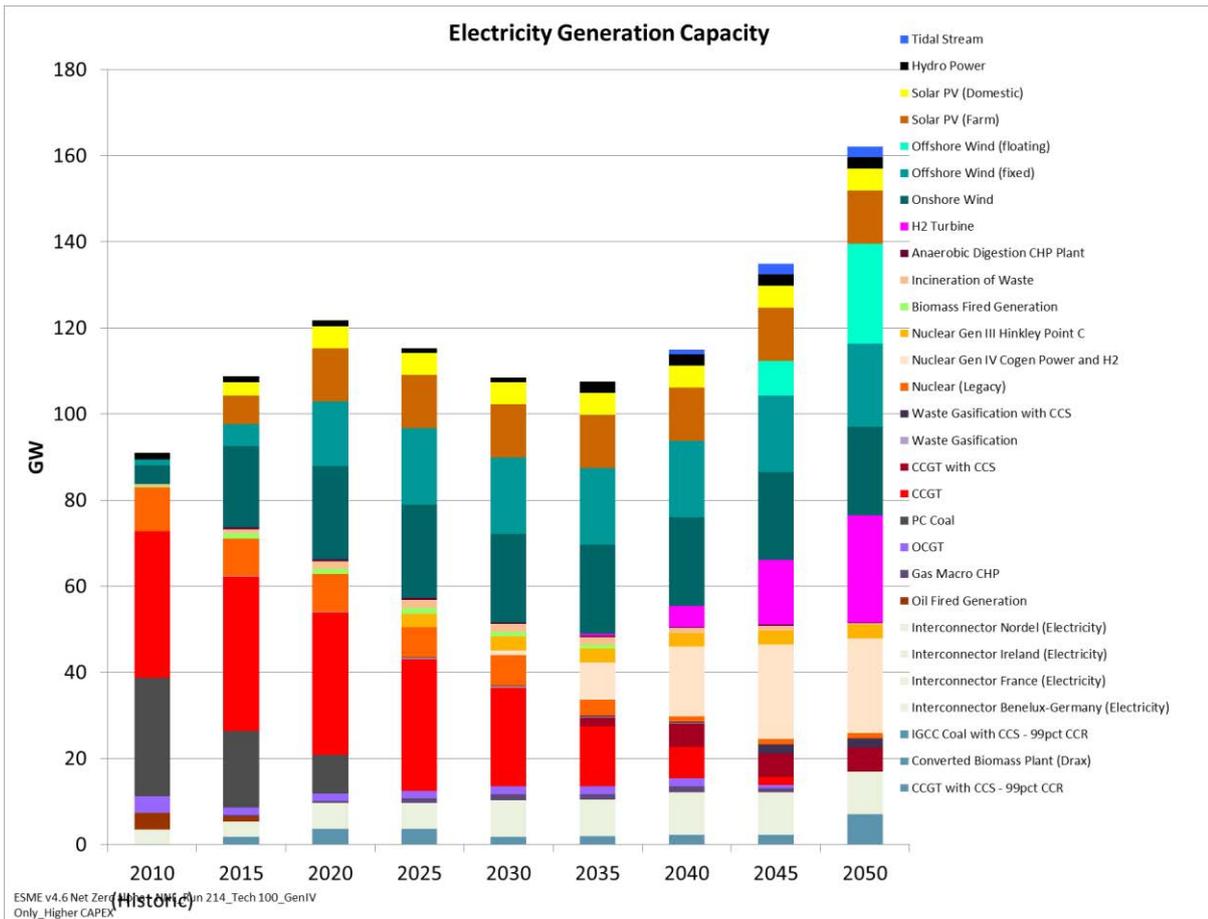
Figure A3-119 – Run 214 electricity generation capacity
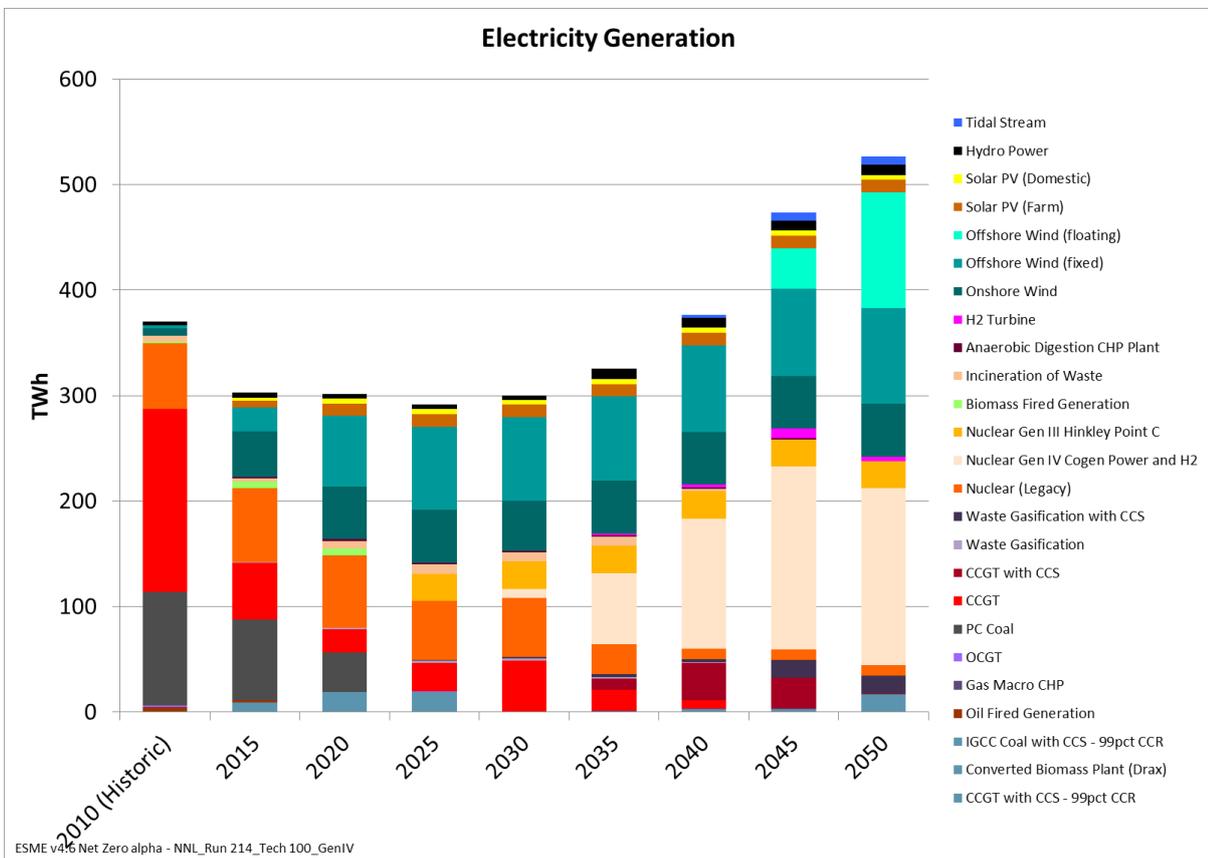
Figure A3-120 – Run 214 electricity generation
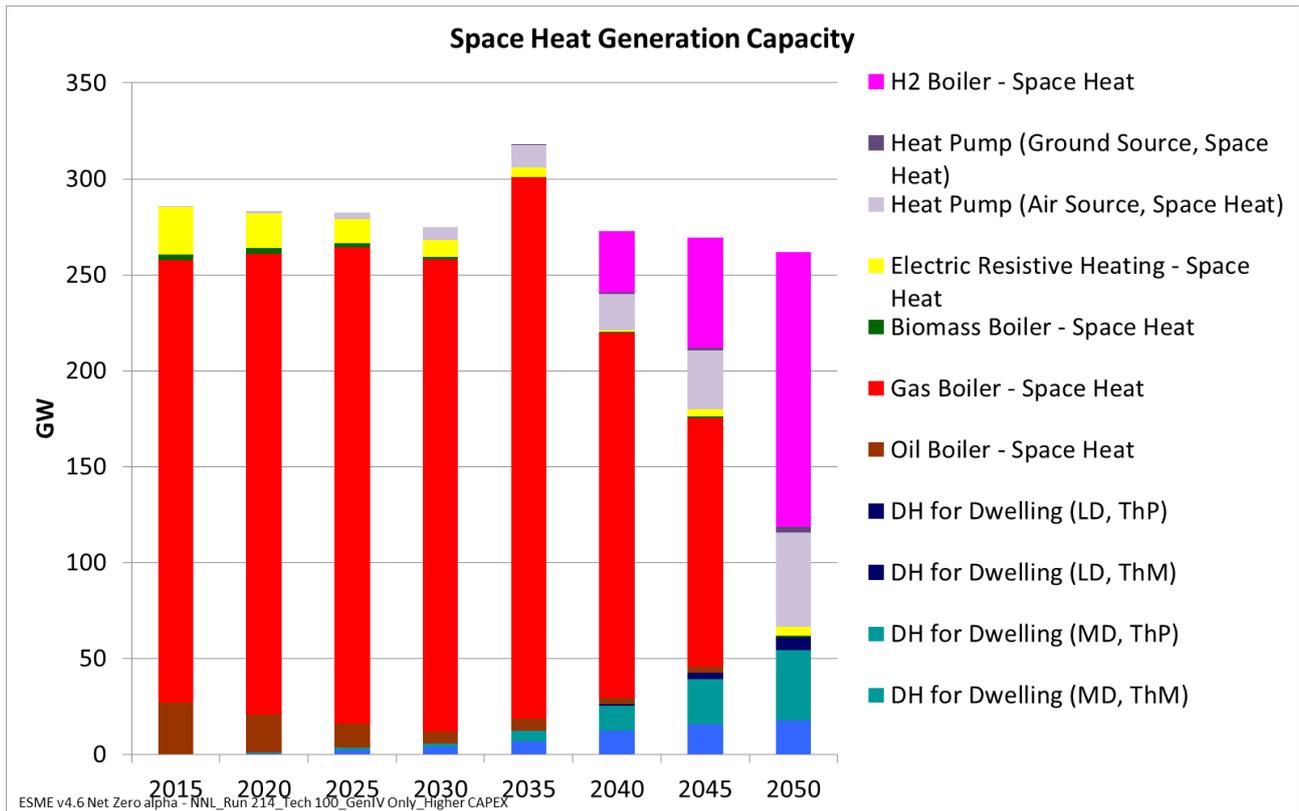
Figure A3-121 – Run 214 space heat generation capacity
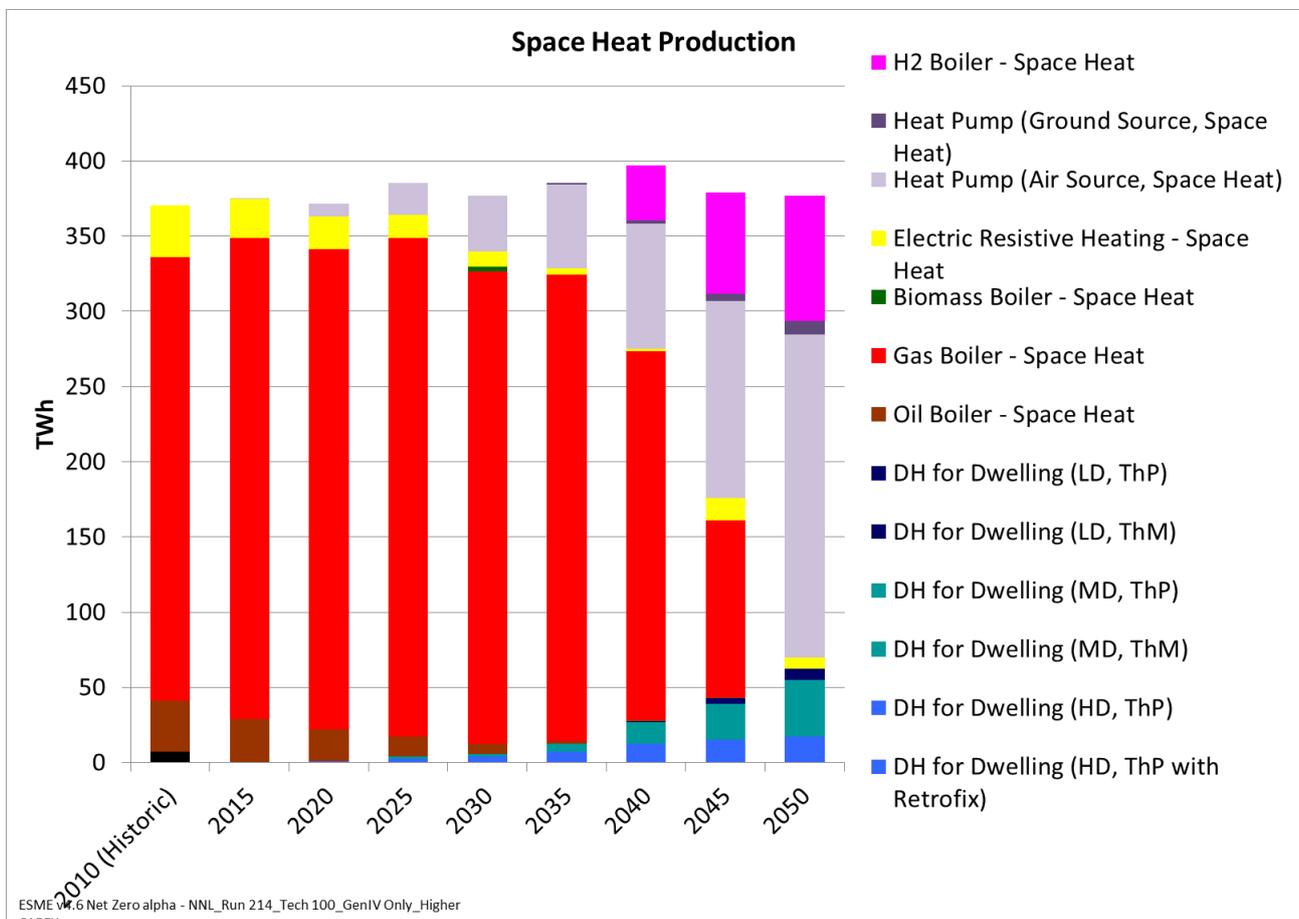
Figure A3-122 – Run 214 space heat production
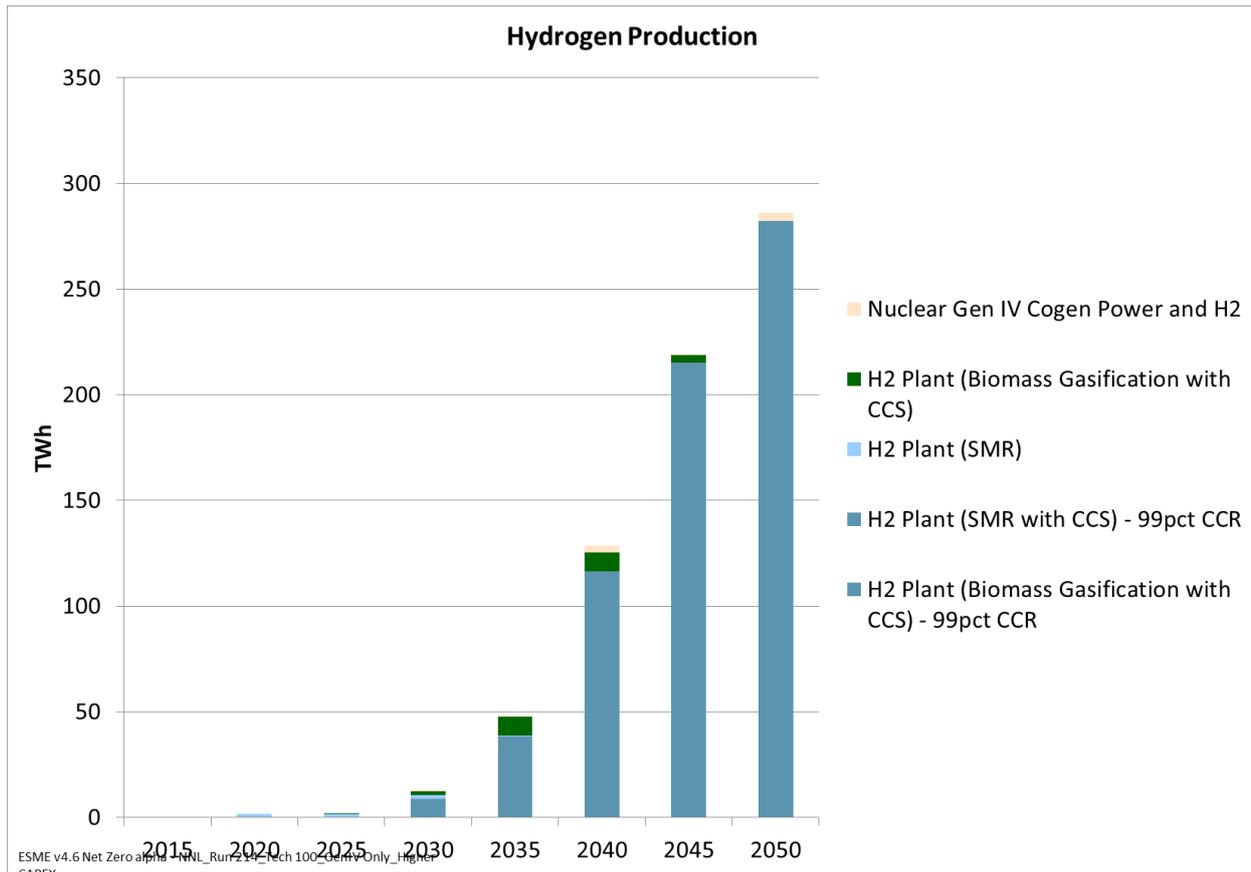
Figure A3-123 – Run 214 hydrogen production
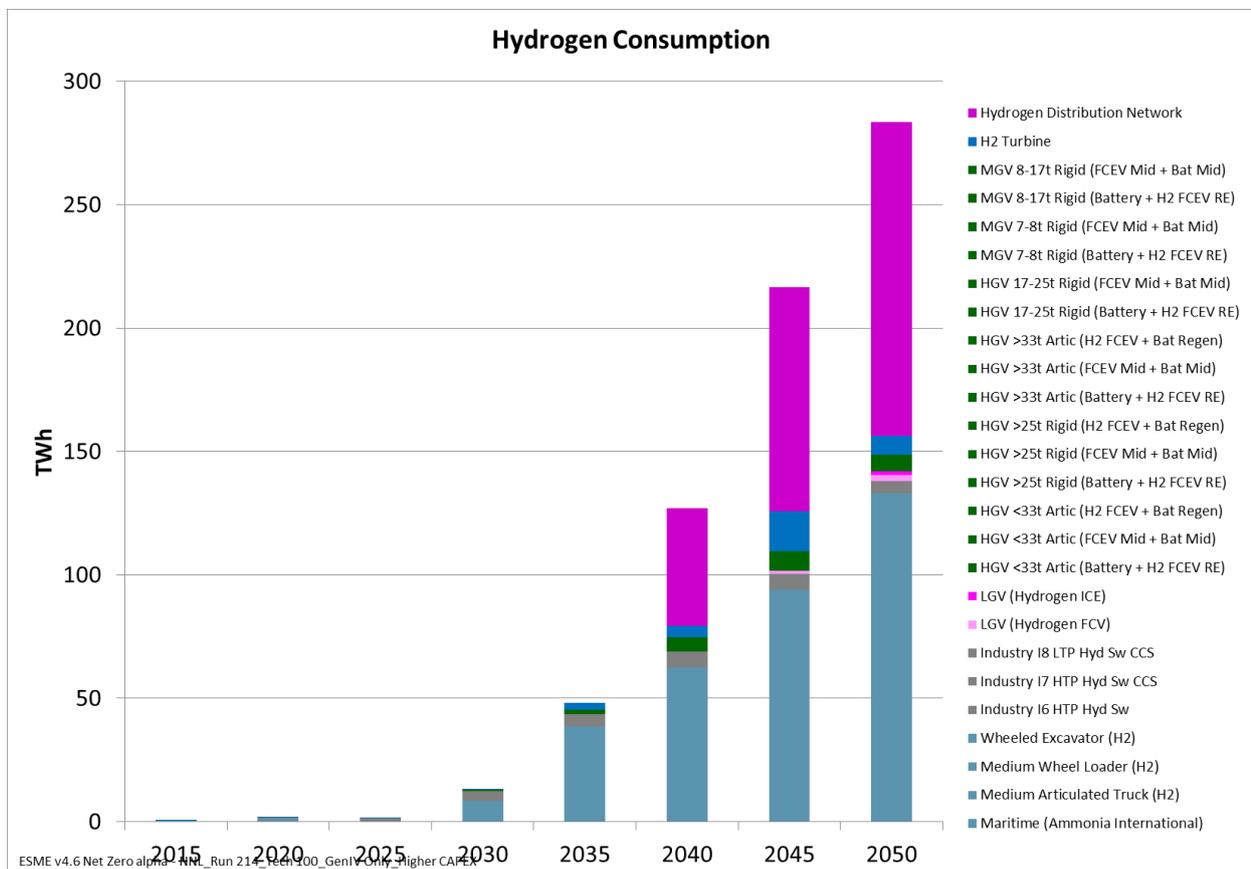
Figure A3-124 – Run 214 hydrogen consumption
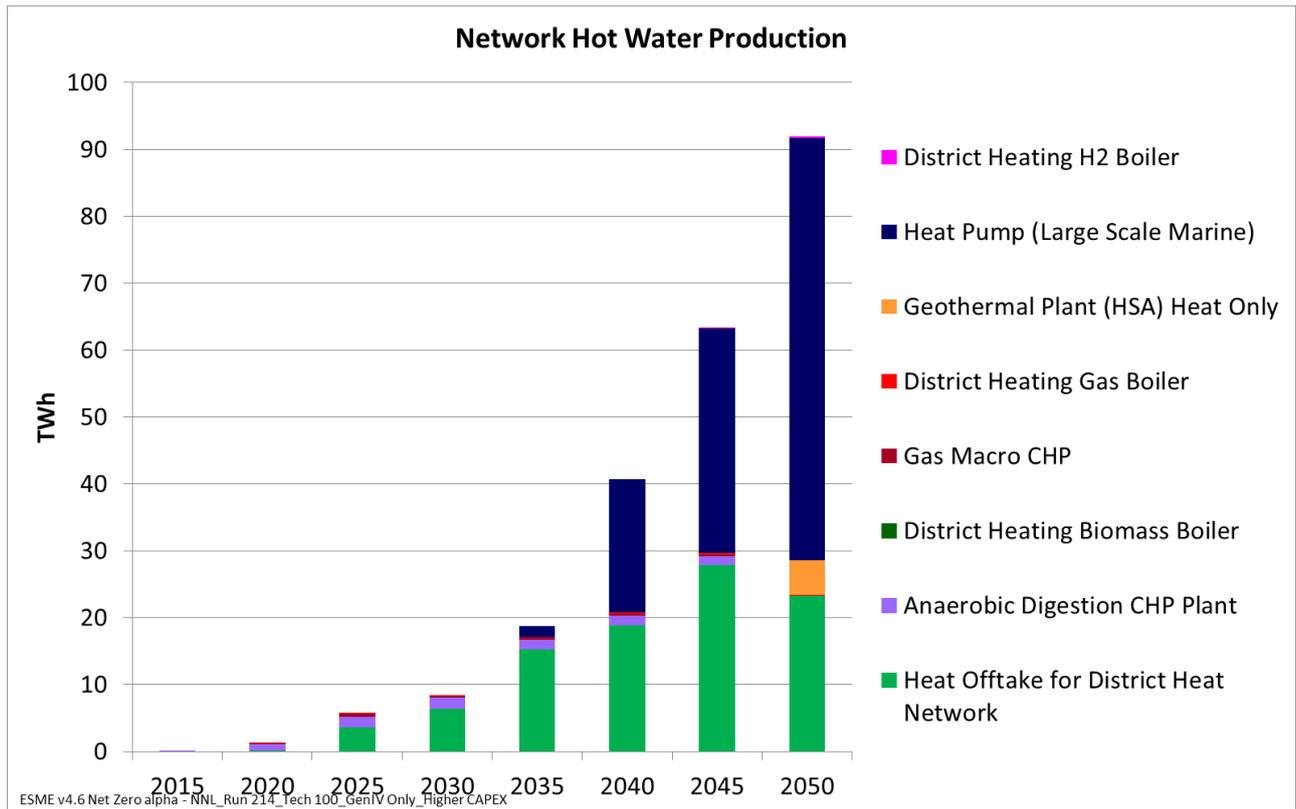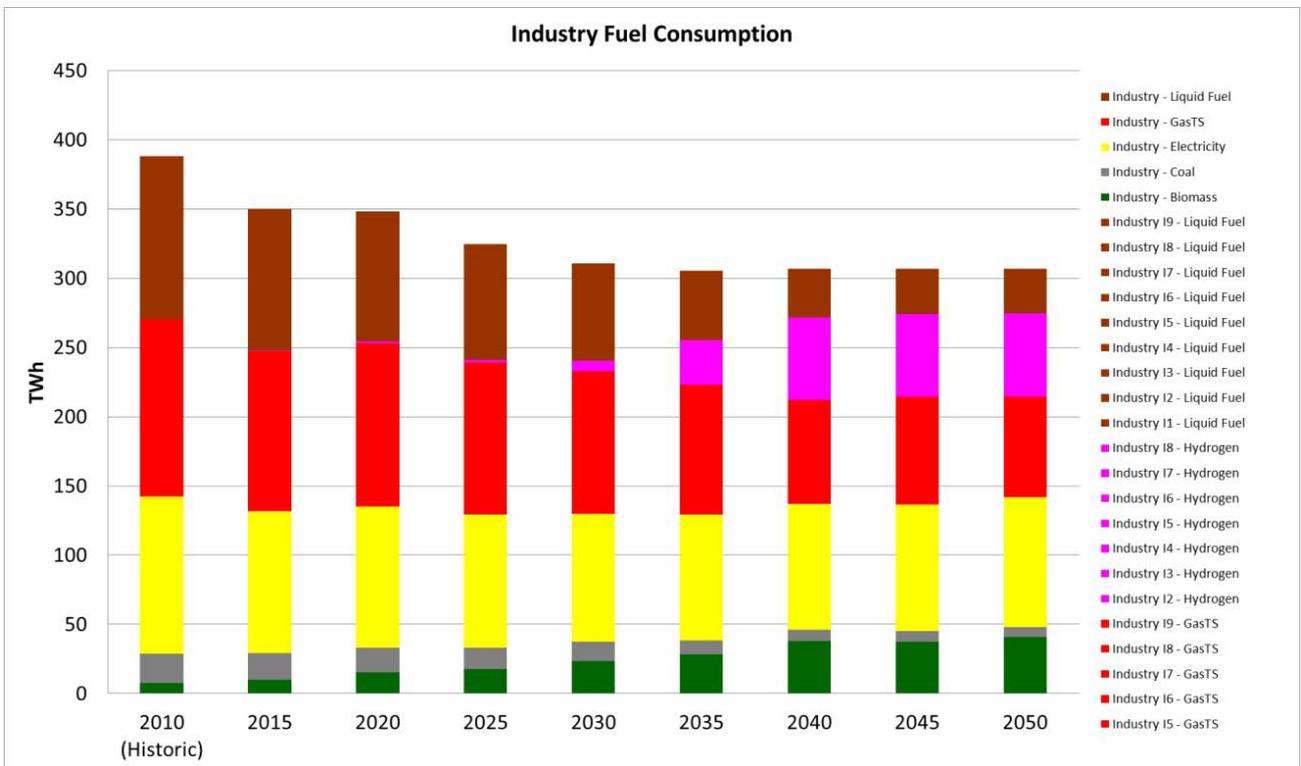
Figure A3-125 – Run 214 network hot water production
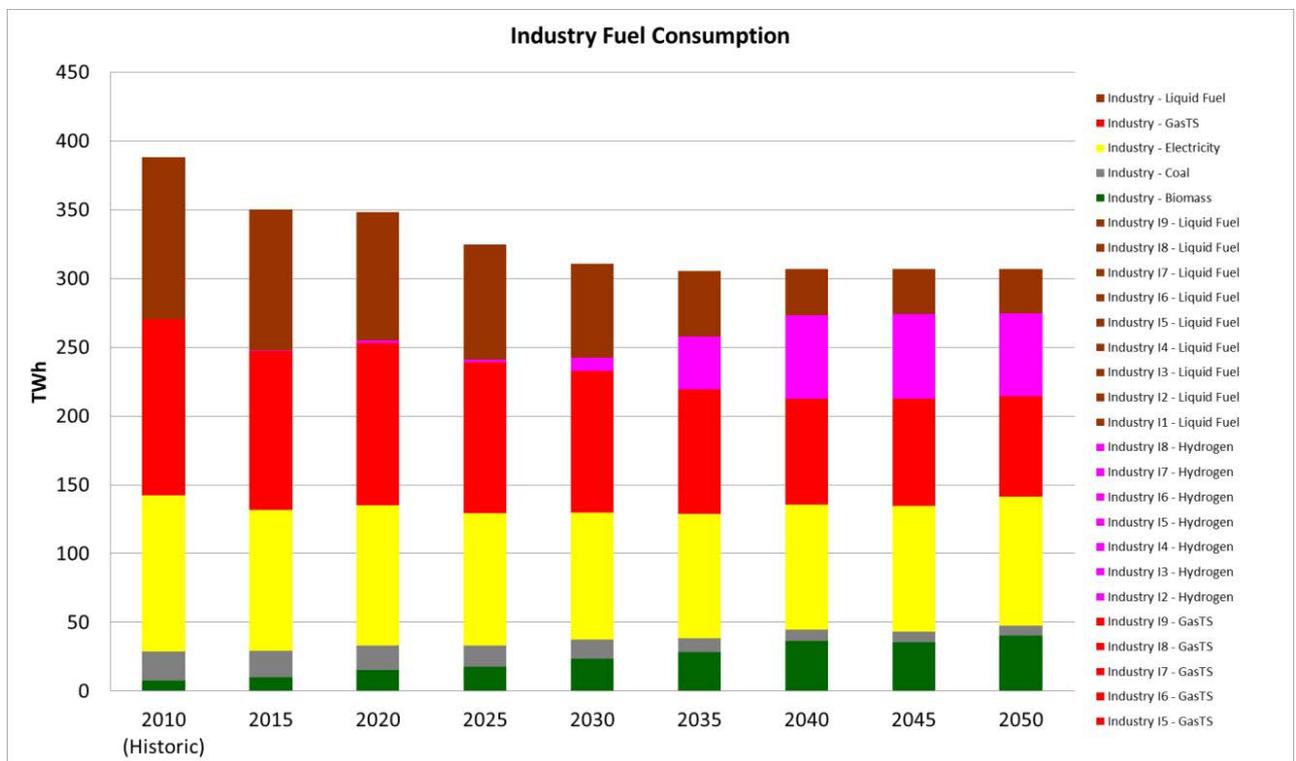
Figure A3-126 – Run 203 industry fuel consumption

Run 215 FA96 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55 GWe and build-out rate to match; base case data
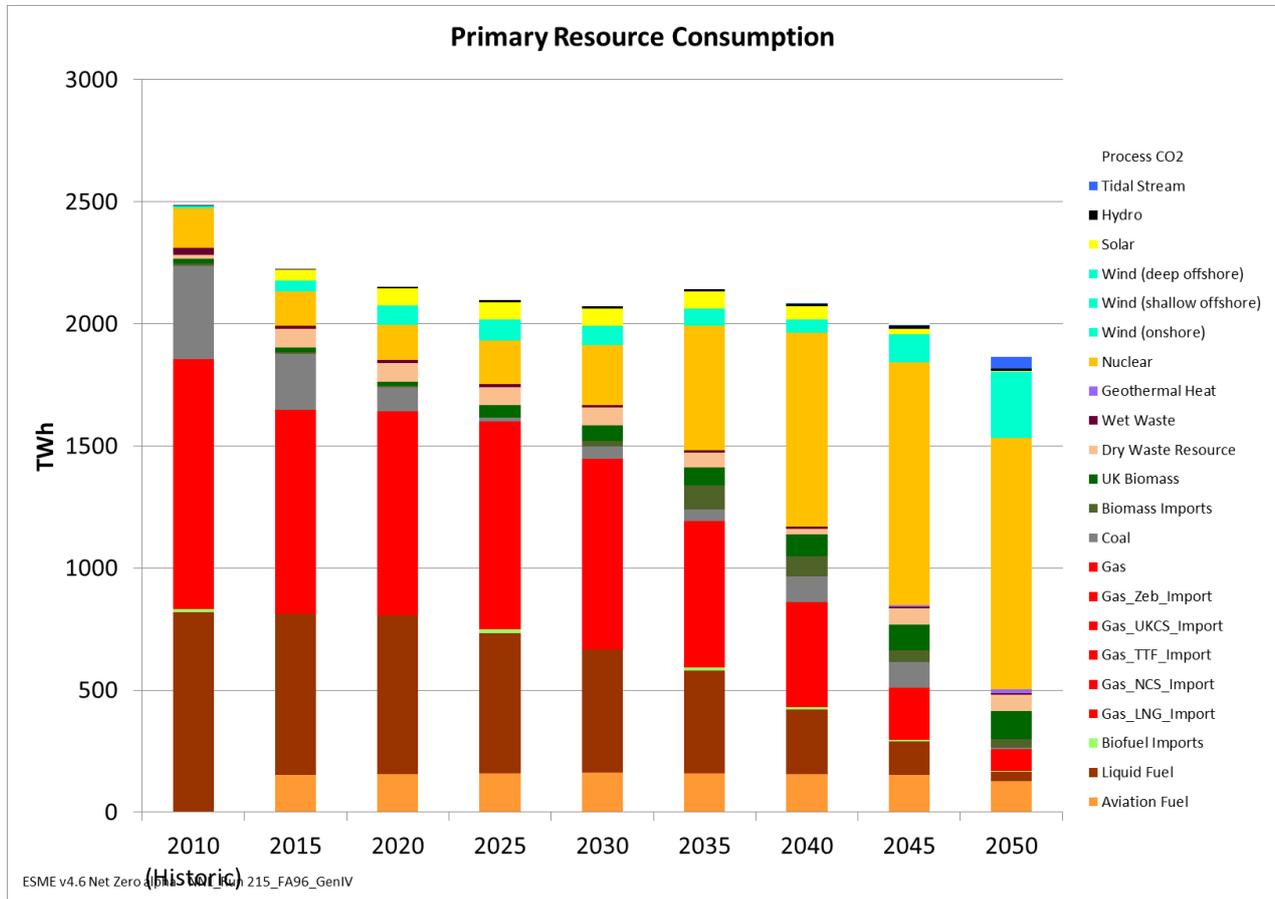
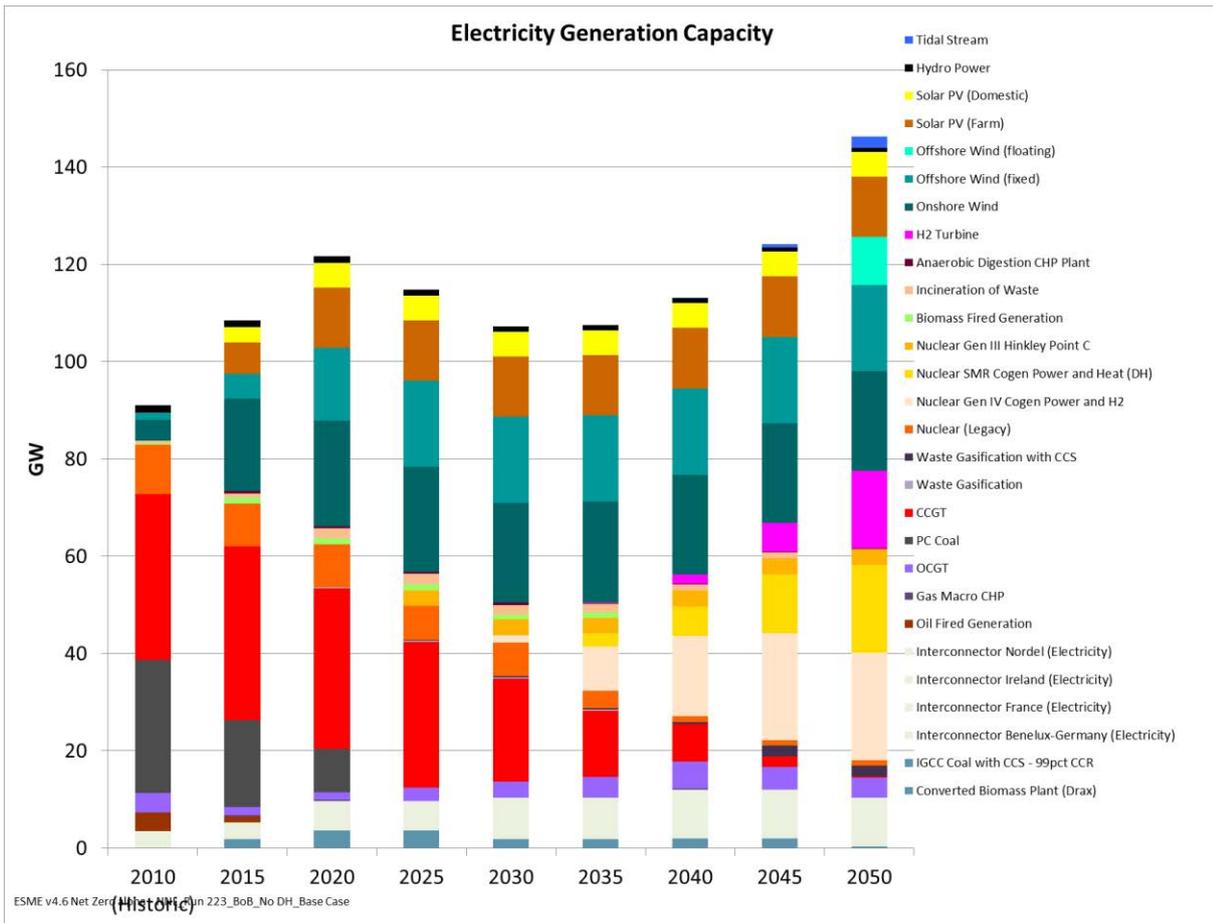Figure A3-127 – Run 215 primary resource consumption
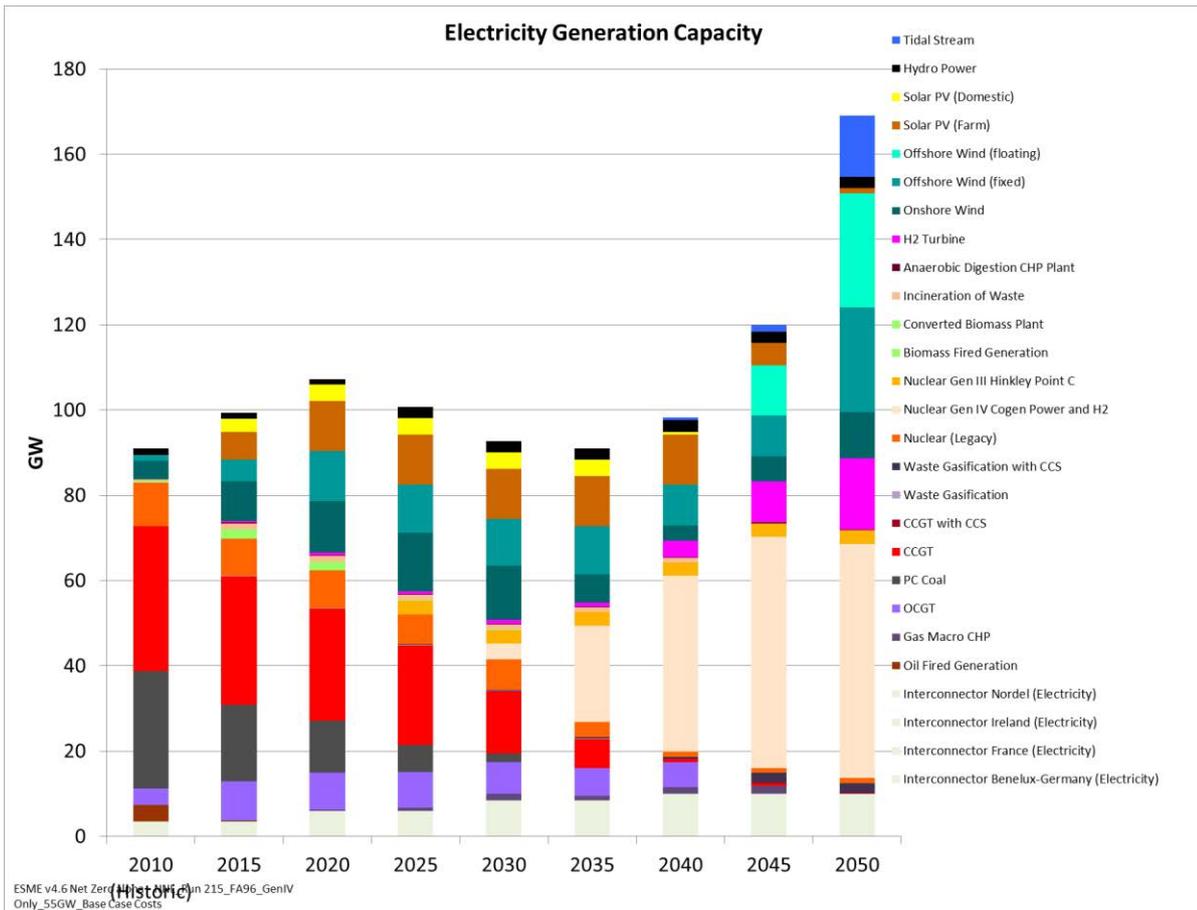
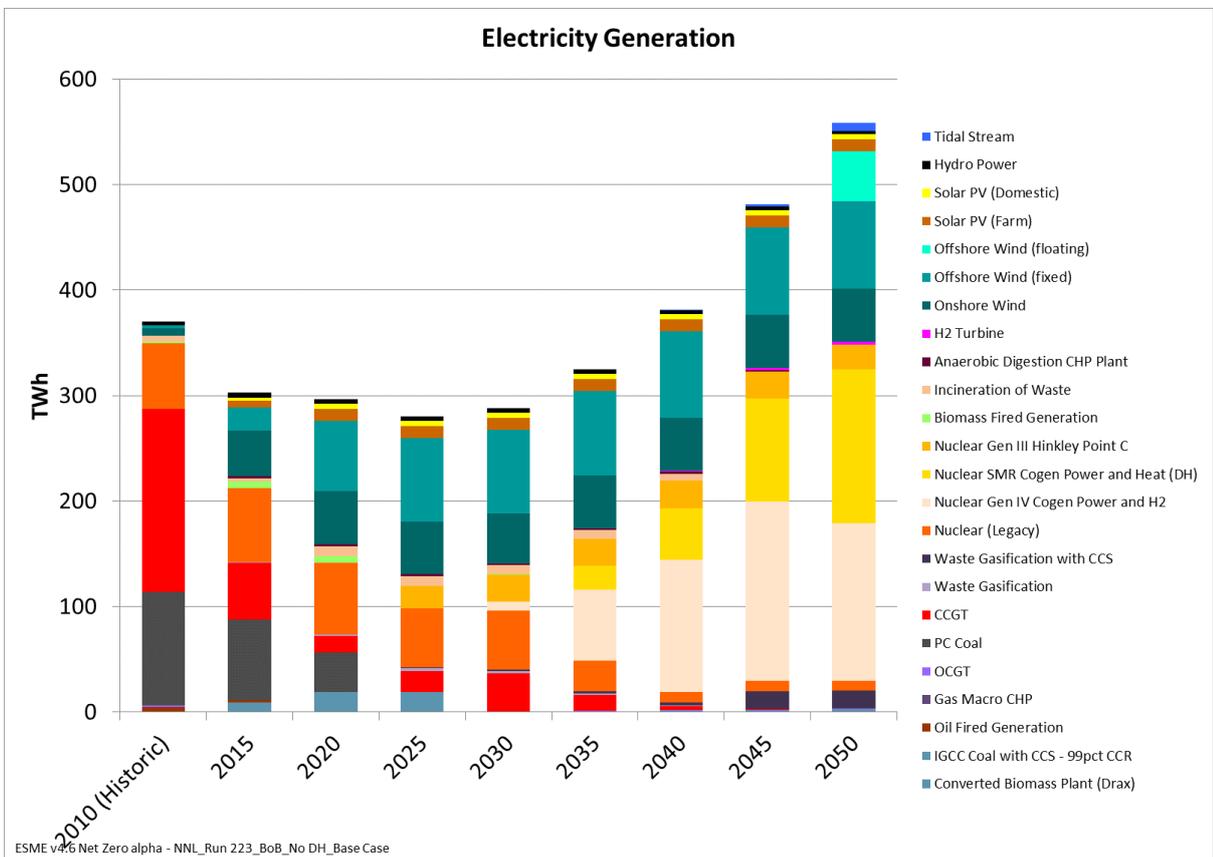Figure A3-128 – Run 215 electricity generation capacity
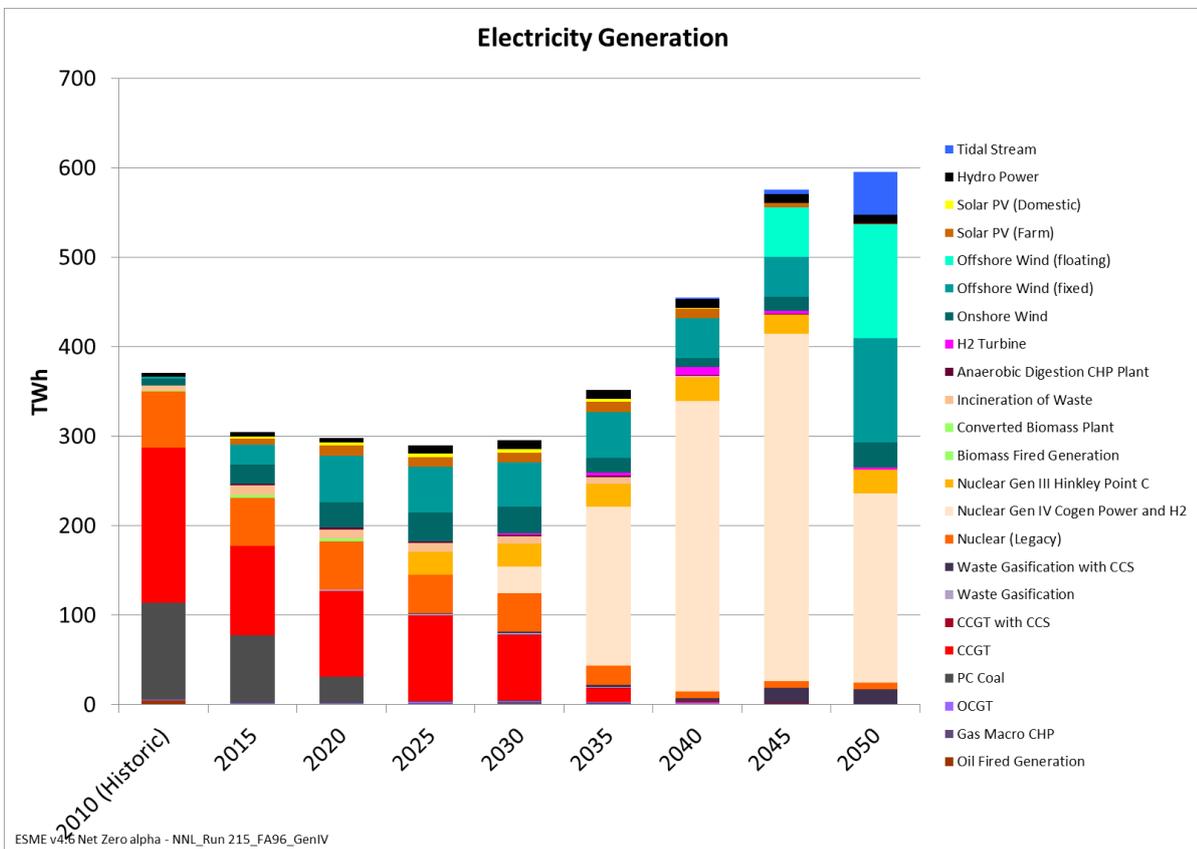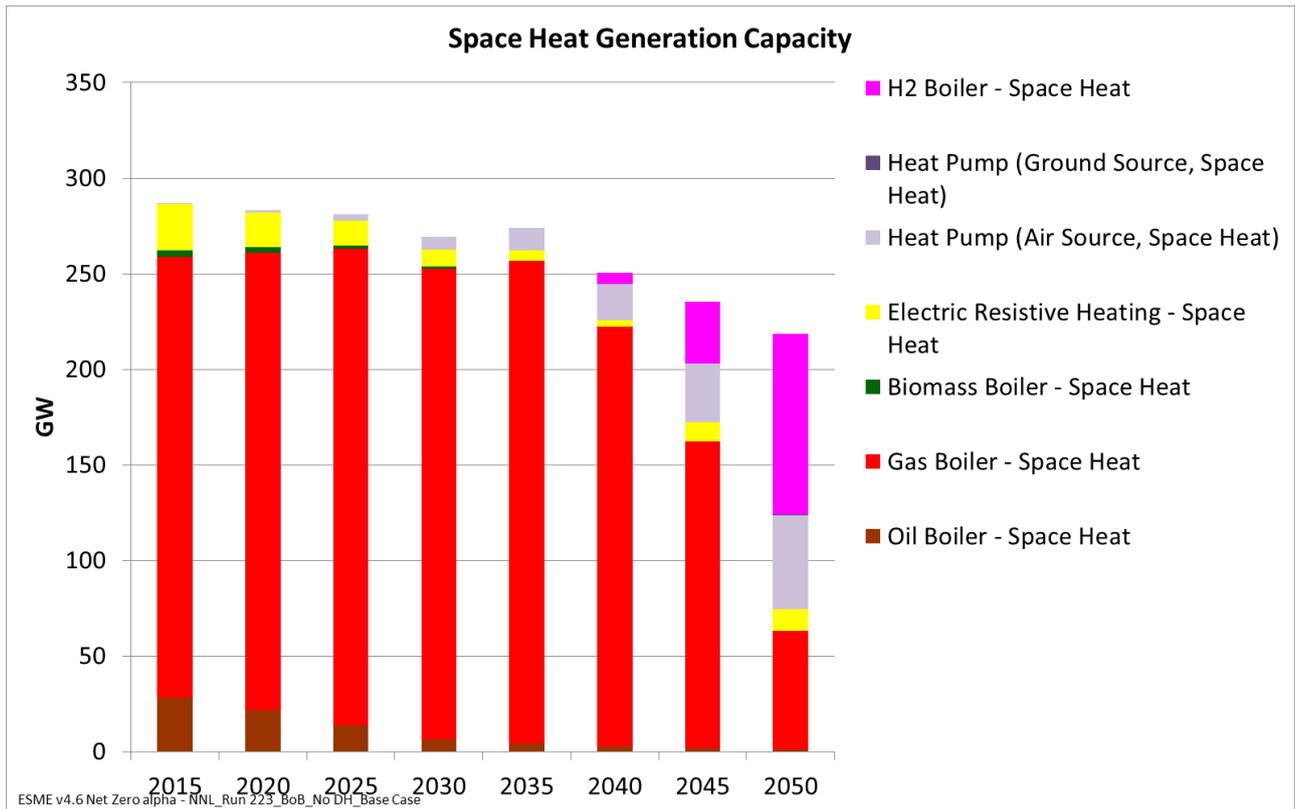

Figure A3-129 – Run 215 electricity generation
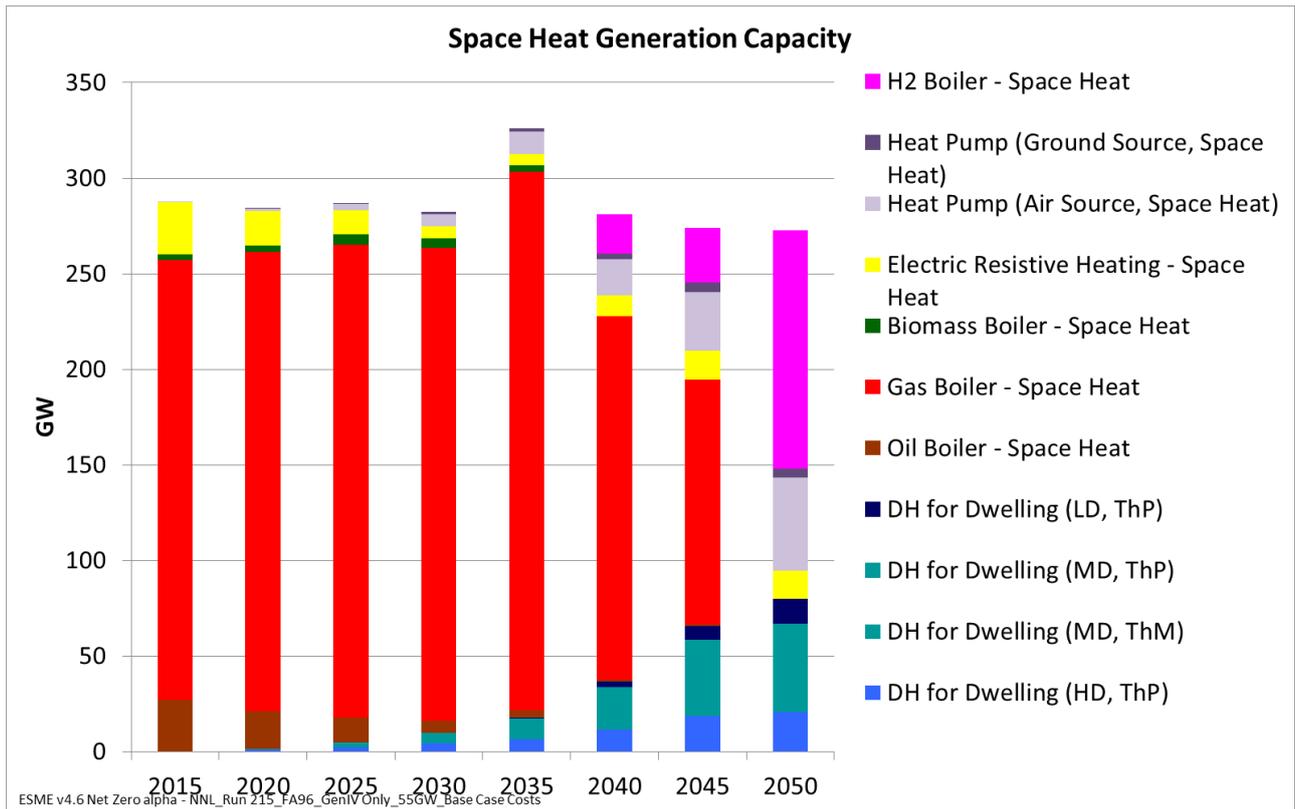
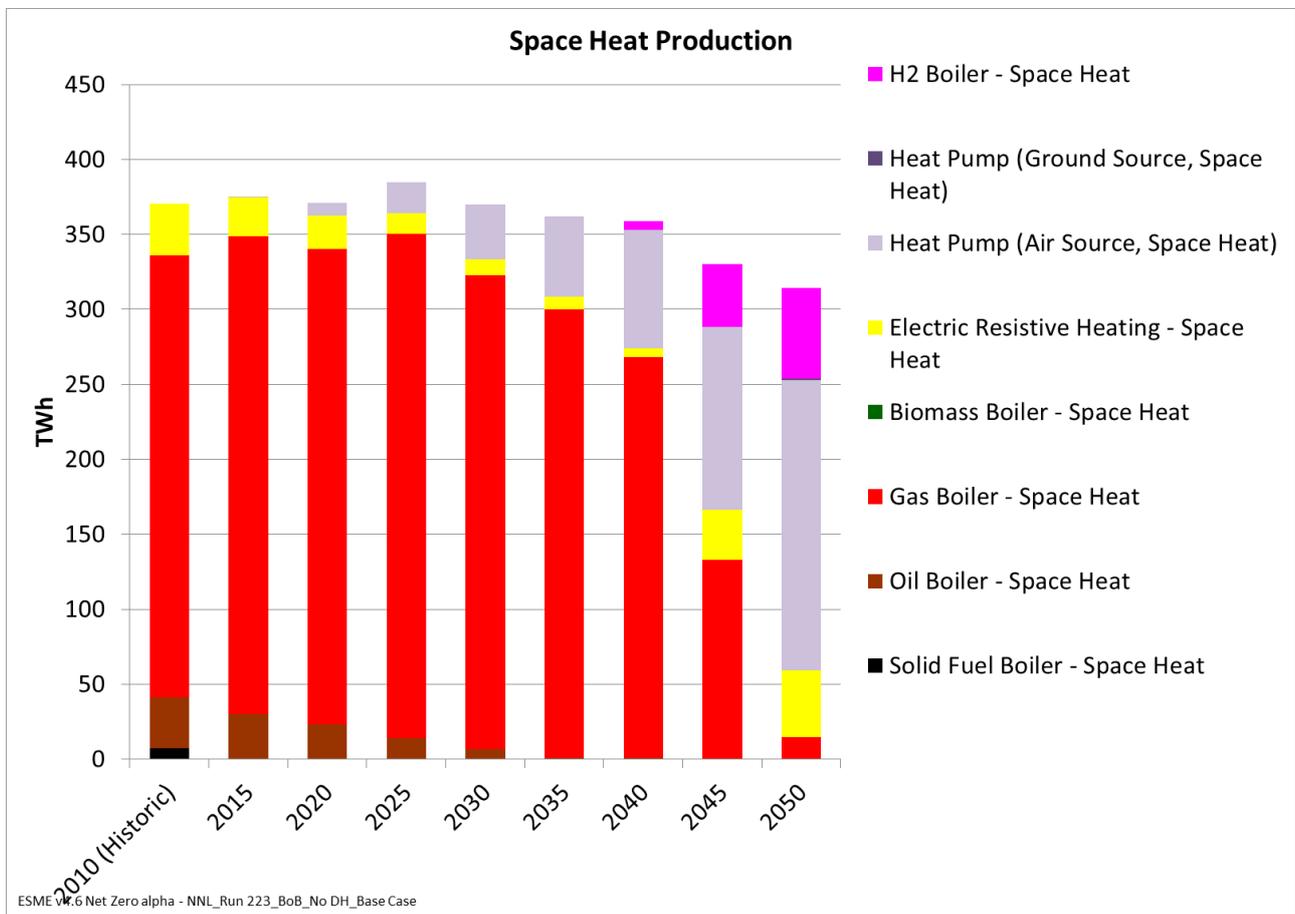Figure A3-130 – Run 215 space heat generation capacity
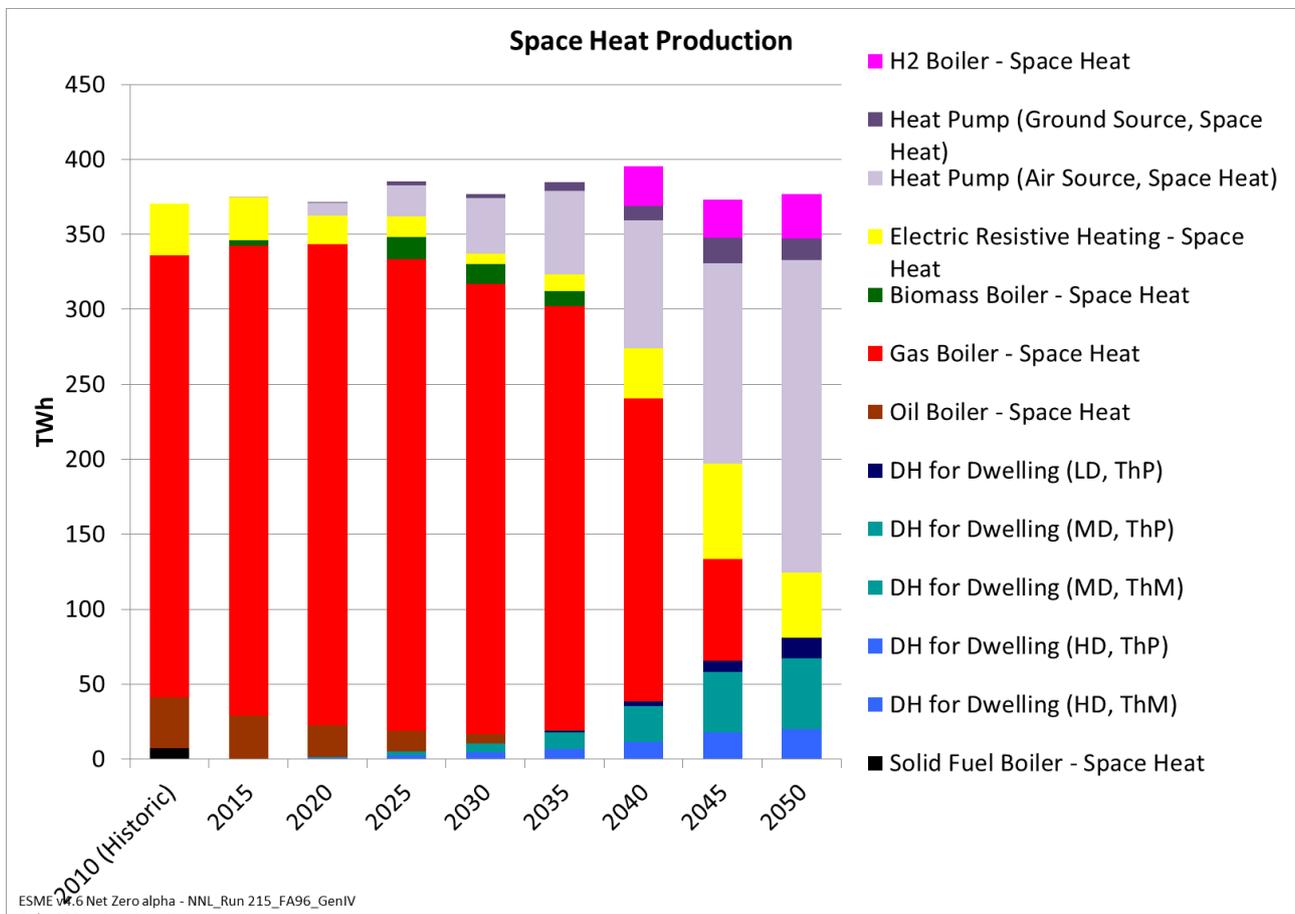
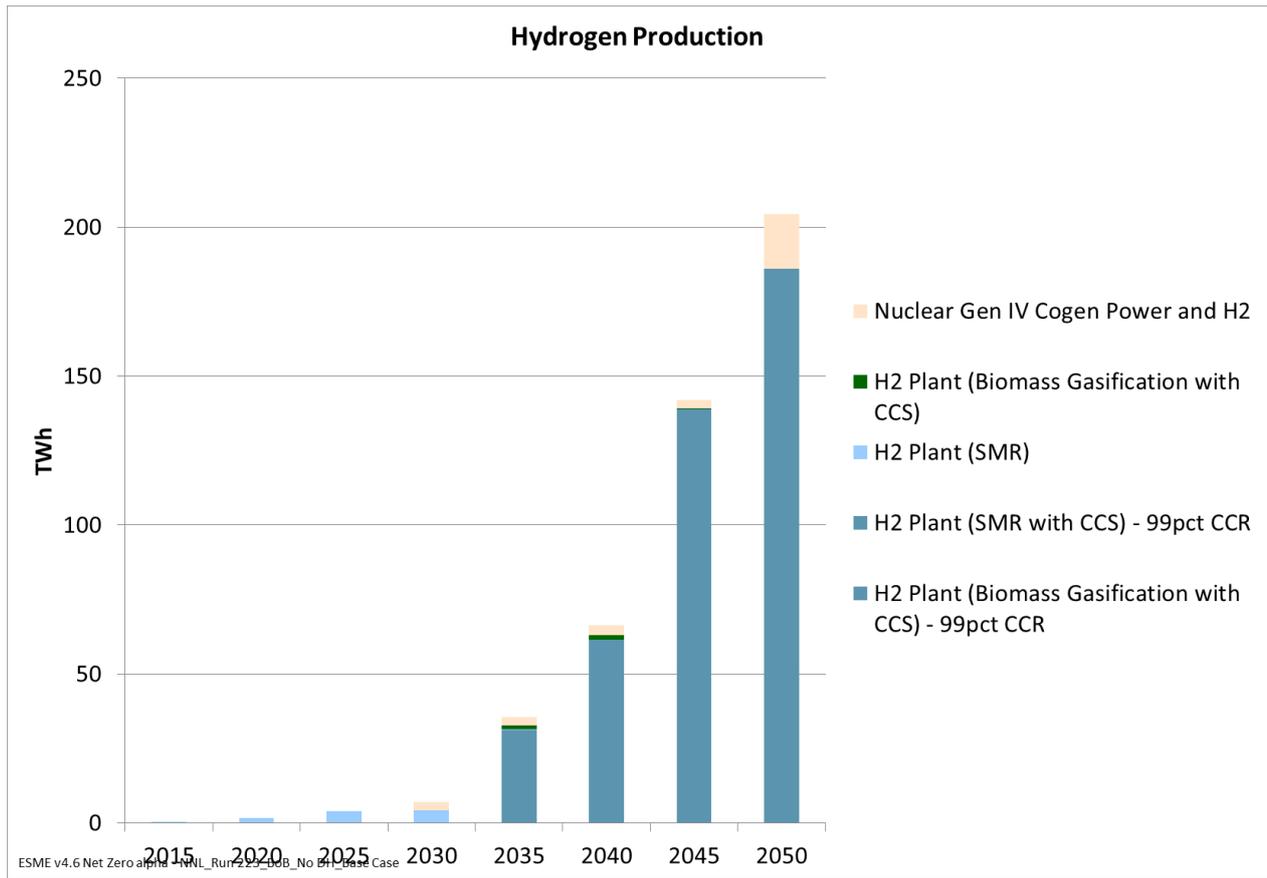

Figure A3-131 – Run 215 space heat production
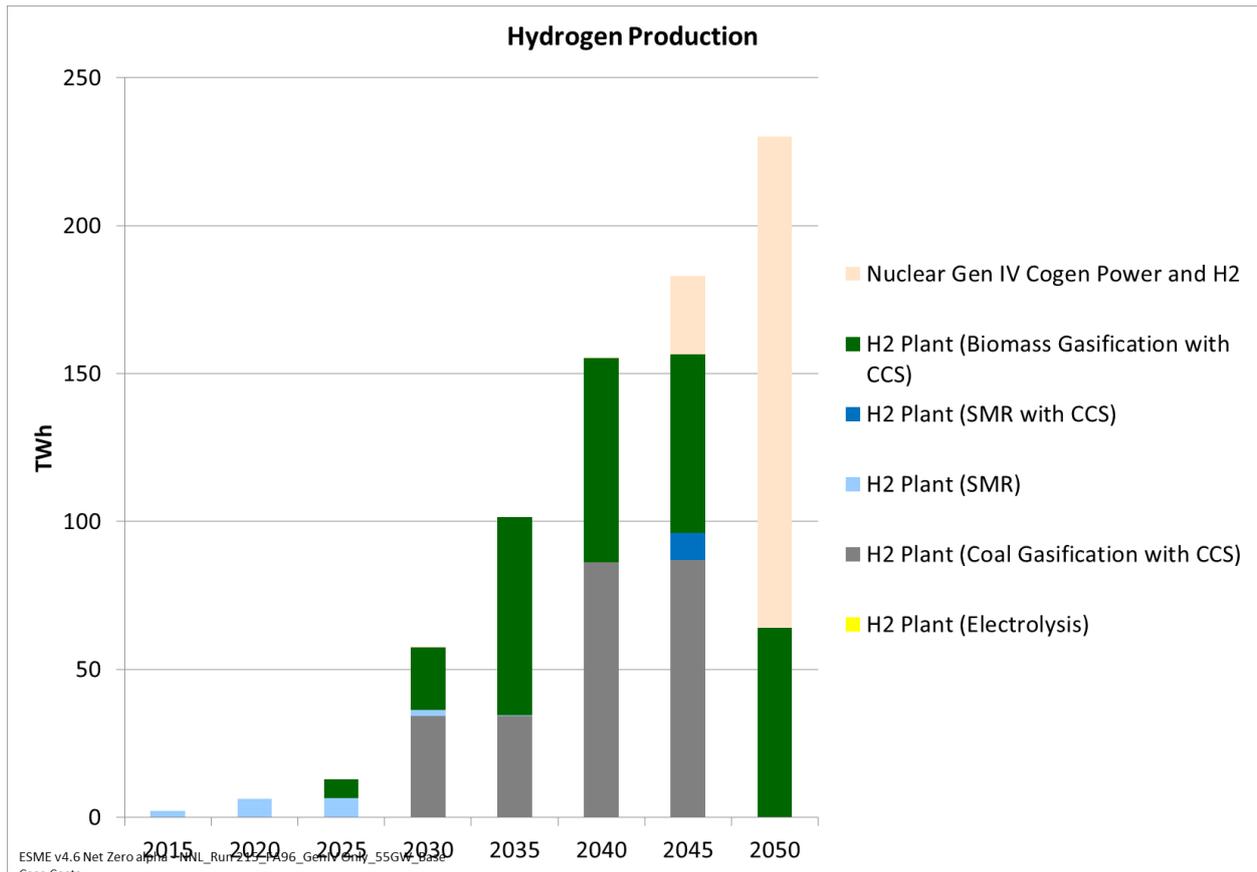
Figure A3-132 – Run 215 hydrogen production
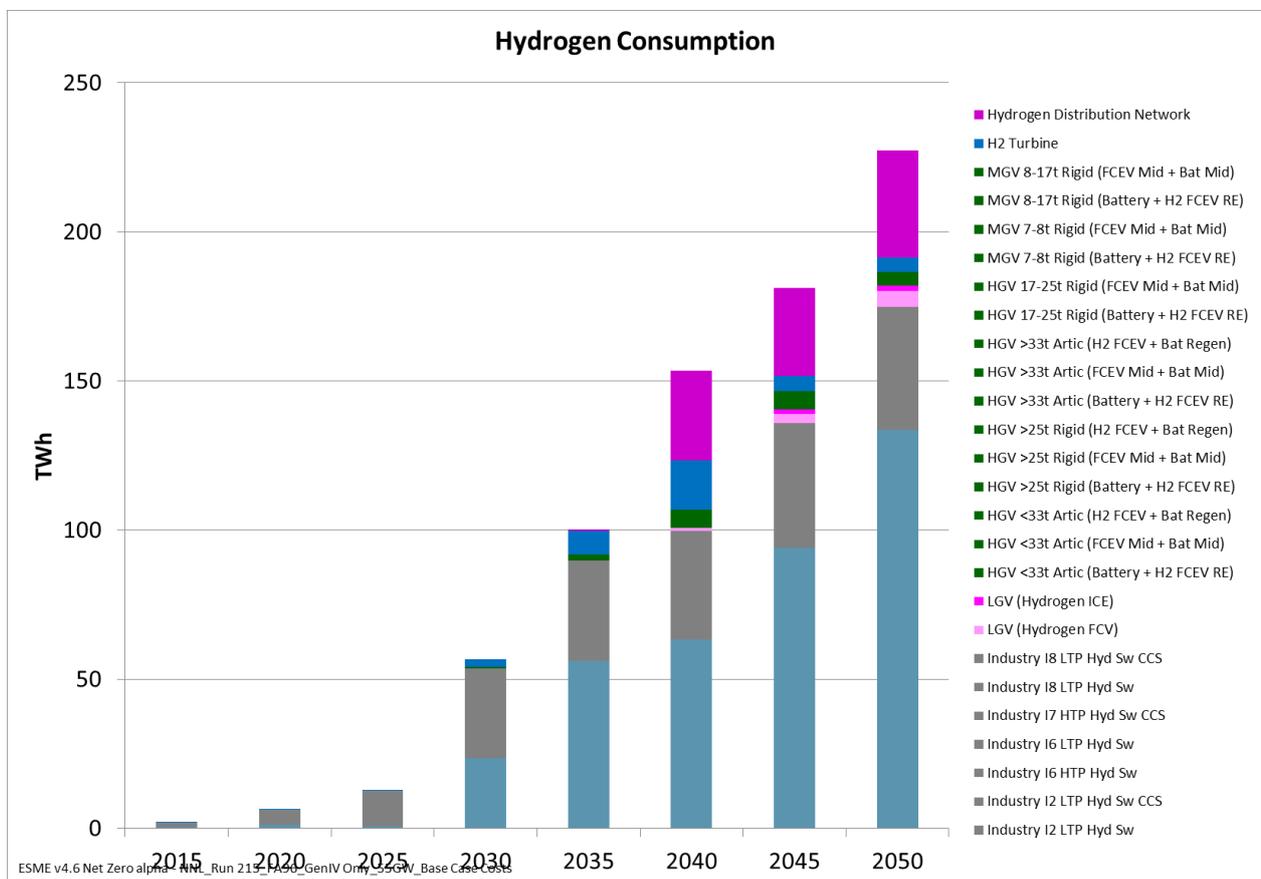
Figure A3-133 – Run 215 hydrogen consumption
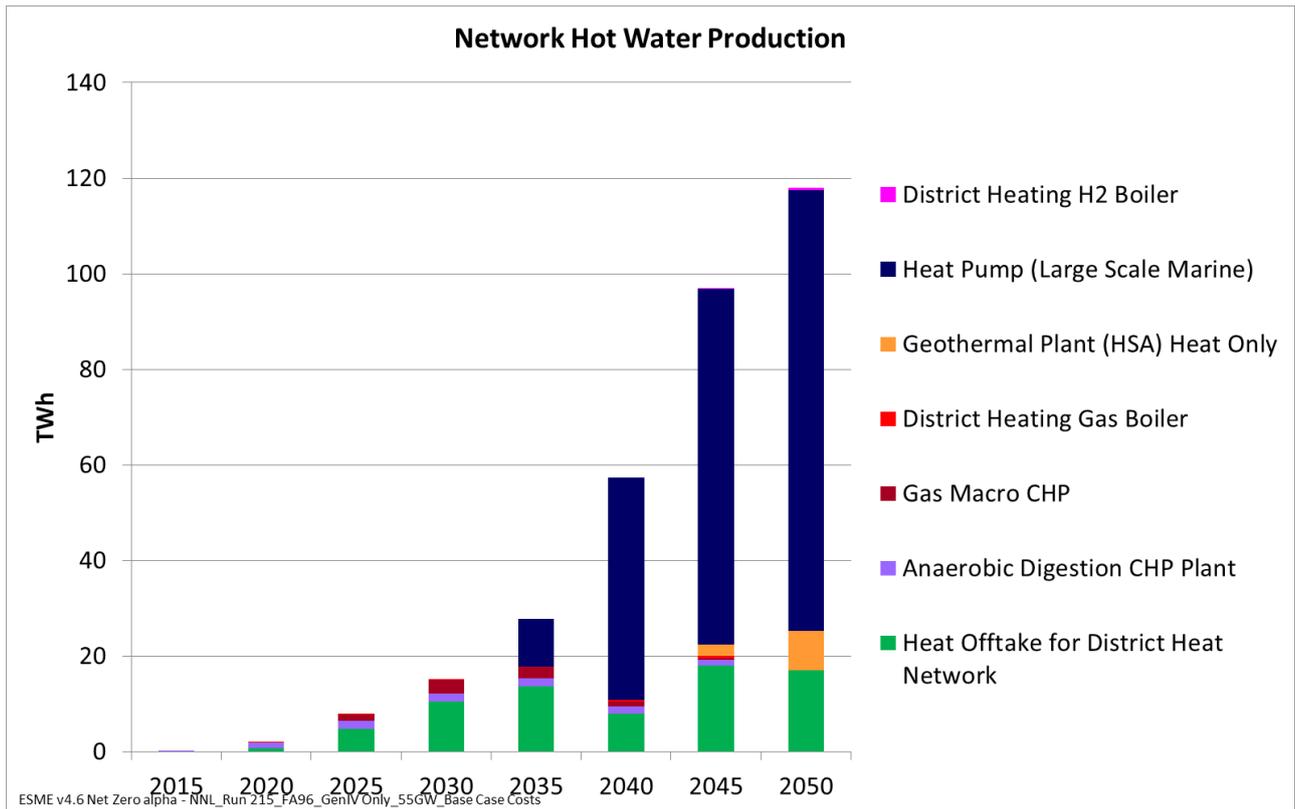
Figure A3-134 – Run 215 network hot water production
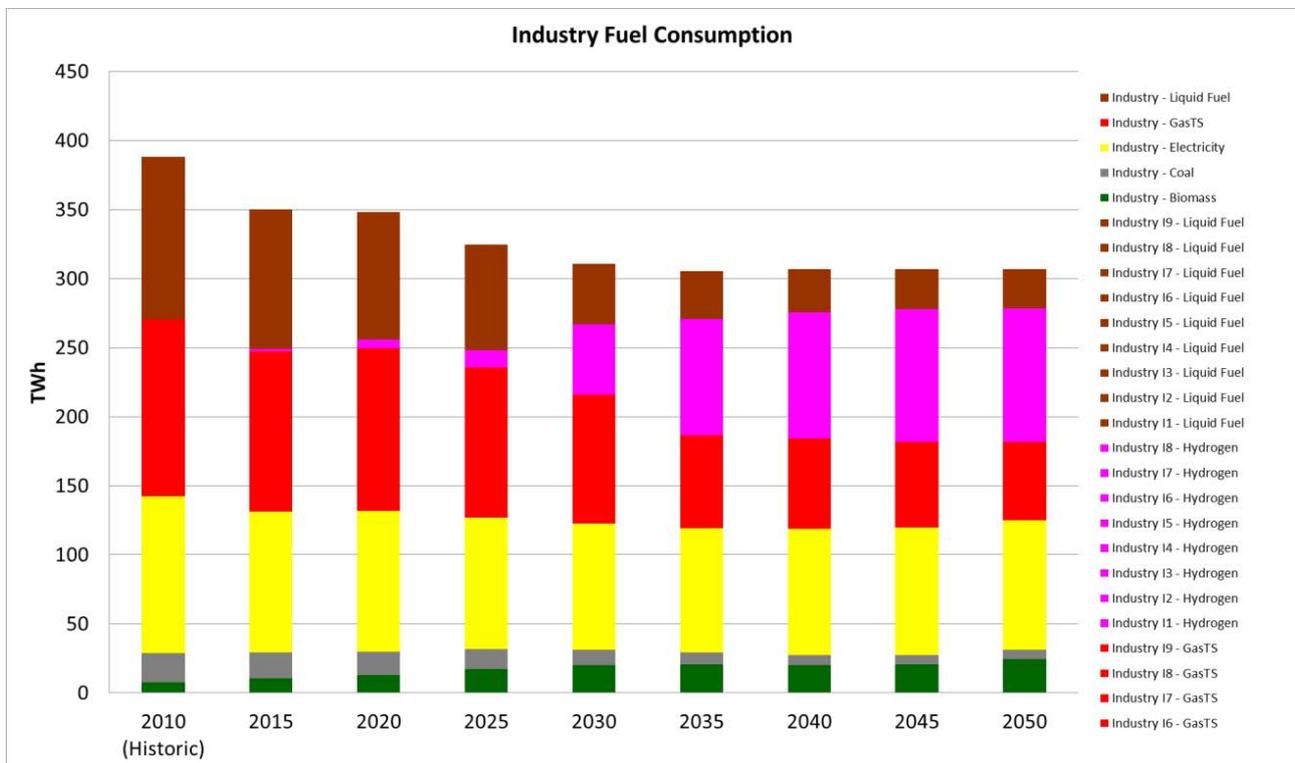
Figure A3-135 – Run 215 industry fuel consumption

Run 216 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55 GWe and build-out rate to match; base case data

Primary Resource Consumption

ESME v4.6 Net Zero Alpha NDA Run 216_Tech 100_GenIV
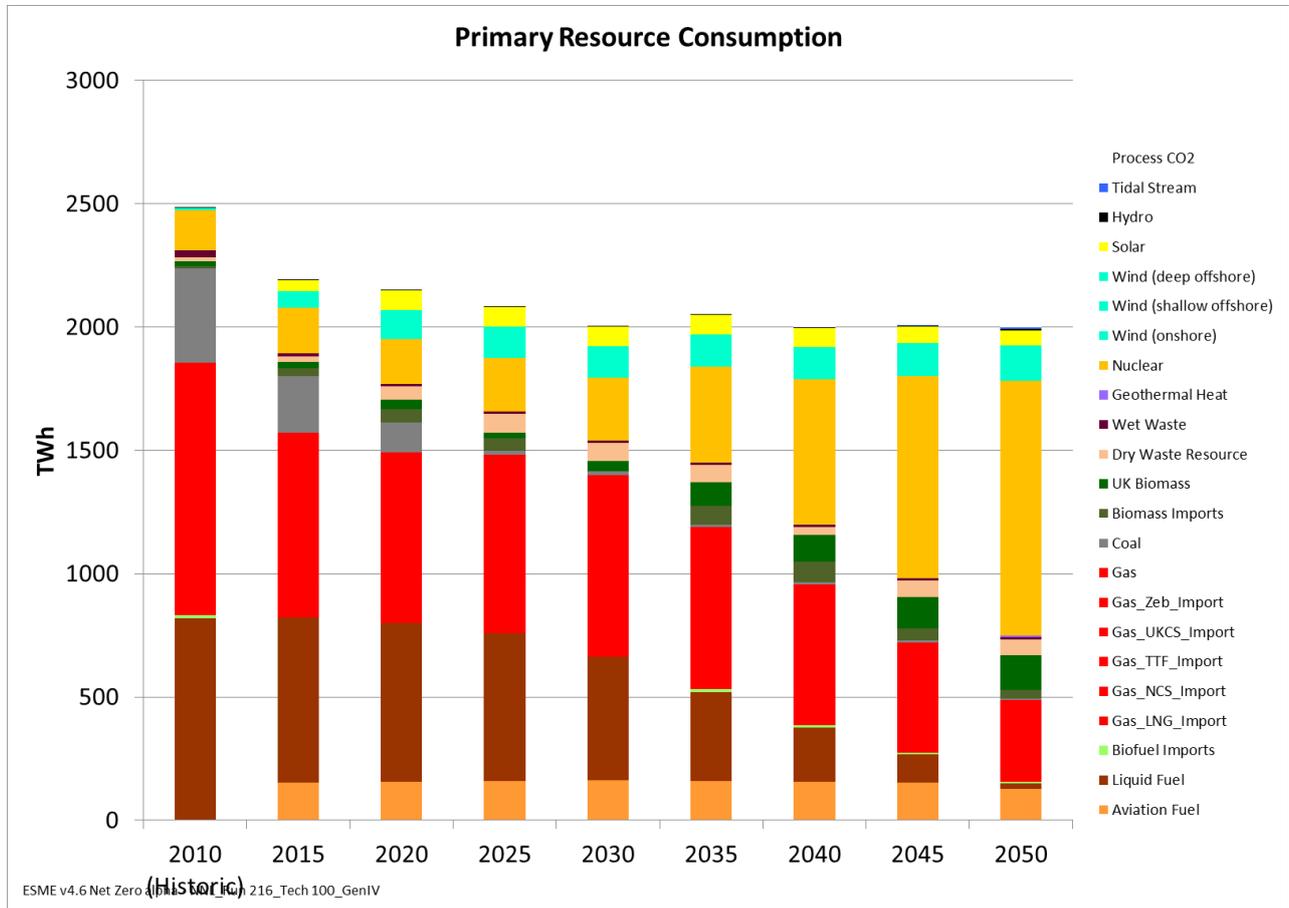
Figure A3-136 – Run 216 primary resource consumption
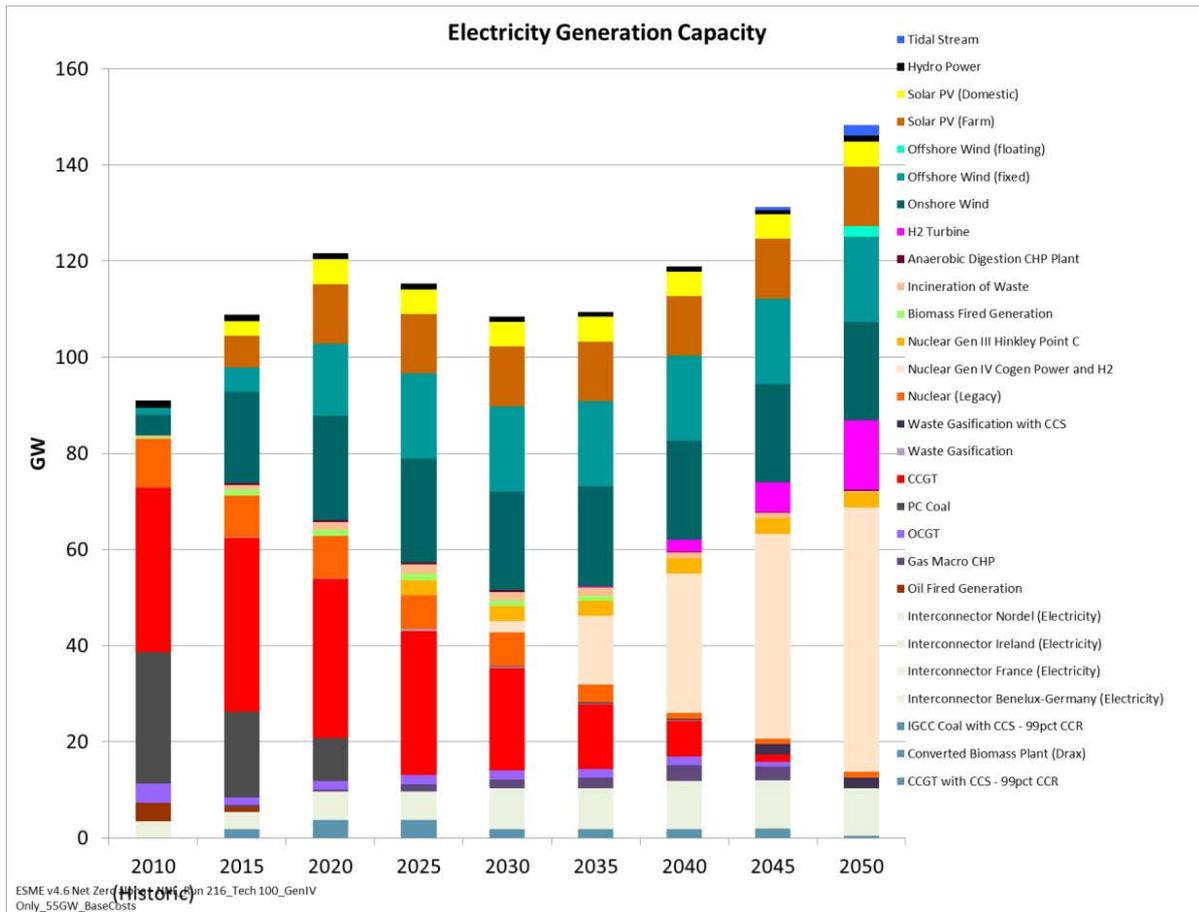
Figure A3-137 – Run 216 electricity generation capacity
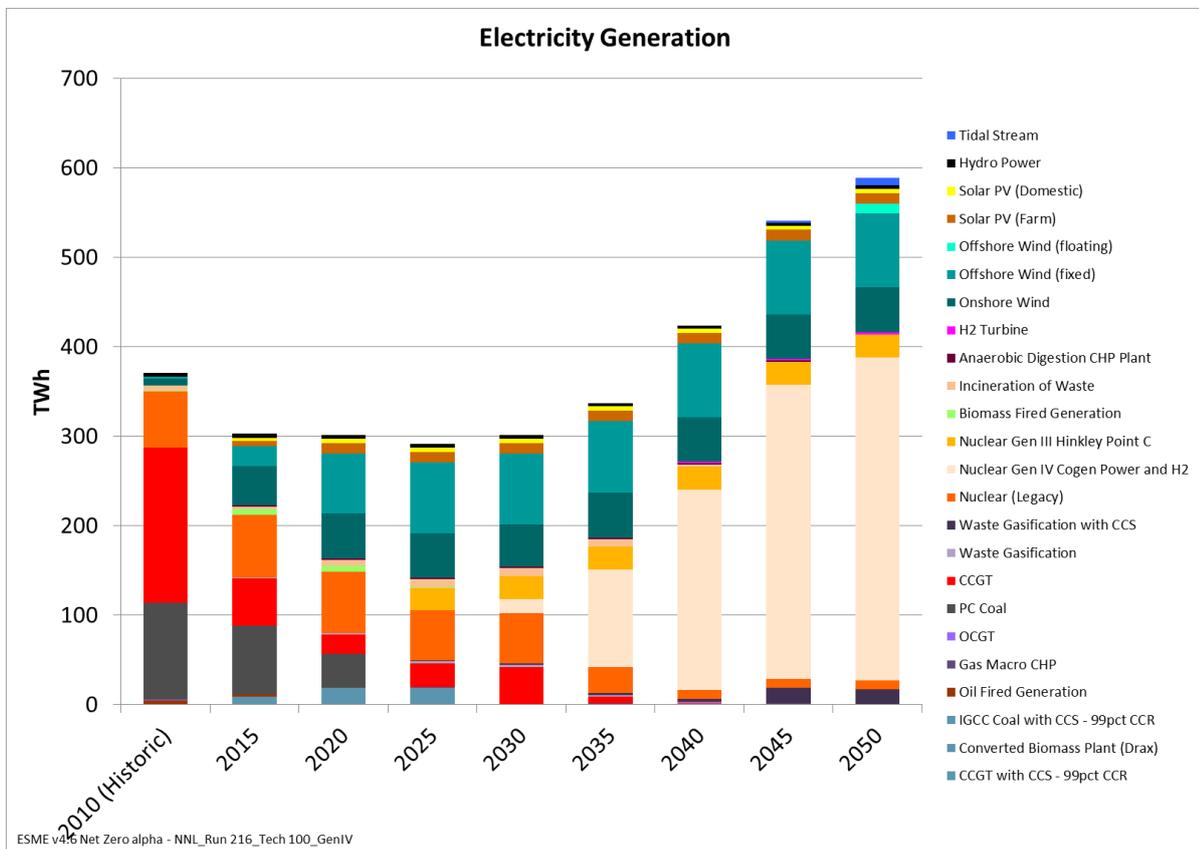
Figure A3-138 – Run 216 electricity generation
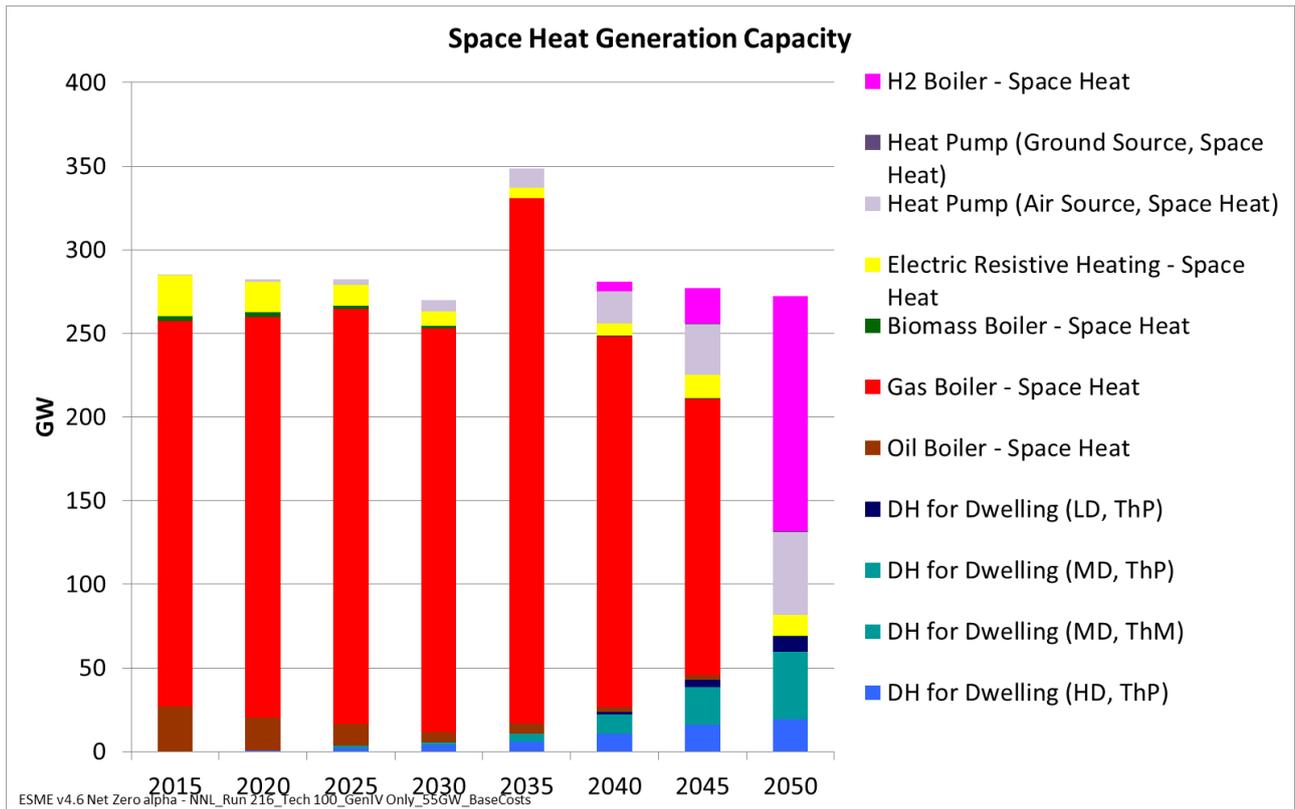
Figure A3-139 – Run 216 space heat generation capacity
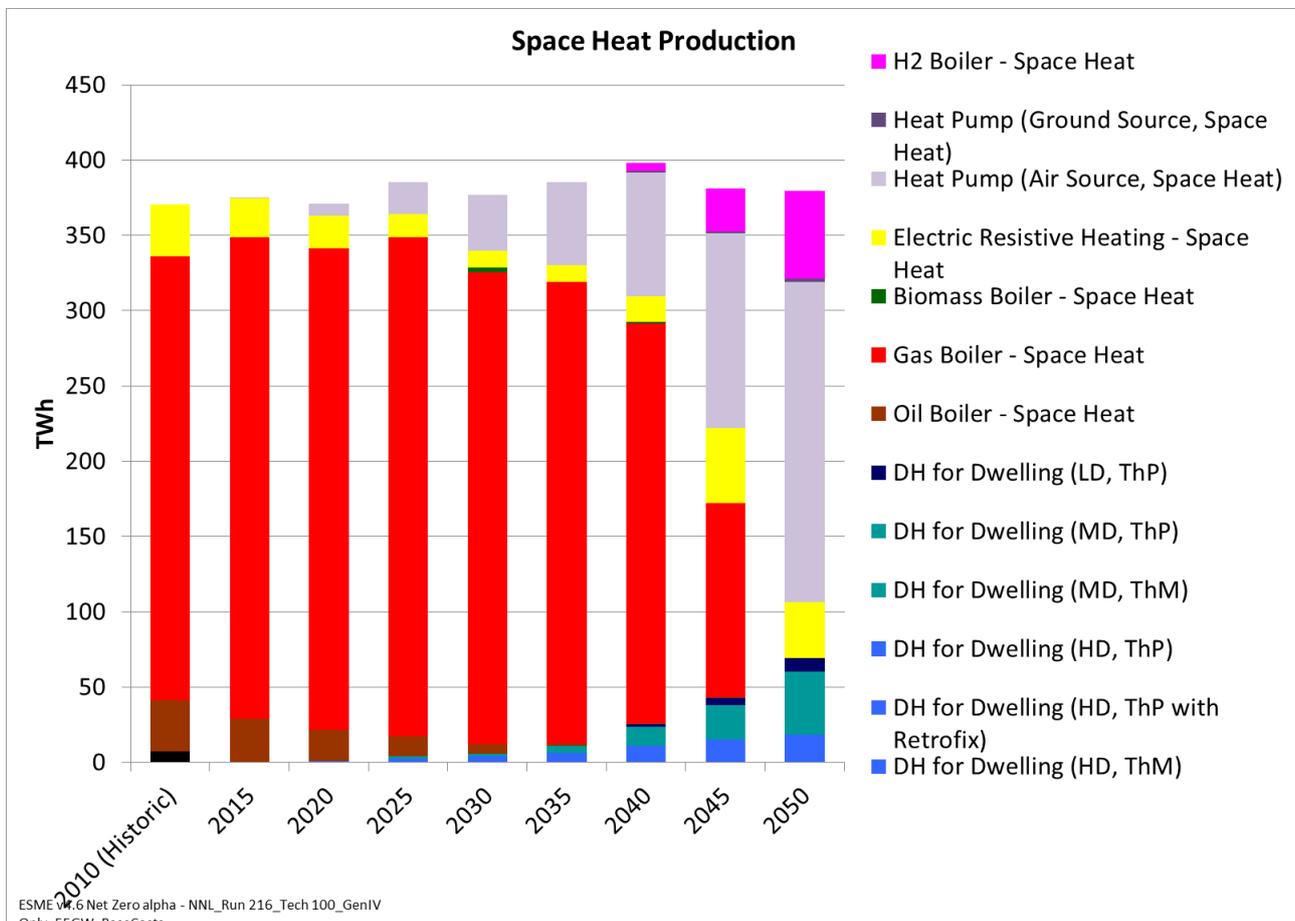
Figure A3-140 – Run 216 space heat production
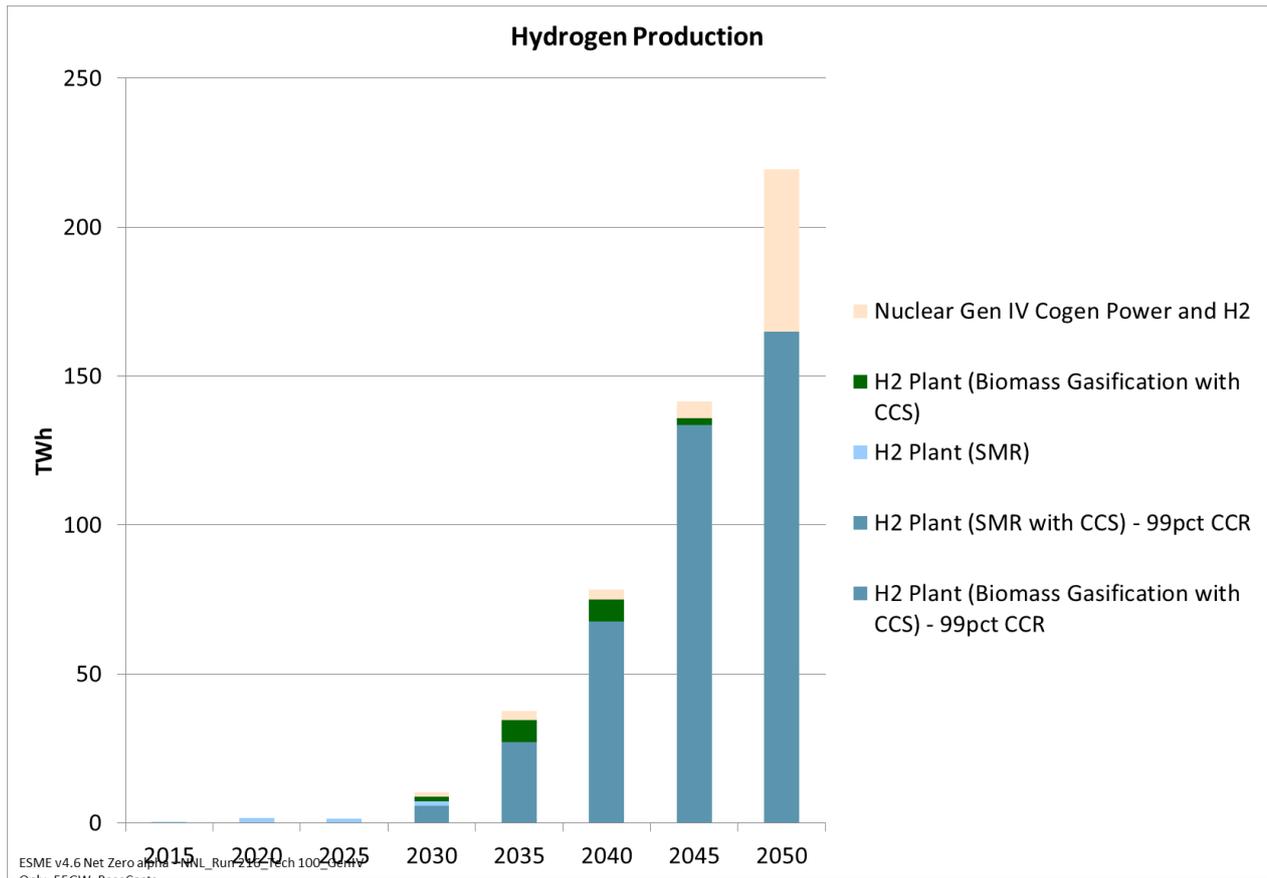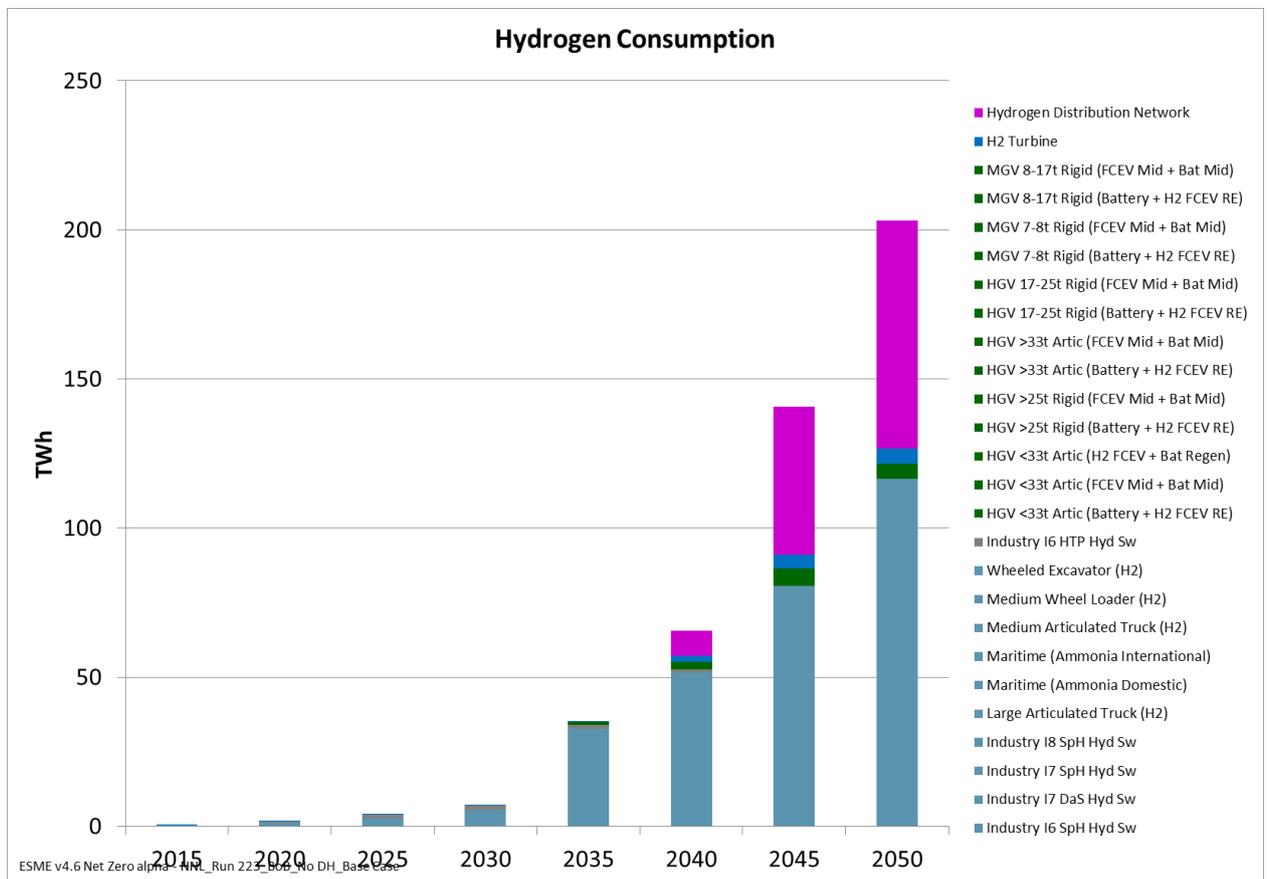
Figure A3-141 – Run 216 hydrogen production
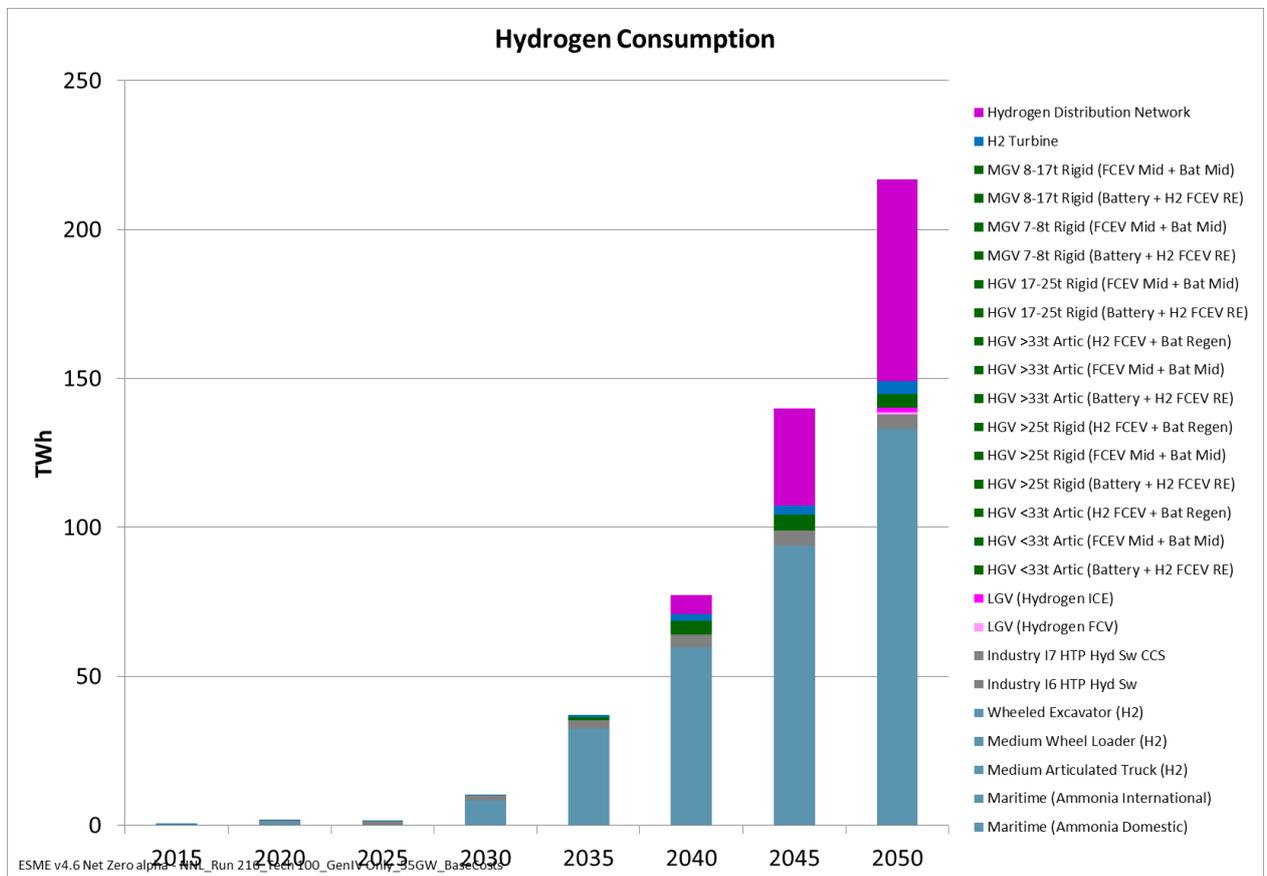
Figure A3-142 – Run 216 hydrogen consumption
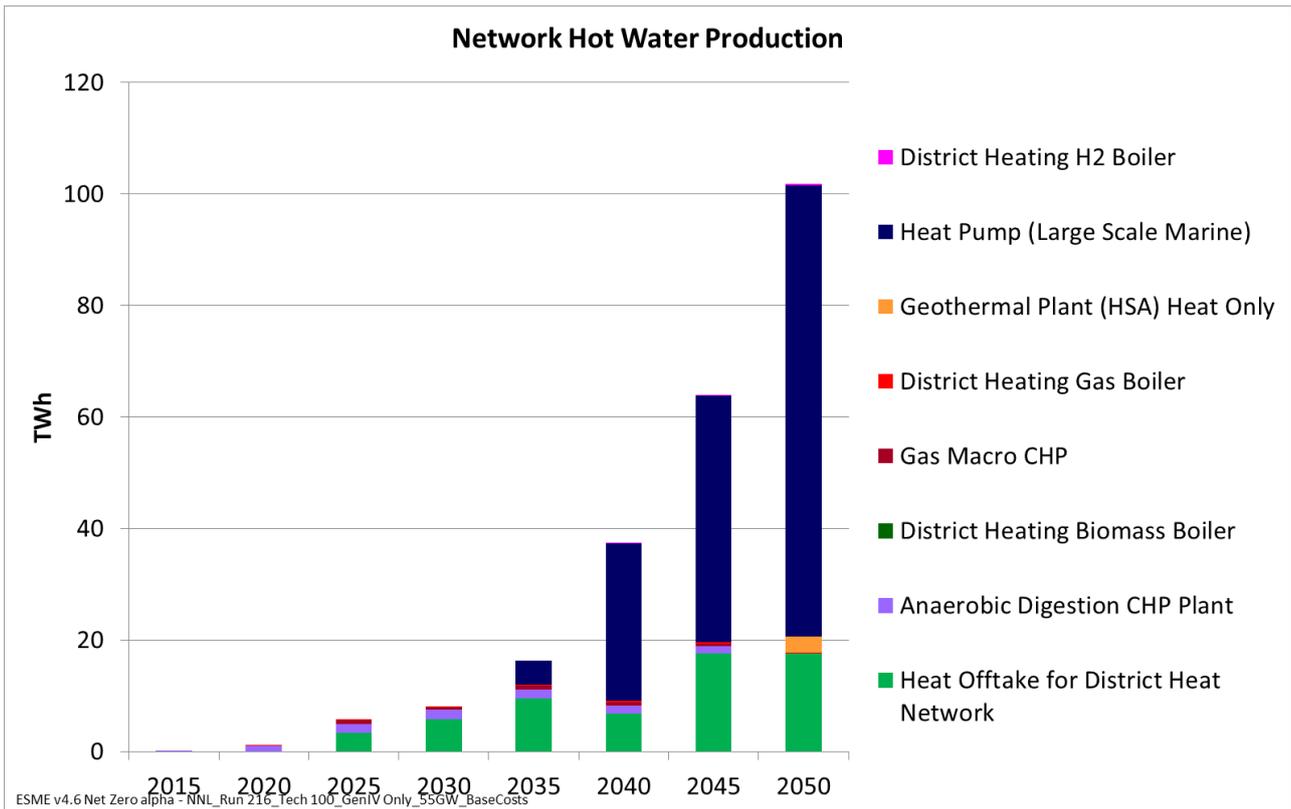
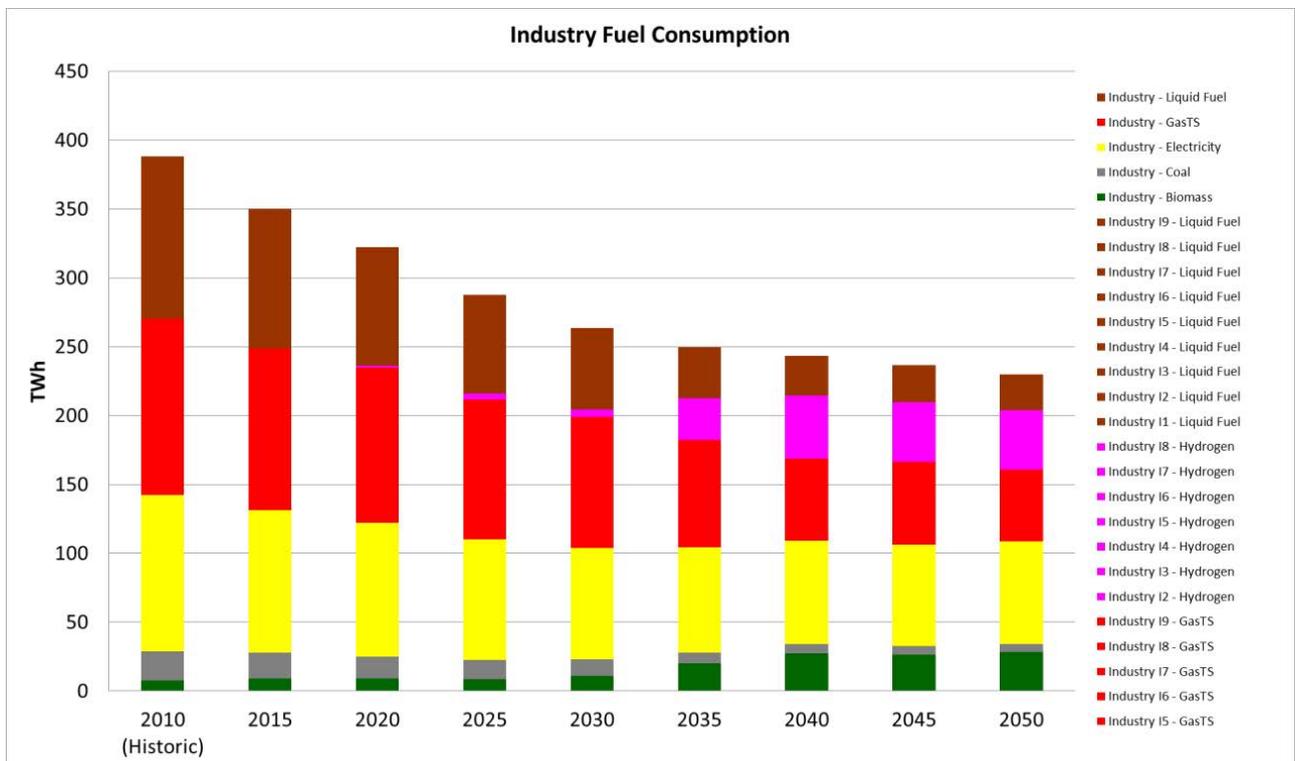Figure A3-143 – Run 216 network hot water production
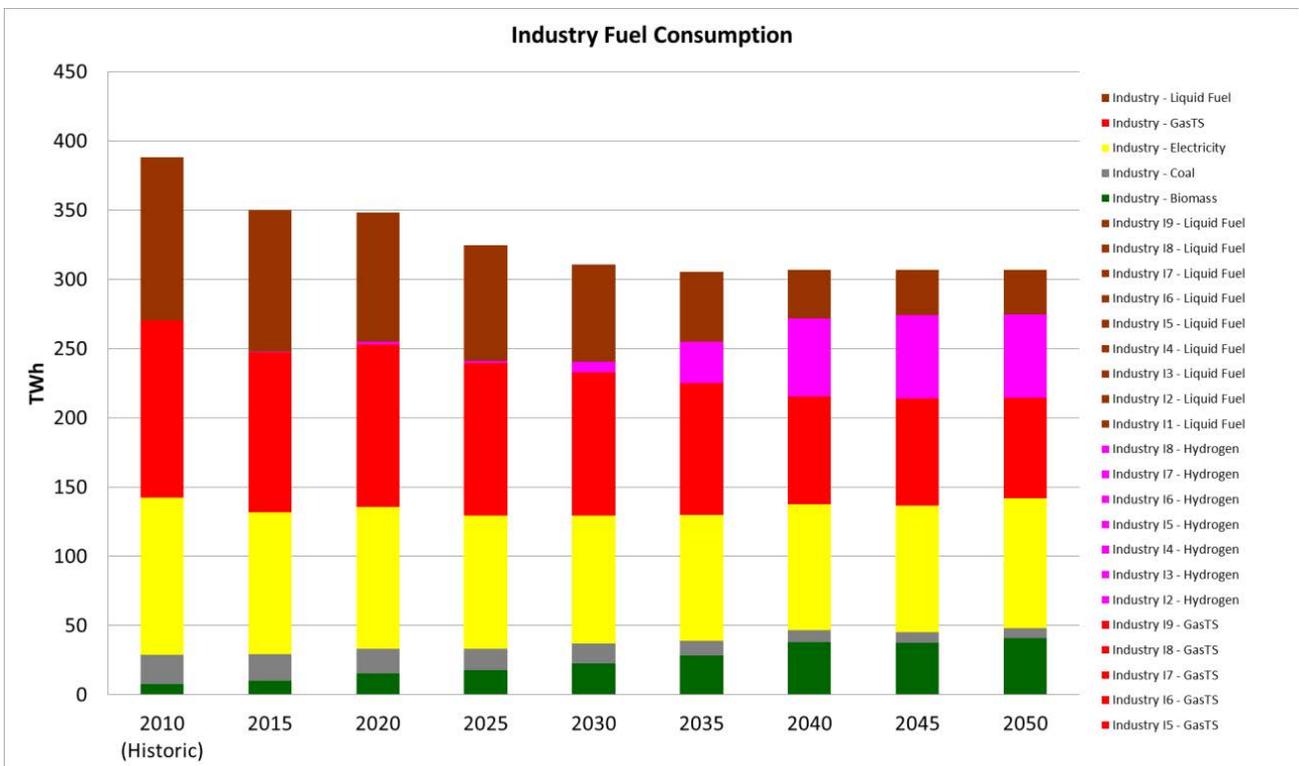
Figure A3-144 – Run 216 industry fuel consumption

Run 217 FA96 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55GWe and build-out rate to match base case data with lower capex
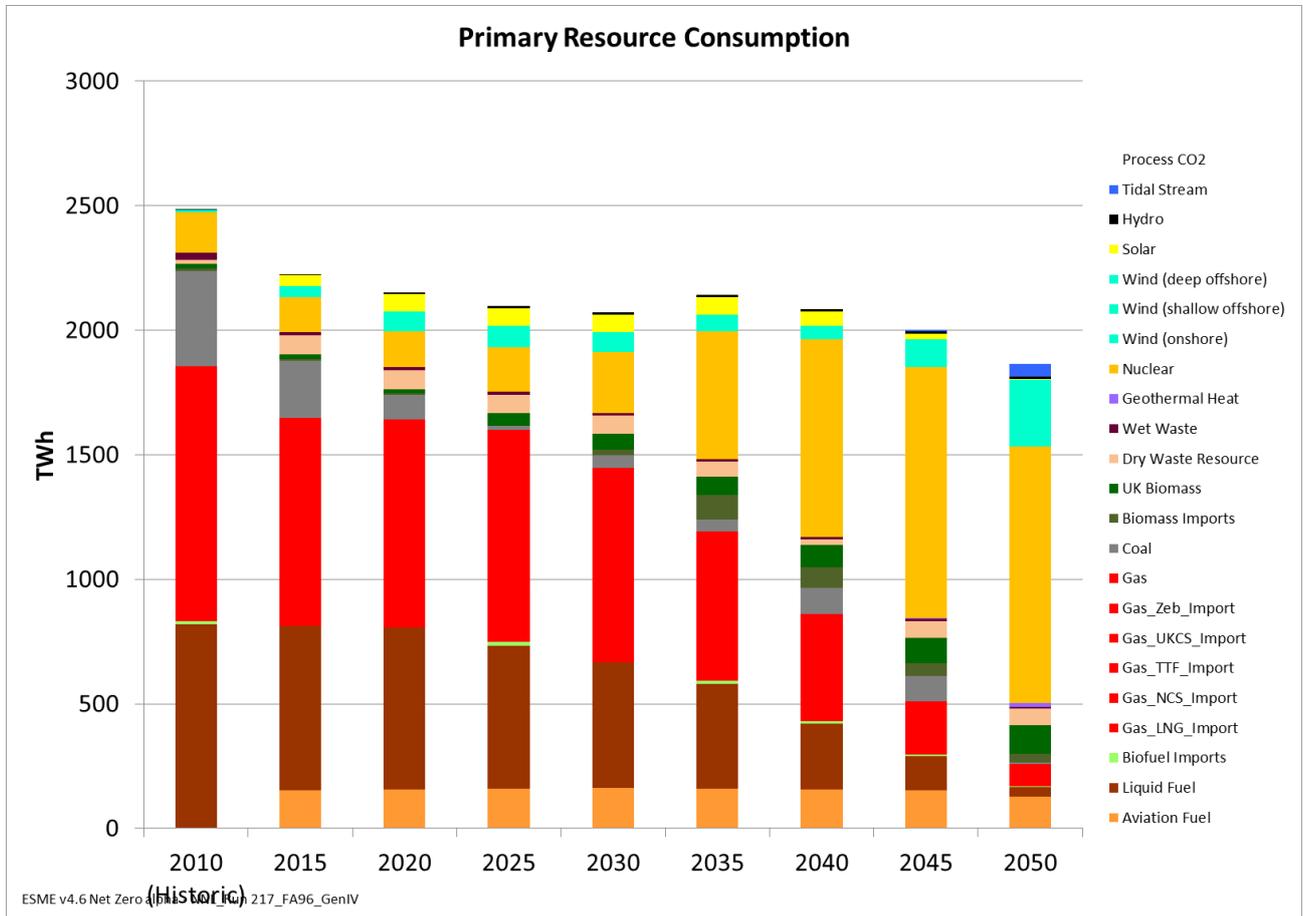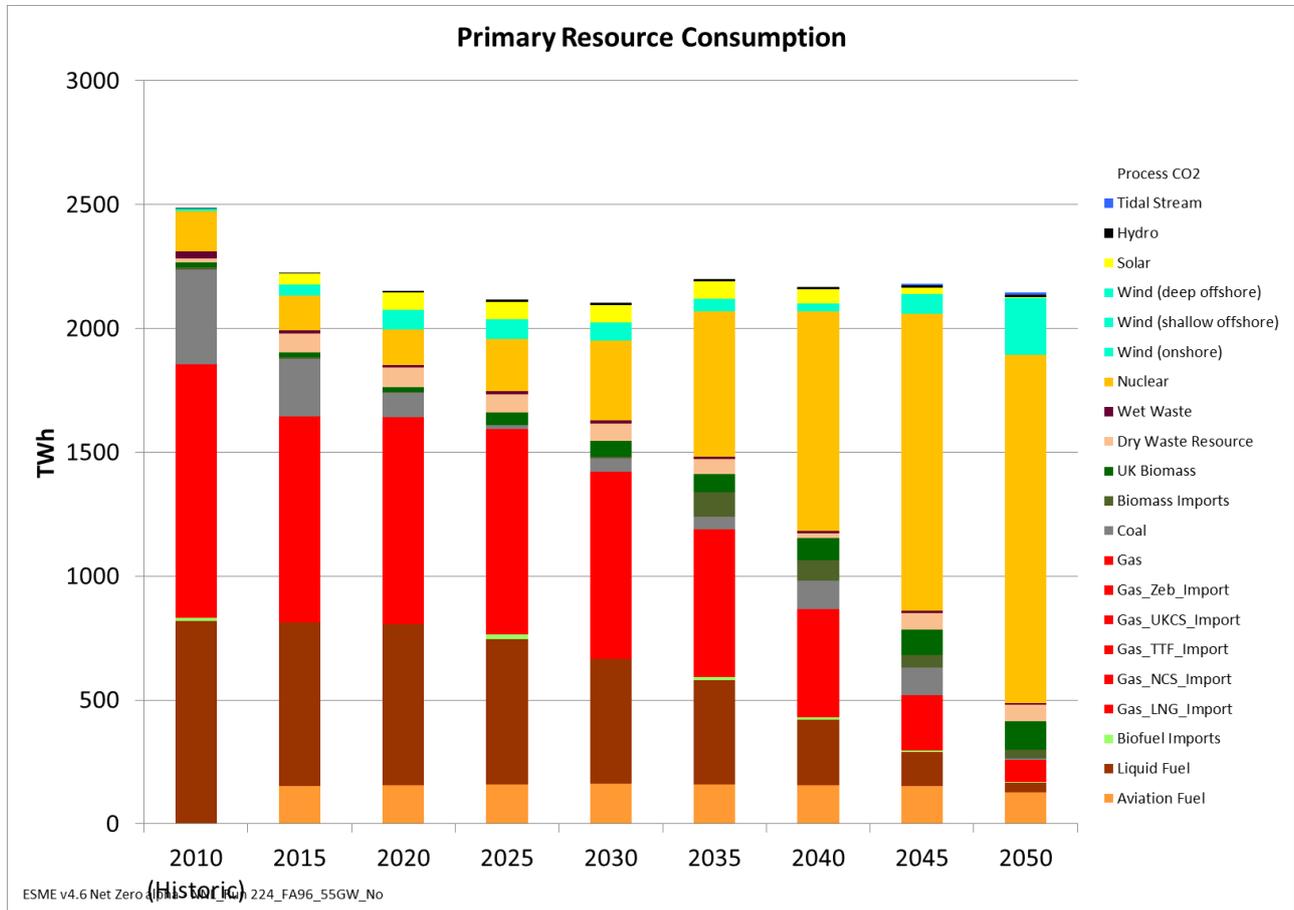

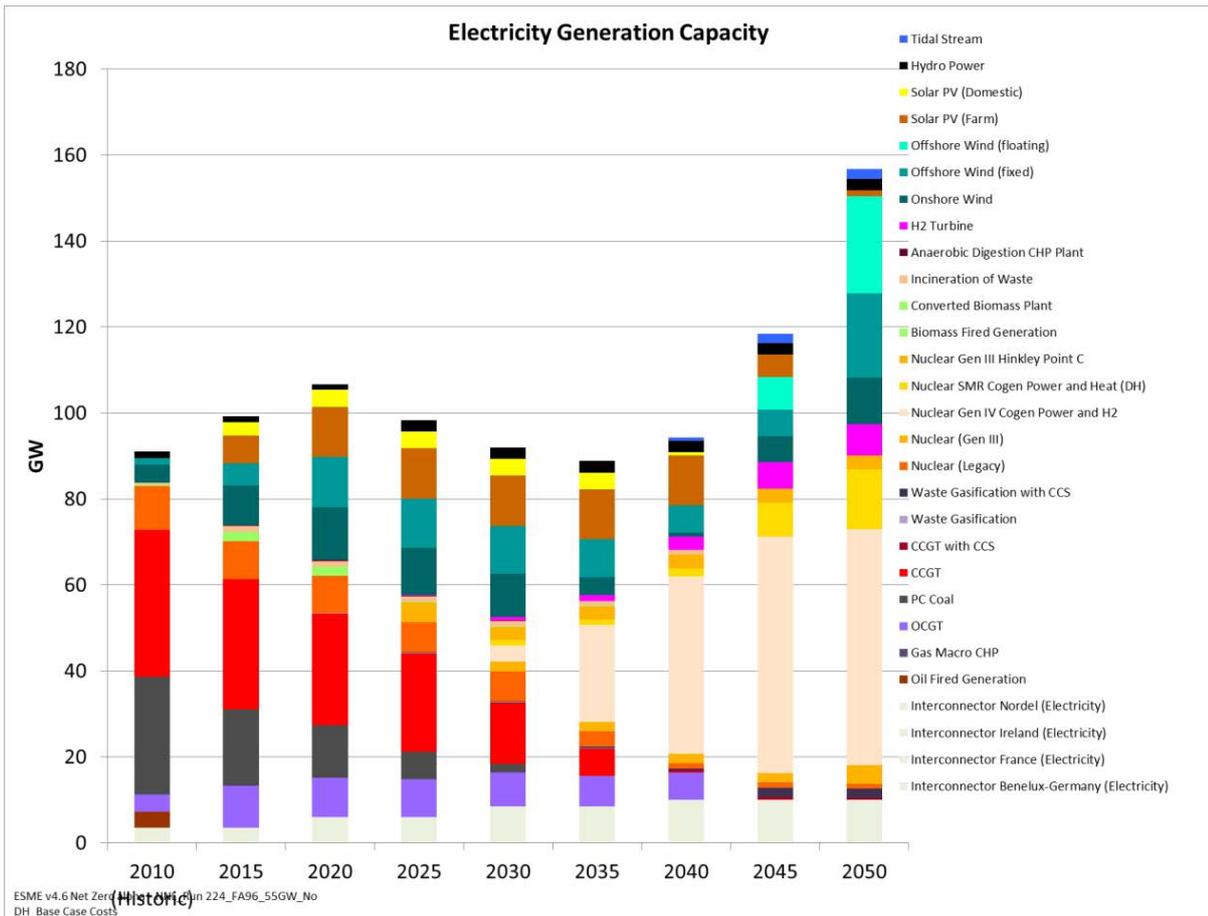Figure A3-145 – Run 217 primary resource consumption

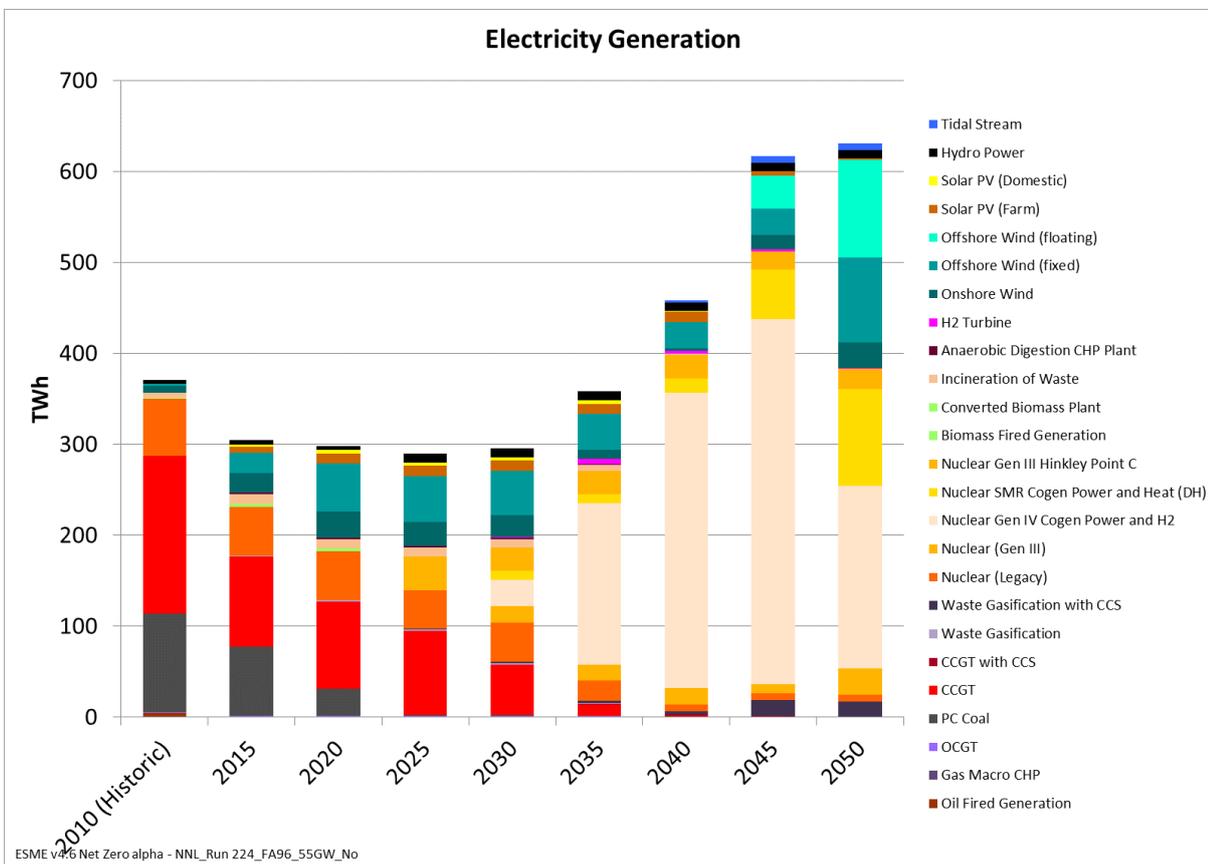Figure A3-146 – Run 217 electricity generation capacity

Figure A3-147 – Run 217 electricity generation

Figure A3-148 – Run 217 space heat generation capacity

Figure A3-149 – Run 217 space heat production

Figure A3-150 – Run 217 hydrogen production

Figure A3-151 – Run 217 hydrogen consumption
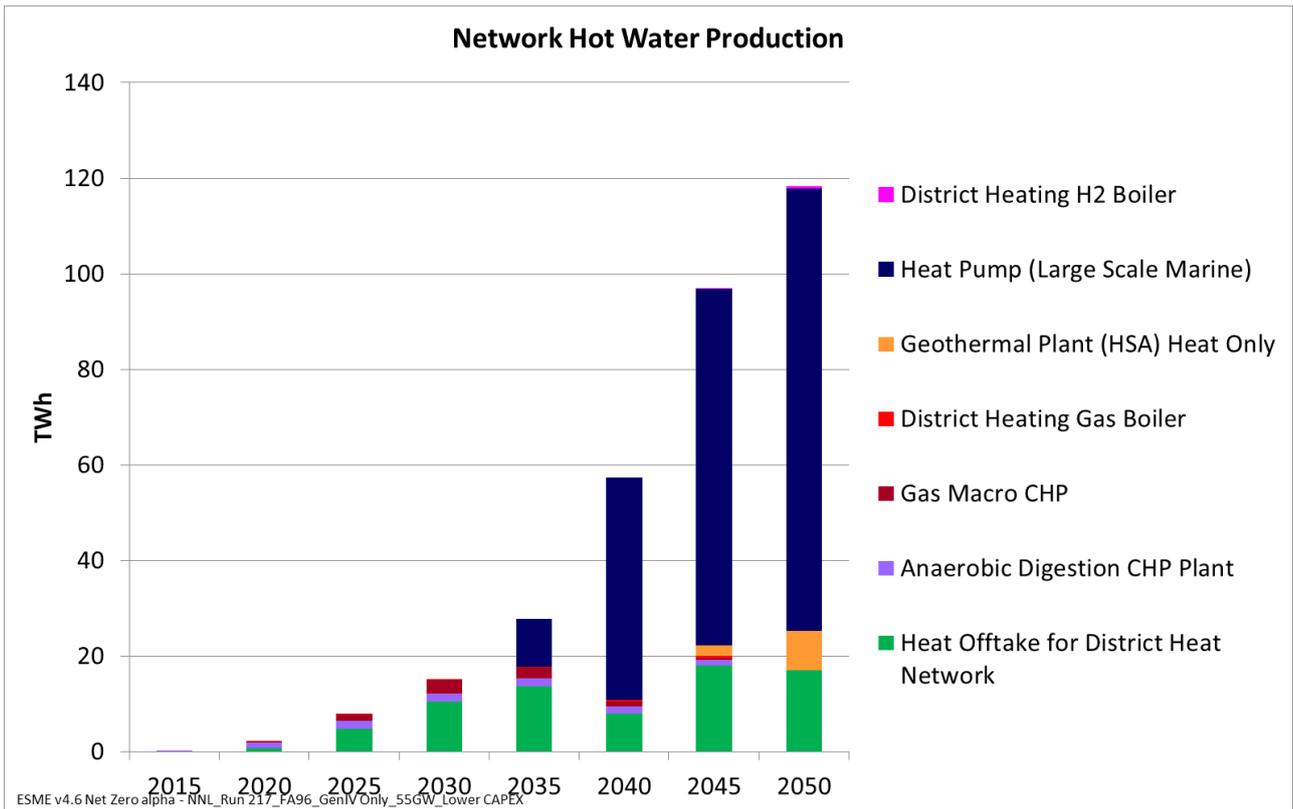
Figure A3-152 – Run 217 network hot water production
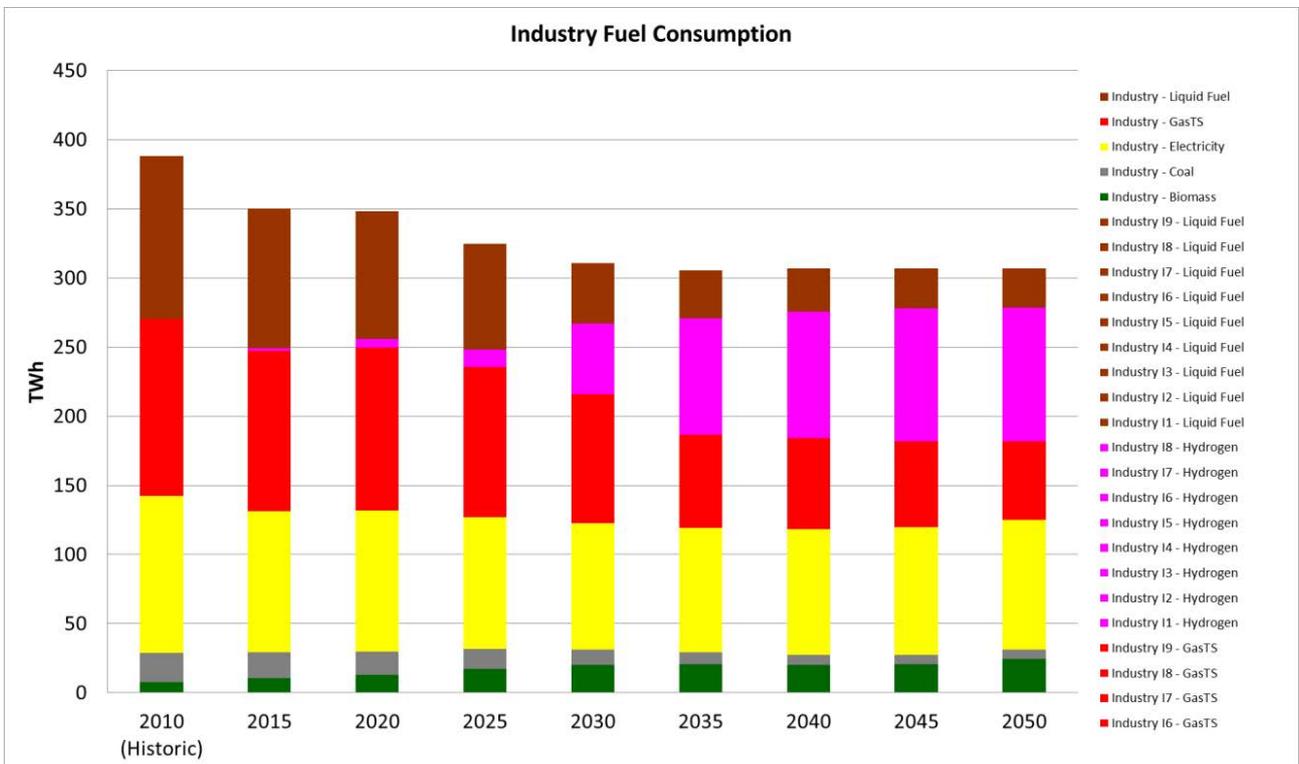
Figure A3-153 – Run 217 industry fuel consumption

Run 218 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55 GWe and build-out rate to match; base case data with lower capex values
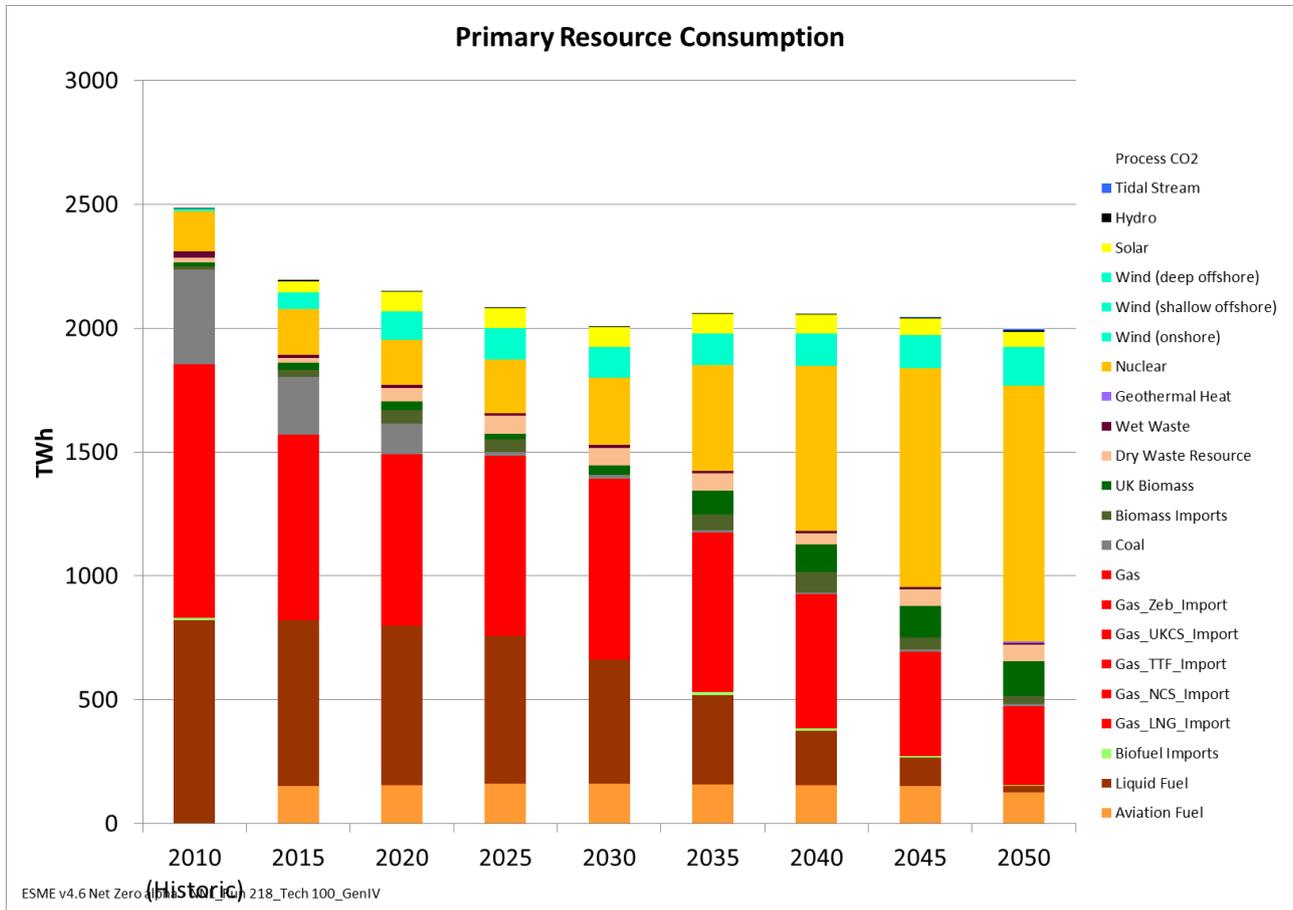
Figure A3-154 – Run 218 primary resource consumption
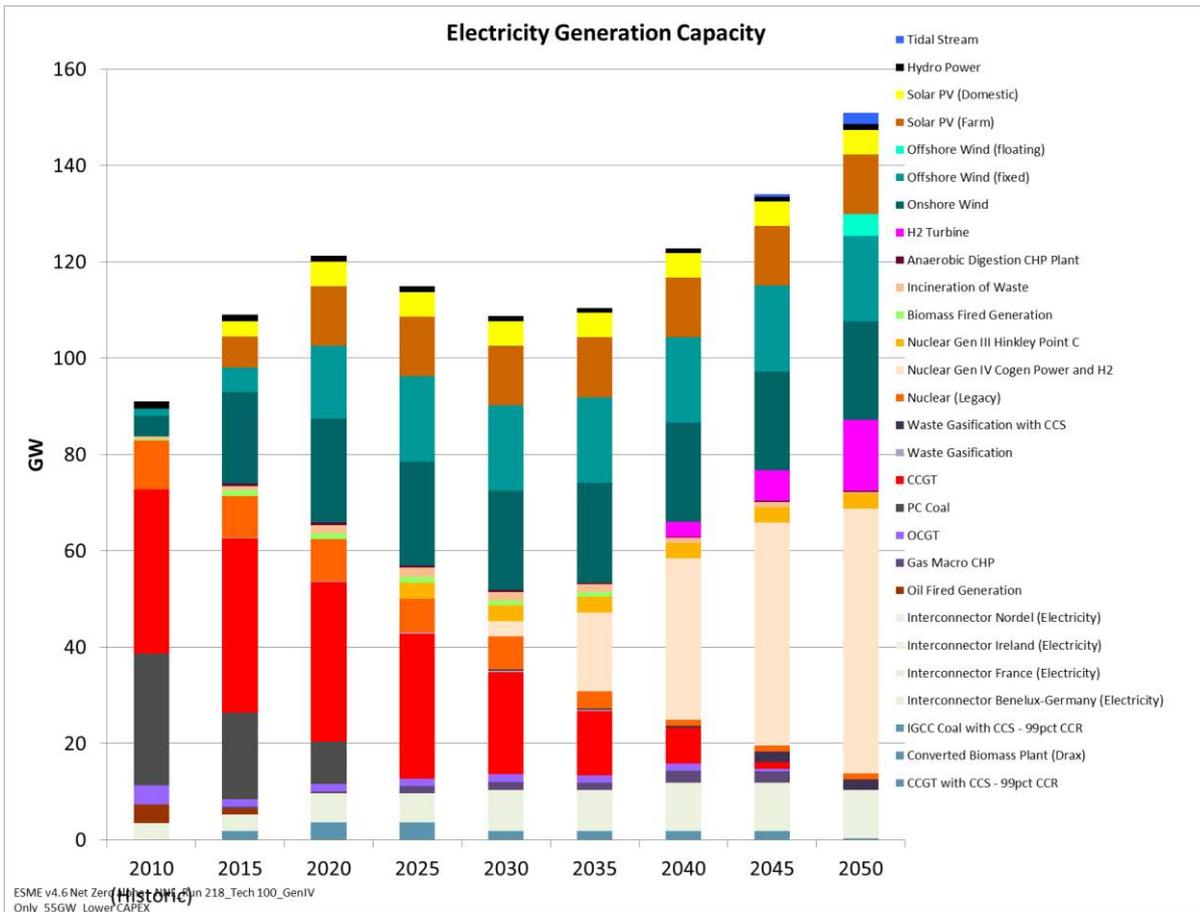
Figure A3-155 – Run 218 electricity generation capacity
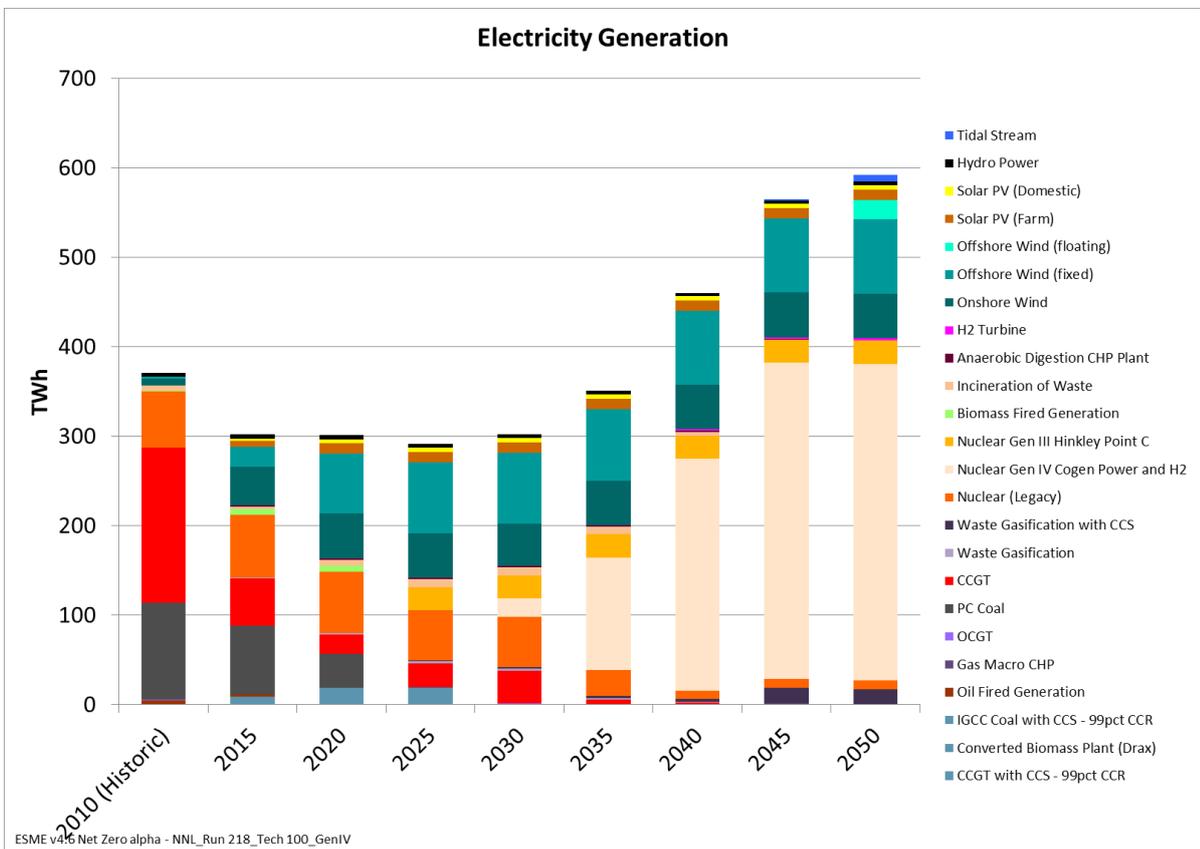
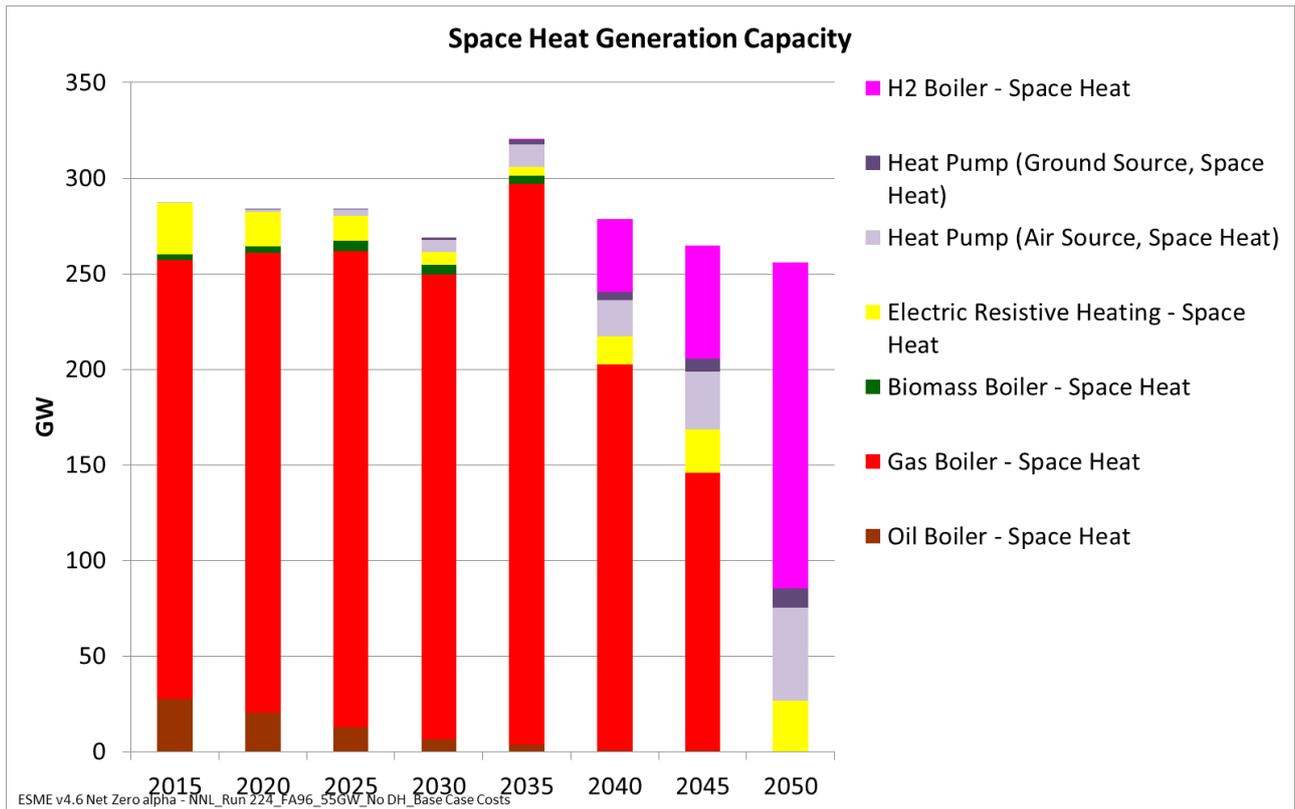Figure A3-156 – Run 218 electricity generation

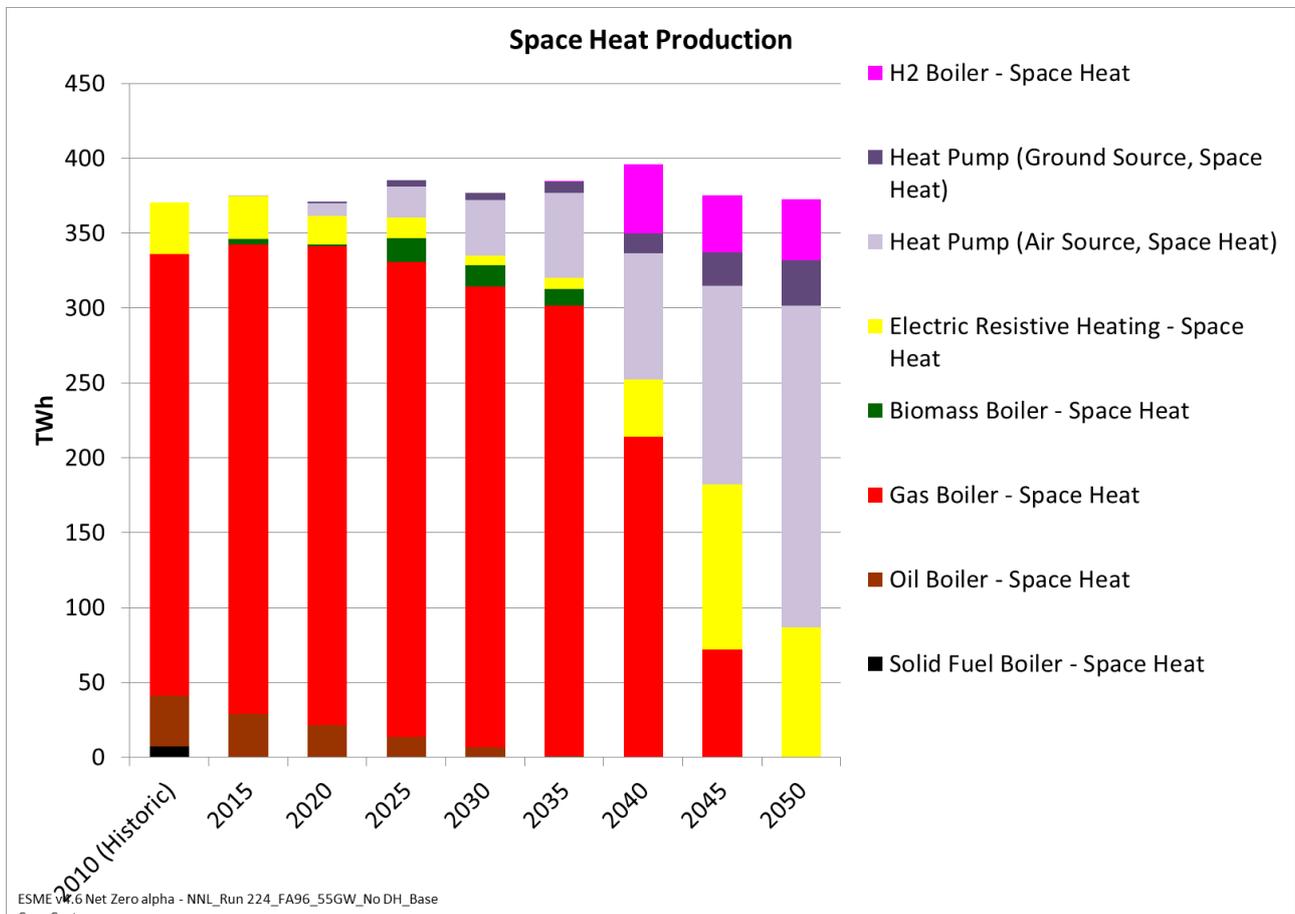Figure A3-157 – Run 218 space heat generation capacity
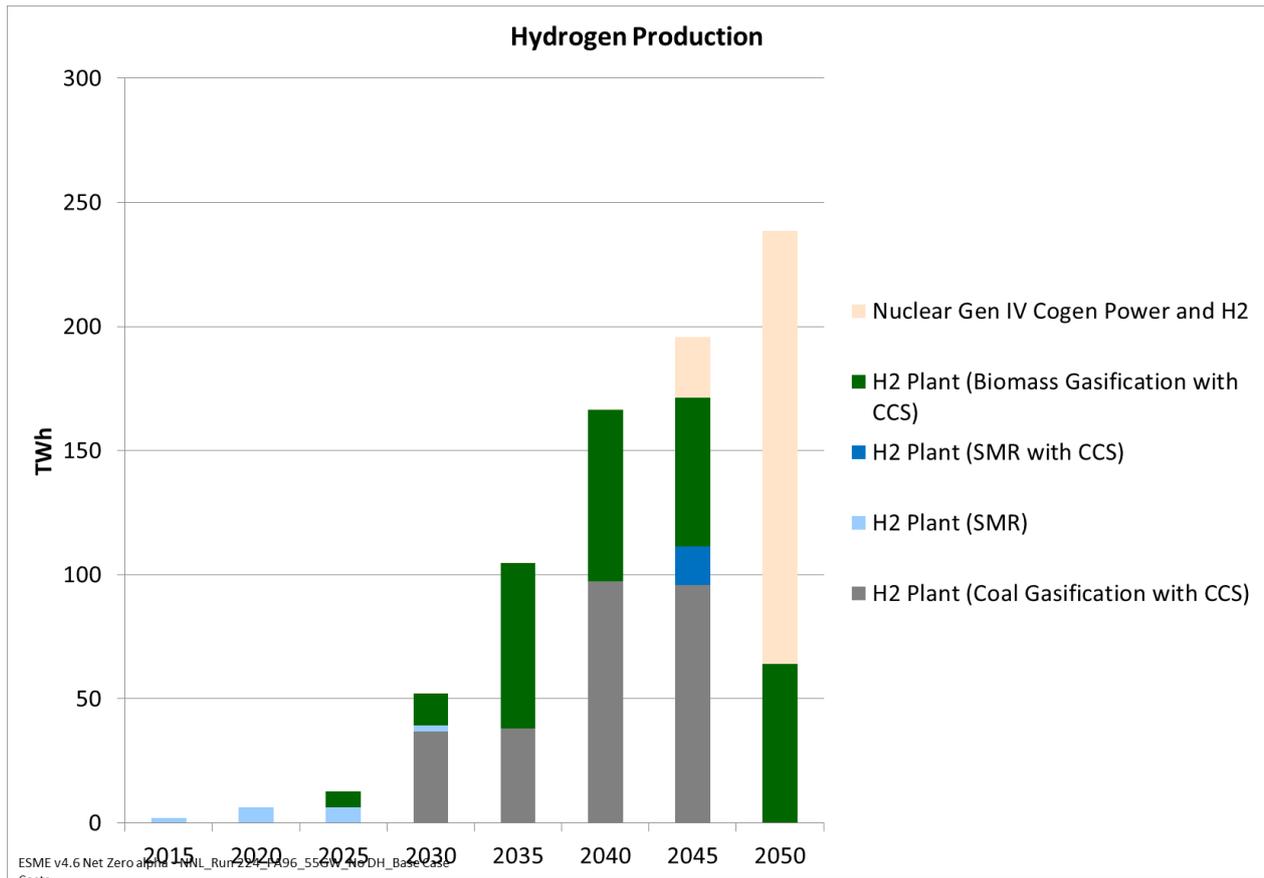

Figure A3-158 – Run 218 space heat production

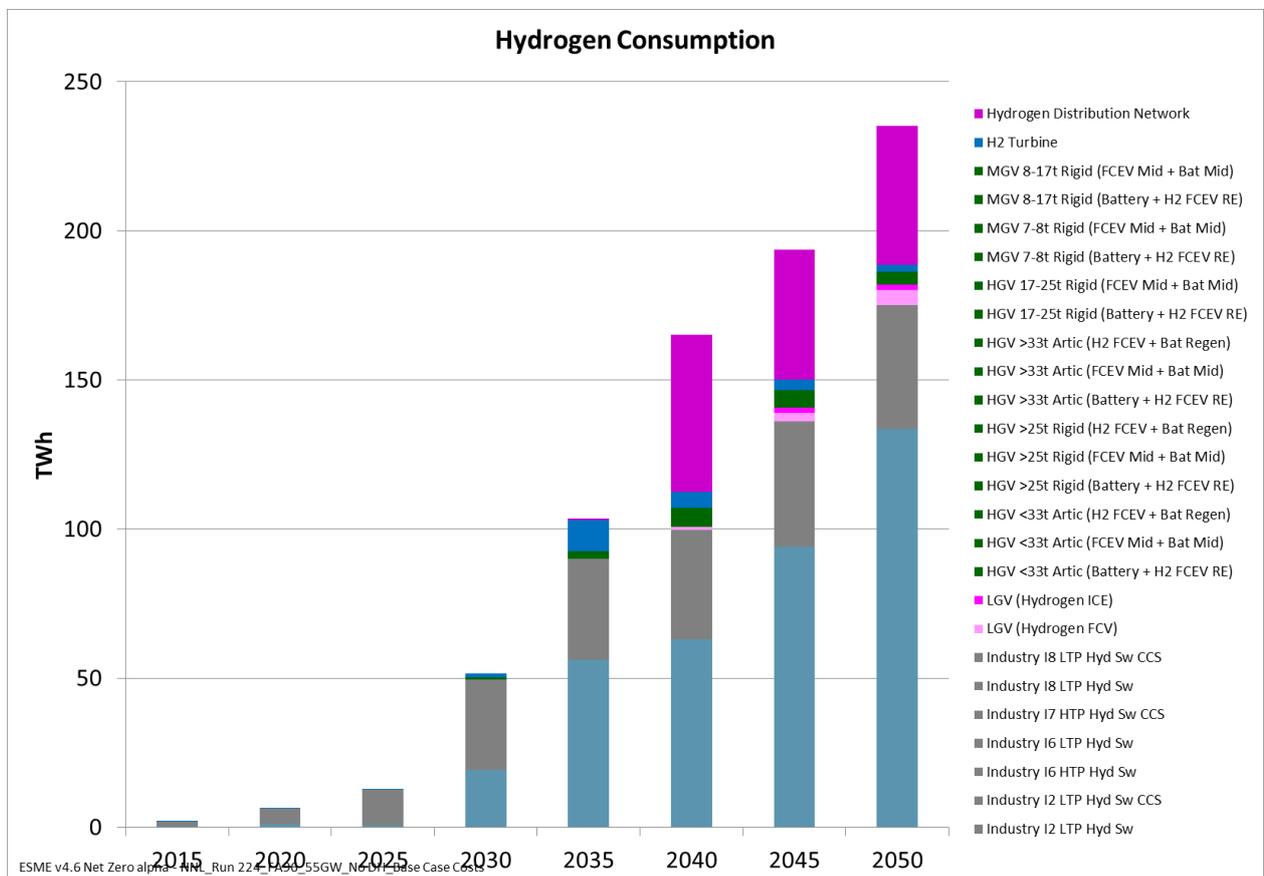**Figure A3-159 – Run 218 hydrogen production**

Figure A3-160 – Run 218 hydrogen consumption

Figure A3-161 – Run 218 network hot water production
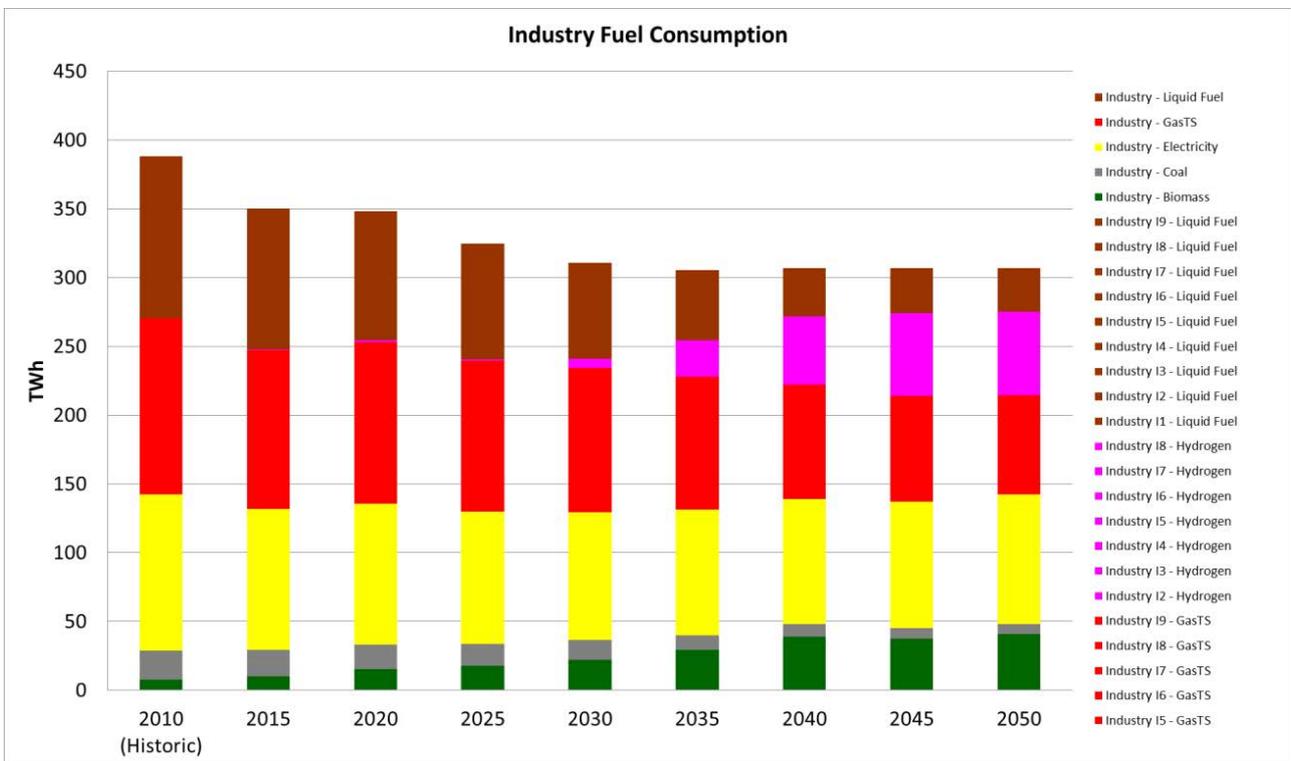
Figure A3-162 – Run 218 industry fuel consumption

Run 219 FA96 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55 GWe and build-out rate to match; base case data with higher capex values
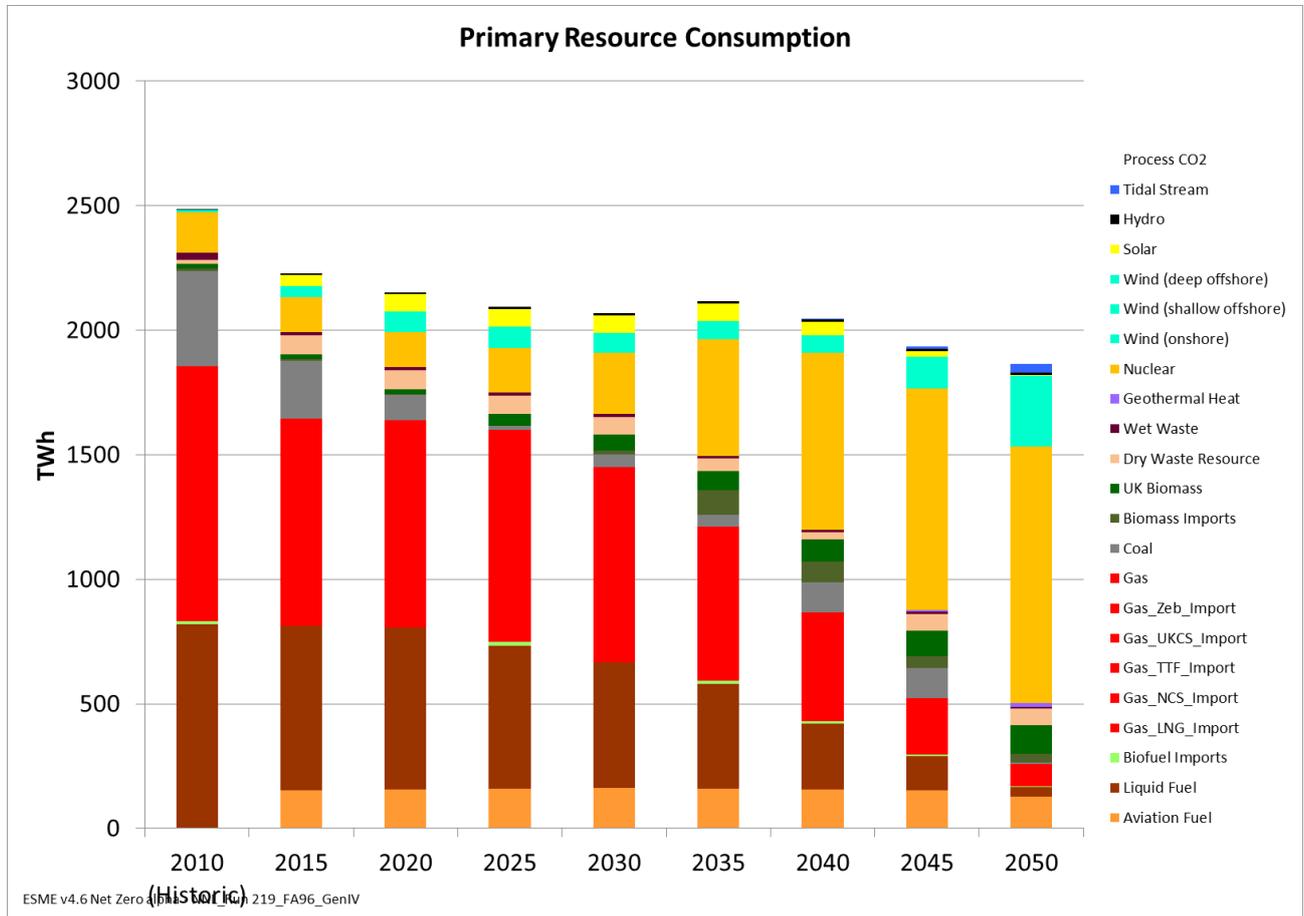
Figure A3-163 – Run 219 primary resource consumption

Figure A3-164 – Run 219 electricity generation capacity

Figure A3-165 – Run 219 electricity generation

Figure A3-166 – Run 219 space heat generation capacity

Figure A3-167 – Run 219 space heat production

Figure A3-168 – Run 219 hydrogen production

Figure A3-169 – Run 219 hydrogen consumption
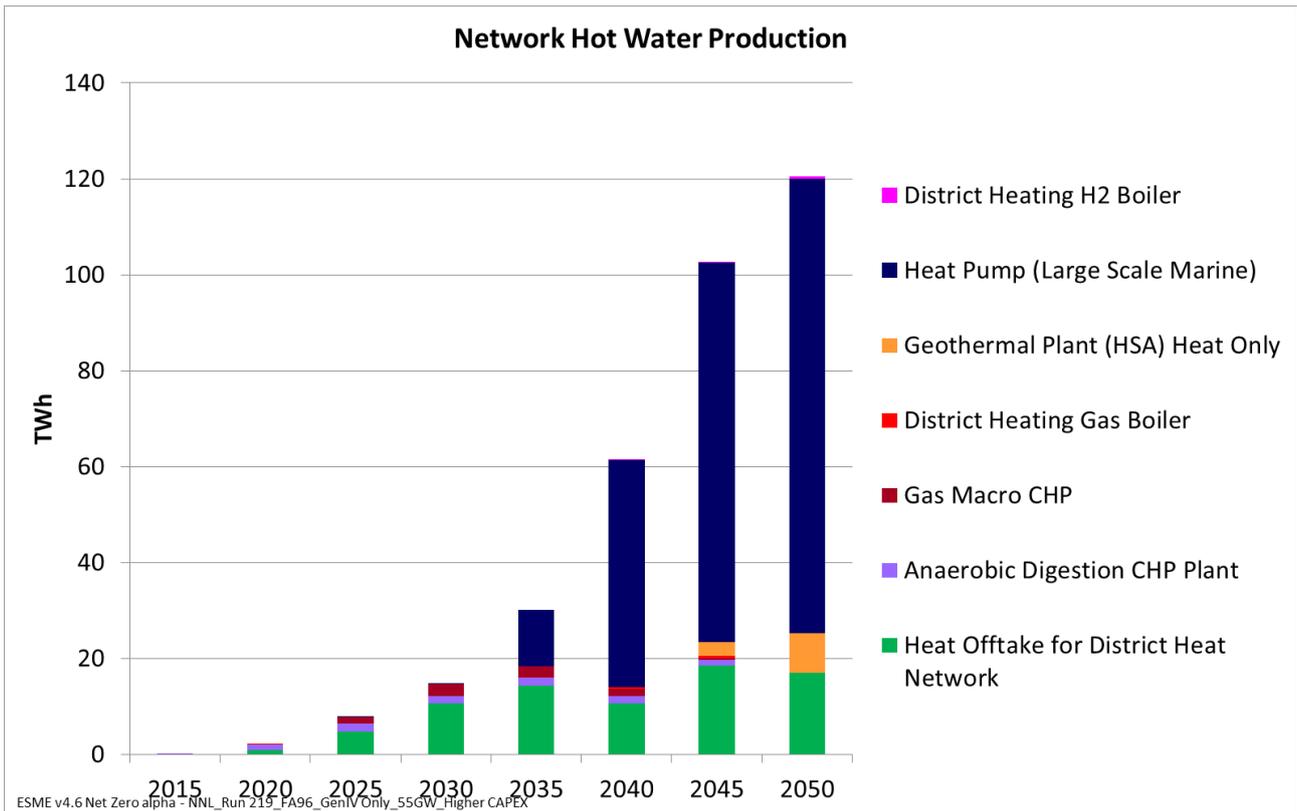
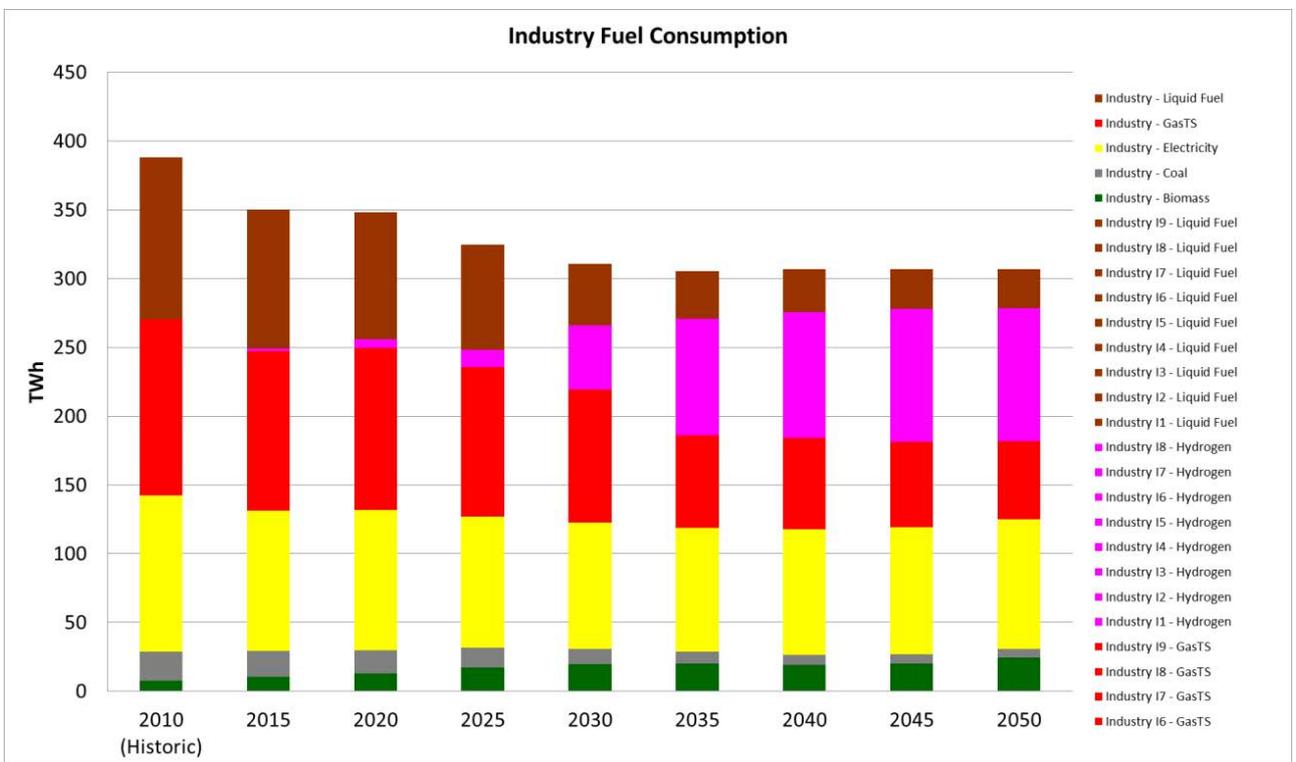Figure A3-170 – Run 219 network hot water production
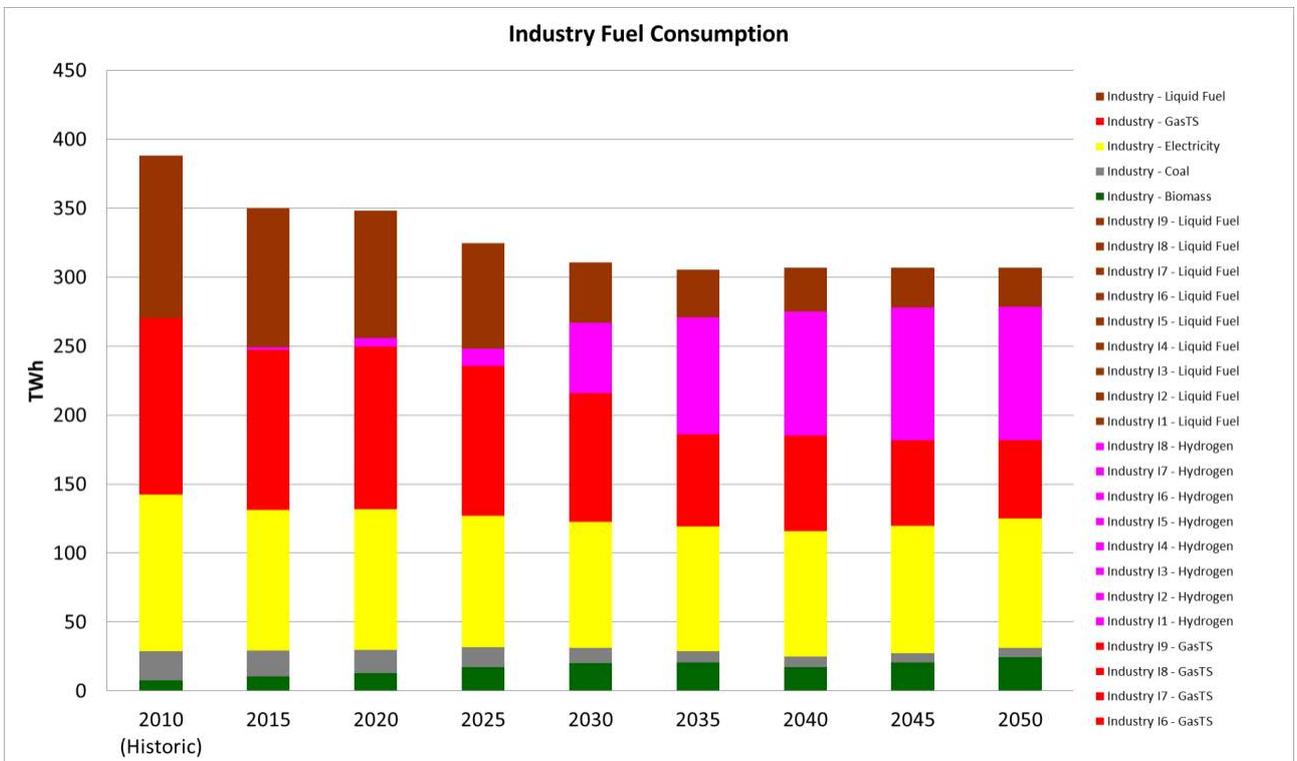
Figure A3-171 – Run 219 industry fuel consumption

Run 220 TECH100 – Gen IV cogen deployment only; no Gen III+ beyond HPC and no LWSMR; raise site capacity limit to 55GWe and build-out rate to match; base case data with higher capex values
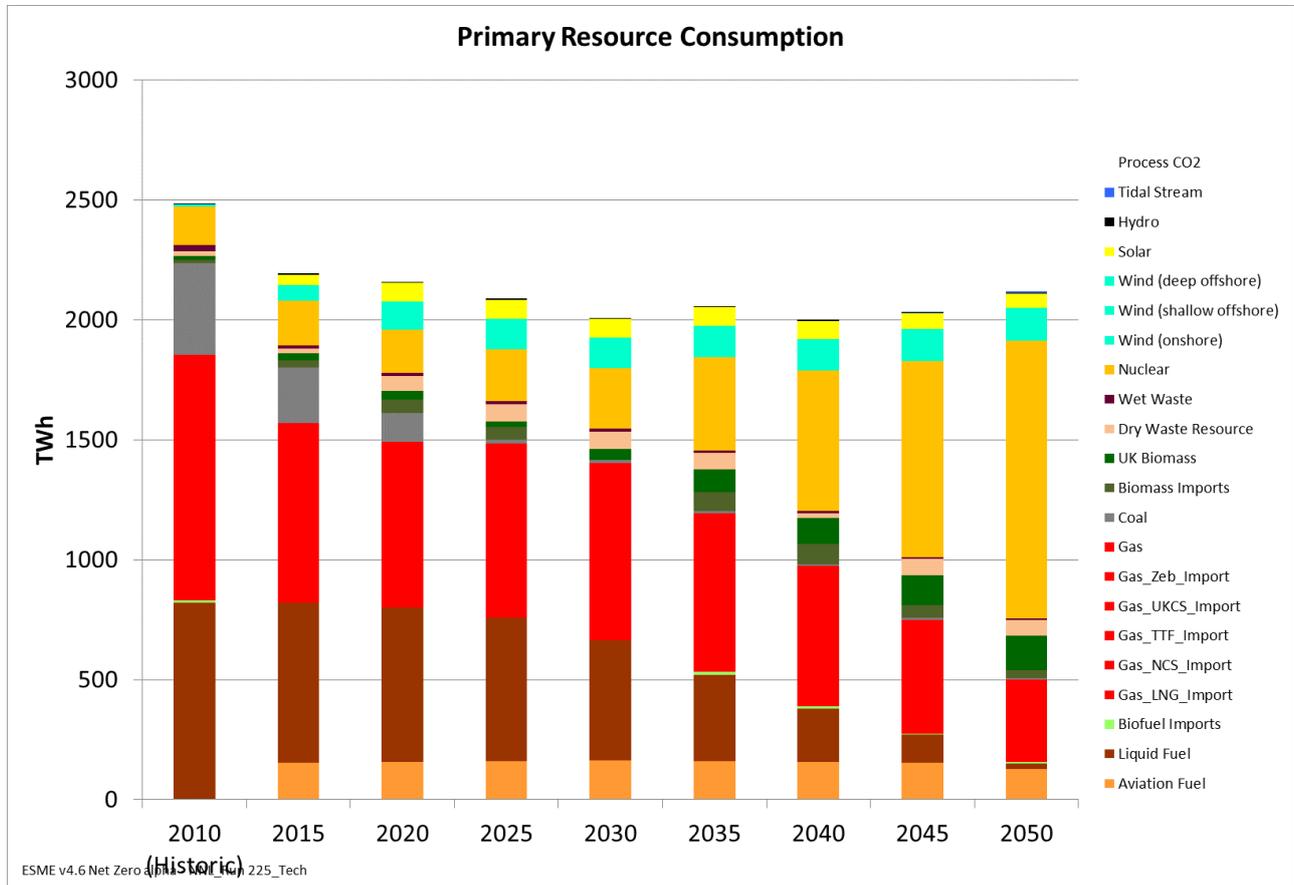

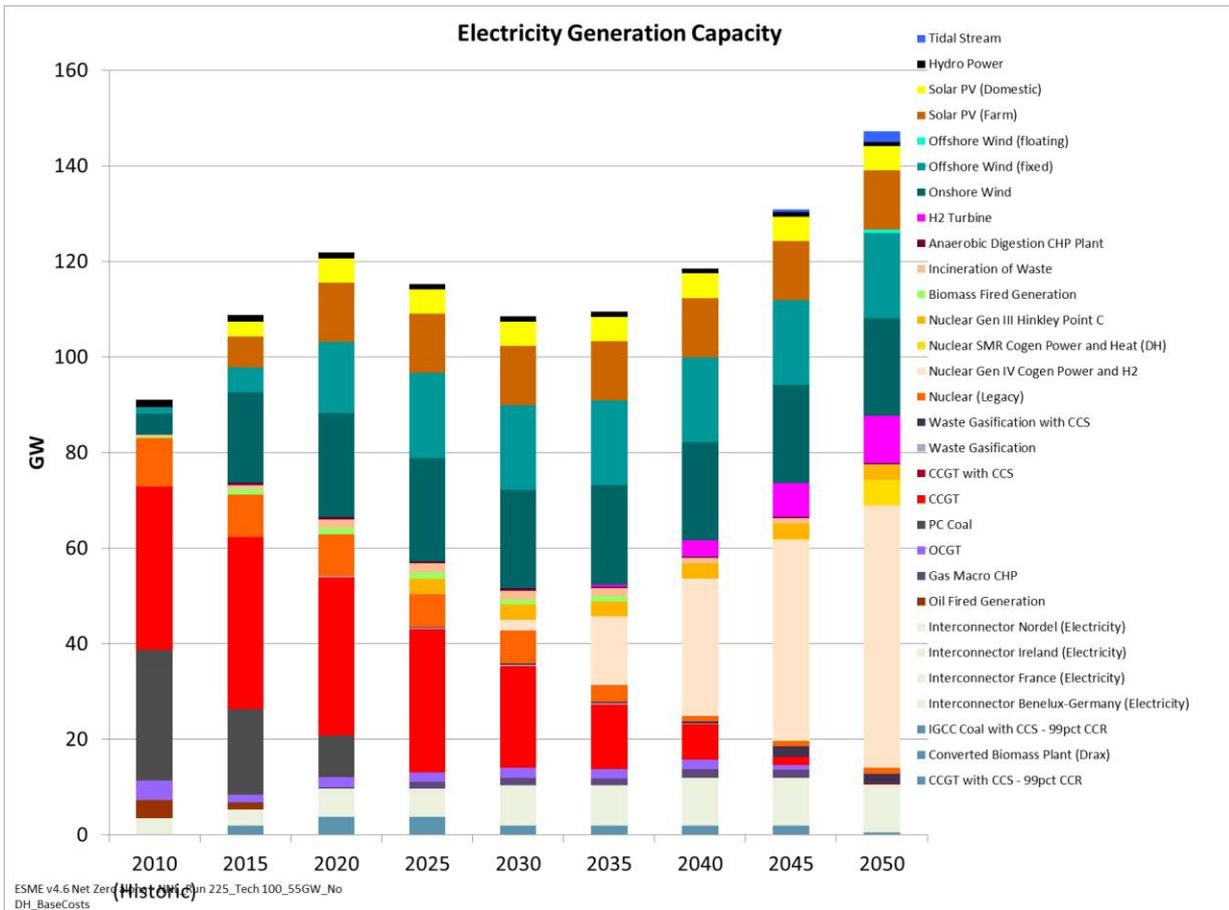Figure A3-172 – Run 220 primary resource consumption

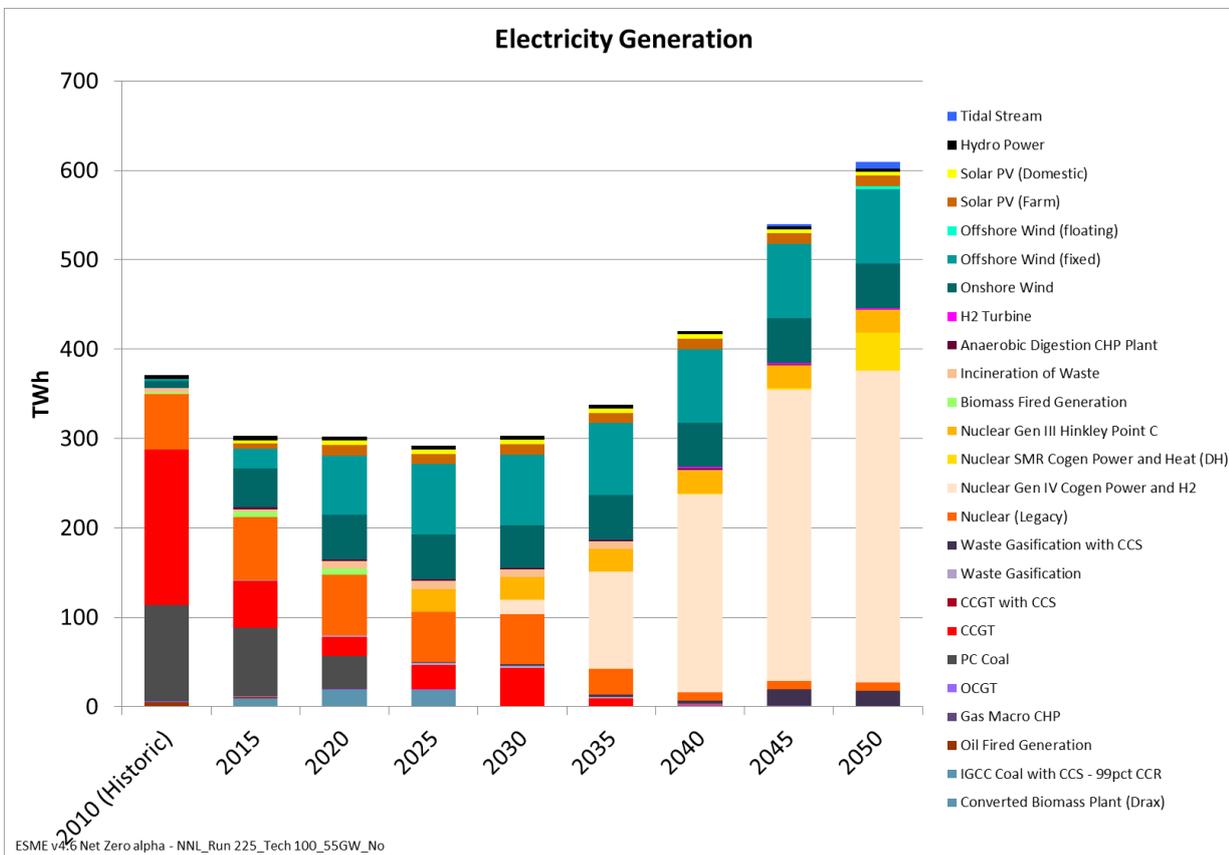Figure A3-173 – Run 220 electricity generation capacity

Figure A3-174 – Run 220 electricity generation

Figure A3-175 – Run 220 space heat generation capacity

FigureA3-176–Run220 space heat production

Figure A3-177 – Run 220 hydrogen production

Figure A3-178 – Run 220 hydrogen consumption
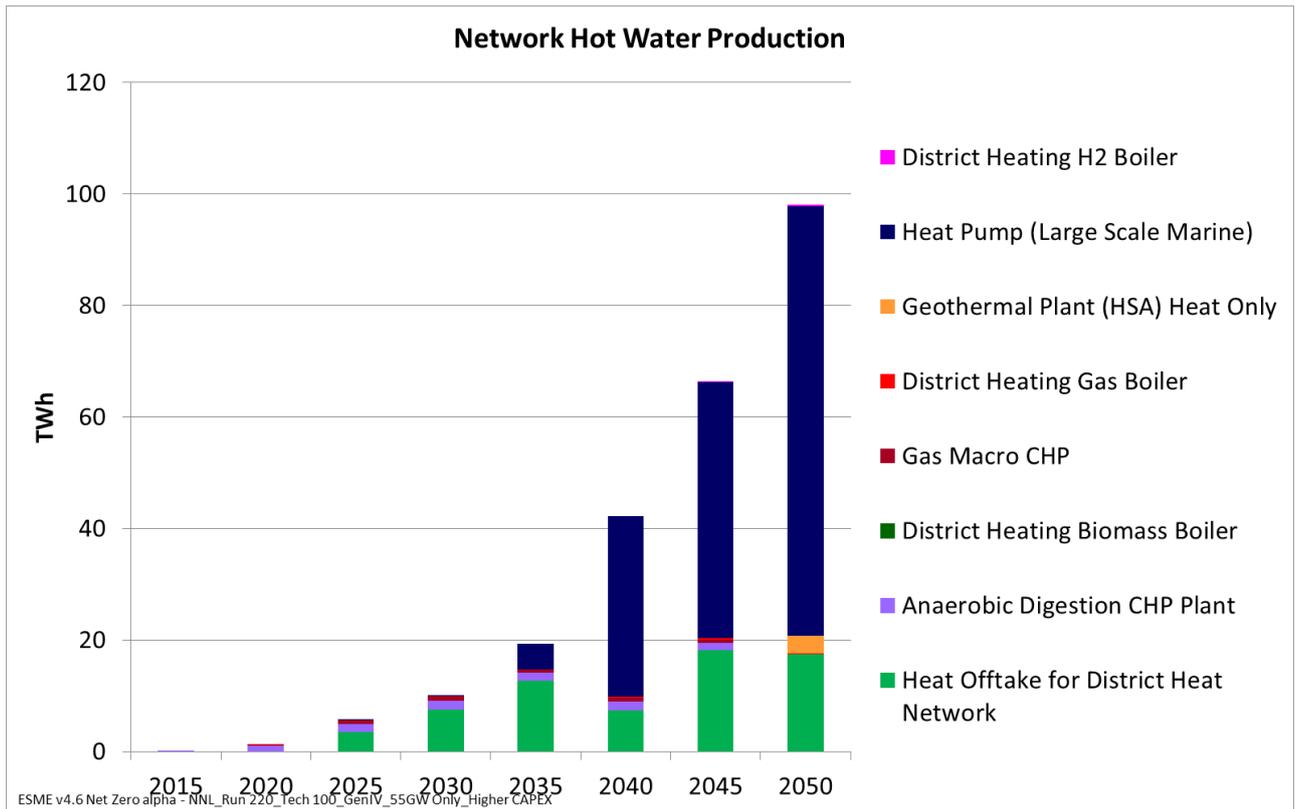
Figure A3-179 – Run 220 network hot water production
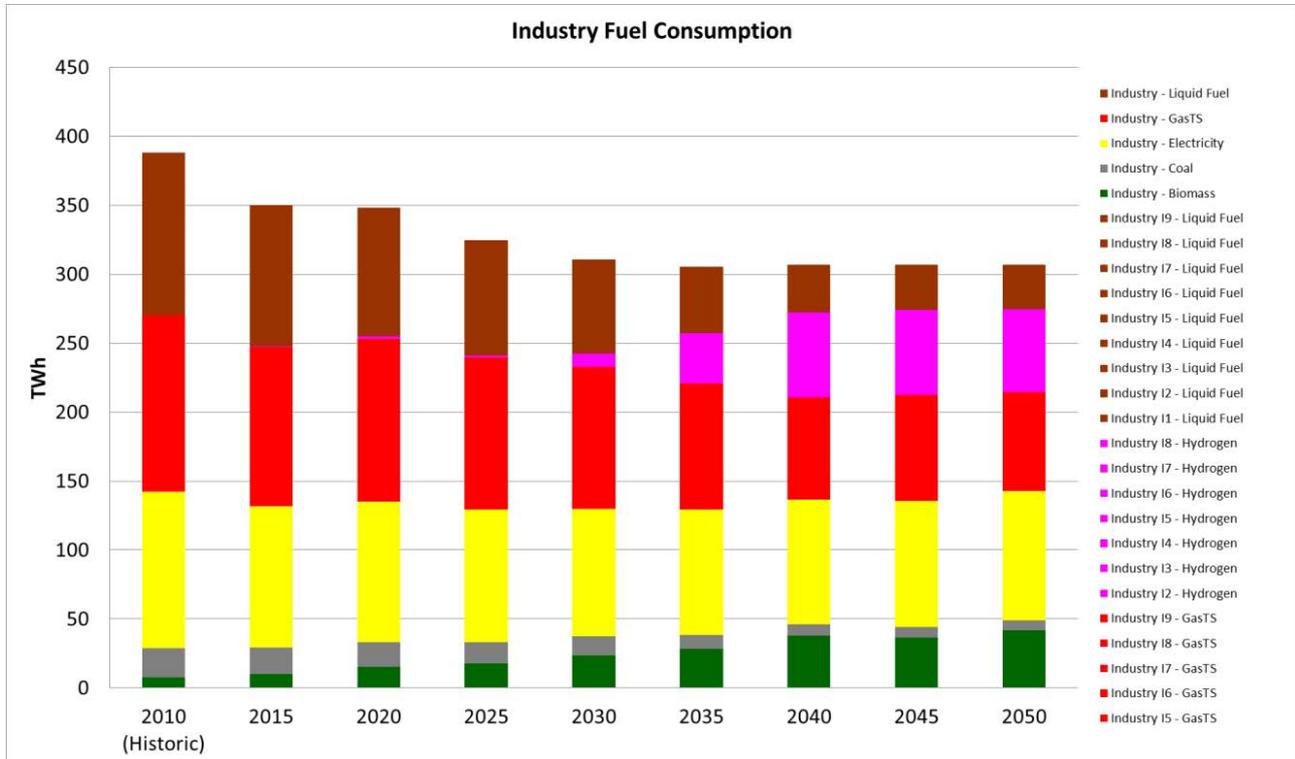
Figure A3-180 – Run 220 industry fuel consumption

Run 221 FA96 – No DH deployment; all nuclear technologies with LWSMR as electricity only; base case data

Figure A3-181 – Run 221 primary resource consumption

Figure A3-182 – Run 221 electricity generation capacity

Figure A3-183 – Run 221 electricity generation

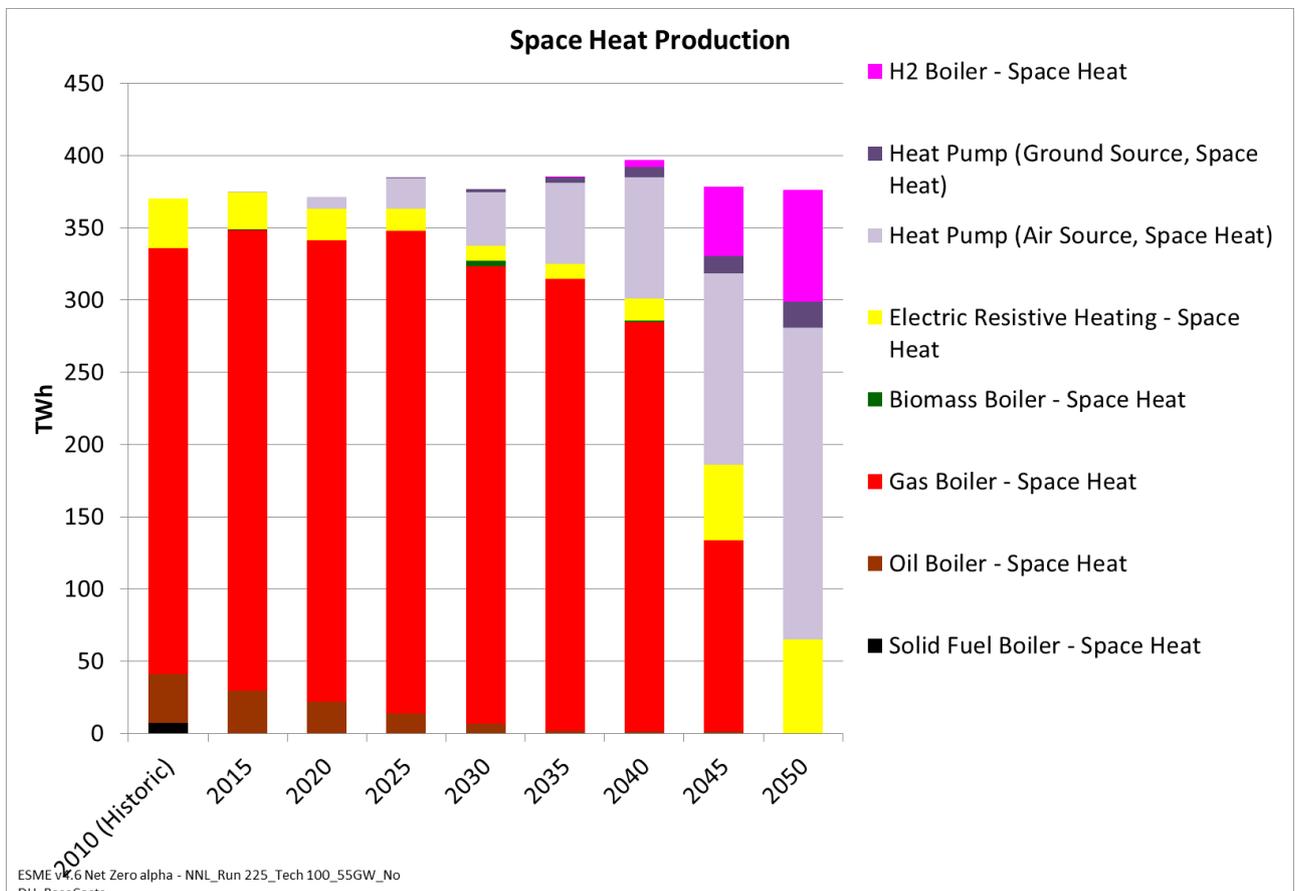Figure A3-184 – Run 221 space heat generation capacity
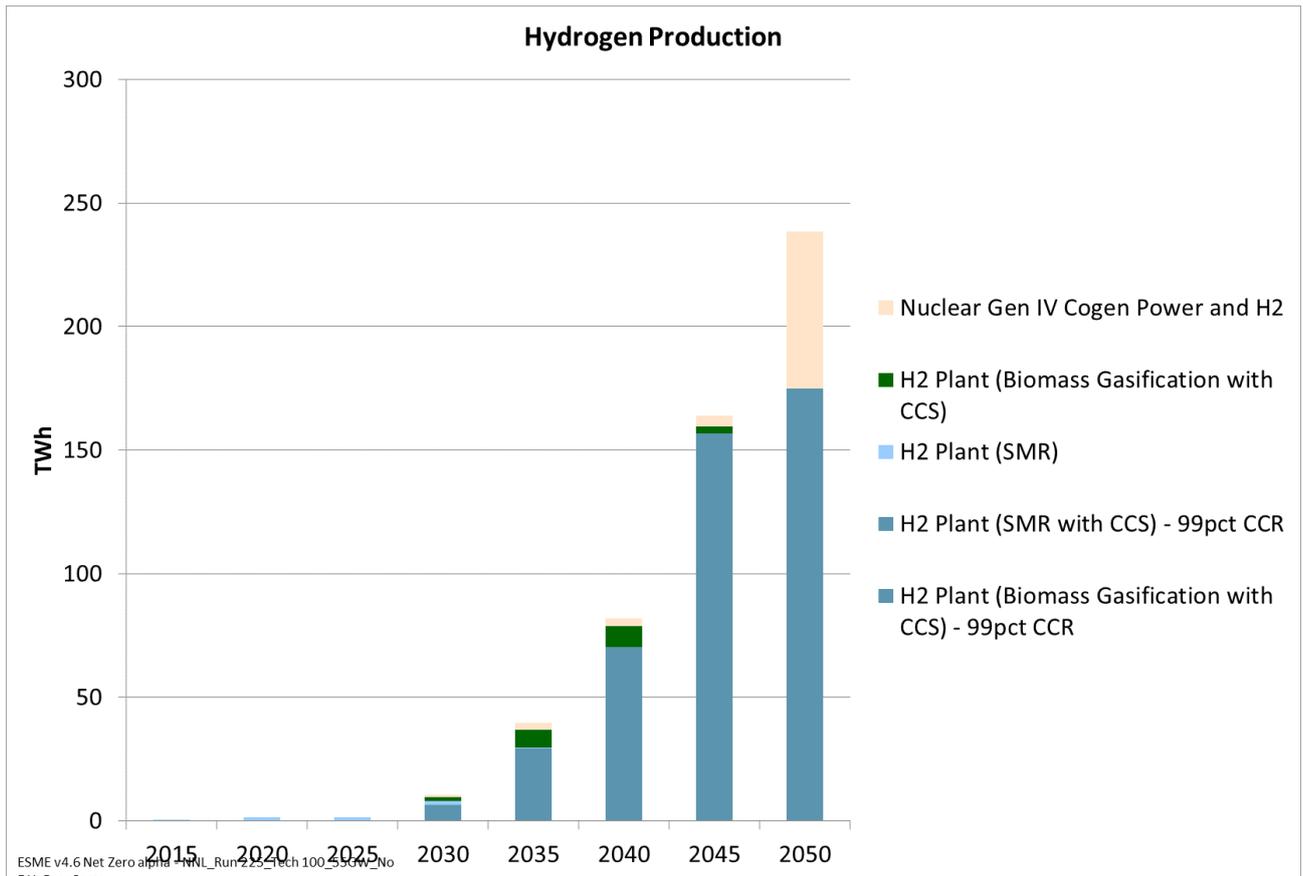

Figure A3-185 – Run 221 space heat production

Hydrogen Production

Legend:
- Nuclear Gen IV Cogen Power and H2
- H2 Plant (Biomass Gasification with CCS)
- H2 Plant (SMR with CCS)
- H2 Plant (SMR)
- H2 Plant (Coal Gasification with CCS)
- H2 Plant (Electrolysis)

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Figure A3-186 – Run 221 hydrogen production

Hydrogen Consumption

Legend:
- Hydrogen Distribution Network
- H2 Turbine
- MGV 8-17t Rigid (FCEV Mid + Bat Mid)
- MGV 8-17t Rigid (Battery + H2 FCEV RE)
- MGV 7-8t Rigid (FCEV Mid + Bat Mid)
- MGV 7-8t Rigid (Battery + H2 FCEV RE)
- HGV 17-25t Rigid (FCEV Mid + Bat Mid)
- HGV 17-25t Rigid (Battery + H2 FCEV RE)
- HGV >33t Artic (H2 FCEV + Bat Regen)
- HGV >33t Artic (FCEV Mid + Bat Mid)
- HGV >33t Artic (Battery + H2 FCEV RE)
- HGV >25t Rigid (H2 FCEV + Bat Regen)
- HGV >25t Rigid (FCEV Mid + Bat Mid)
- HGV >25t Rigid (Battery + H2 FCEV RE)
- HGV <33t Artic (H2 FCEV + Bat Regen)
- HGV <33t Artic (FCEV Mid + Bat Mid)
- HGV <33t Artic (Battery + H2 FCEV RE)
- LGV (Hydrogen ICE)
- LGV (Hydrogen FCV)
- Industry I8 LTP Hyd Sw CCS
- Industry I8 LTP Hyd Sw
- Industry I7 HTP Hyd Sw CCS
- Industry I6 LTP Hyd Sw
- Industry I6 HTP Hyd Sw
- Industry I2 LTP Hyd Sw CCS
- Industry I2 LTP Hyd Sw

ESME v4.6 Net Zero alpha – NNL_Run 221_FA96_No DH_Base CostsV2

Figure A3-187 – Run 221 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 221_FA96_No DH_Base CostsV2

Figure A3-188 – Run 221 network hot water production

Figure A3-189 – Run 221 industry fuel consumption

Run 222 TECH100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; base case data

Figure A3-190 – Run 222 primary resource consumption

Figure A3-191 – Run 222 electricity generation capacity

Figure A3-192 – Run 222 electricity generation
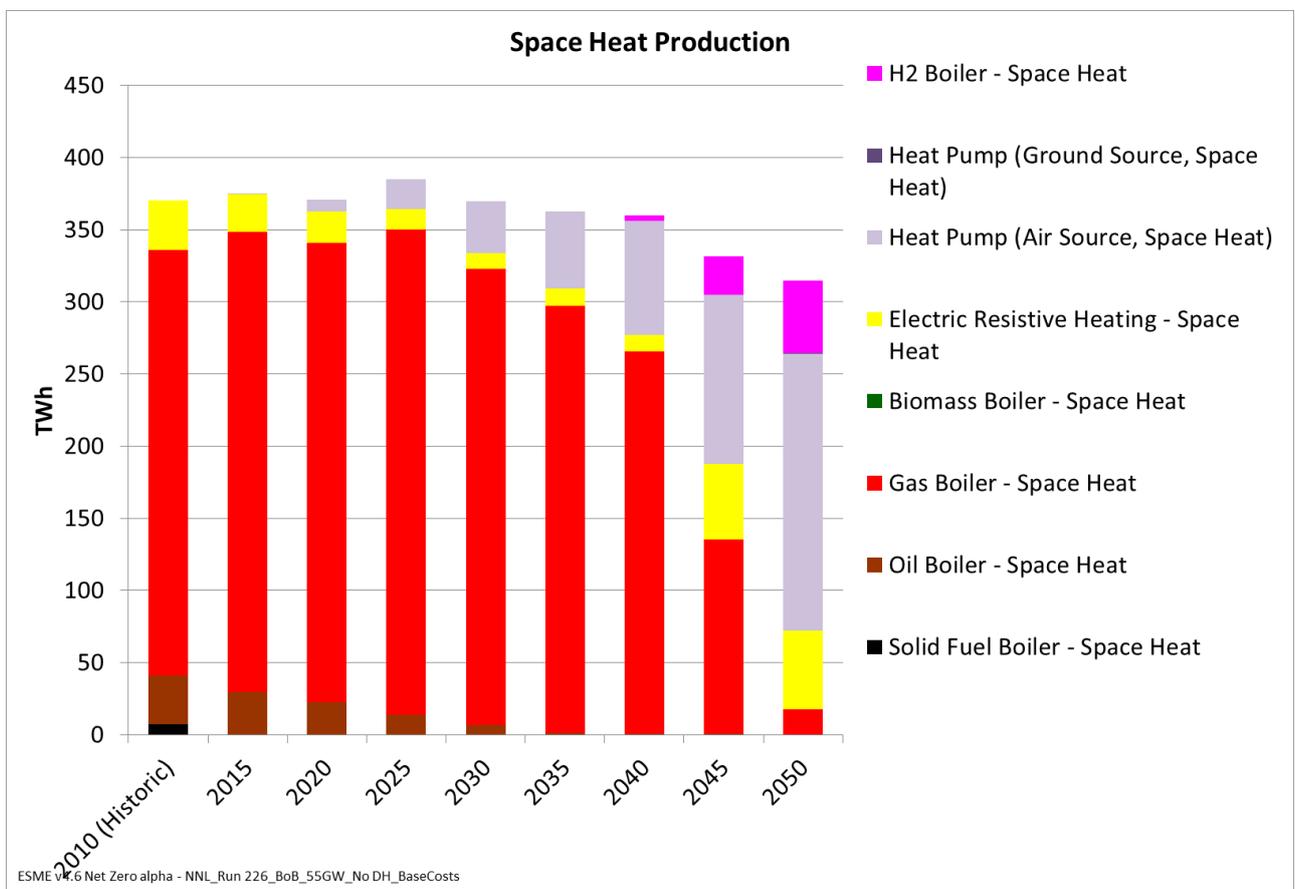
Figure A3-193 – Run 222 space heat generation capacity


Figure A3-194 – Run 222 space heat production
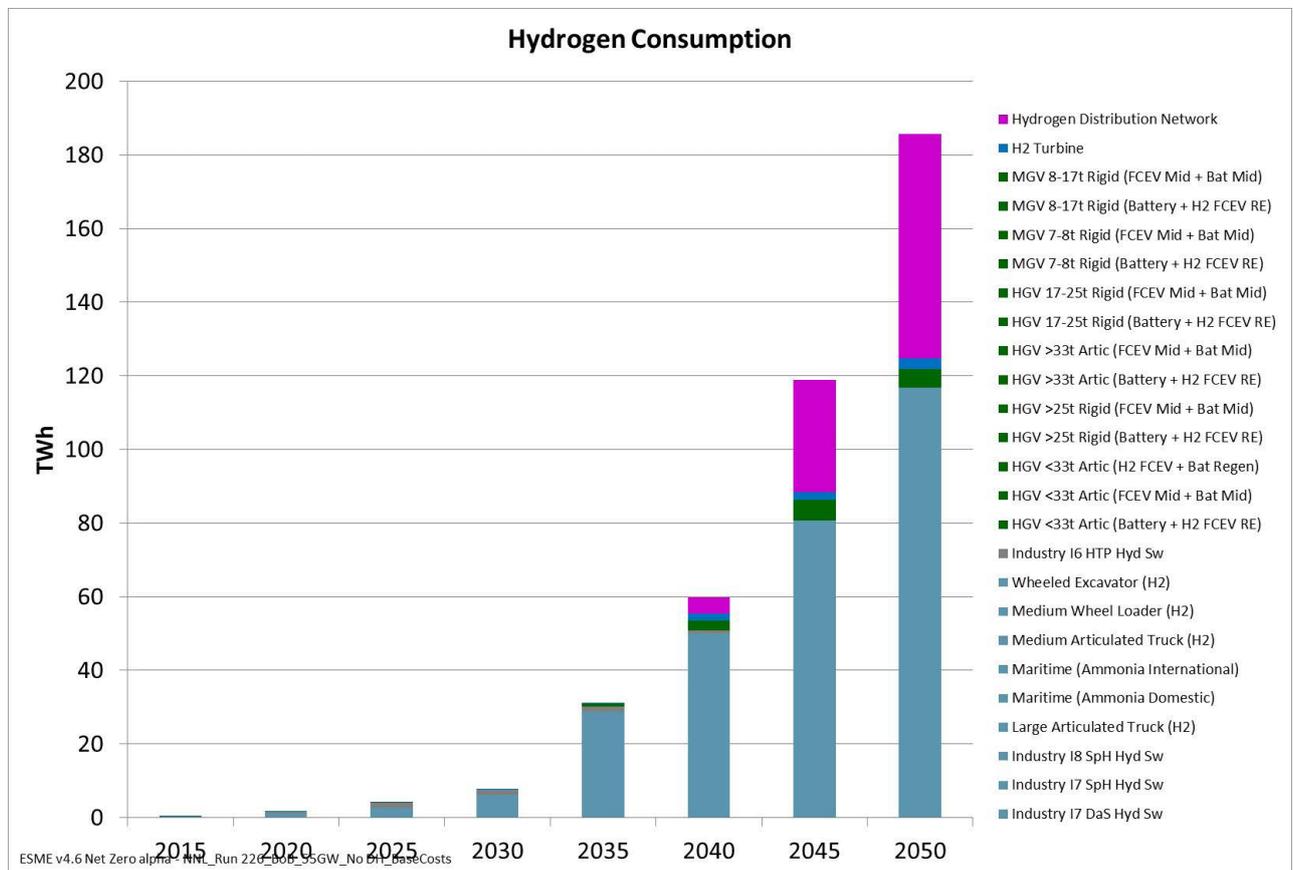
Figure A3-196 – Run 222 hydrogen consumption

Figure A3-196 – Run 222 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 222_Tech 100_No DH_Base Case
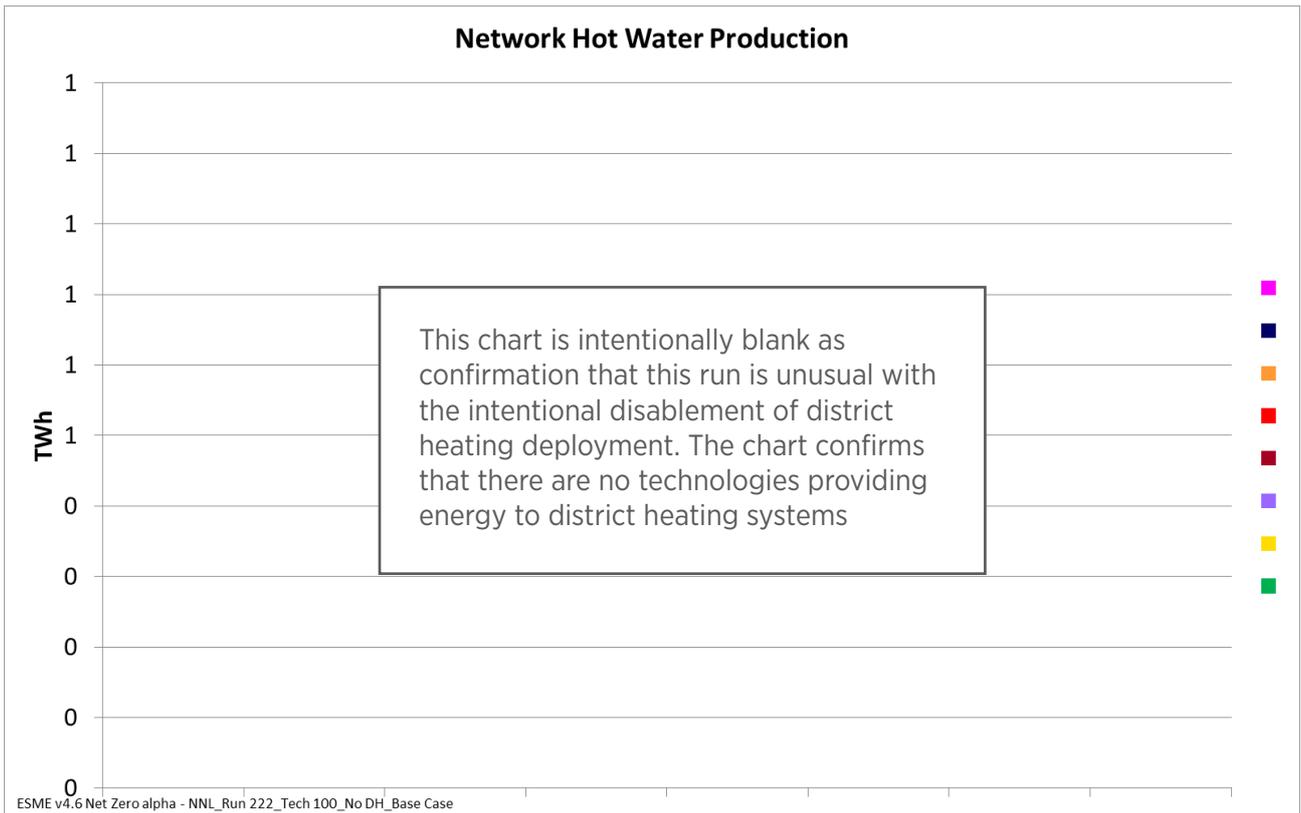
Figure A3-197 – Run 222 network hot water production

Industry Fuel Consumption

Figure A3-198 – Run 222 industry fuel consumption

Run 223 BOB100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; base case data
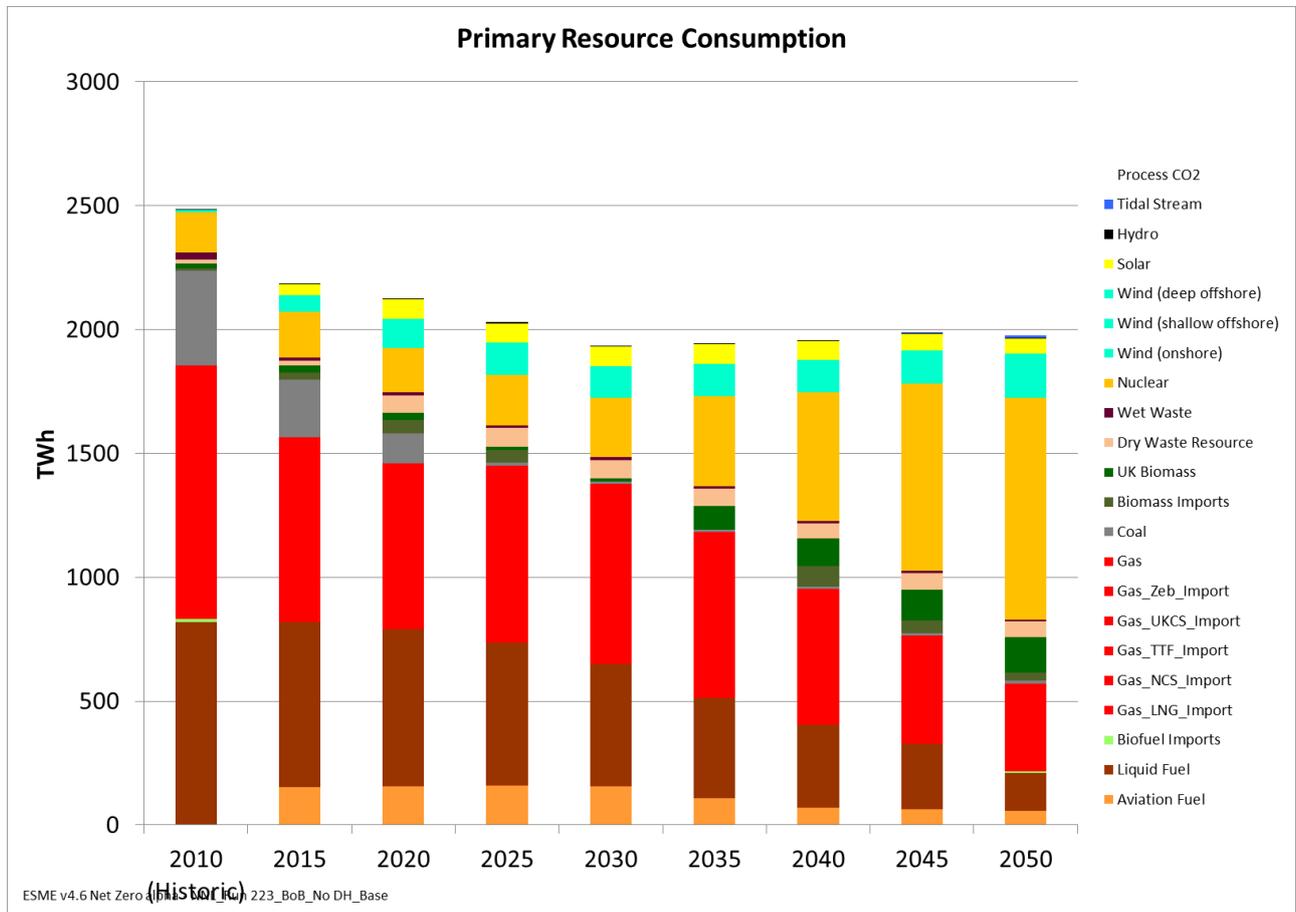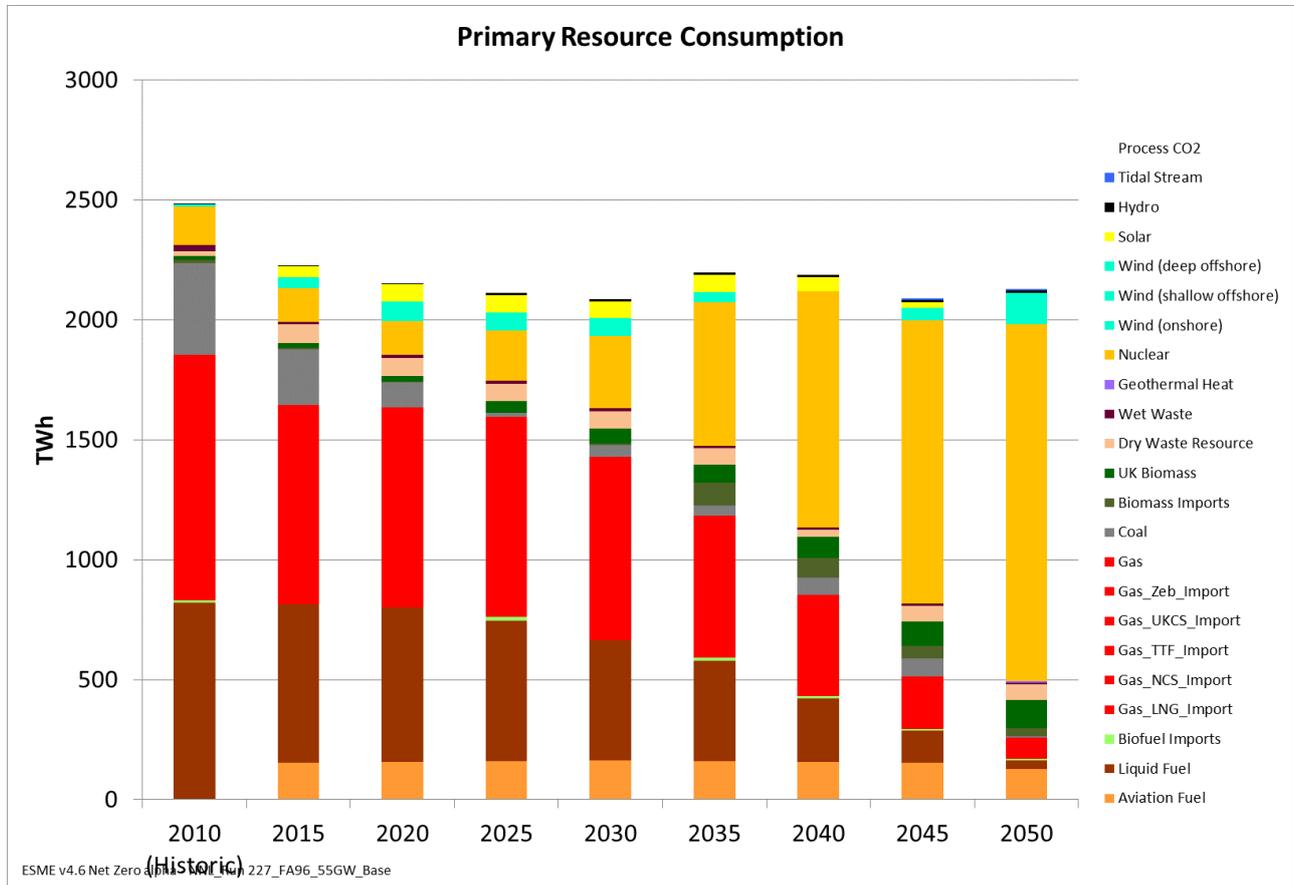

Figure A3-199 – Run 223 primary resource consumption
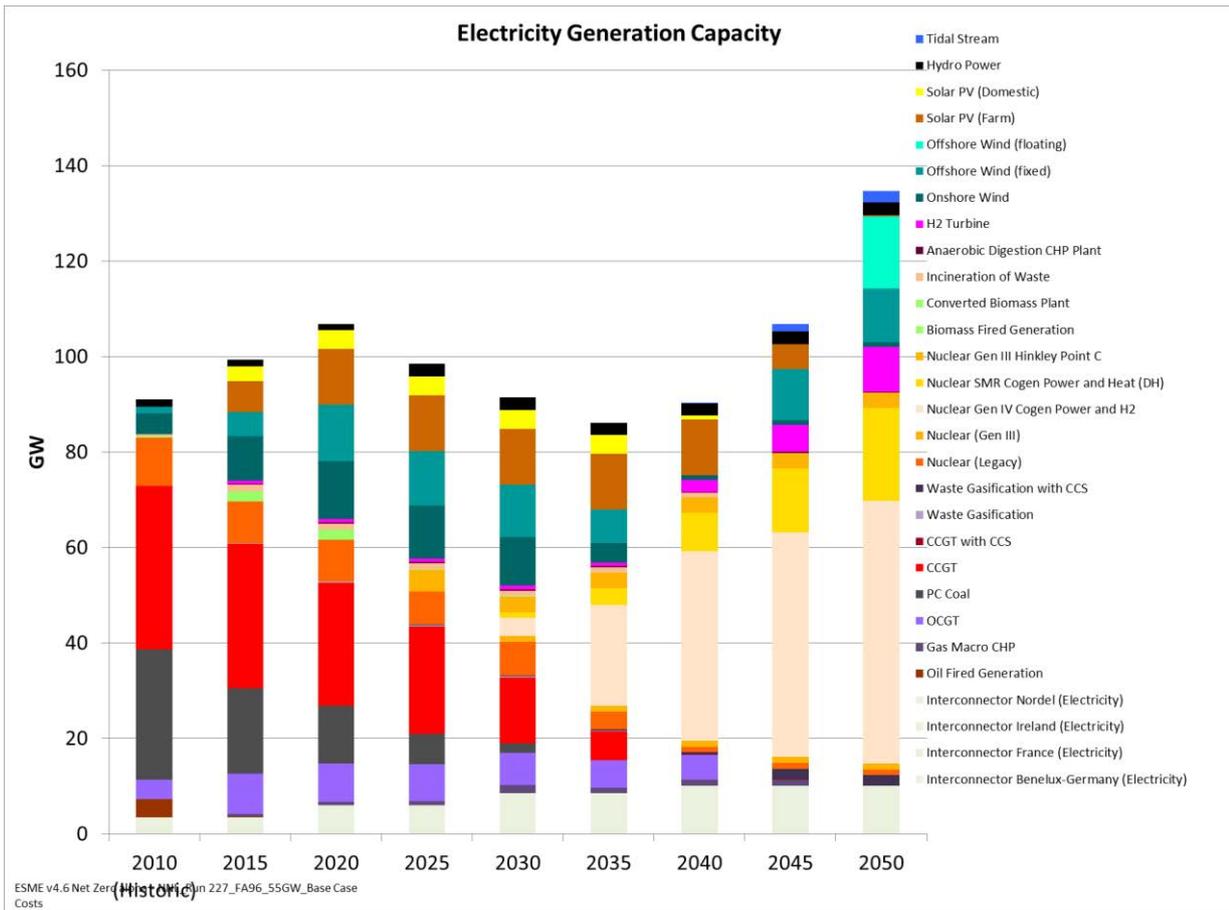
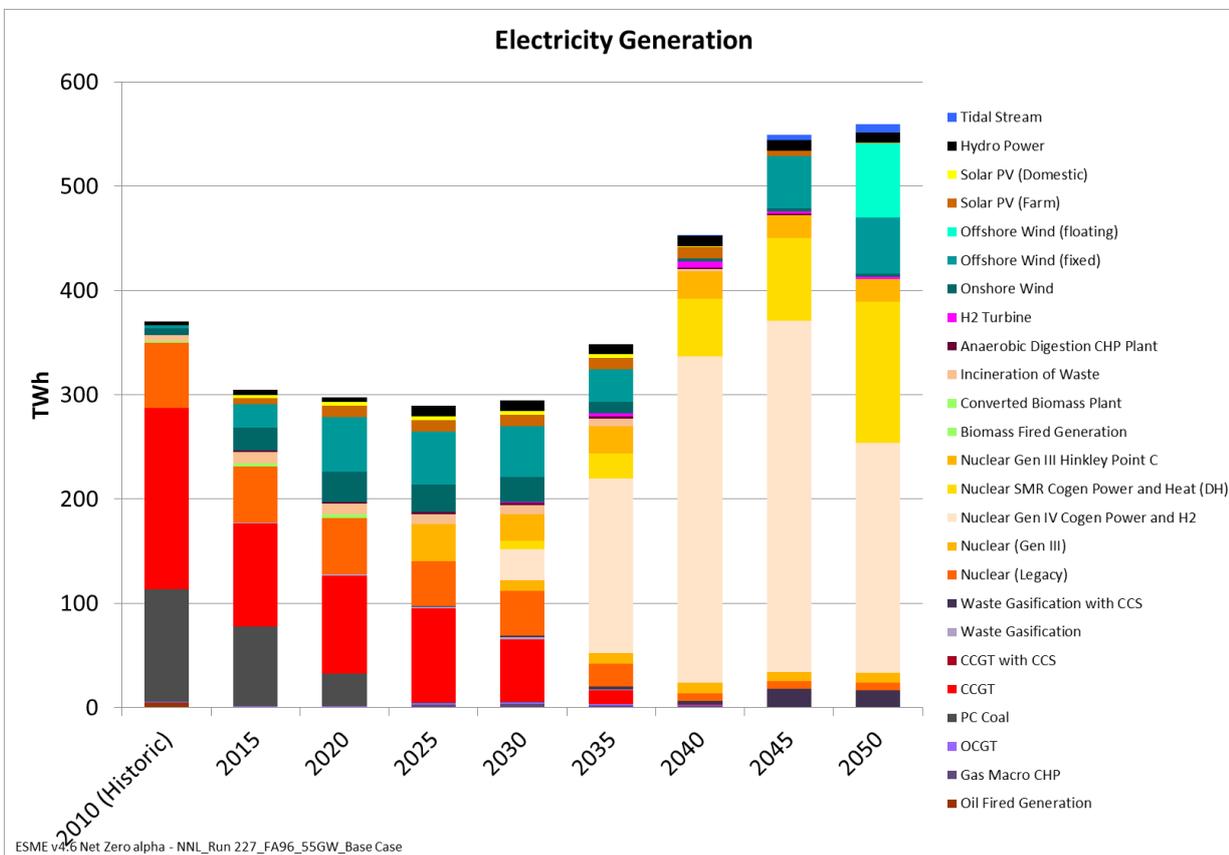**Figure A3-200 – Run 223 electricity generation capacity**

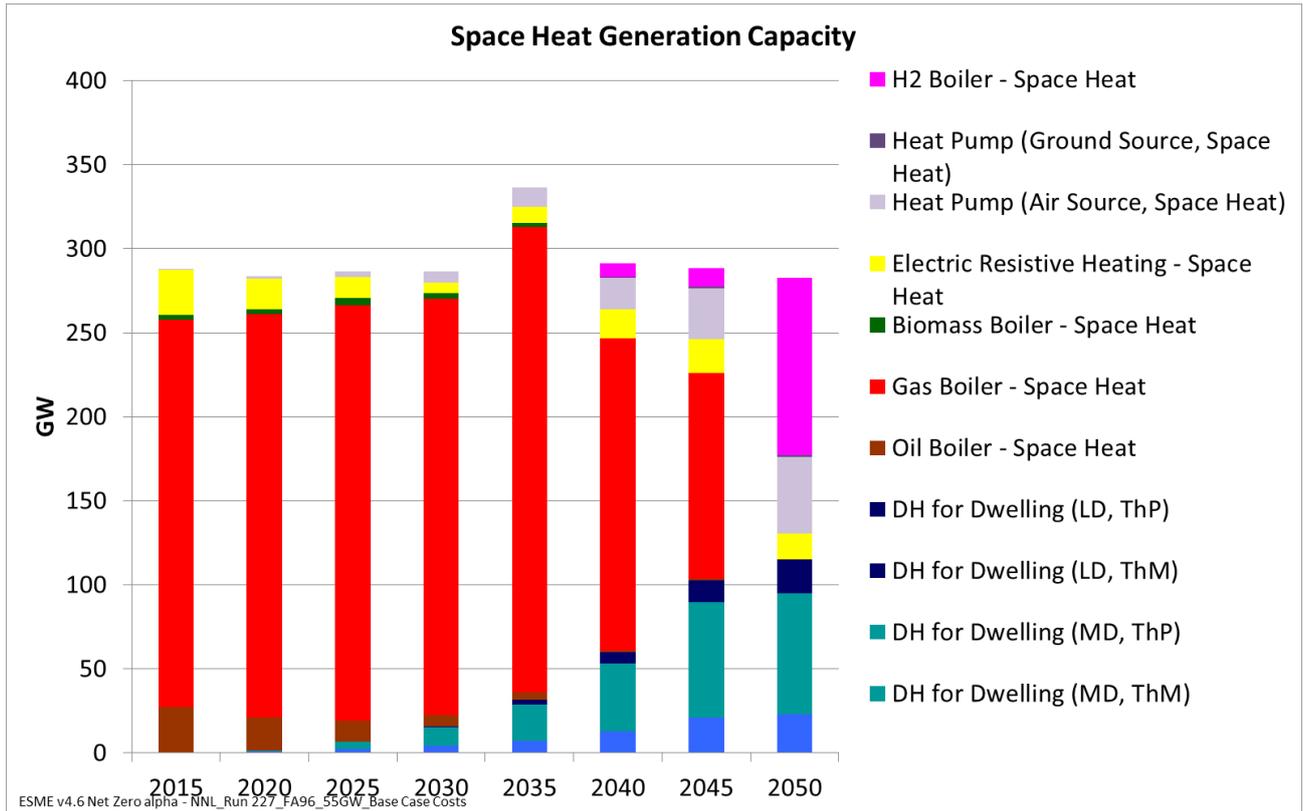**Figure A3-201 – Run 223 electricity generation**

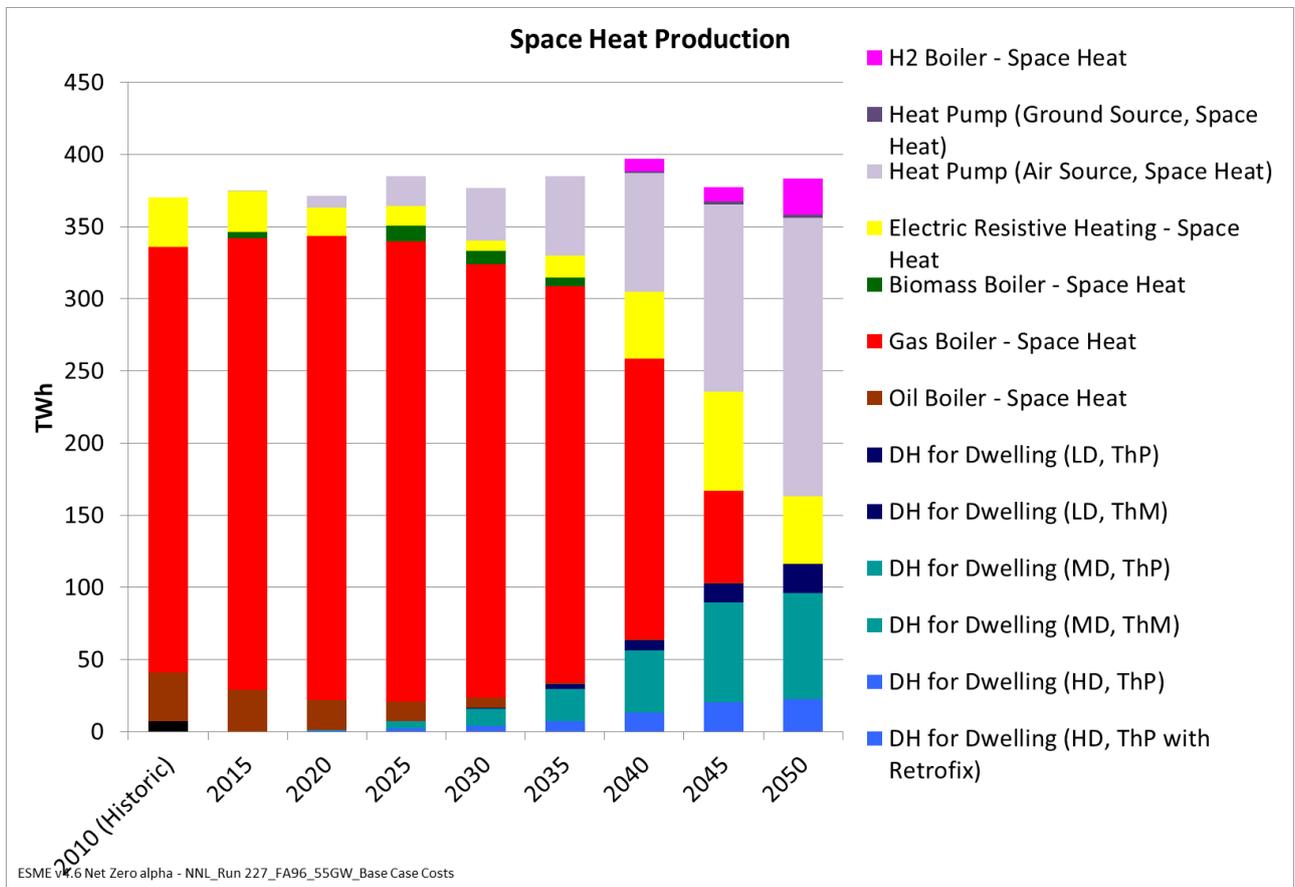Figure A3-202 – Run 223 space heat generation capacity

Figure A3-203 – Run 223 space heat production

Figure A3-204 – Run 223 hydrogen production

Figure A3-205 – Run 223 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 223_BoB_No DH_Base Case
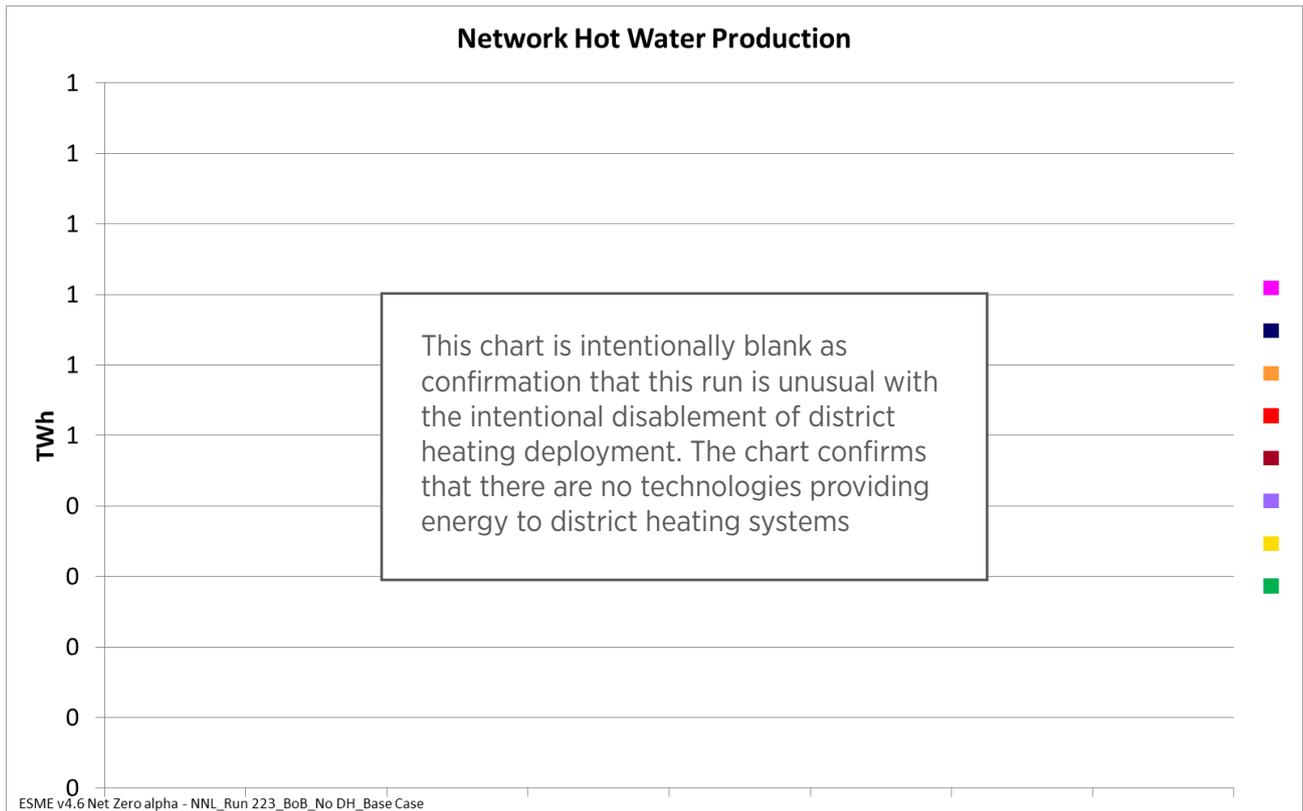
Figure A3-206 – Run 223 network hot water production

Figure A3-207 – Run 223 industry fuel consumption

Run 224 FA96 – No DH deployment; all nuclear technologies with LWSMR as electricity only; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data

Figure A3-208 – Run 224 primary resource consumption

Figure A3-209 – Run 224 electricity generation capacity

Figure A3-210 – Run 224 electricity generation

Figure A3-211 – Run 224 space heat generation capacity


Figure A3-212 – Run 224 space heat production
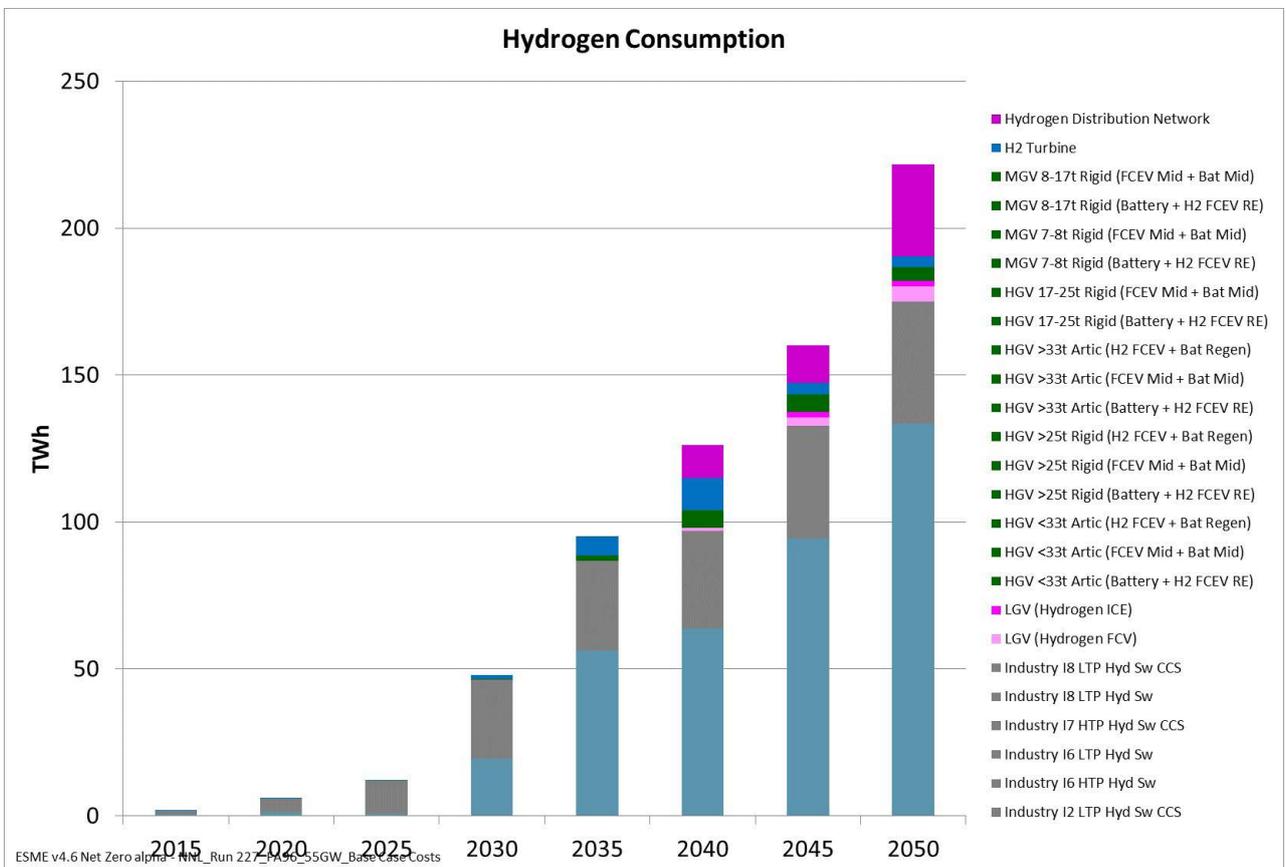
Figure A3-213 – Run 224 hydrogen production

Figure A3-214 – Run 224 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 224_FA96_55GW_No DH_Base Case Costs
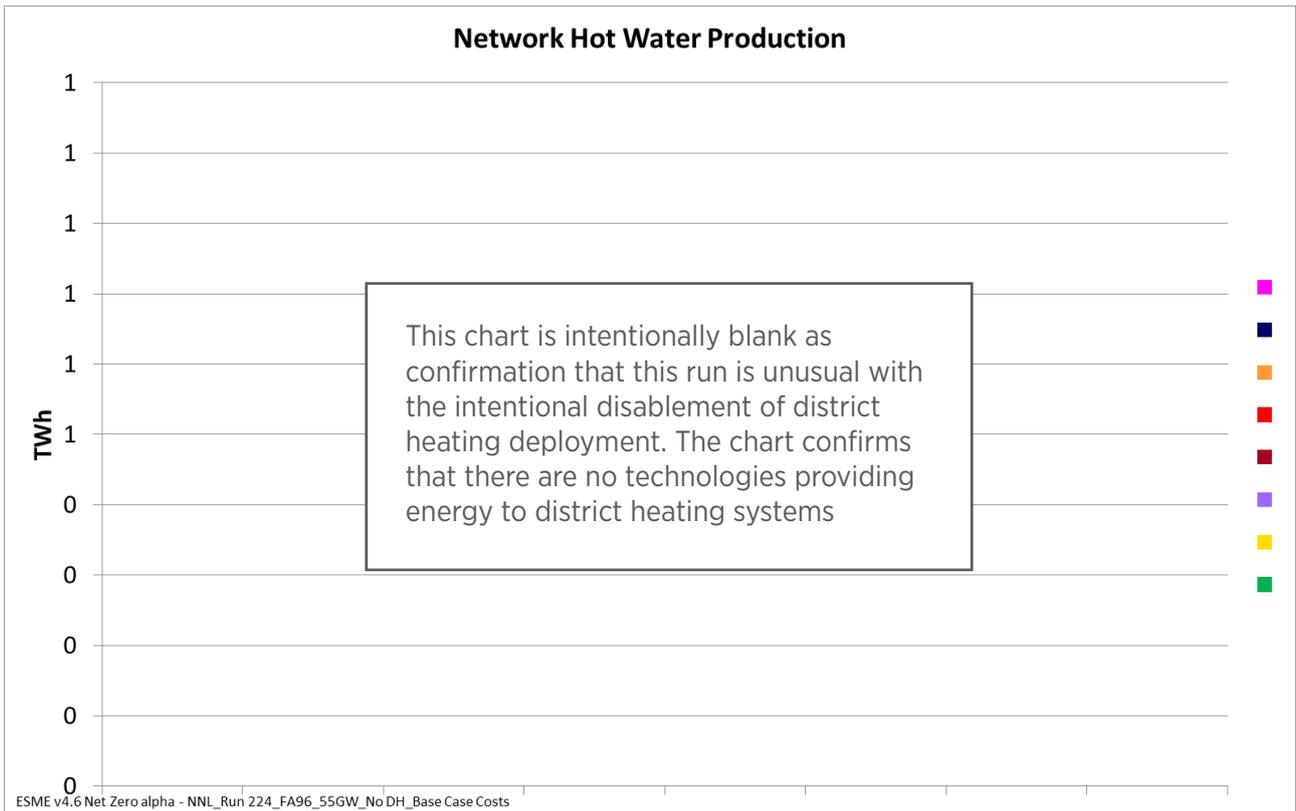
Figure A3-215 – Run 224 network hot water production

Figure A3-216 – Run 224 industry fuel consumption

Run 225 TECH100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data
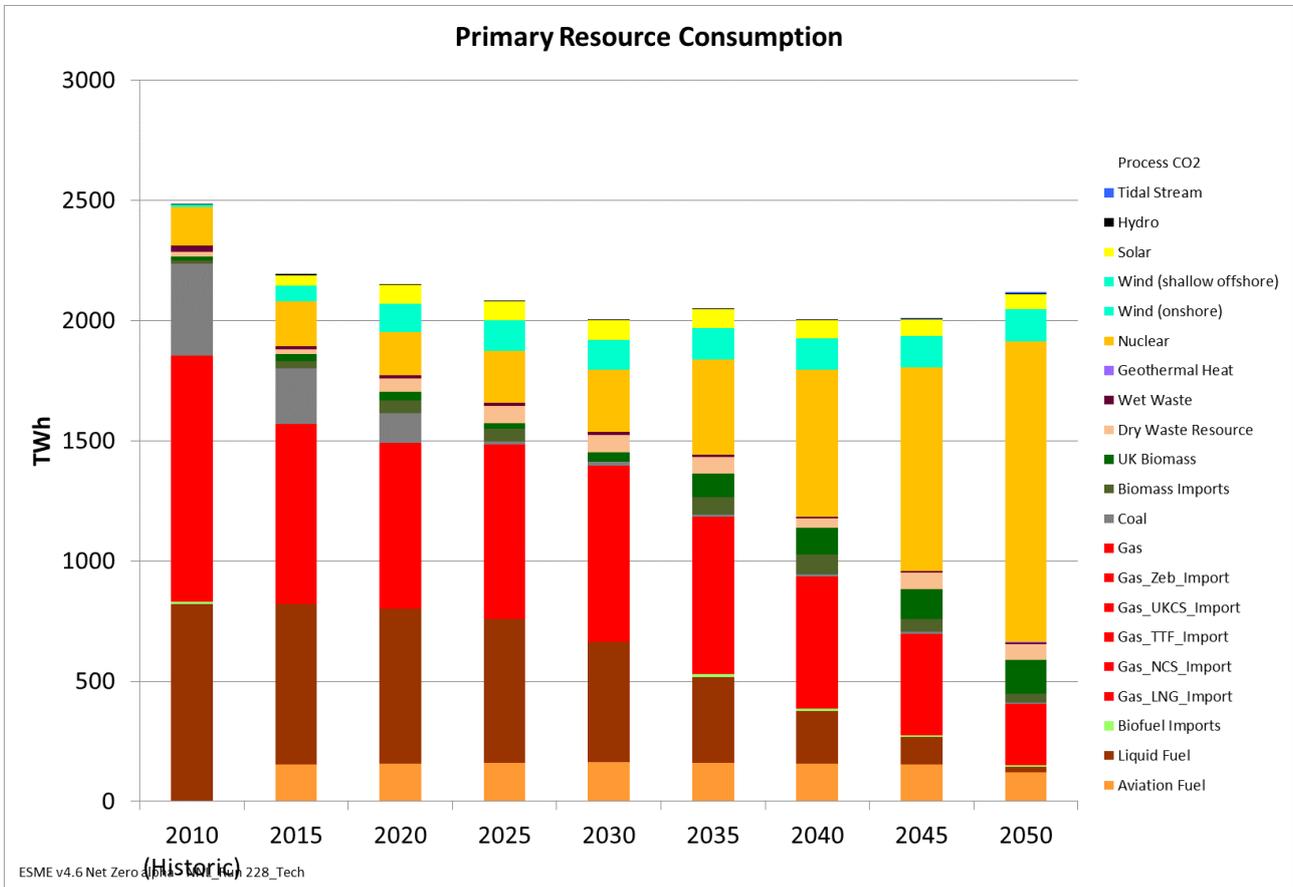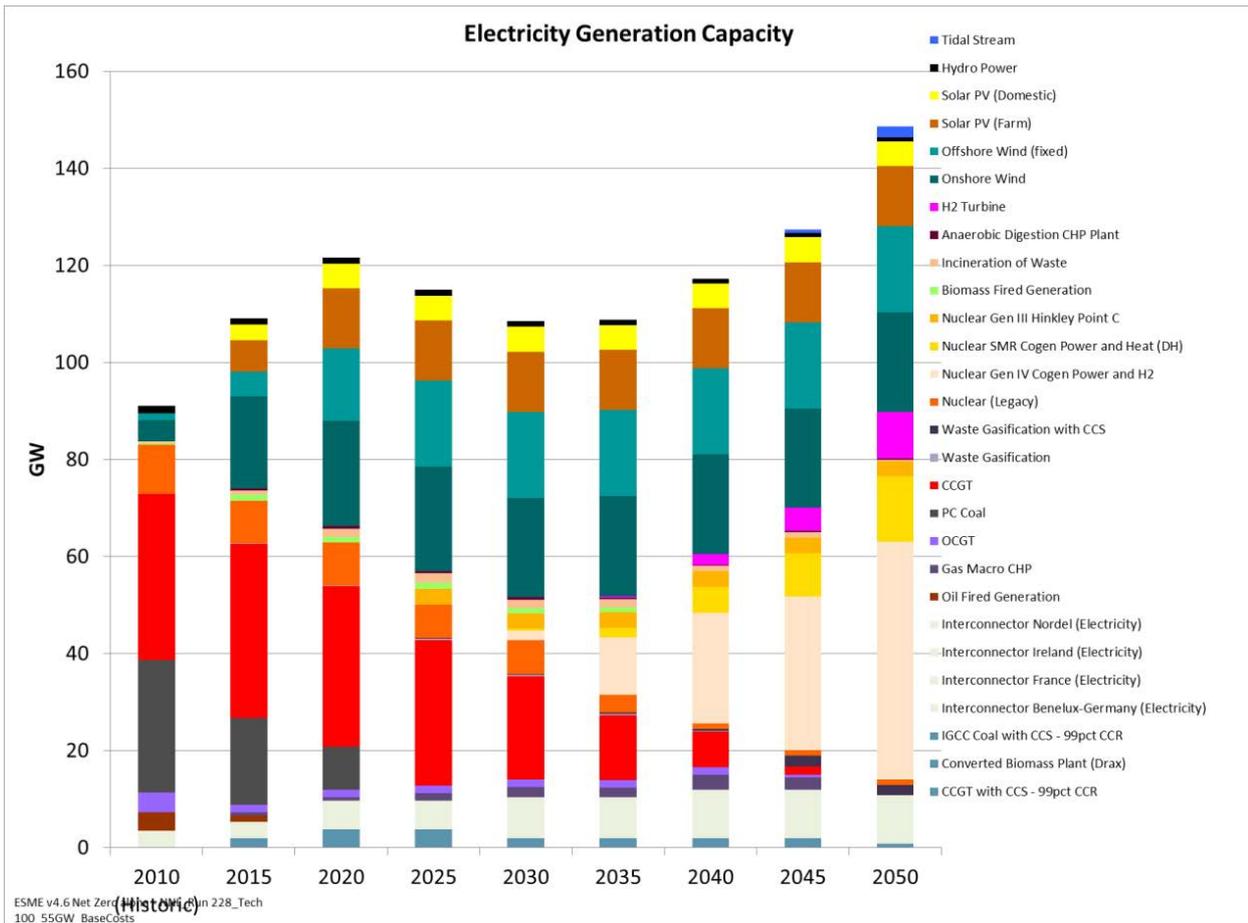

Figure A3-217 – Run 225 primary resource consumption

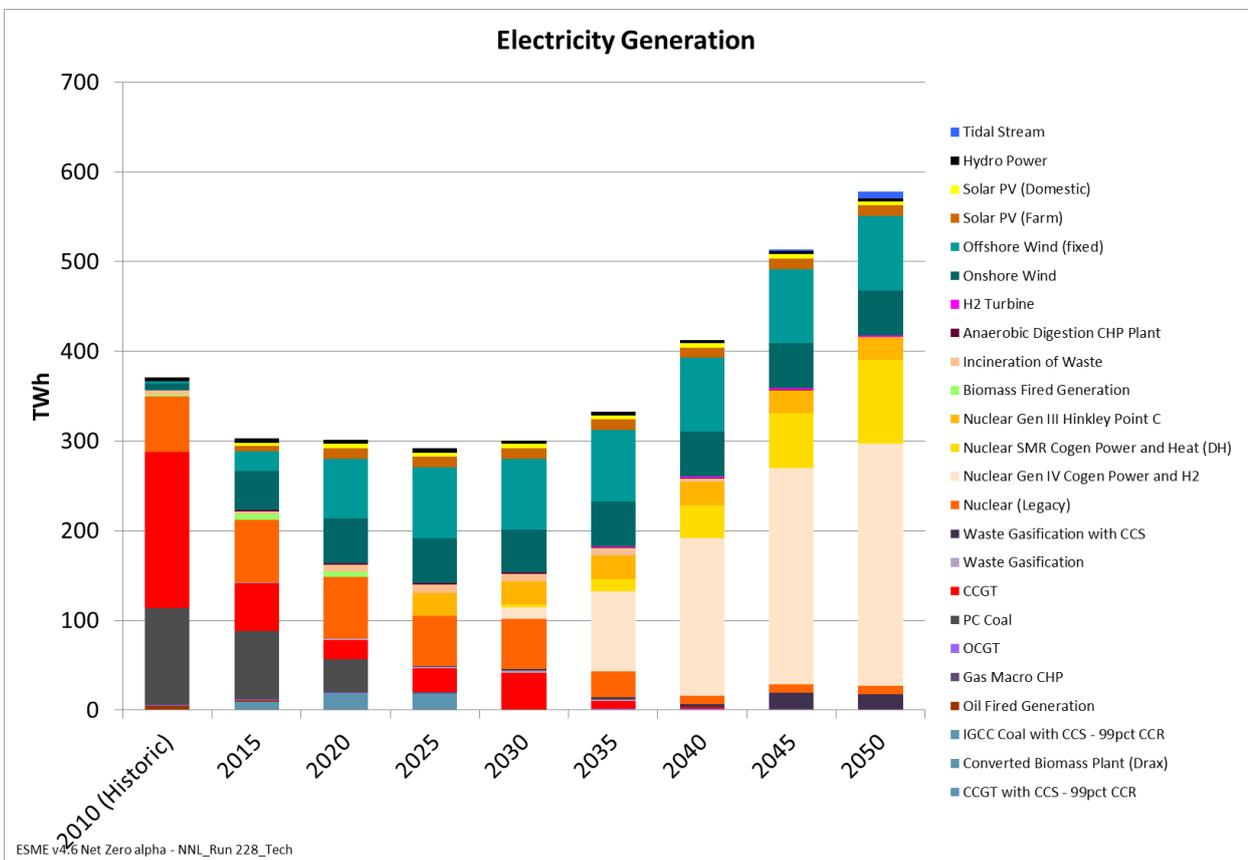Figure A3-218 – Run 225 electricity generation capacity
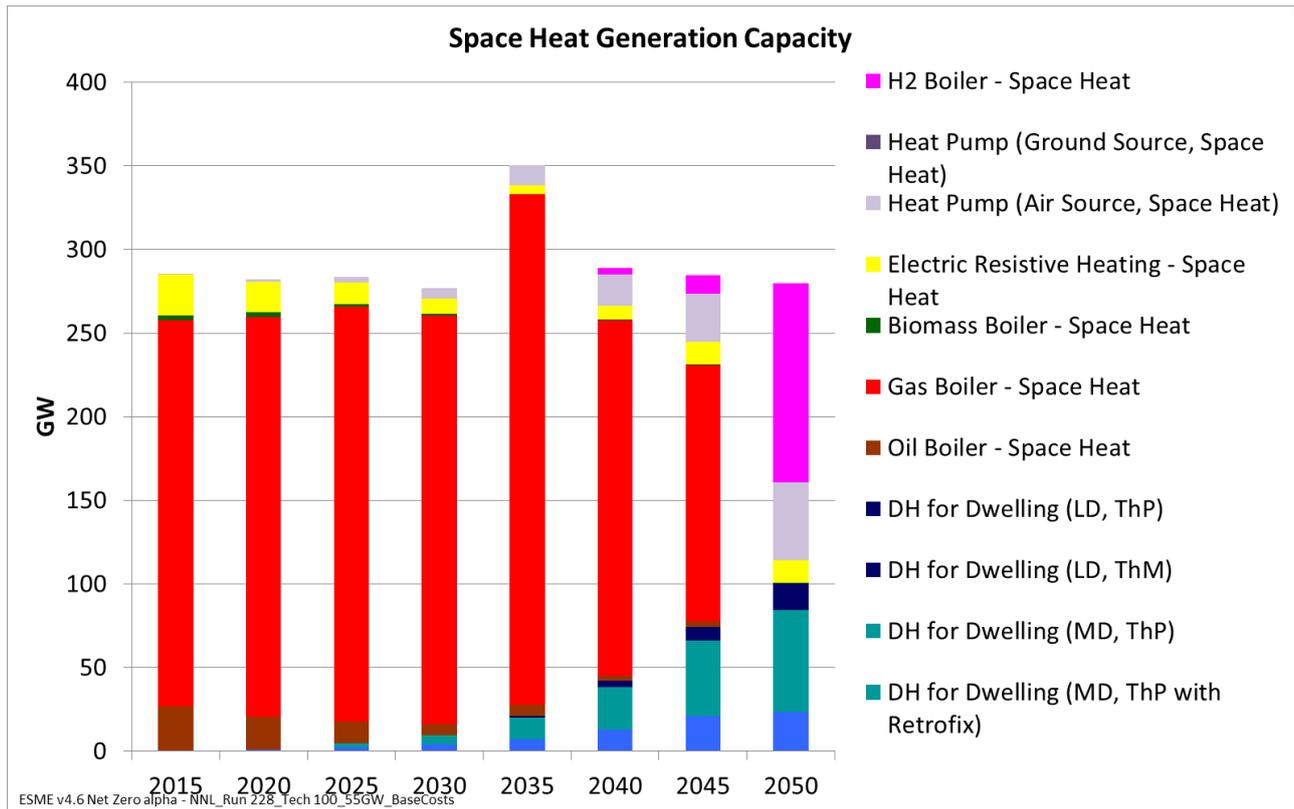

Figure A3-219 – Run 225 electricity generation
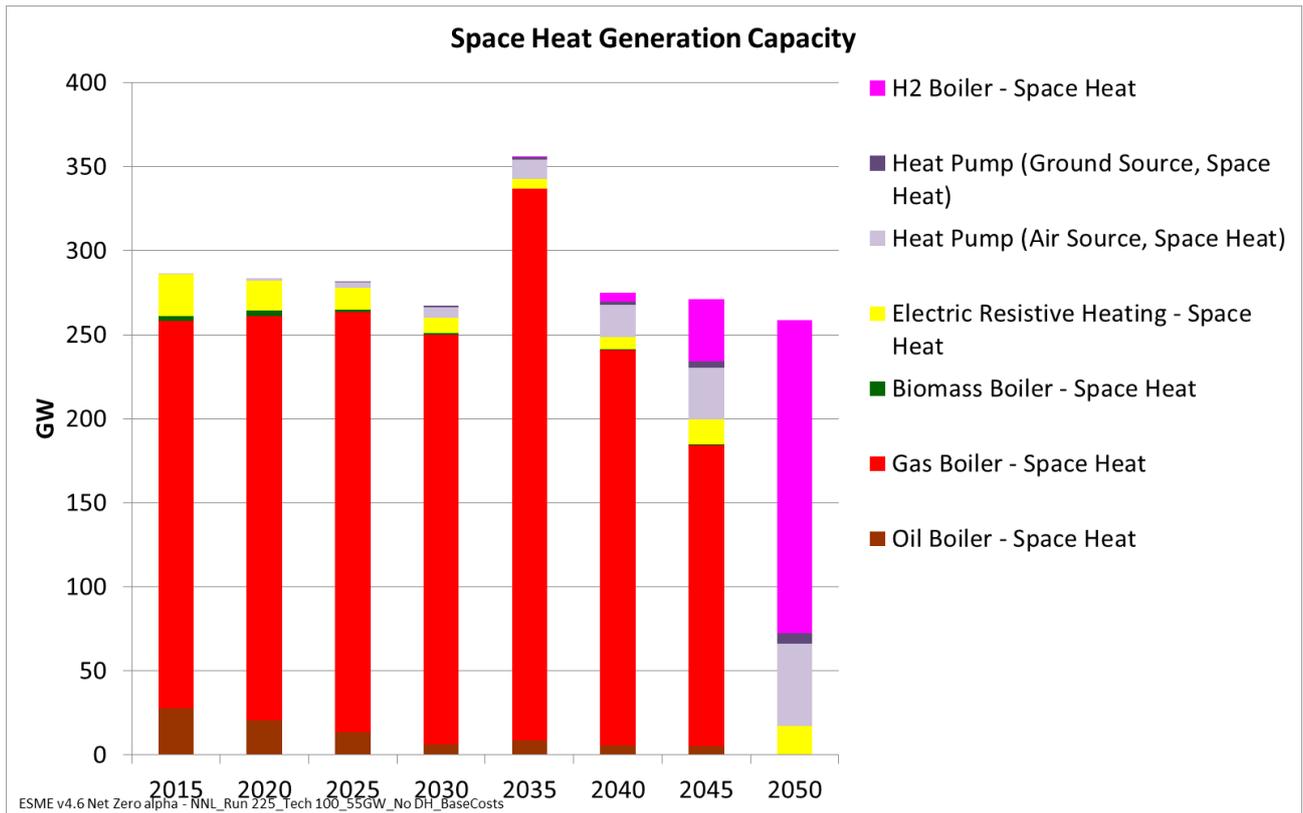
**Figure A3-220 – Run 225 space heat generation capacity**

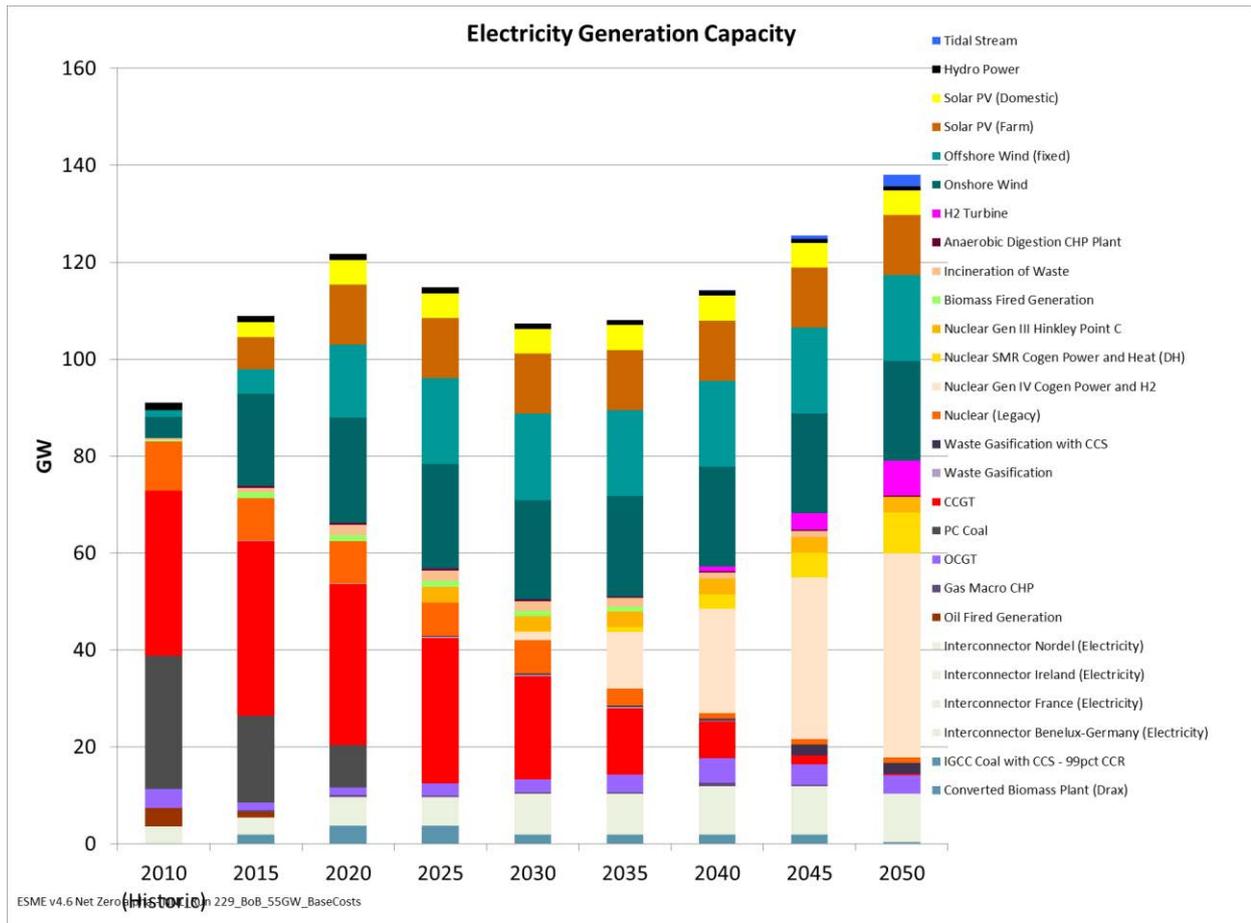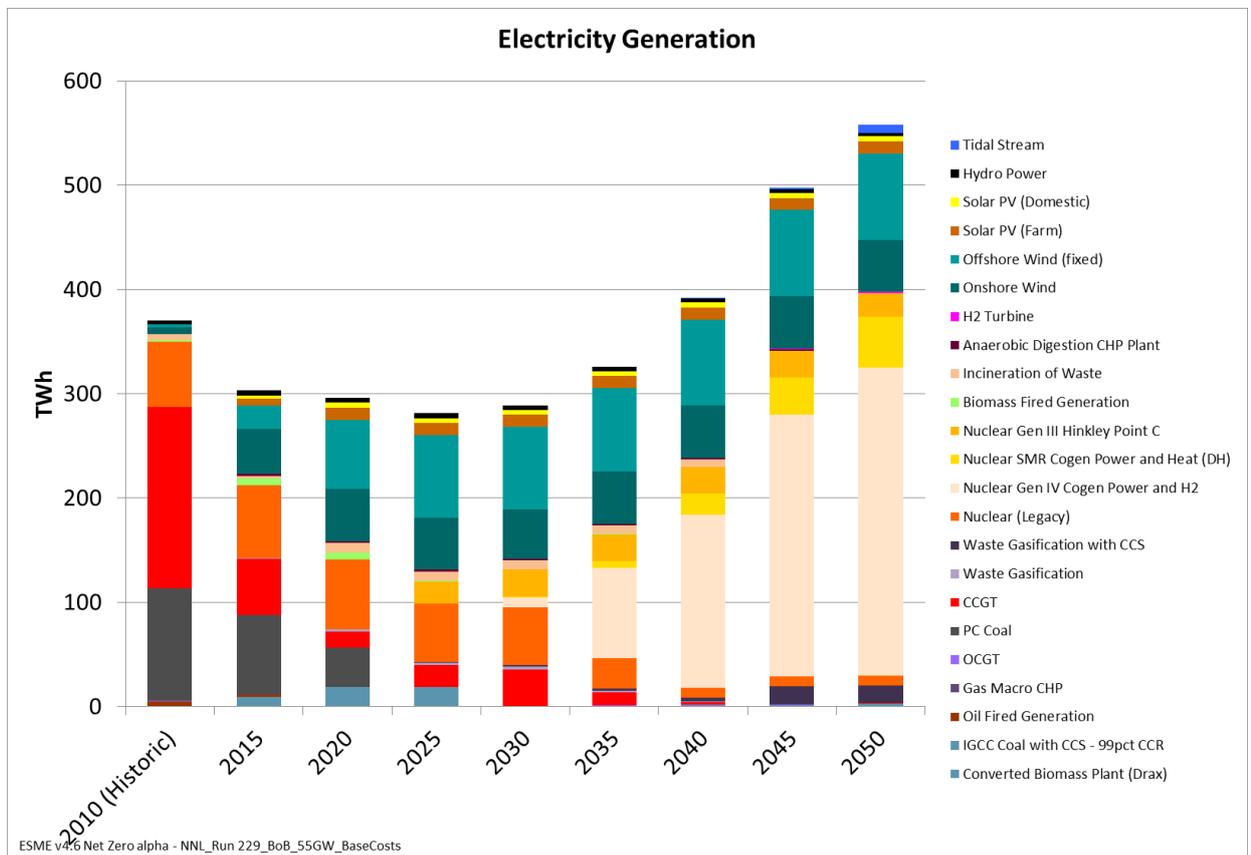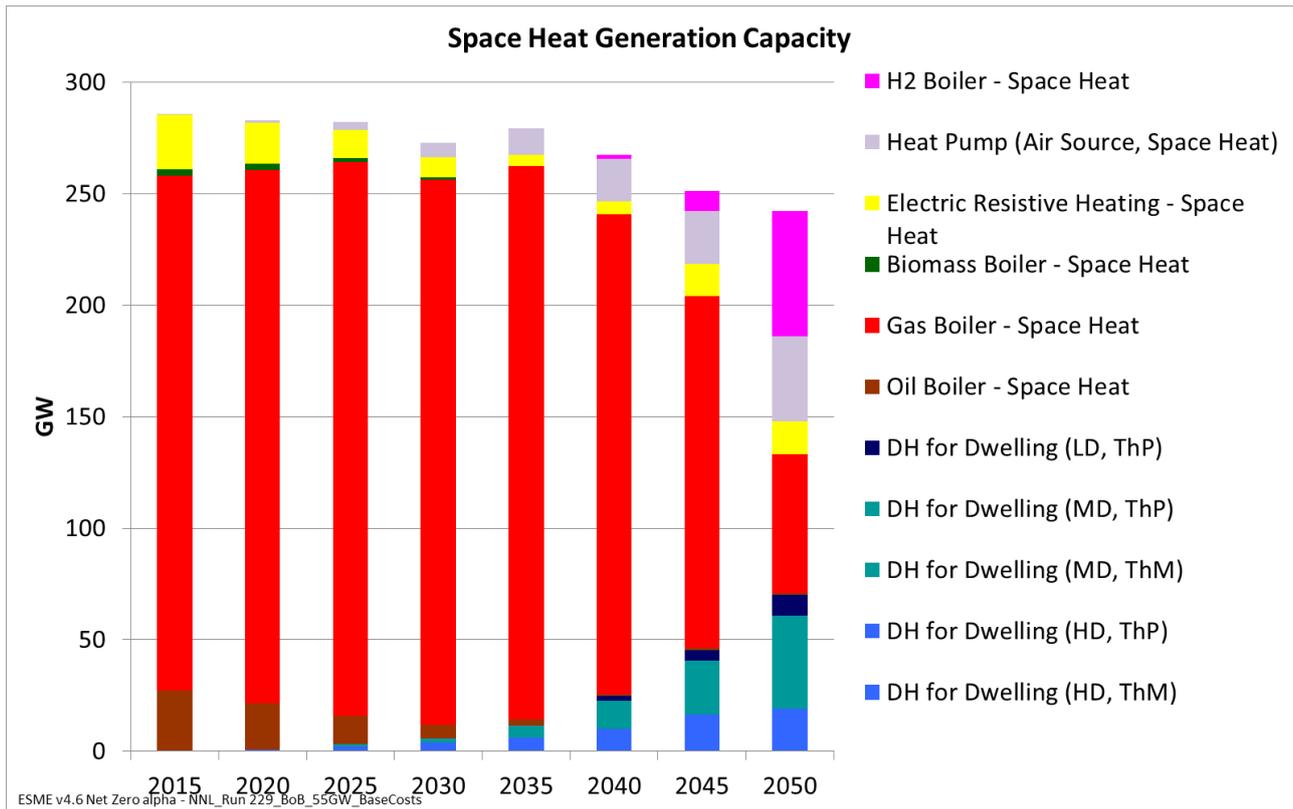**Figure A3-221 – Run 225 space heat production**

Hydrogen Production

Legend:
- Nuclear Gen IV Cogen Power and H2
- H2 Plant (Biomass Gasification with CCS)
- H2 Plant (SMR)
- H2 Plant (SMR with CCS) - 99pct CCR
- H2 Plant (Biomass Gasification with CCS) - 99pct CCR

ESME v4.6 Net Zero alpha – NNL_Run 225_Tech 100_55GW_No DH_BaseCosts

Figure A3-222 – Run 225 hydrogen production

Hydrogen Consumption

Legend:
- Hydrogen Distribution Network
- H2 Turbine
- MGV 8-17t Rigid (FCEV Mid + Bat Mid)
- MGV 8-17t Rigid (Battery + H2 FCEV RE)
- MGV 7-8t Rigid (FCEV Mid + Bat Mid)
- MGV 7-8t Rigid (Battery + H2 FCEV RE)
- HGV 17-25t Rigid (FCEV Mid + Bat Mid)
- HGV 17-25t Rigid (Battery + H2 FCEV RE)
- HGV >33t Artic (H2 FCEV + Bat Regen)
- HGV >33t Artic (FCEV Mid + Bat Mid)
- HGV >33t Artic (Battery + H2 FCEV RE)
- HGV >25t Rigid (H2 FCEV + Bat Regen)
- HGV >25t Rigid (FCEV Mid + Bat Mid)
- HGV >25t Rigid (Battery + H2 FCEV RE)
- HGV <33t Artic (H2 FCEV + Bat Regen)
- HGV <33t Artic (FCEV Mid + Bat Mid)
- HGV <33t Artic (Battery + H2 FCEV RE)
- LGV (Hydrogen ICE)
- LGV (Hydrogen FCV)
- Industry I7 HTP Hyd Sw CCS
- Industry I6 HTP Hyd Sw
- Wheeled Excavator (H2)
- Medium Wheel Loader (H2)
- Medium Articulated Truck (H2)
- Maritime (Ammonia International)

ESME v4.6 Net Zero alpha – NNL_Run 225_Tech 100_55GW_No DH_BaseCosts

Figure A3-223 – Run 225 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 225_Tech 100_55GW_No DH_BaseCosts
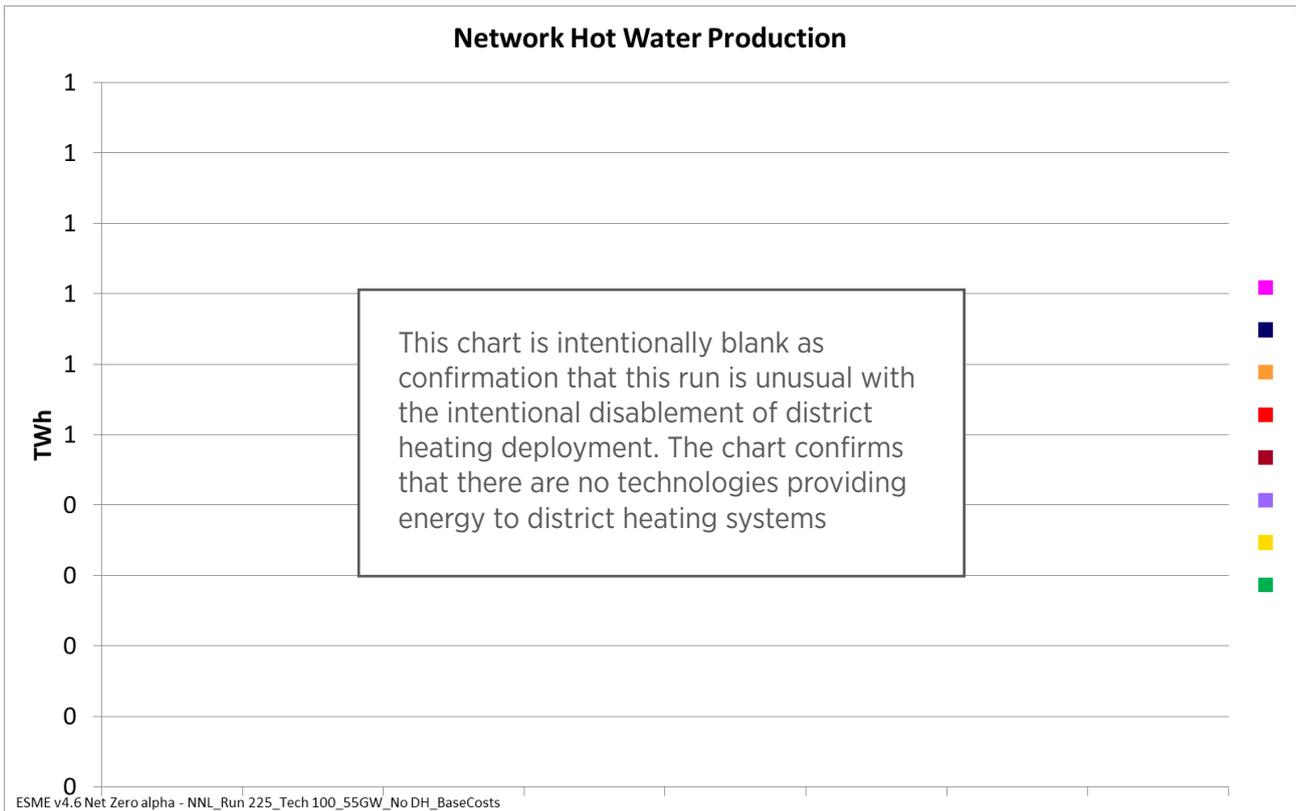
Figure A3-224 – Run 225 network hot water production
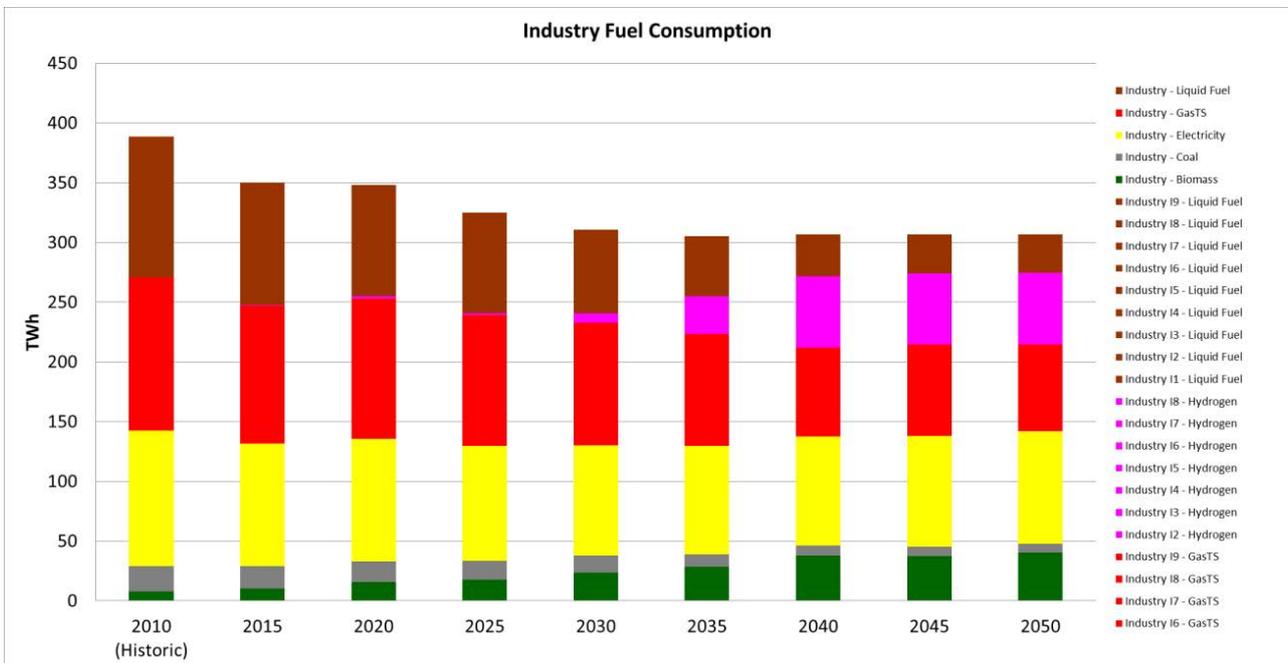
Figure A3-225 – Run 225 industry fuel consumption

Run 226 BOB100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data
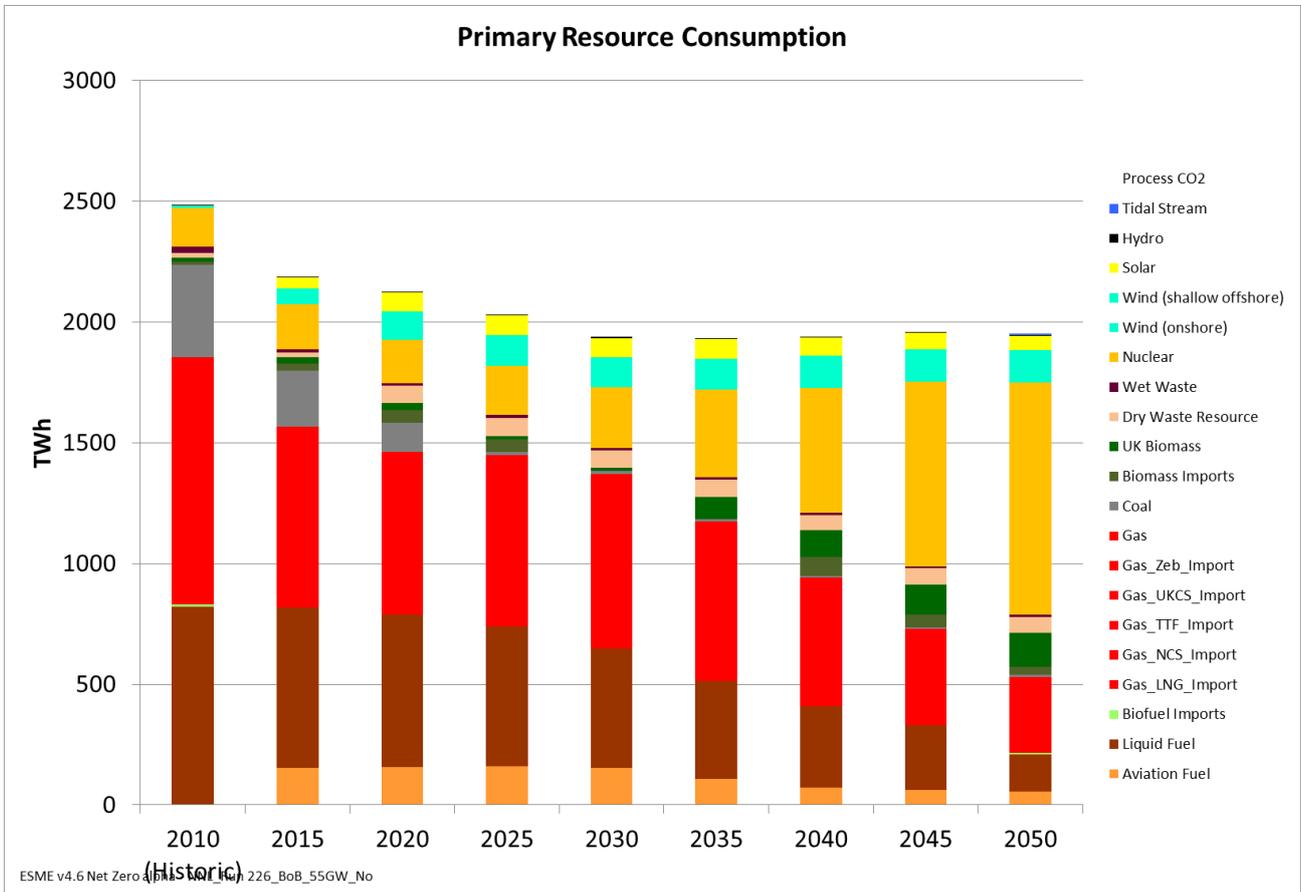
Figure A3-226 – Run 226 primary resource consumption
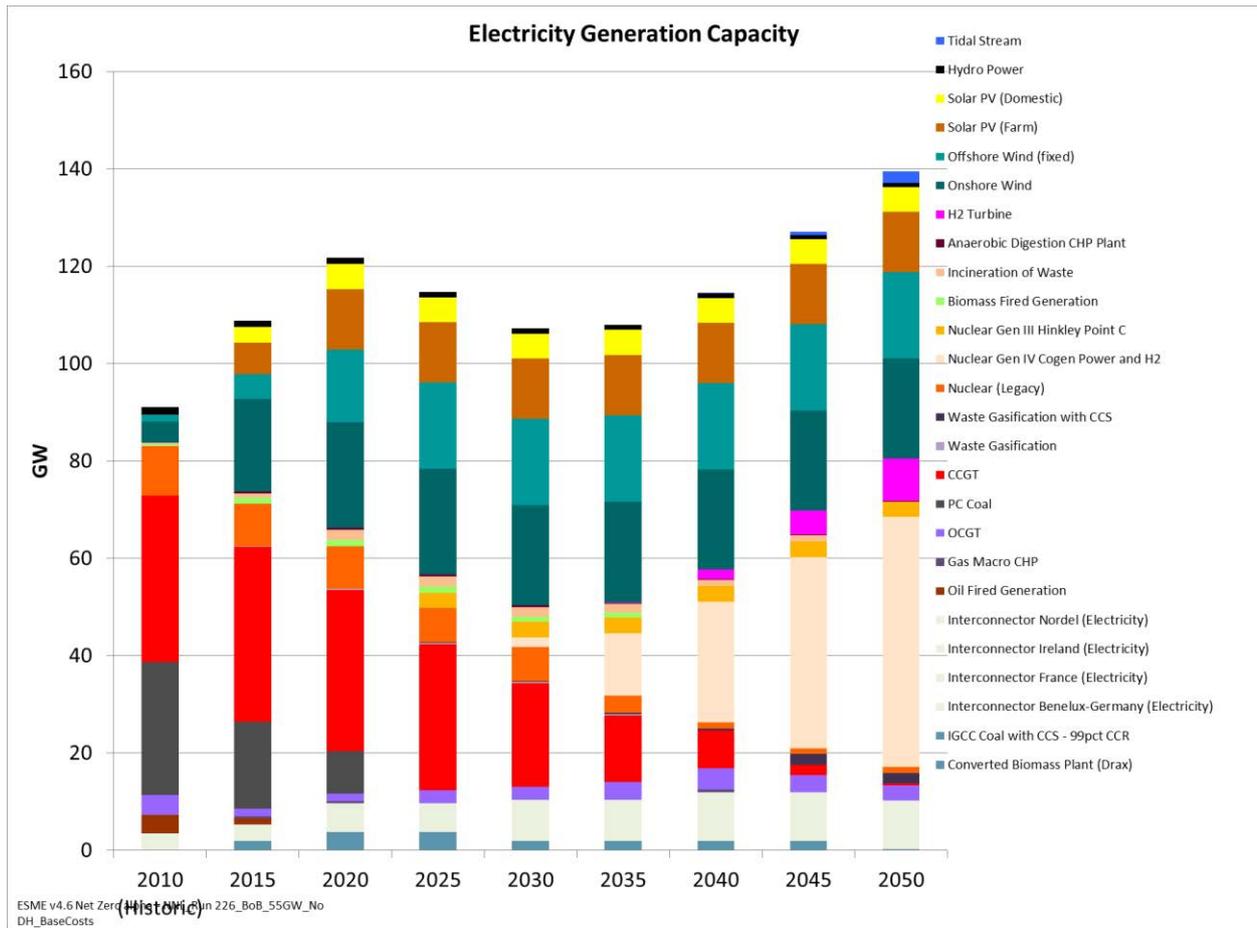
Figure A3-227 – Run 226 electricity generation capacity
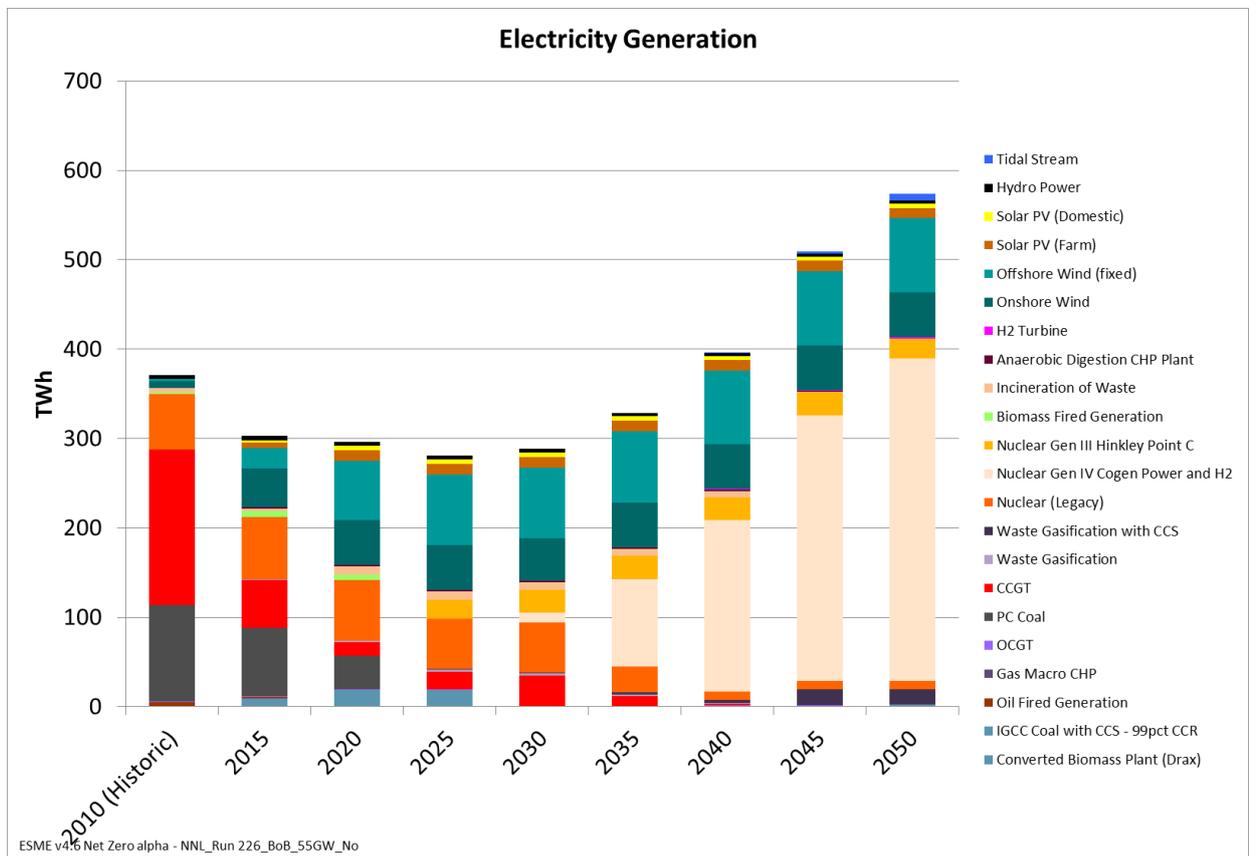
Figure A3-228 – Run 226 electricity generation
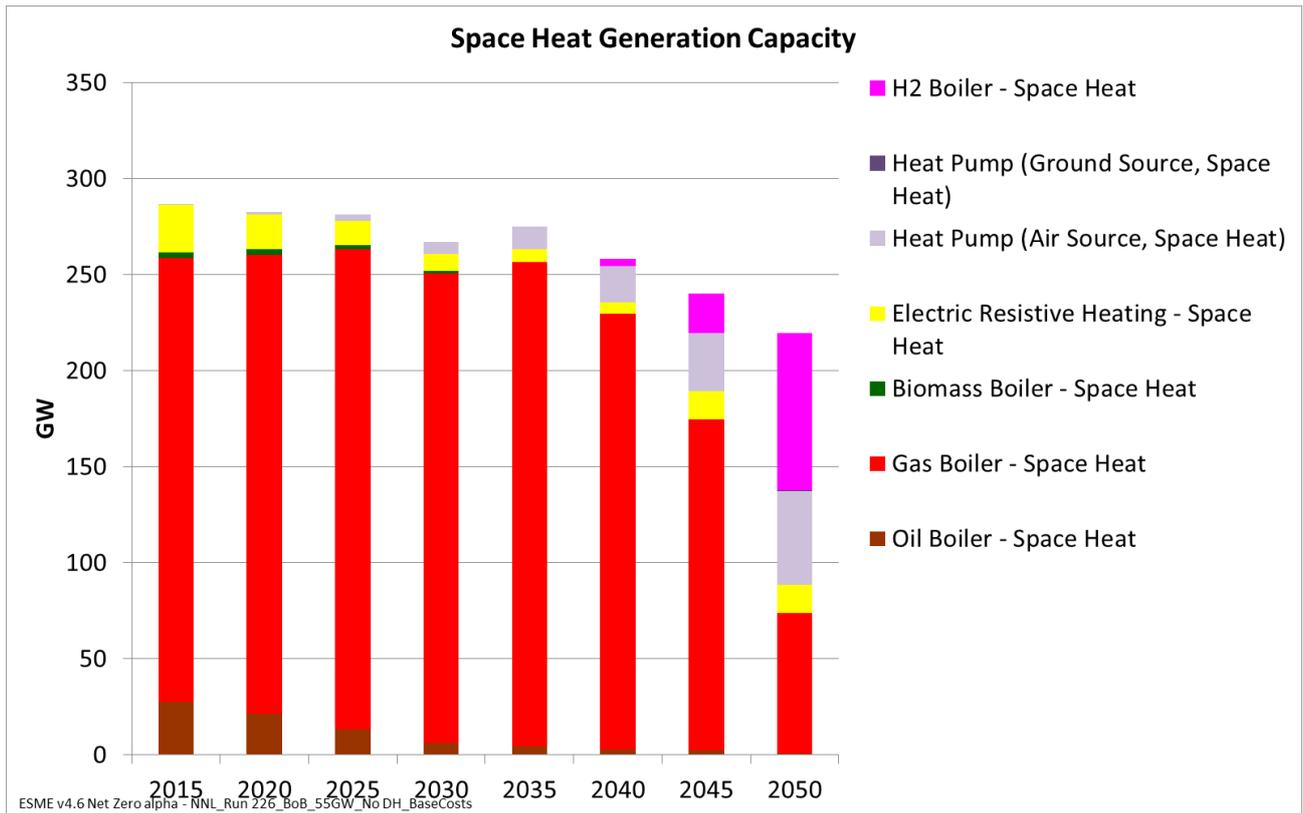
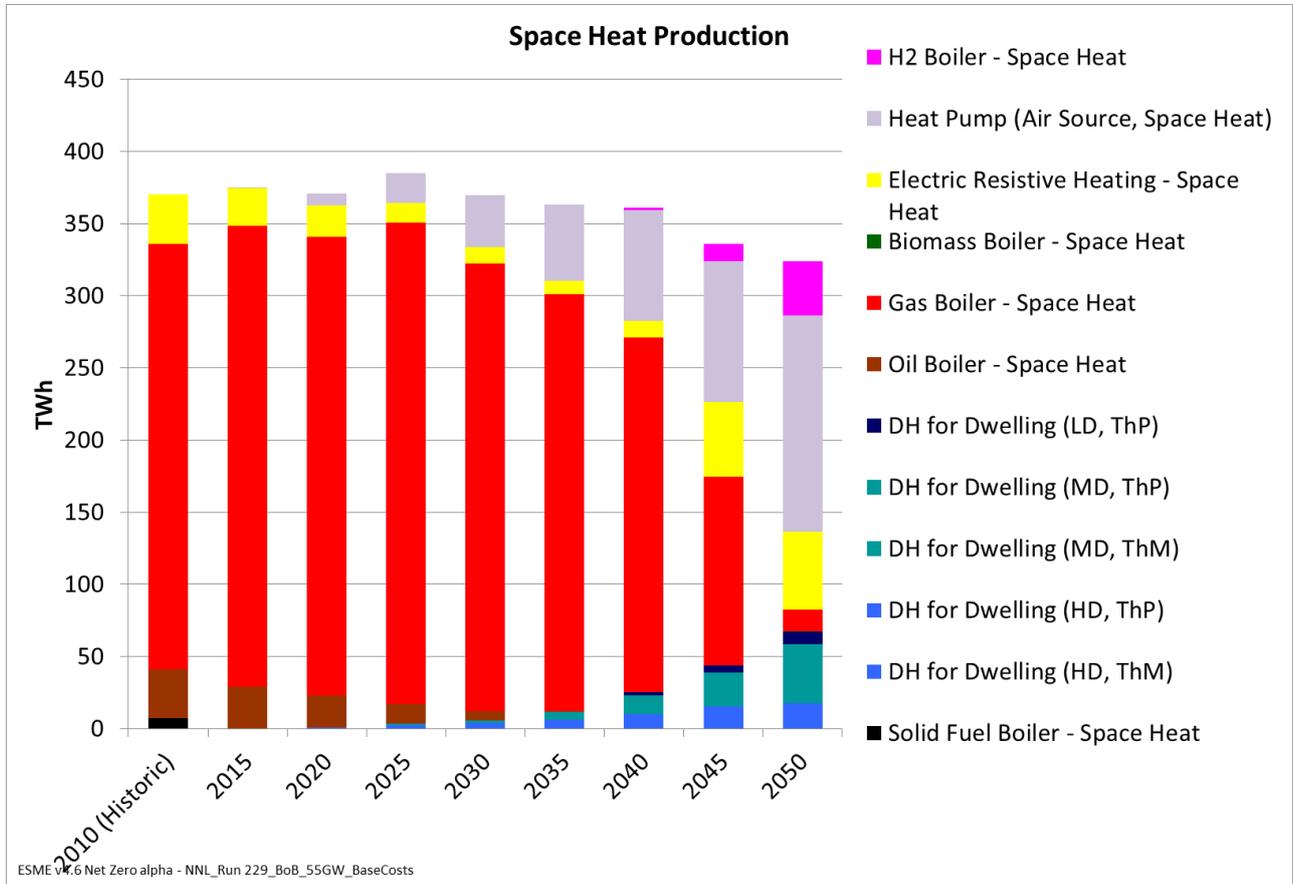Figure A3-229 – Run 226 space heat generation capacity


Figure A3-230 – Run 226 space heat production
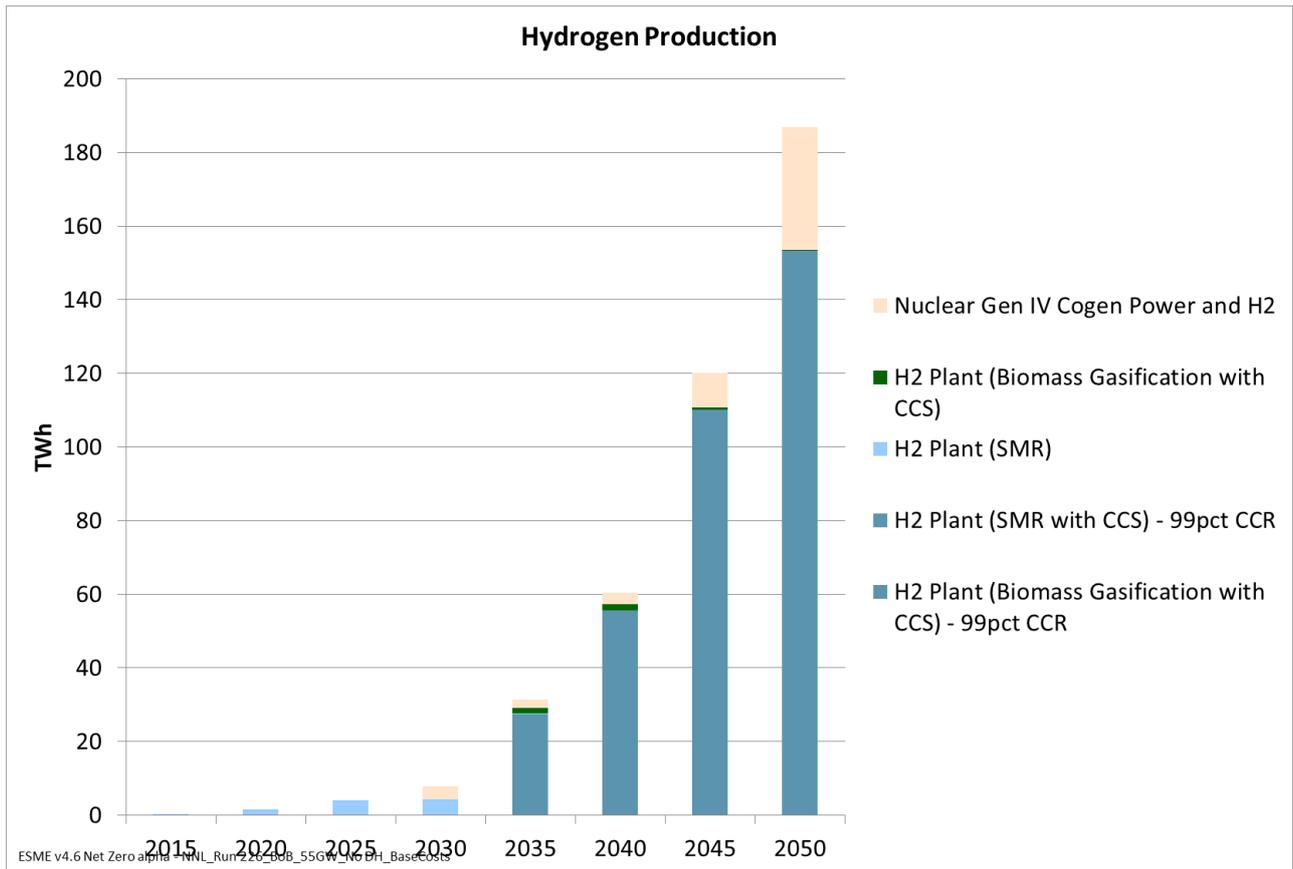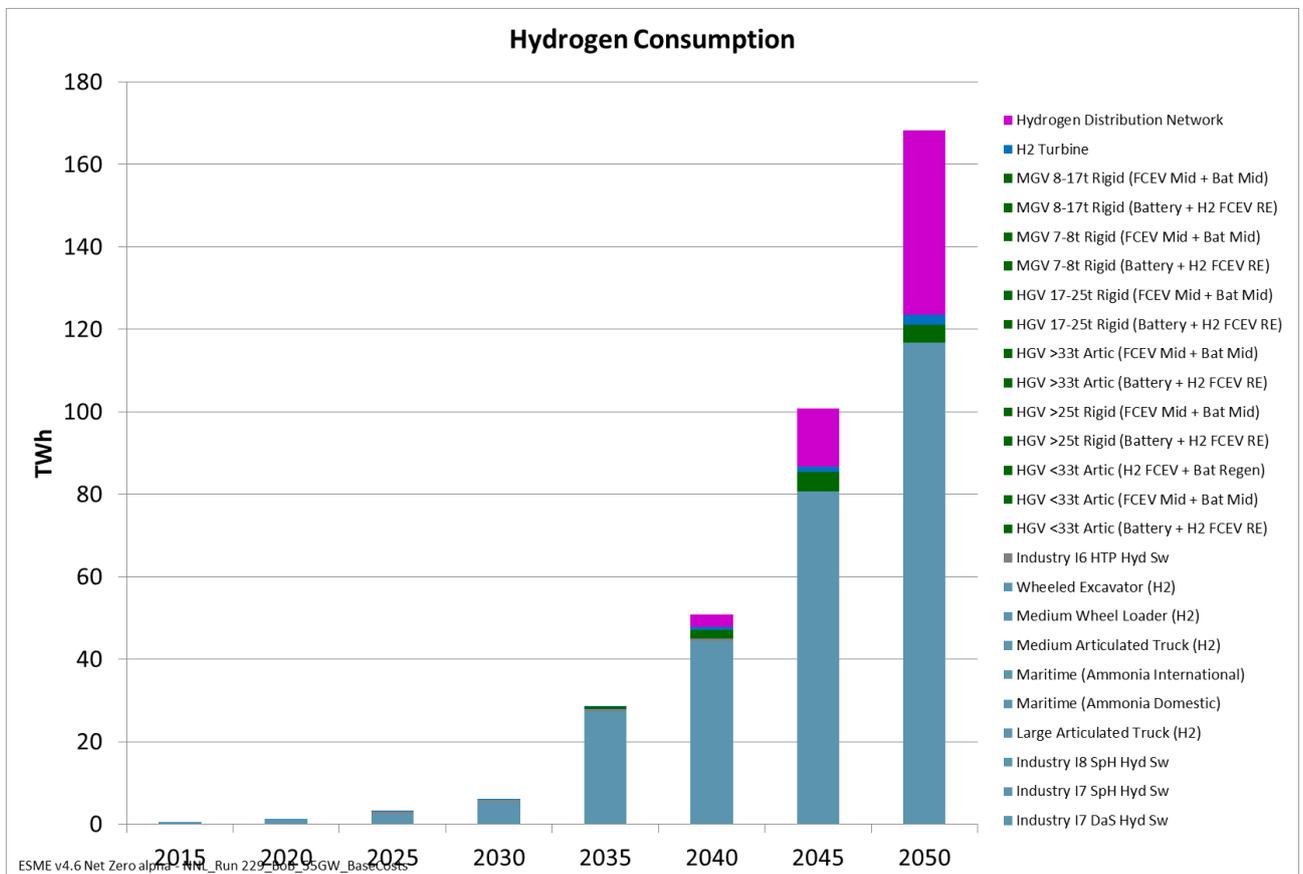
Figure A3-231 – Run 226 hydrogen production

Figure A3-232 – Run 226 hydrogen consumption

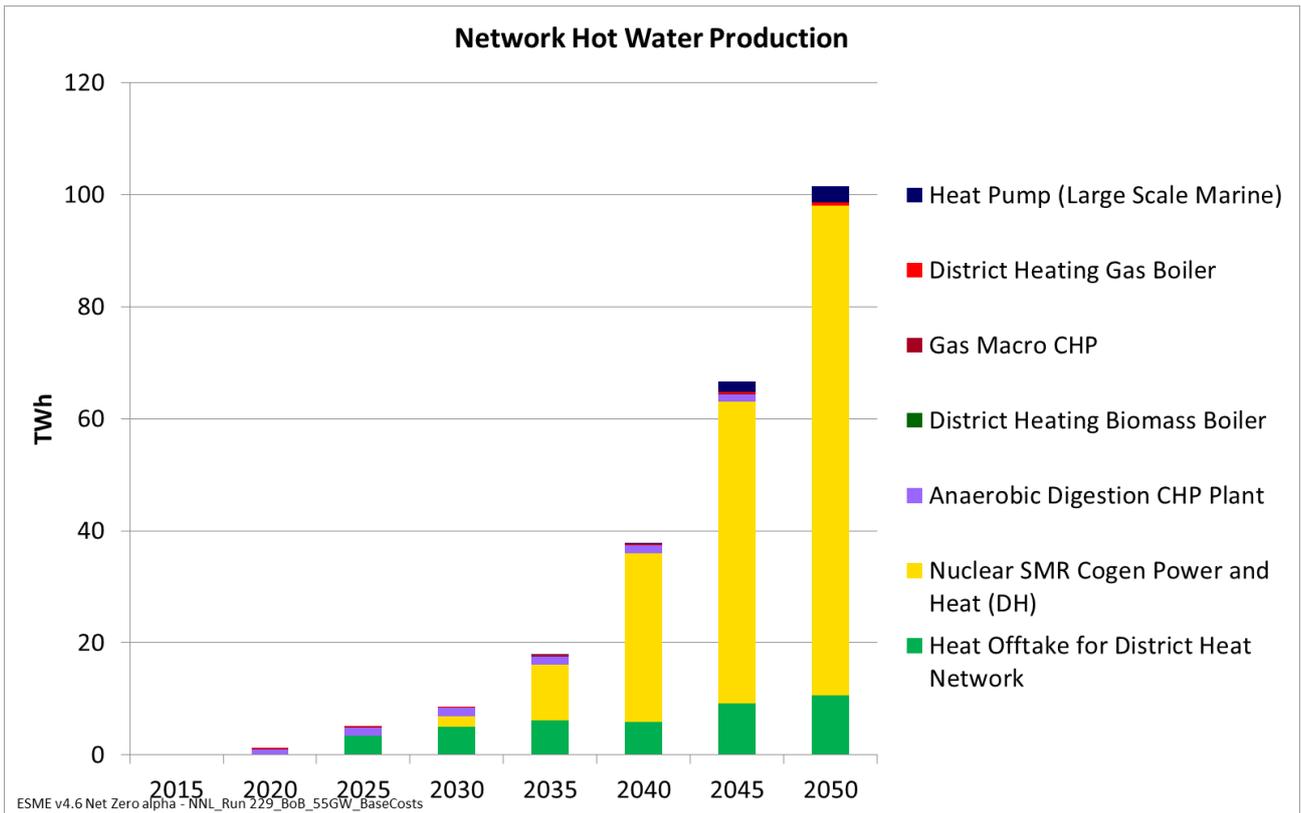## Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 226_BoB_55GW_No DH_BaseCosts
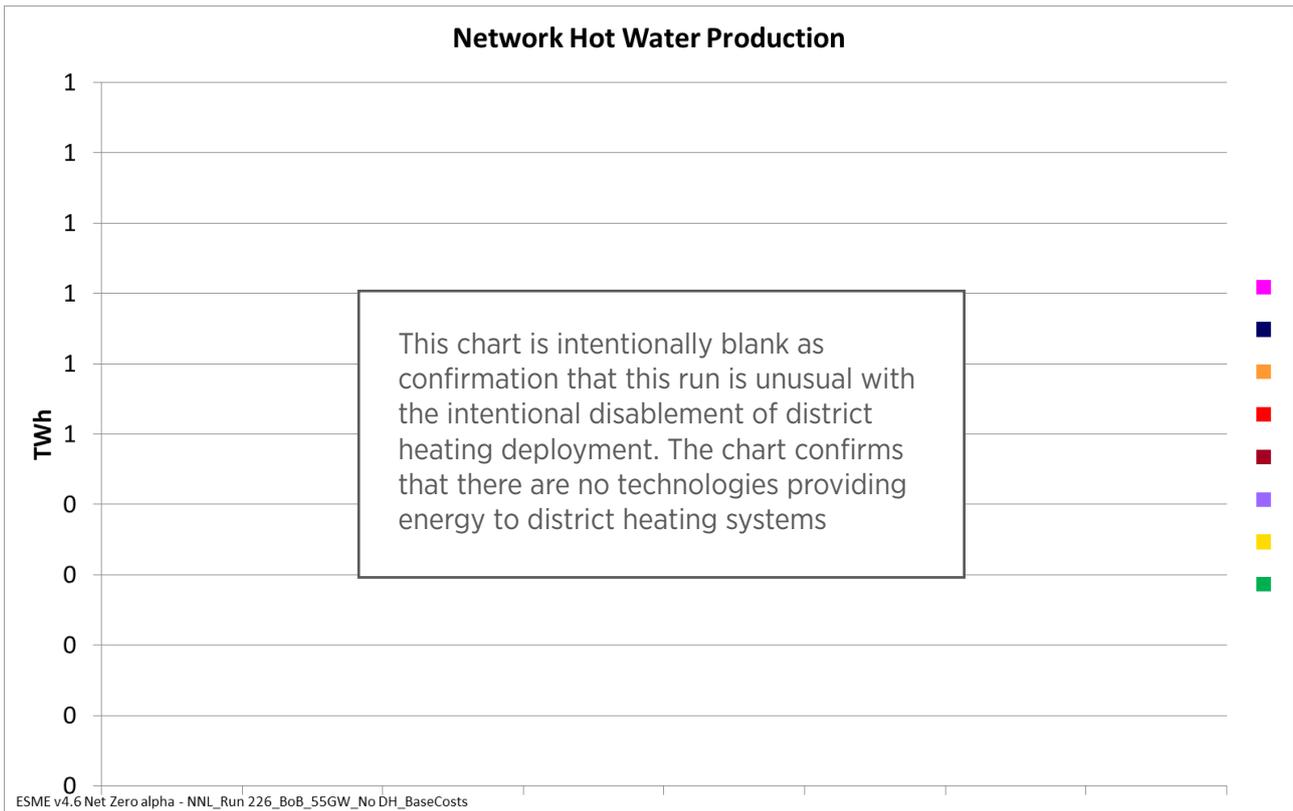
Figure A3-233 – Run 226 network hot water production
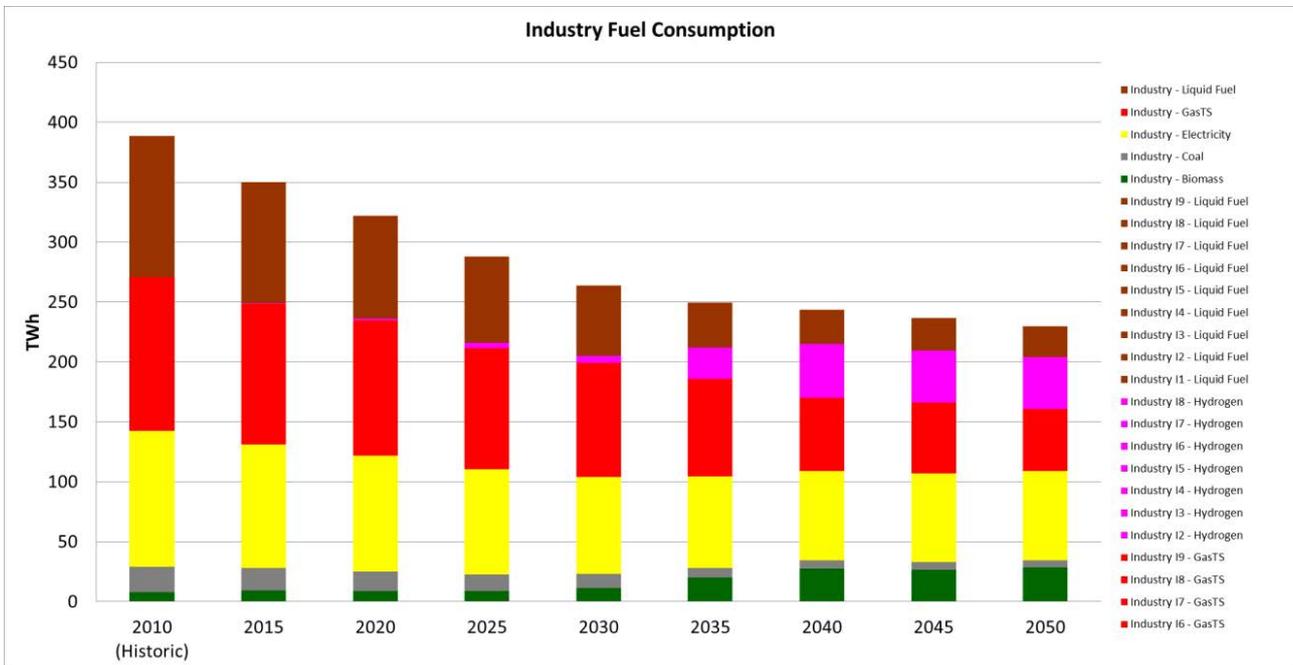
Figure A3-234 – Run 226 industry fuel consumption

Run 227 FA96 – DH deployment re-enabled; all nuclear technologies with LWSMR as cogen power and heat; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data
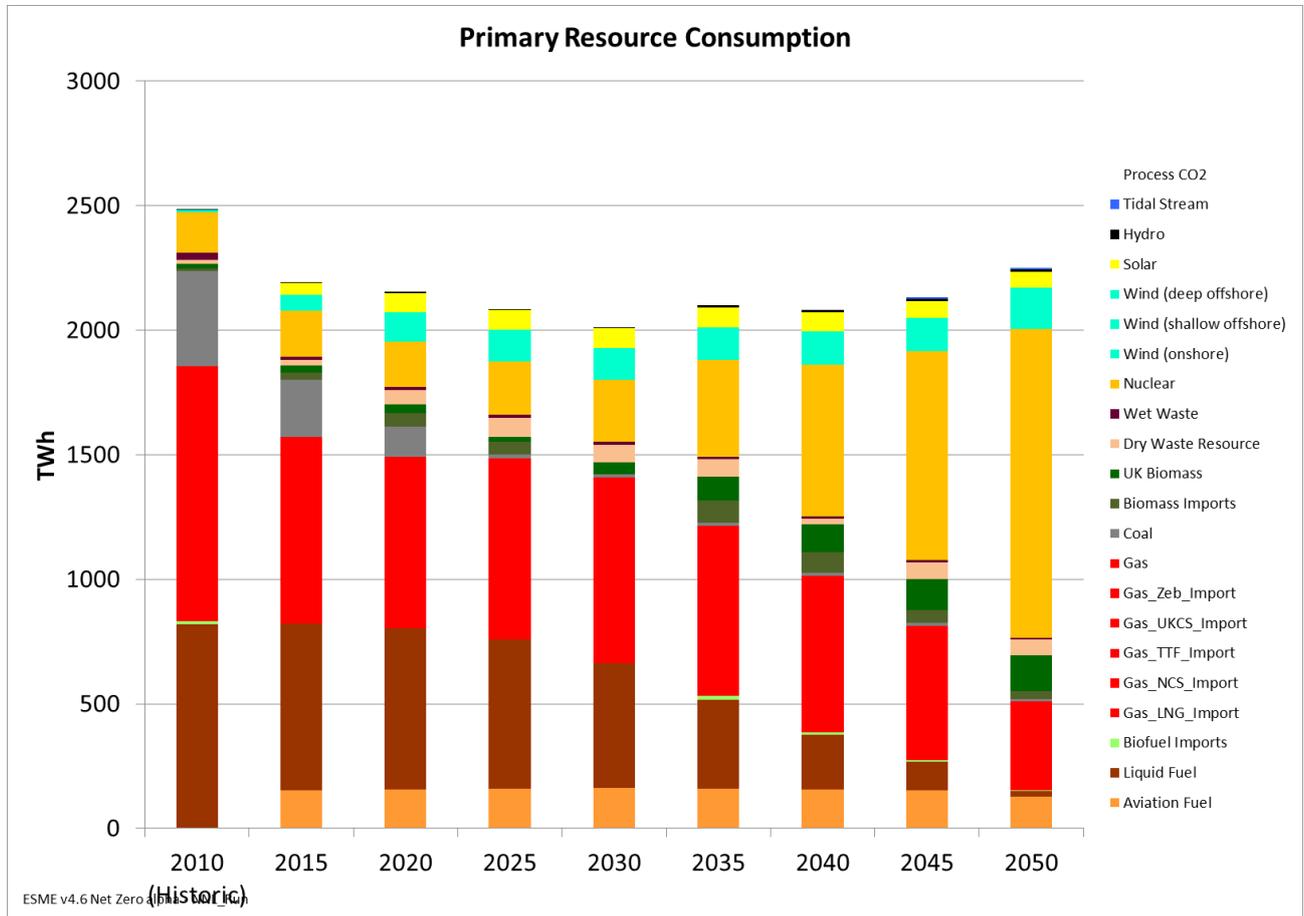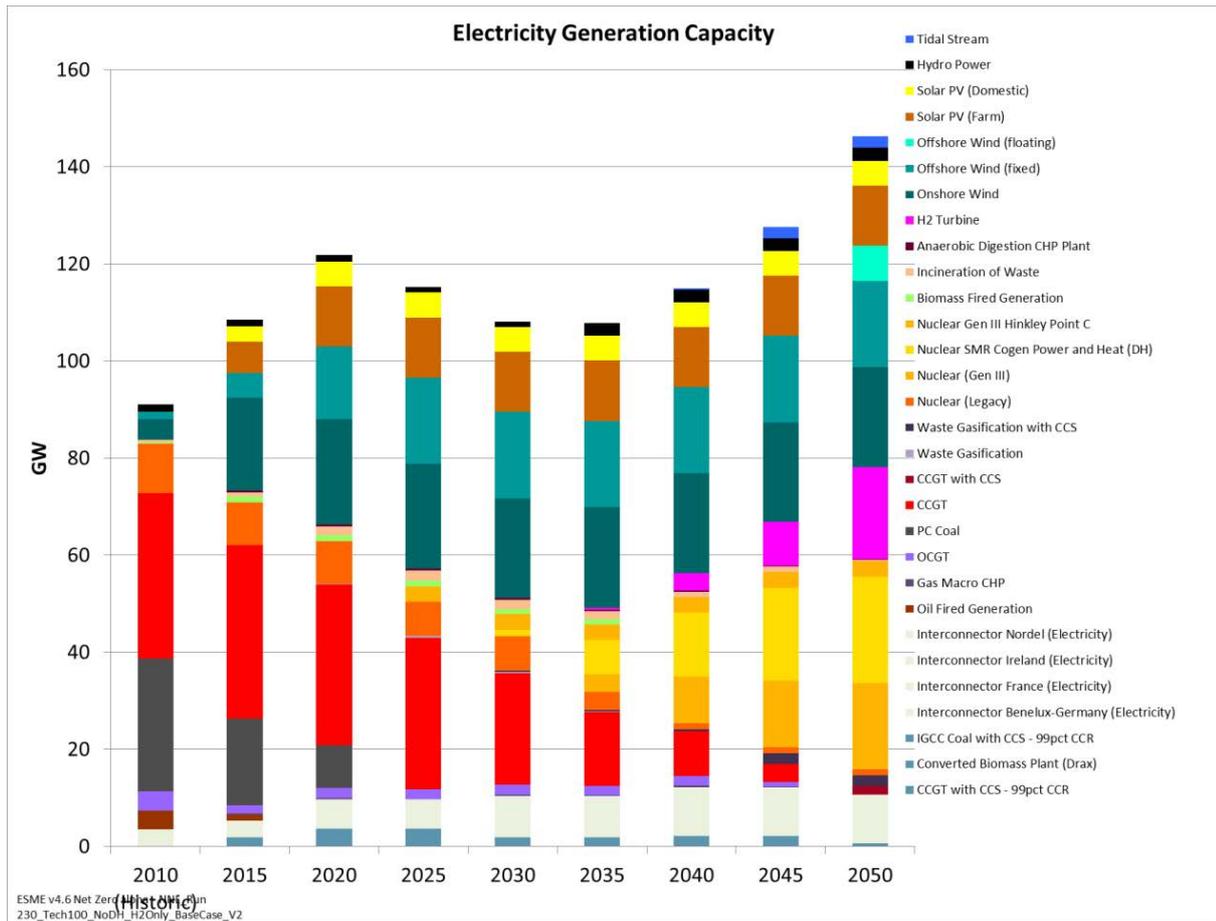

Figure A3-235 – Run 227 primary resource consumption

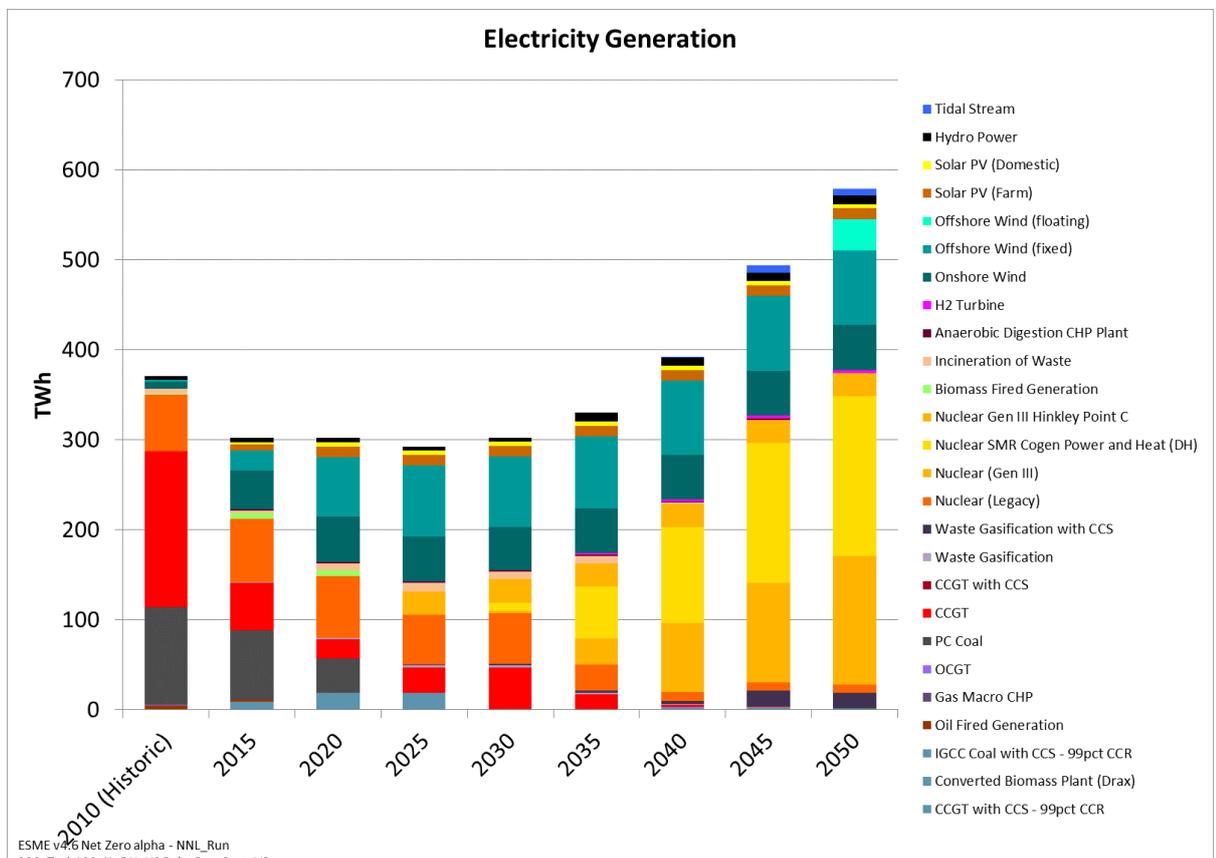Figure A3-236 – Run 227 electricity generation capacity
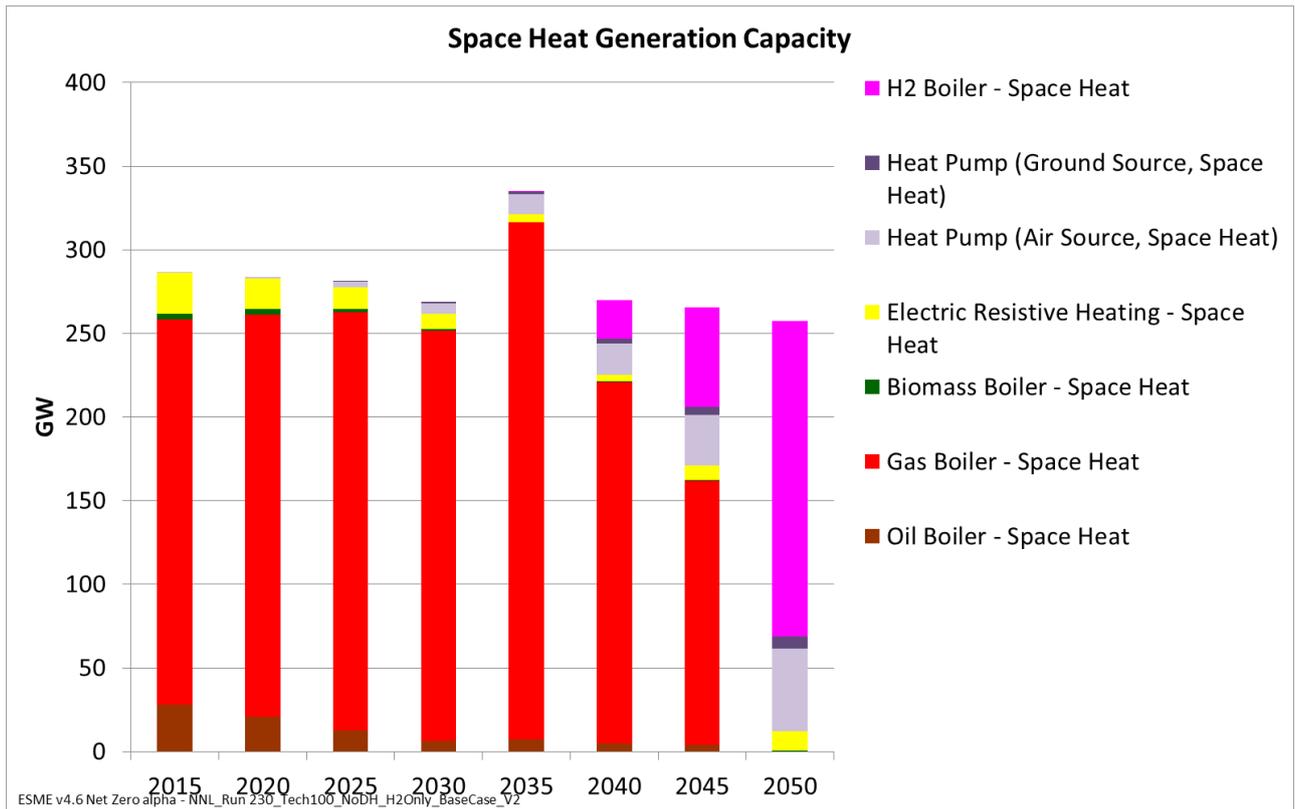

Figure A3-237 – Run 227 electricity generation

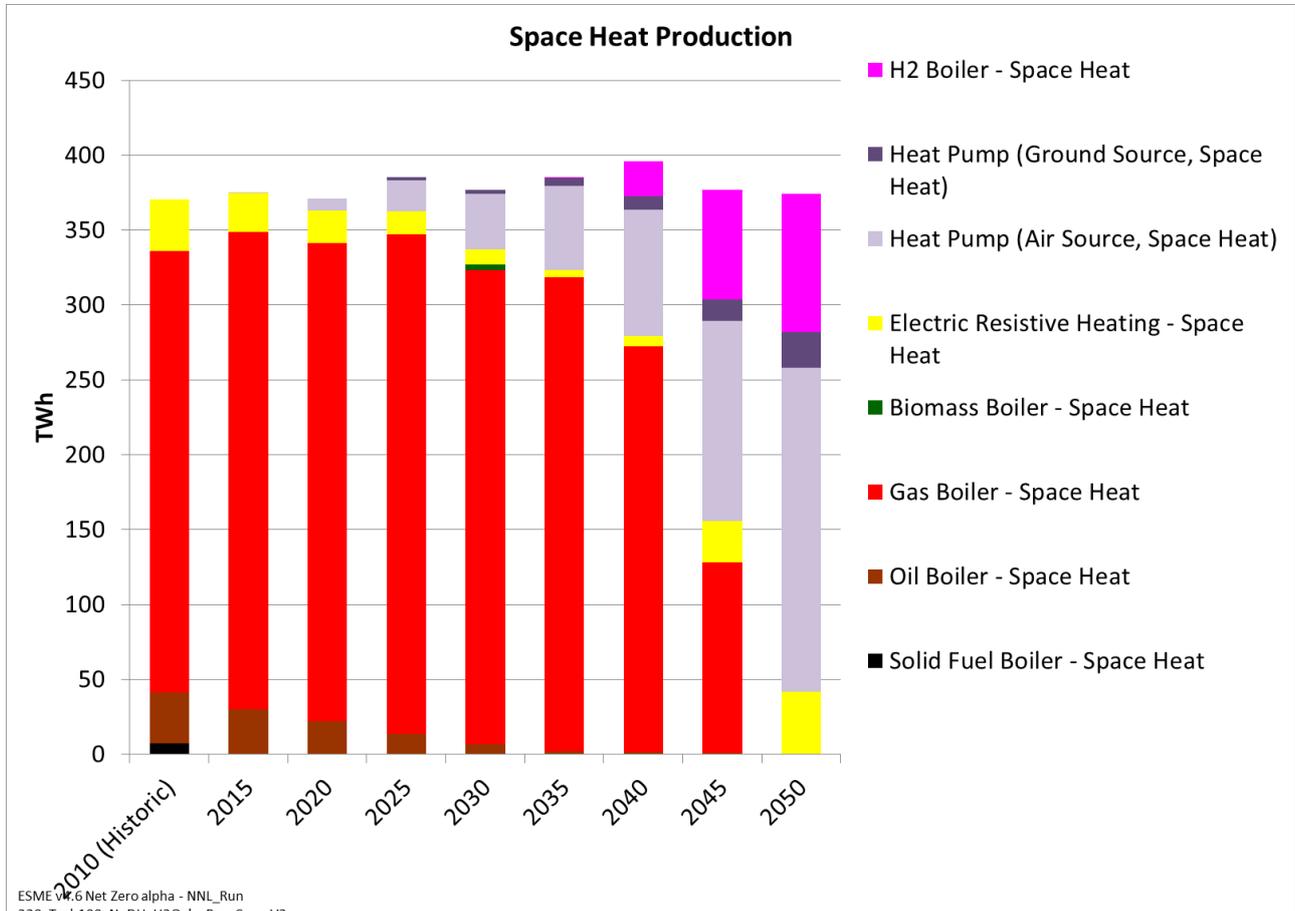Figure A3-238 – Run 227 space heat generation capacity

Figure A3-239 – Run 227 space heat production
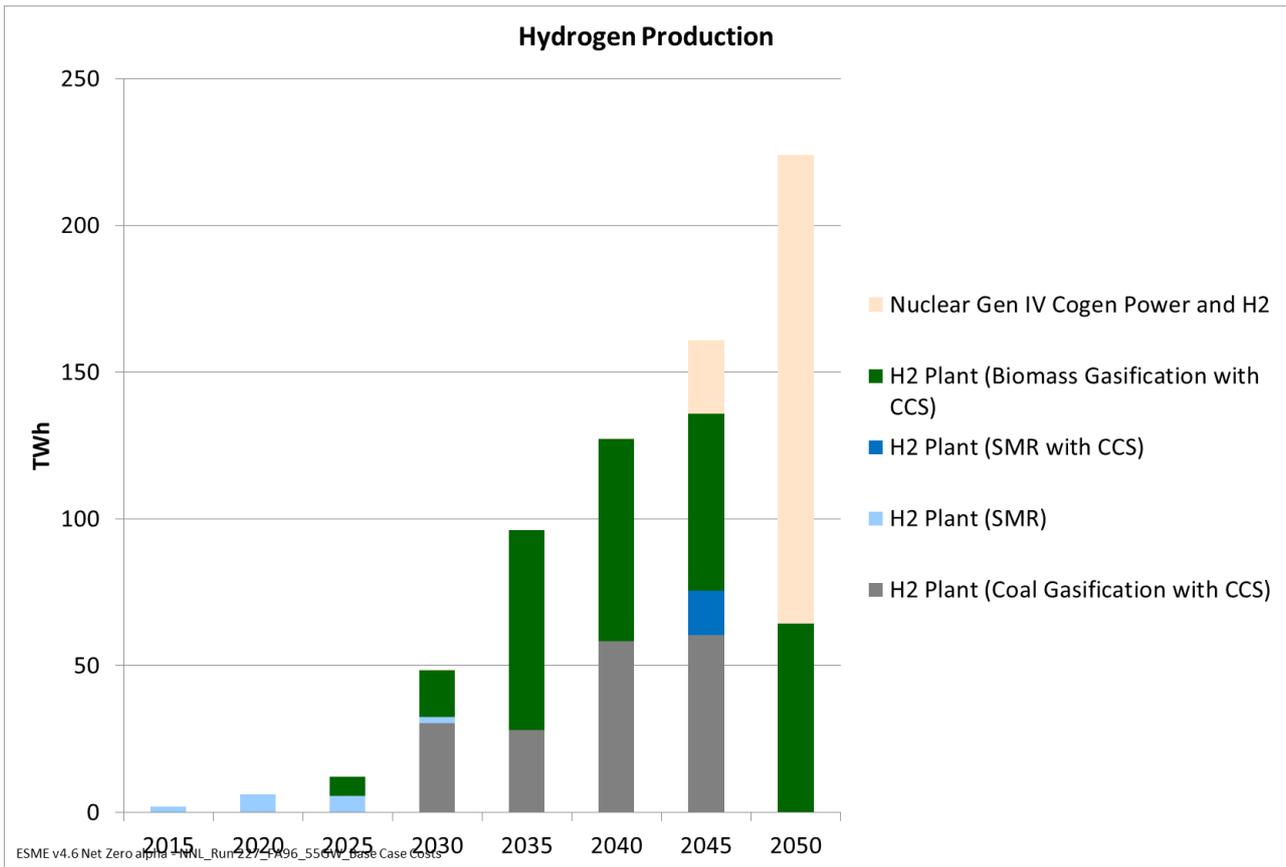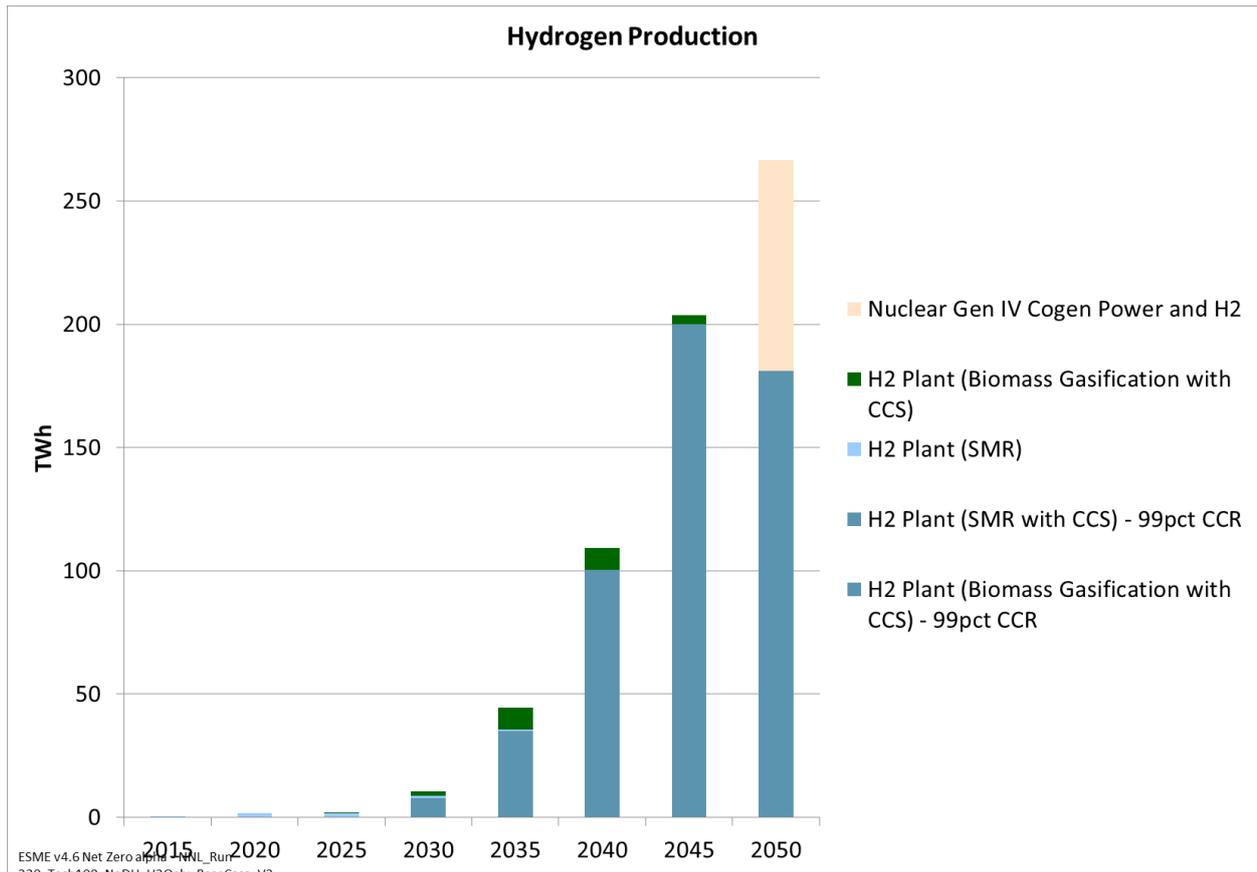
Figure A3-240 – Run 227 hydrogen production

Figure A3-241 – Run 227 hydrogen consumption
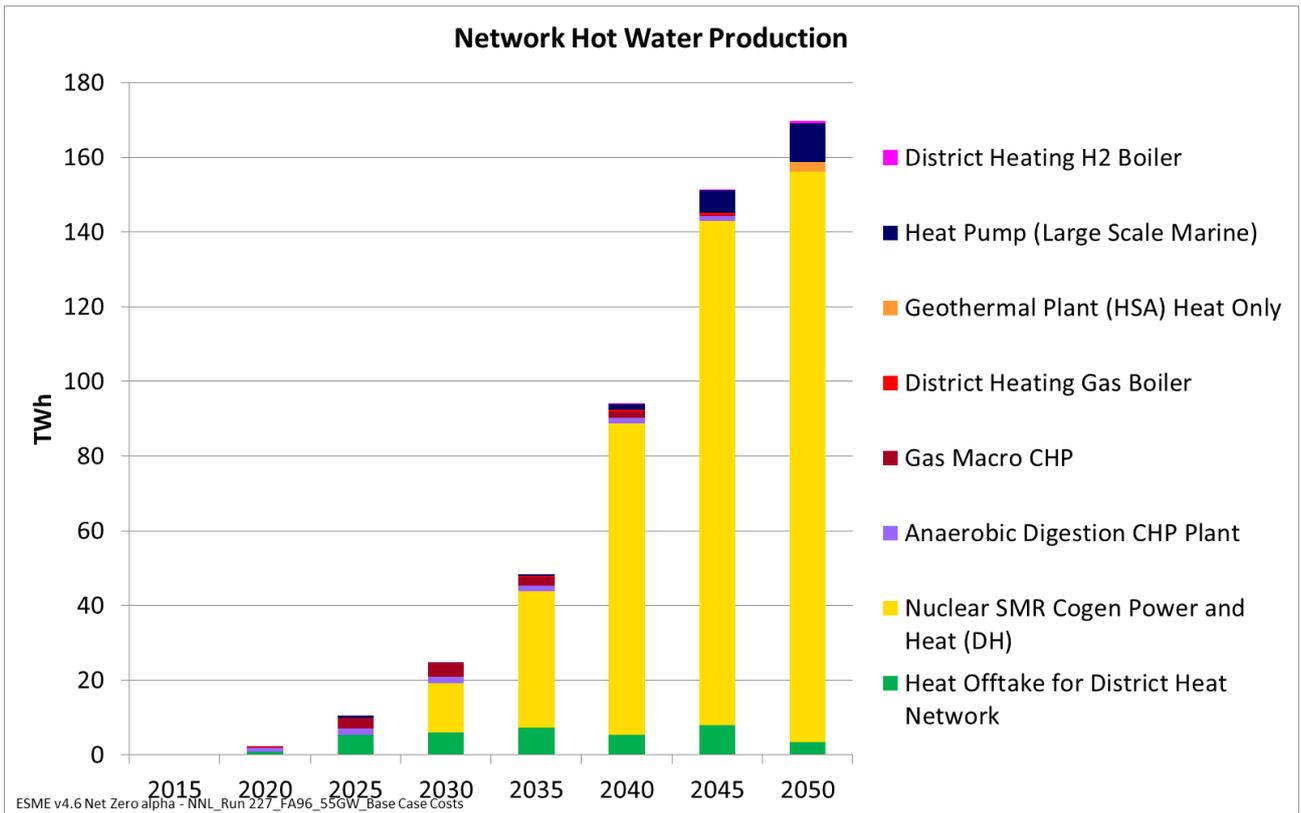
Figure A3-242 – Run 227 network hot water production
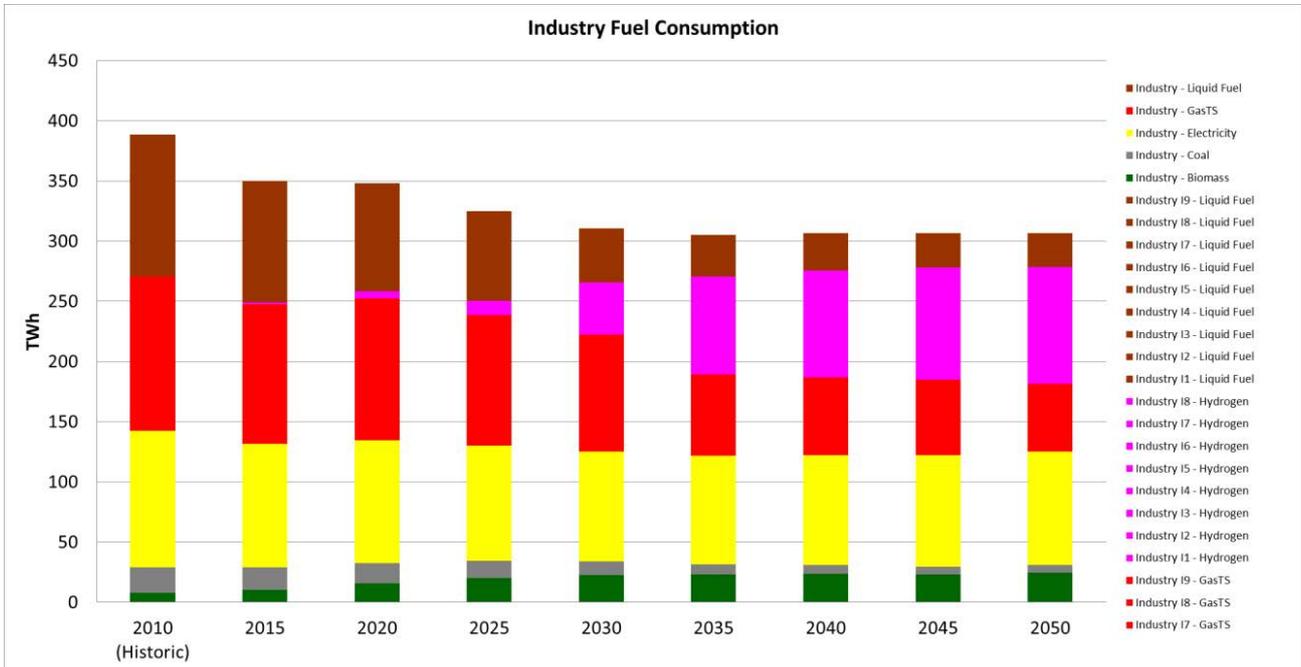
Figure A3-243 – Run 227 industry fuel consumption

Run 228 FA96 – DH deployment re-enabled; all nuclear technologies with LWSMR as cogen power and heat; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data

Figure A3-244 – Run 228 primary resource consumption

Figure A3-245 – Run 228 electricity generation capacity

Figure A3-246 – Run 228 electricity generation

Figure A3-247 – Run 228 space heat generation capacity
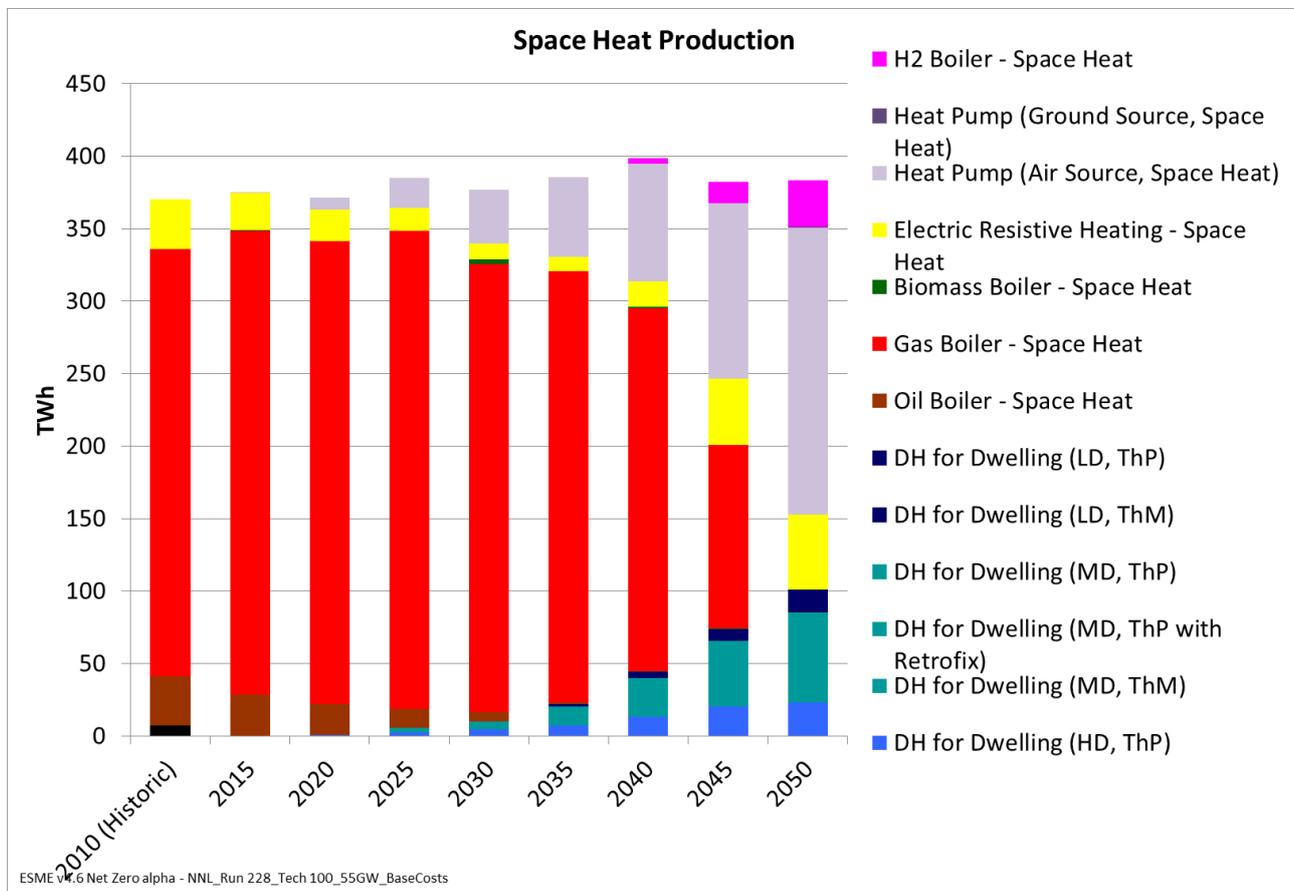
Figure A3-248 – Run 228 space heat production
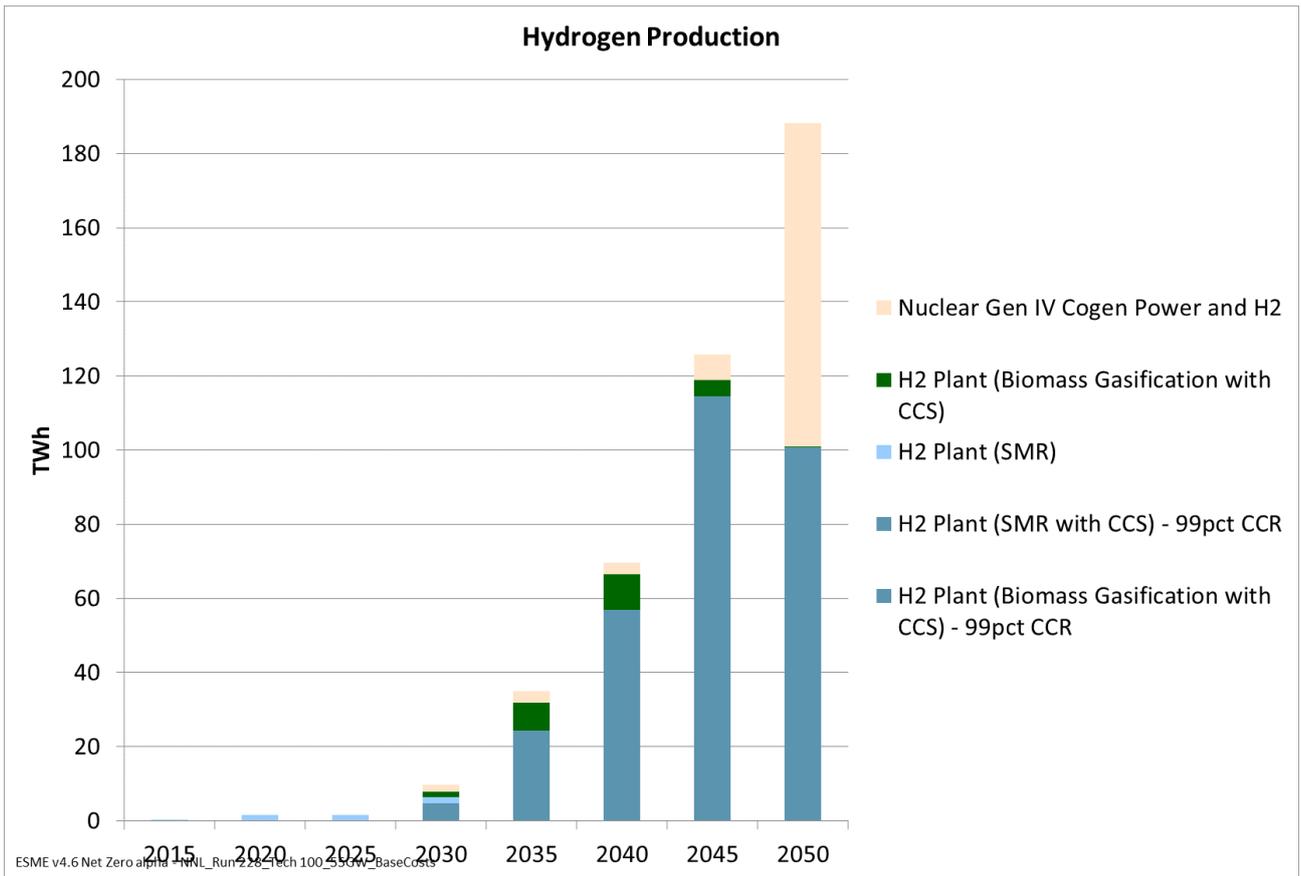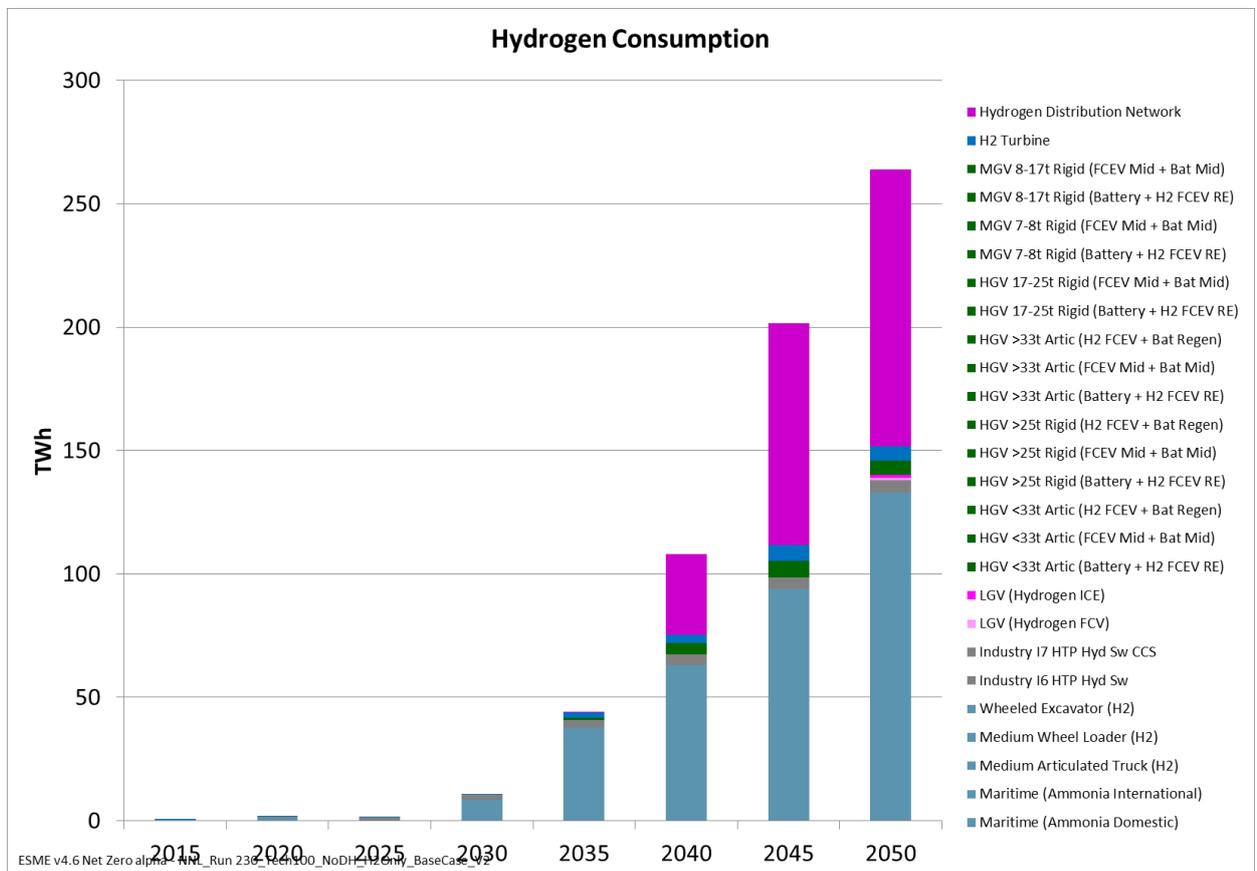
Figure A3-249 – Run 228 hydrogen production
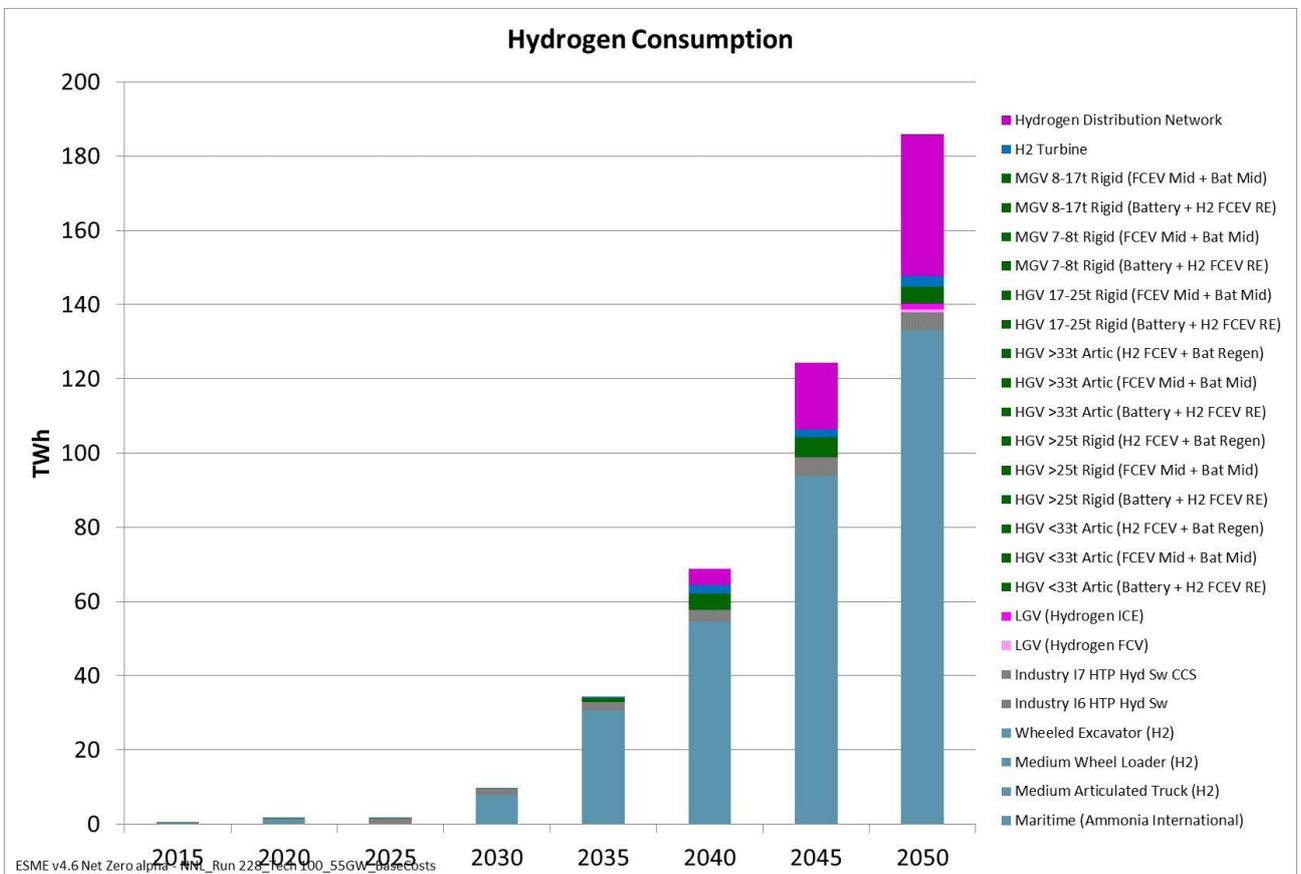
Figure A3-250 – Run 228 hydrogen consumption
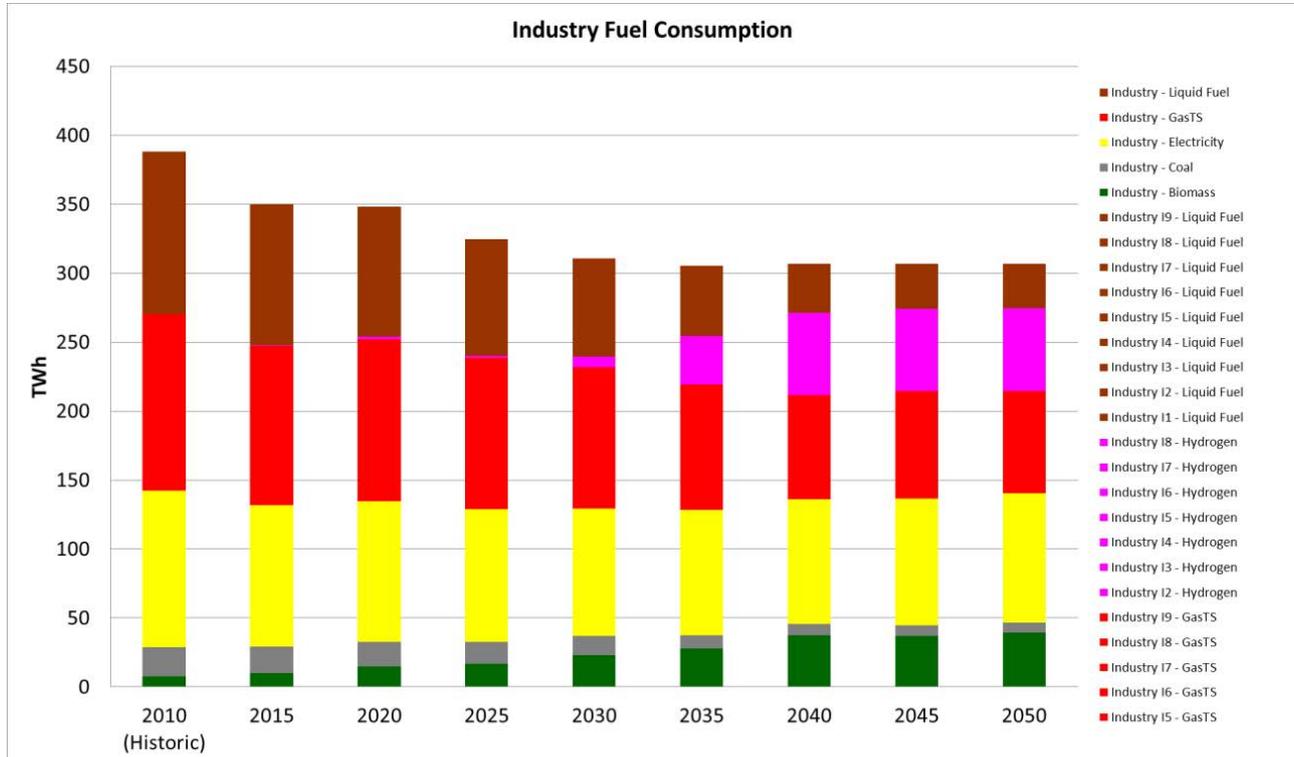
Figure A3-251 – Run 228 network hot water production

Figure A3-252 – Run 228 industry fuel consumption

Run 229 BOB100 – DH deployment re-enabled; all nuclear technologies with LWSMR as cogen power and heat; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; otherwise base case data
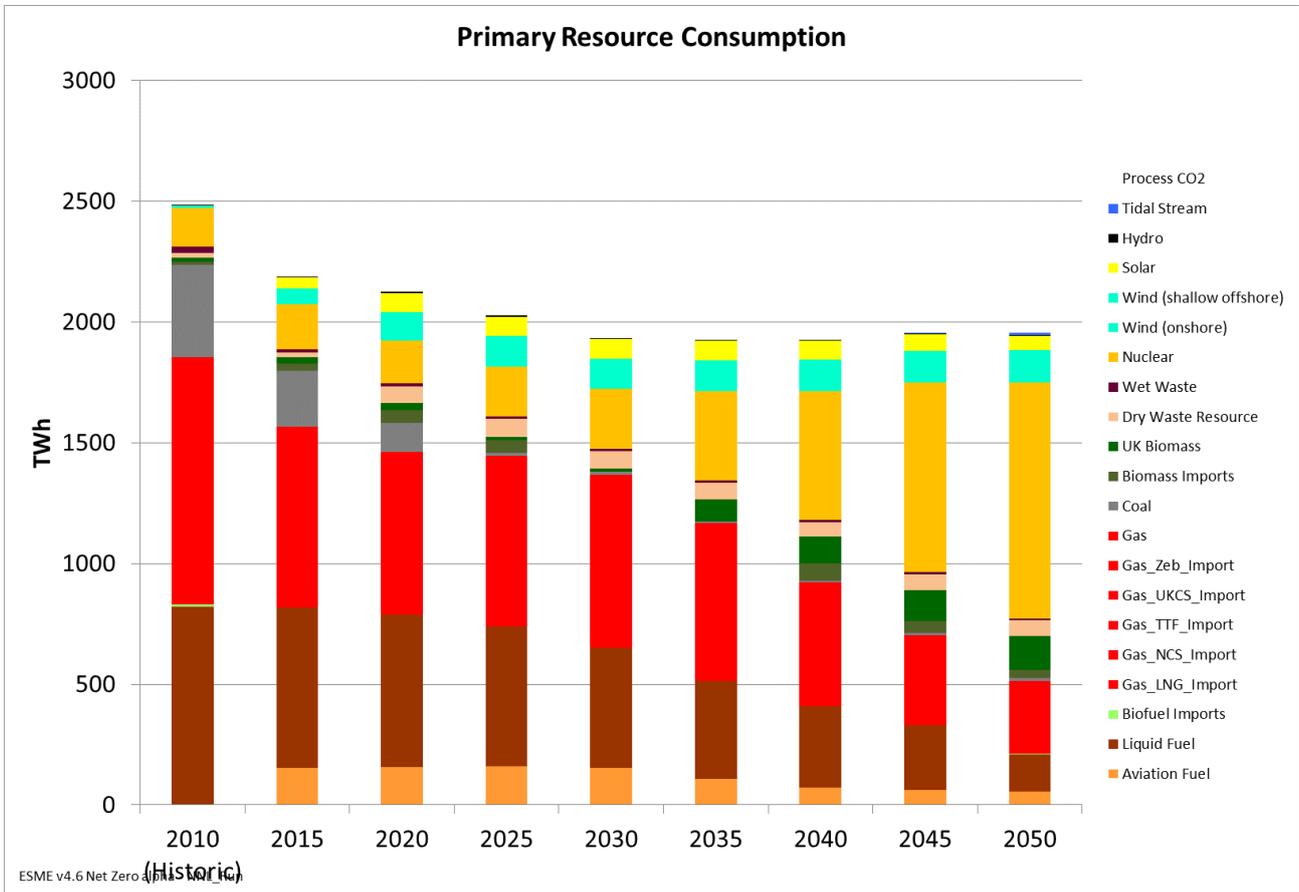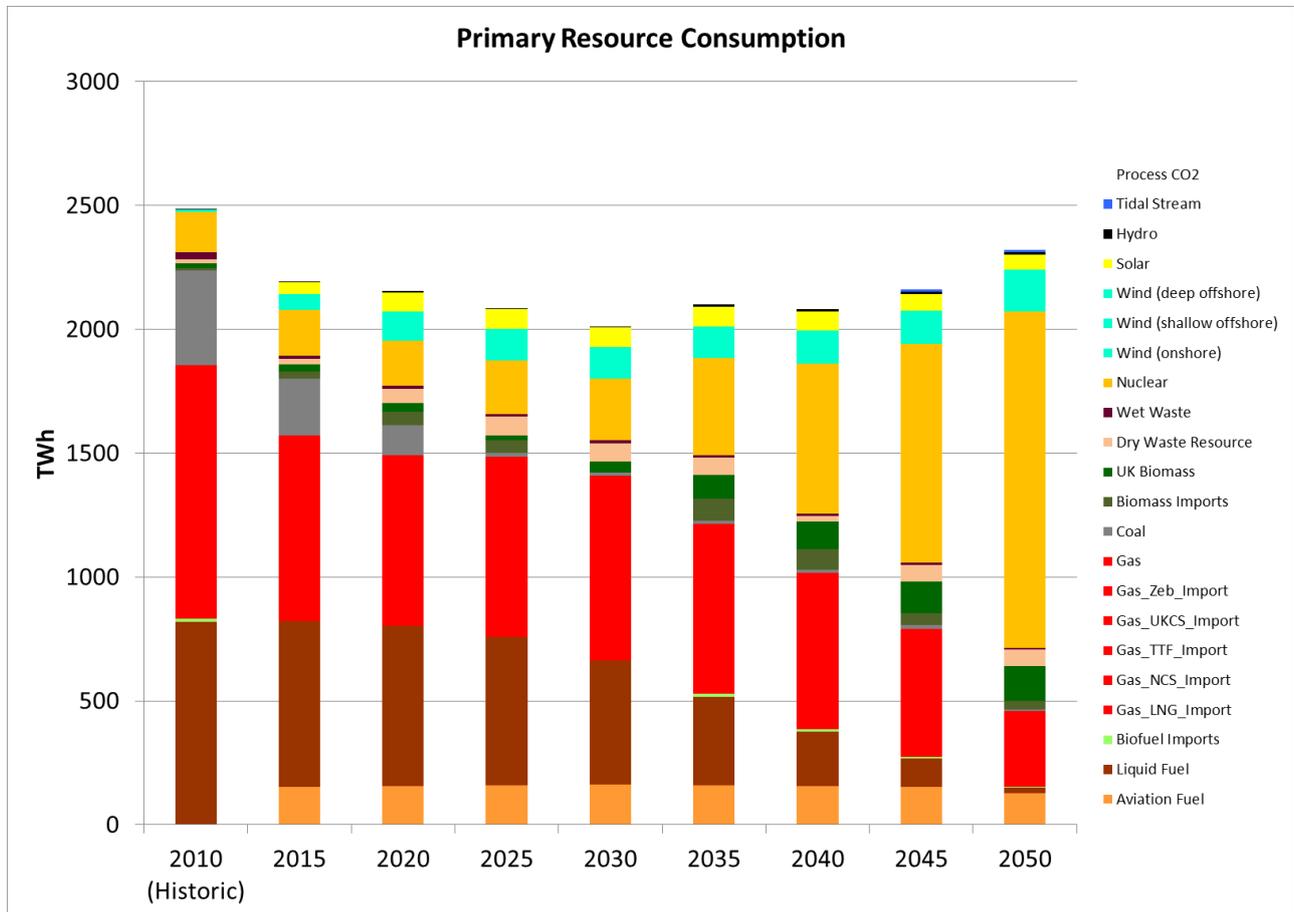

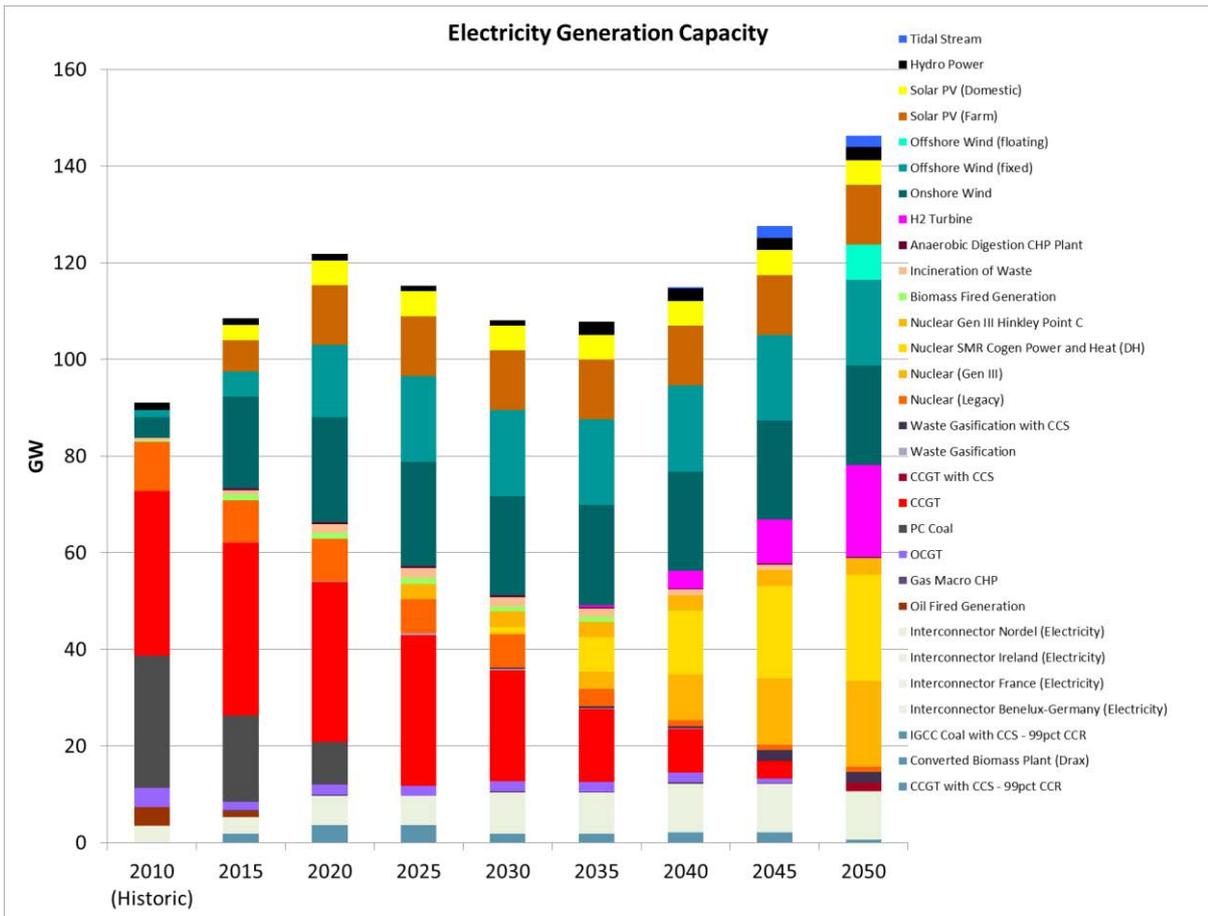Figure A3-253 – Run 229 primary resource consumption

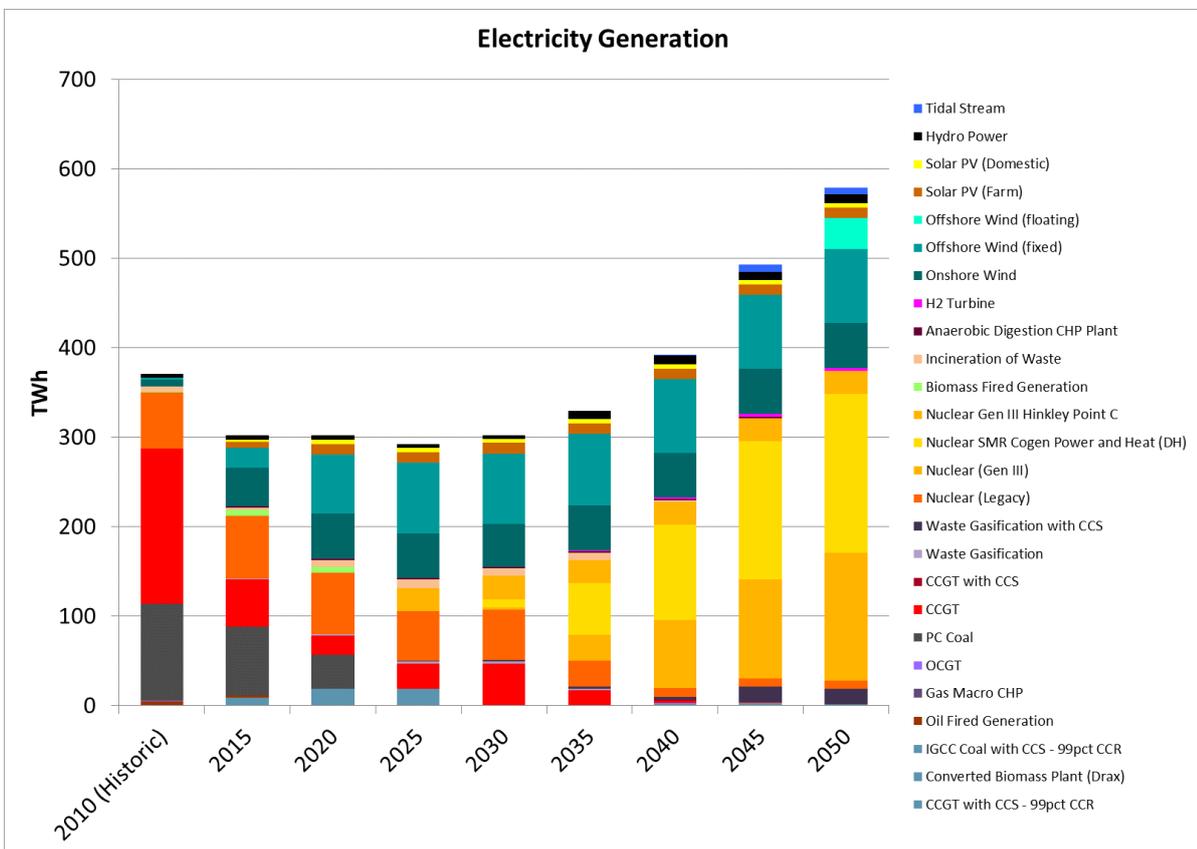Figure A3-254 – Run 229 electricity generation capacity

Figure A3-255 – Run 229 electricity generation

Figure A3-256 – Run 229 space heat generation capacity

Figure A3-257 – Run 229 space heat production
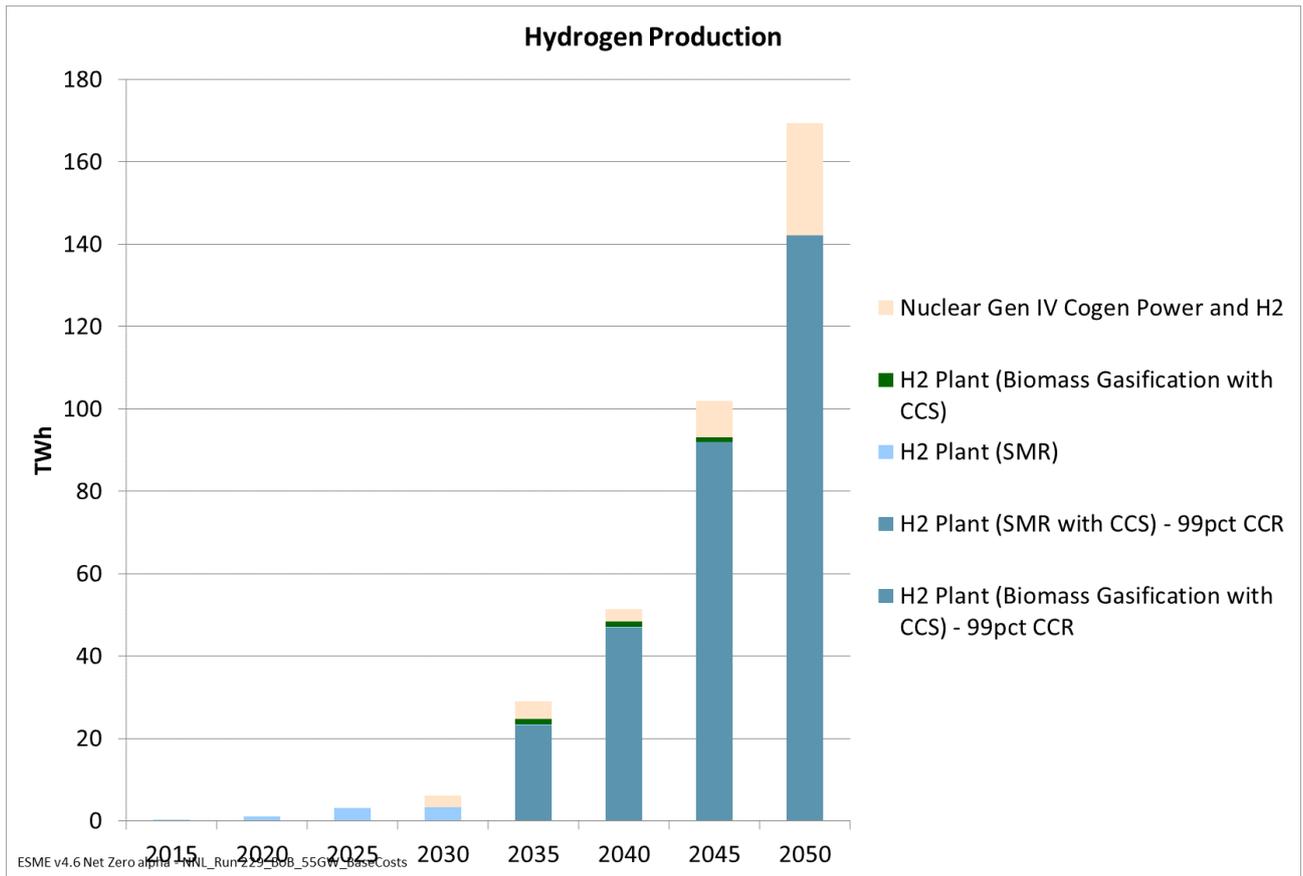
Figure A3-258 – Run 229 hydrogen production

Figure A3-259 – Run 229 hydrogen consumption

Figure A3-260 – Run 229 network hot water production
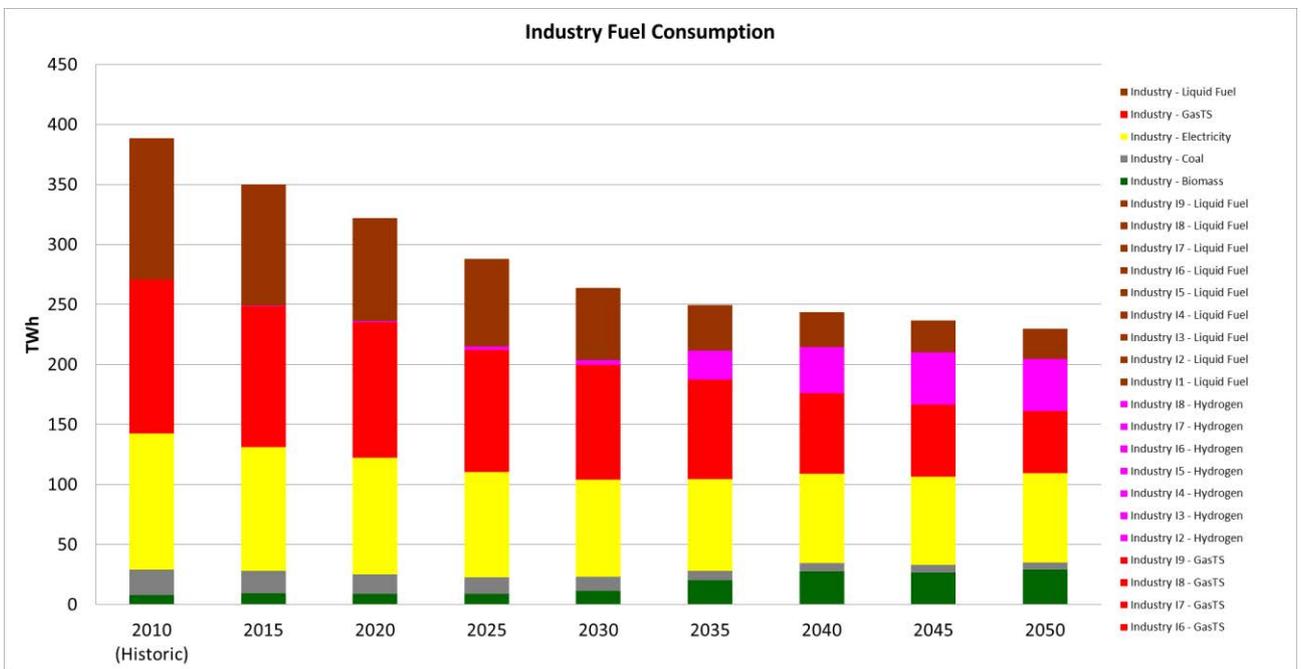
Figure A3-261 – Run 229 industry fuel consumption

Run 230 TECH100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data

Figure A3-262 – Run 230 primary resource consumption

Figure A3-263 – Run 230 electricity generation capacity
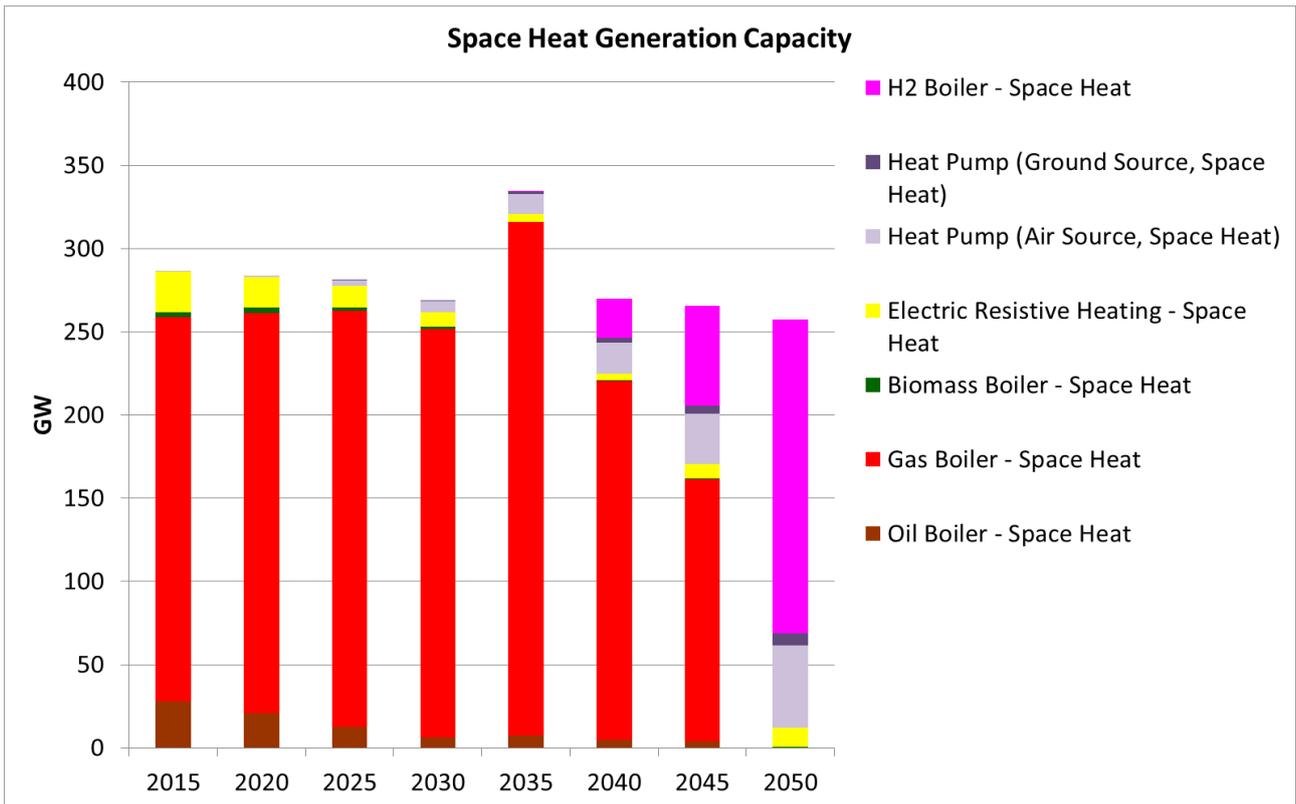

Figure A3-264 – Run 230 electricity generation

Figure A3-265 – Run 230 space heat generation capacity


Figure A3-266 – Run 230 space heat production
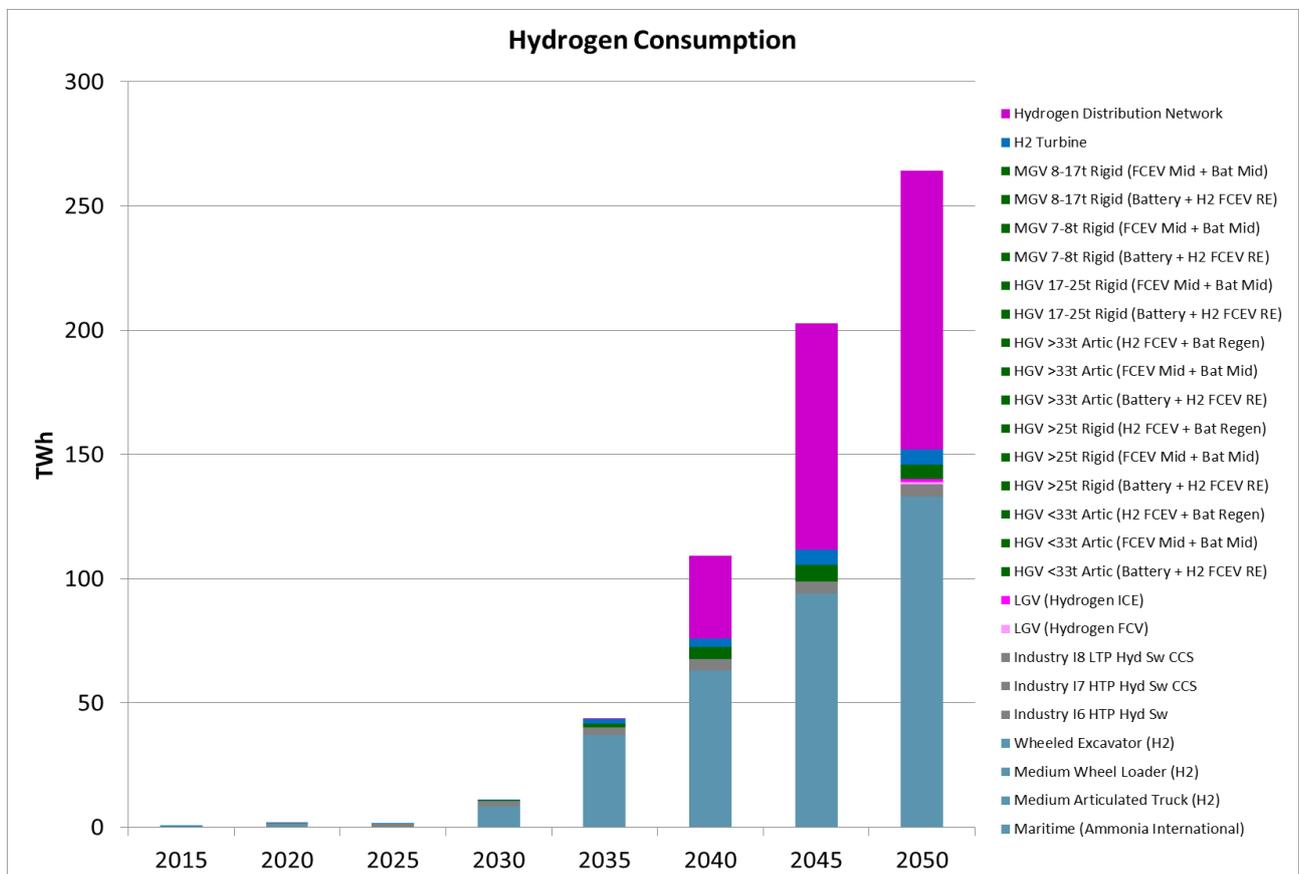
Figure A3-267 – Run 230 hydrogen production
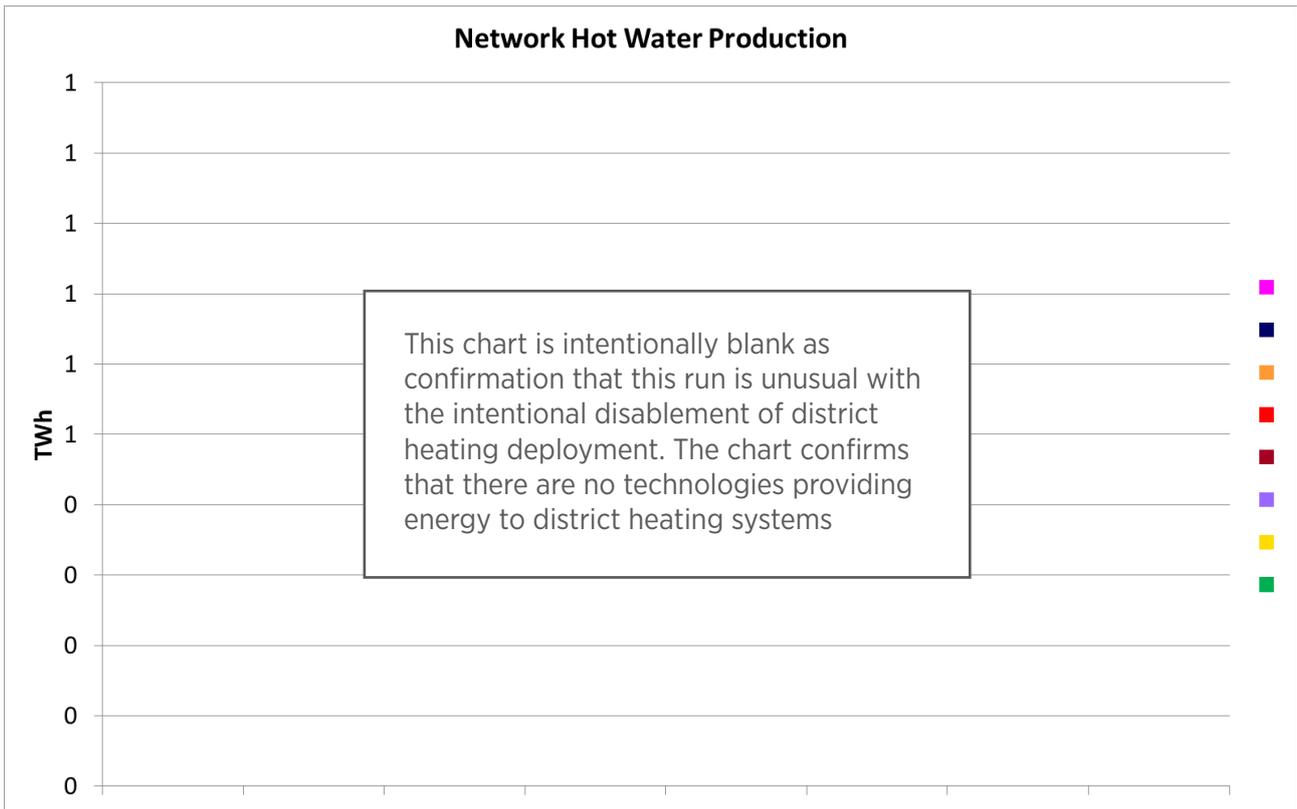

Figure A3-268 – Run 230 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

ESME v4.6 Net Zero alpha - NNL_Run 230_Tech100_NoDH_H2Only_BaseCase_V2
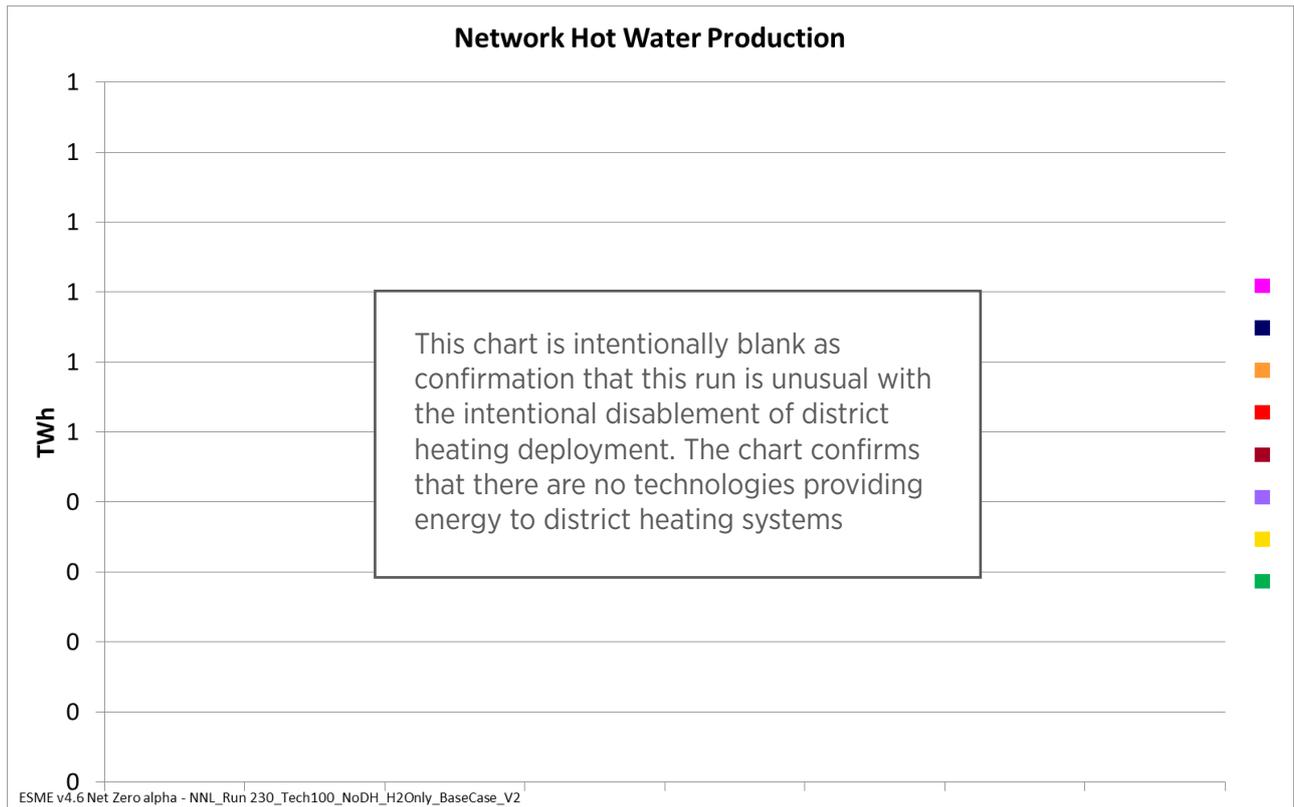
Figure A3-269 – Run 230 network hot water production

Figure A3-270 – Run 230 industry fuel consumption

Run 231 TECH100 – No DH deployment; all nuclear technologies with LWSMR as electricity only; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; Gen IV lower capex levels; otherwise base case data

Figure A3-271 – Run 231 primary resource consumption

Figure A3-272 – Run 231 electricity generation capacity

Figure A3-273 – Run 231 electricity generation

Figure A3-274 – Run 231 space heat generation capacity
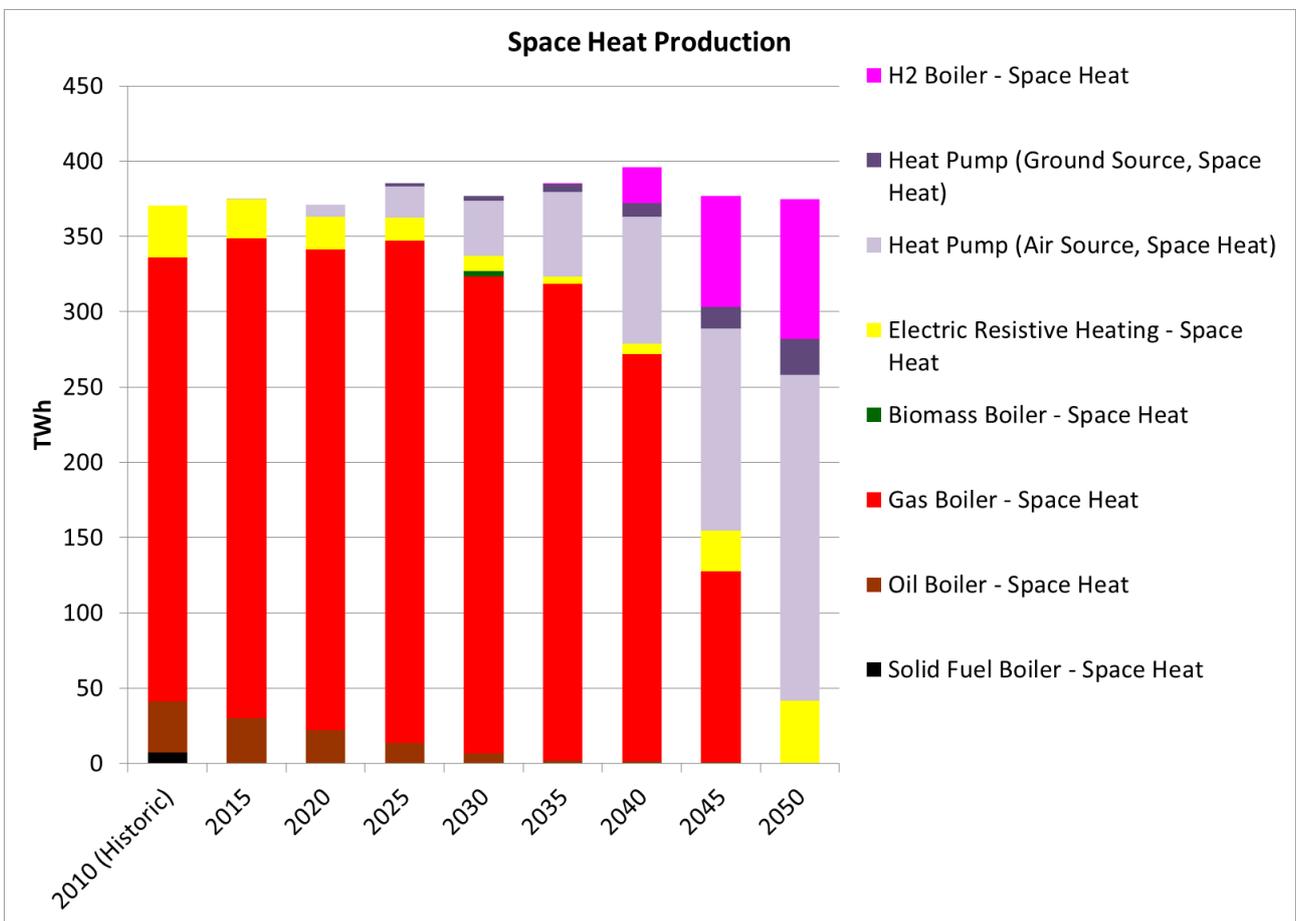
Figure A3-275 – Run 231 space heat production
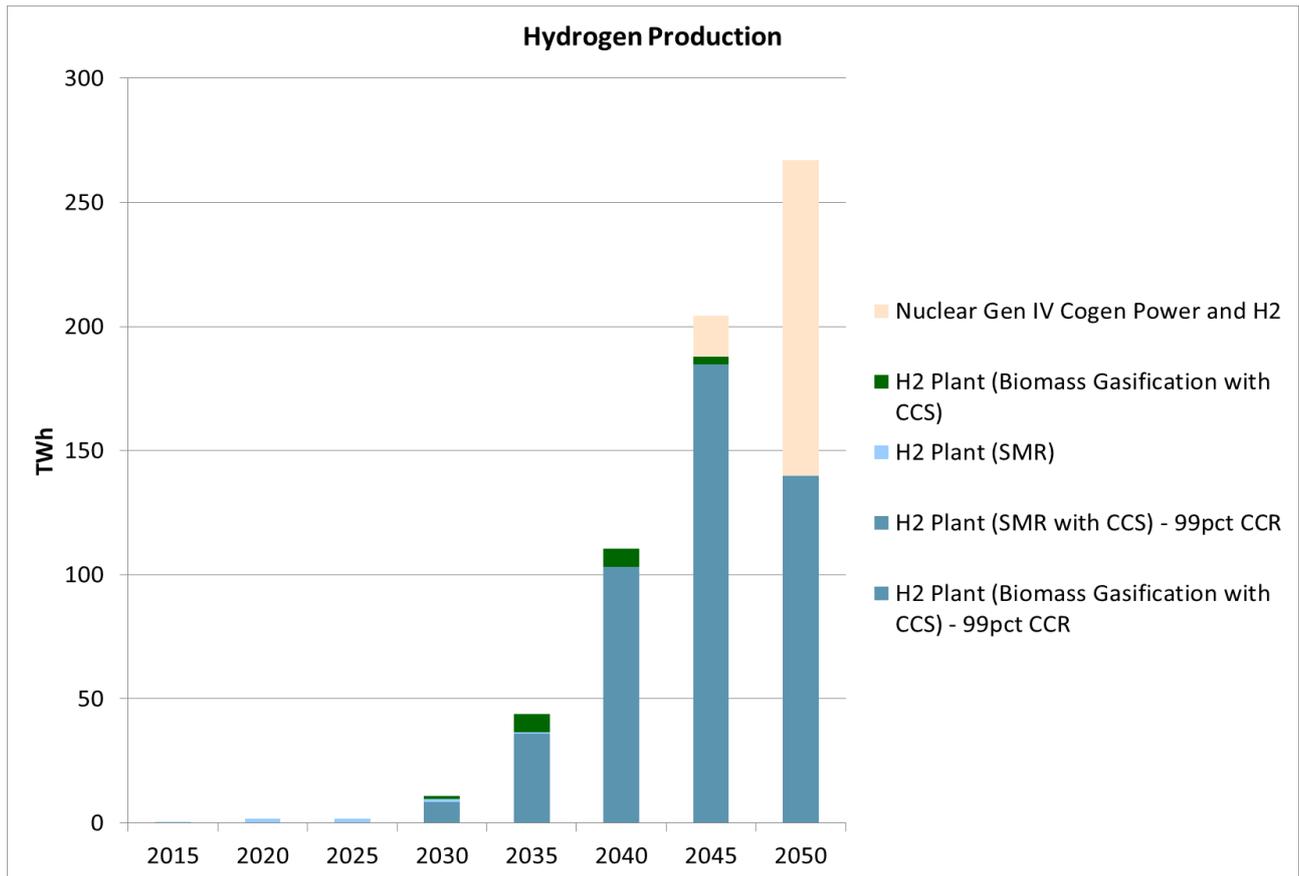
Figure A3-276 – Run 231 hydrogen production

Figure A3-277 – Run 231 hydrogen consumption

Network Hot Water Production

This chart is intentionally blank as confirmation that this run is unusual with the intentional disablement of district heating deployment. The chart confirms that there are no technologies providing energy to district heating systems

Figure A3-278 – Run 231 network hot water production
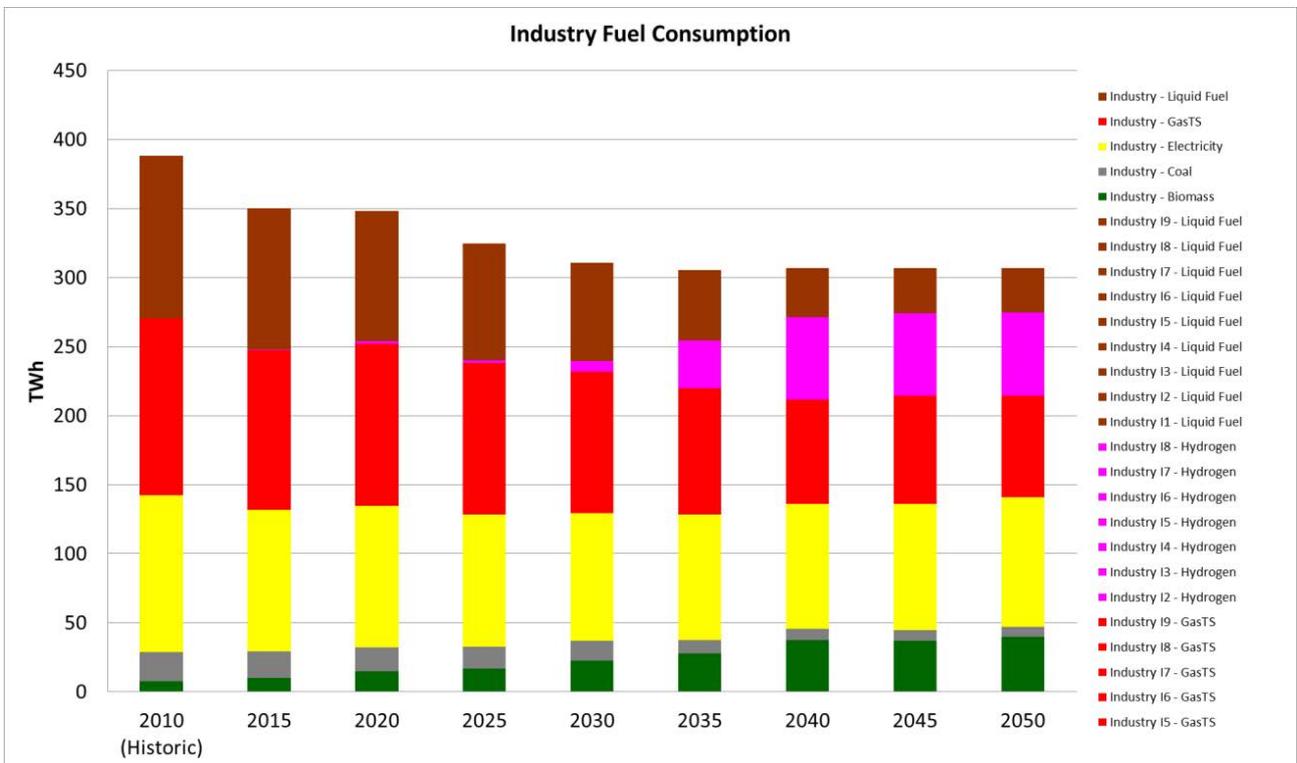
Figure A3-279 – Run 231 industry fuel consumption

Monte Carlo Run TECH100 – All nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR deployed as electricity only; Gen IV advanced nuclear plants as cogen power and hydrogen production; Gen IV site capacity limit raised to 55 GWe with build-out rate to match; otherwise baseline data with -25%/+40% spread applied to capex for all nuclear new build technologies
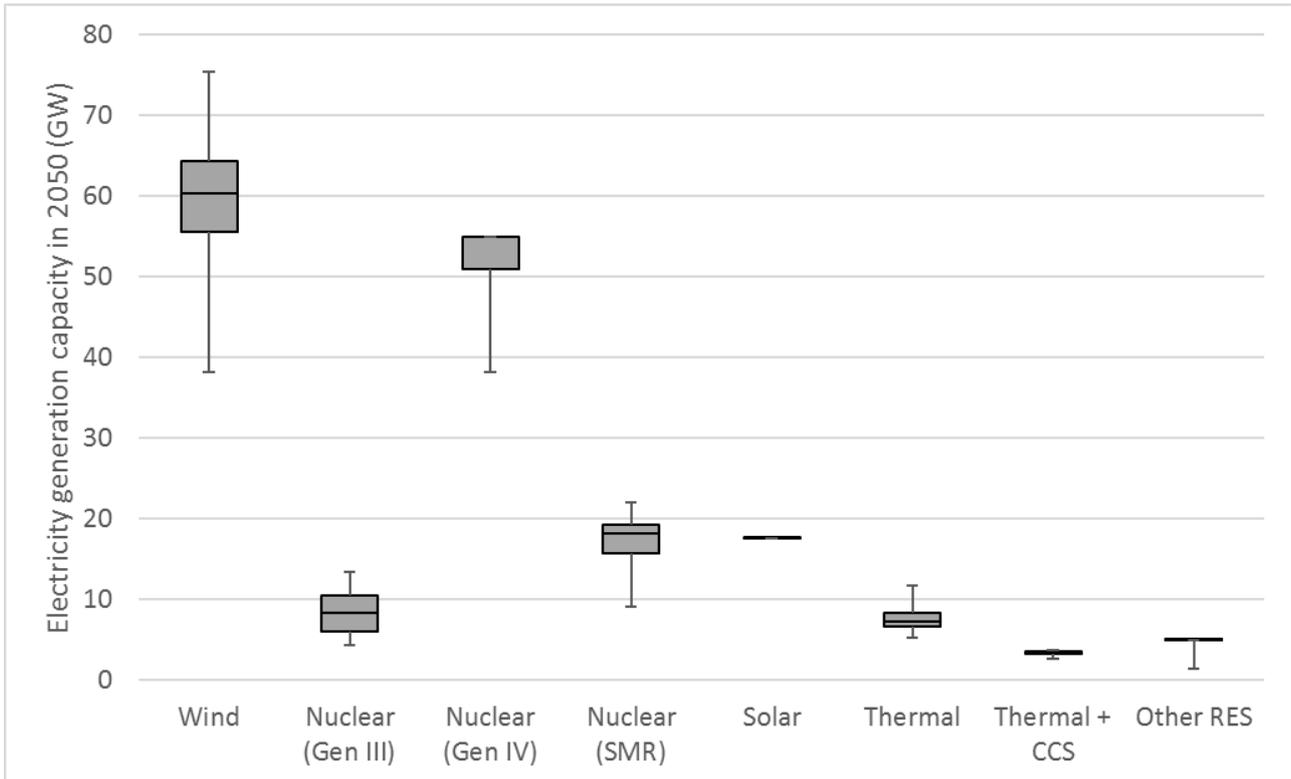
Figure A3-280 – SR No.2 Probabilistic (Monte Carlo) run showing electricity generation capacity in 2050 – using TECH100

Figure A3-281 – SR No.2 Probabilistic (Monte Carlo) run showing district heat supply in 2050 – using TECH100
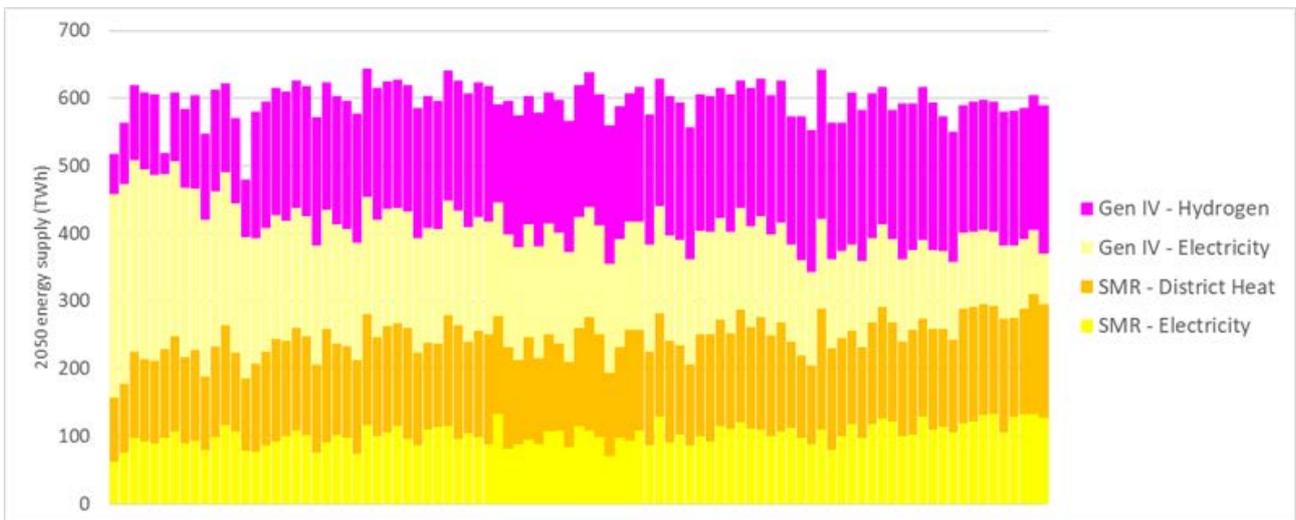

Figure A3-282 – Probabilistic (Monte Carlo) run showing LWSMR electricity and heat supply together with Gen IV electricity and hydrogen production in 2050 – using TECH100 with nuclear technologies deployed in combination as per Run 22

SUPPLEMENTARY REPORT NO.3:

ADDITIONAL TECHNOLOGIES – GREATER NUCLEAR AMBITION

NNL ENERGY SYSTEM MODELLING REPORT

Contents

1. Executive summary

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme including a Futures Roadmap. NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements. These scenarios are defined through NNL's Energy System Modelling project as:

0. No new nuclear

1. Constrained by policy to a capped level of nuclear deployment

2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral

3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market

4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies new potential pathway options as part of the approach to Net Zero.

These scenarios are partly delivered through ESC's Nuclear for Net Zero (NFNZ) technical report which is available to NNL. The balance of the analysis to define these four scenarios is to be delivered through 3 Supplementary Reports. Supplementary Report No.3 delivers additional scenarios using additional advanced nuclear technologies and associated datasets based on expert input from LucidCatalyst. The additional advanced nuclear technologies incorporated into ESME comprise:

- The concept of a Hydrogen Gigafactory for dedicated production of high-volume low-cost hydrogen with a low carbon footprint

- A technology for the production of liquid synthetic fuel, or Jet A, for "drop-in" application within the aviation sector as an alternative fuel with no net carbon emissions.

This project makes assumptions regarding the technical and economic performance of these two technologies but the scope of this project excludes the underpinning technical and economic substantiation to support these assumptions. The scope of further work to explore the merit of these assumptions is detailed in Annex 5.

The conclusions from the analysis in this report are summarised as follows:

Conclusion 1 – at the baseline cost level assumptions for the Hydrogen Gigafactory, this technology delivers high-volume low-cost hydrogen into the hydrogen economy modelled in ESME. Sensitivity testing was undertaken by widely varying the cost assumptions. As hydrogen production cost reduces from $4/kg or more, then there is a clear sequence in the take-up of hydrogen to support decarbonisation across multiple sectors. Industry, transport and hybrid-heating technologies are established applications for hydrogen as a decarbonisation vector for hydrogen cost around $2 to $3/kg. As hydrogen production costs reduce below $2/kg, hydrogen is more widely used through domestic boilers for space heating and hot water production. Continued reduction in cost towards $1/kg shows increasing hydrogen use for power generation.

Conclusion 2 – at the baseline cost level assumptions for the liquid synthetic fuel plant, this technology delivers a "drop-in" replacement fuel for Jet A for aviation use with no net emissions. Sensitivity testing in ESME comprised increasing the assumed production costs by many multiples to a level at which the technology was not deployed. This technology appears to be so useful that even when it is ten times more expensive than the baseline cost assumption, it is still deployed. Aviation emissions are hard to decarbonise, therefore driving additional effort to reduce residual carbon emissions elsewhere in the system. The learning is that at a system level, the value of decarbonising aviation emissions is defined by avoiding the need to decarbonise other "hard to treat" technologies with their associated residual emissions.

Conclusion 3 – at a system level, the combined deployment of the Gigafactory and the liquid synthetic fuel plant has a significant impact on the overall system characteristics of a typical 2050 energy system. Growth of electricity generating capacity through to 2050 is less dramatic compared with previous scenarios and much of the space heating demand is delivered through the use of hydrogen rather than greater application of electrification via heat pumps as seen with previous scenarios. The decarbonisation of aviation emissions relieves some of the pressure on remaining Greenhouse Gas emissions which is more usually associated with the necessary deployment of more expensive technologies and system solutions for the elimination of hard to treat residual emissions.

Conclusion 4 – while the technical and economic parameters for nuclear hydrogen production are based on existing studies of the underlying technology, the development of a systematic evidence base for the innovative delivery model is still required to substantiate the techno-economic assumption that nuclear energy can be used to deliver high-volume, low-cost hydrogen in a Gigafactory, or that nuclear derived "drop-in" synthetic aviation fuels can be cost effectively supplied to decarbonise the aviation sector. Reference is made to such concepts defined elsewhere in forthcoming reports. Analysis within this report does indicate the market value associated with delivery of these fuels at their respective target prices. The economic analysis in this report should be used to frame market requirements for hydrogen and liquid synthetic fuels and the low-cost technologies used to produce them. Technical innovation and associated evidence in these areas should be focussed against such future market requirements.

Conclusion 5 – detail is provided on the scope of a potential subsequent project to generate additional techno-economic evidence to substantiate the techno-economic assumptions used in this analysis. The scope of this potential subsequent project includes some further energy system analysis to explore potential system wide benefits.

Conclusion 6 – because the scope of this report is based on techno-economic assumptions not yet adequately substantiated, it is inappropriate to make new recommendations regarding markets, policy and regulation based on the analysis in this report. But the analysis in this report does further support previous Market, Policy and Regulation (MPR) recommendations in ESC's Nuclear for Net Zero report and Supplementary Report No.2.

Conclusion 7 – the nuclear technology datasets used in the analysis for this report were carried forward from Supplementary Report No.2. It is a feature within these datasets that with the assumption of an aggressive commercialisation programme, High Temperature Gas Reactors (HTGRs) using proven coated particle fuel could be deployed from 2030 with a NOAK cost profile comparable with that of low-cost LWSMRs. Therefore, in the ESME modelling in Supplementary Report No.3, the LWSMR technology deployment shown in the various charts and data outputs could actually be viewed as a proxy for low-cost modular nuclear either as HTGRs or light-water small modular reactors, when deployed for the cogeneration of electricity and lower grade heat supply for the energisation of district heating systems. This is relevant in that the parallel stage-gated development of LWSMR and advanced nuclear should focus on the realisation of the most important benefits including; lowest costs in deployment and operation for hydrogen production or electricity production (or both); compatibility with best compromise technology for higher temperature hydrogen production available for commercial deployment from 2030, and; potential deployment at brownfield industrial sites not traditionally associated with nuclear energy.

Conclusion 8 – the analysis in this report is used to define the final nuclear deployment scenario defined as "Greater Nuclear Ambition". Alongside previous scenarios developed from NFNZ and Supplementary Reports Nos. 1 and 2, these potential scenarios are provided for consideration of potential 2050 nuclear energy production within NNL's Advanced Fuel Cycle Programme:

- No new nuclear – zero

- Constrained – 154 TWh

- Base Case – 498 TWh

- Higher Optimism – 617 TWh

- Greater Nuclear Ambition – 974 TWh

2. Introduction

2.1. Introduction to Energy Systems Catapult

Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.

The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research.

We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, to decarbonise the energy system at the lowest cost.

2.2. NNL's Energy System Modelling Project

The National Nuclear Laboratory (NNL) is progressing an Advanced Fuel Cycle Programme (AFCP) as part of its research activities. This programme supports 8 strategic outcomes from NNL's research programme:

1. People
2. Infrastructure
3. Ideas
4. Supply Chain
5. Stakeholder Engagement
6. Industry Alignment
7. International Influence
8. Futures Roadmap

NNL has commissioned ESC working with LucidCatalyst to deliver its Energy Systems Modelling project to support the Futures Roadmap outcome within the AFCP. The Energy Systems Modelling project will deliver potential nuclear deployment scenarios in a UK transition to Net Zero by 2050. These scenarios are needed to better understand the potential long-term impacts on UK nuclear fuel and fuel cycle requirements.

2.3. NNL's Energy System Modelling Project objective

The objective of NNL's Energy System Modelling project is to inform 5 potential nuclear deployment scenarios defined as:

0. No new nuclear deployment
1. Constrained by policy to a capped level of nuclear deployment
2. Base case informed by a level of deployment consistent with a Net Zero whole energy system analysis which is optimised for minimum cost whilst being technology and policy neutral
3. Higher optimism reflecting lower nuclear costs and a more aggressive schedule for bringing advanced nuclear technologies to market

4. Greater nuclear ambition, which introduces a new industrial approach for exploiting the high energy density and low carbon emissions from nuclear and identifies potential new pathway options as part of the approach to Net Zero. Nuclear deployment in a scenario of "no new nuclear" as indicated above is of little benefit to an advanced fuel cycle programme, other than cognisance of the circumstances that could make such a scenario more likely. Such a scenario is defined later in this report in Section 2.2.2 but otherwise not considered further as part of this project.

2.2.1. Technical starting point for NNL's Energy System Modelling Project

ESC owns, operates and maintains a whole energy system model known as Energy System Modelling Environment1 (ESME) which has been developed over a decade for the purpose of better understanding the pathways and options for decarbonising the UK economy. ESME has been internationally peer reviewed and is used under licence by various organisations. Analysis using ESME has been considered by the Committee on Climate Change as part of its deliberations.

The process flow necessary to deliver the 4 nuclear deployment scenarios is illustrated in Figure 1.
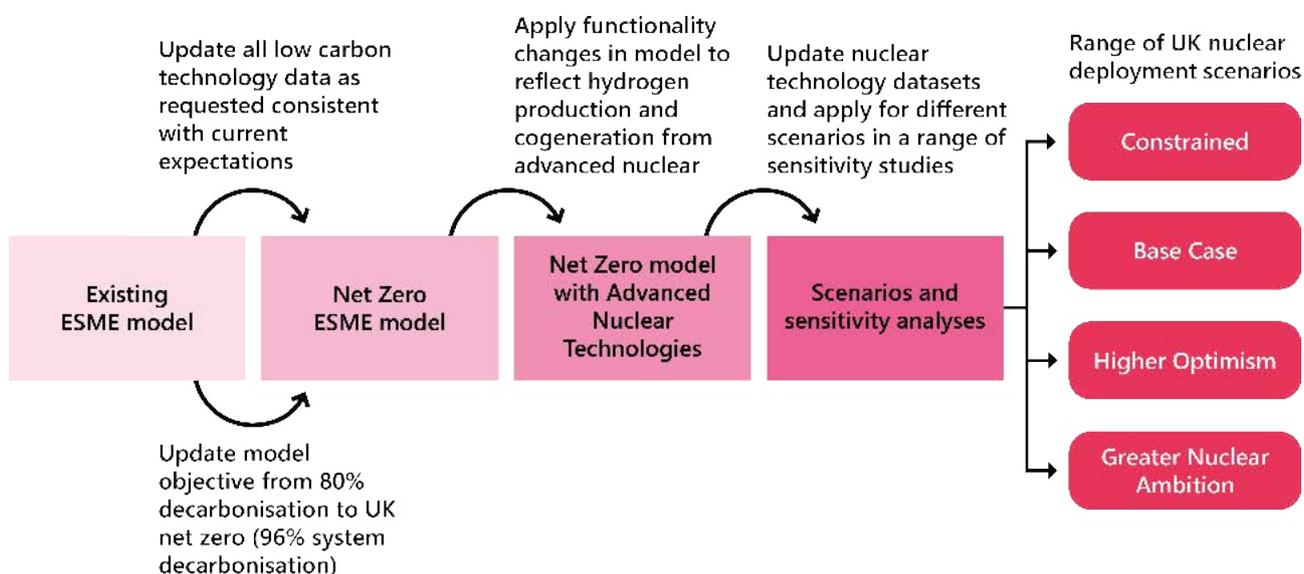

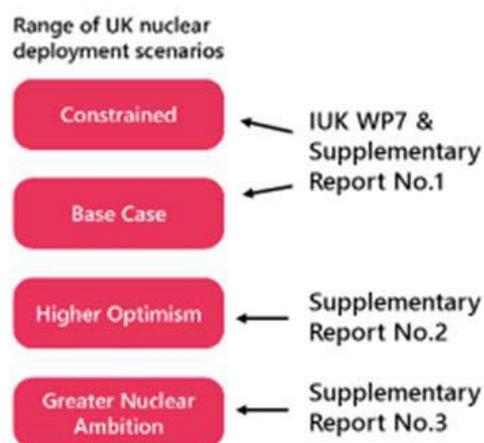Figure 1 – Process flow to deliver four potential UK nuclear deployment scenarios

However, in 2019 ESC launched a programme of projects as part of a Net Zero programme to reflect the amendment in June 2019 to the Climate Change Act 2008. This legislation adjusted the performance objective of 80% decarbonisation compared with historic reference levels to Net Zero by 2050. This ESC programme in response to this new legislation delivered the first step in the process flow illustrated in Figure 1 by delivering four new ESME decarbonisation scenarios:

- FA96 – using core technologies for 80% decarbonisation and stretched to deliver 96%

- TECH100 – introduction of additional speculative technologies to deliver 100% decarbonisation

- SOC100 – introduction of speculative changes to societal behaviours for 100% decarbonisation

- BOB100 – combination of both TECH100 and SOC100

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1   Further information on ESME and the evidence base it incorporates can be found on the ESC website: https://es.catapult.org.uk/brochures/esme-data-references-book/

These new scenarios are described in more detail in ESC's Innovating to Net Zero analysis and report[2], and subsequently used in the IUK WP7 project.

ESC's Net Zero programme was delivered through a project known as the Energy Technology Benchmarking project which was grant funded by Innovate UK (IUK). The scope funded by IUK included a further project known as Innovate UK Work Package 7 (IUK WP7). The scope of IUK WP7 delivered the next two steps in the process flow illustrated in Figure 1. Therefore, the technical starting point for NNL's Energy System Modelling Project is ESC's Nuclear for Net Zero (NFNZ) project and associated report3, also known as IUK WP7. The Nuclear for Net Zero project technical report has been made available to NNL for the purpose of its Energy System Modelling project.

The objective of NNL's Energy System Modelling project will be achieved through a combination of the NFNZ project and associated report, and three further Supplementary Reports as illustrated in Figure 2. The Zero Deployment (0) and the Constrained Deployment (1) scenarios are defined within the NFNZ project technical report. This report together with Supplementary Report No.1 delivering additional scenarios informs the Base Case (2) Nuclear Deployment scenario. A second Supplementary Report (No.2) will document indicative nuclear deployment with further revised data provided by industry experts at LucidCatalyst to inform a nuclear deployment scenario known as (3) Higher Optimism. This final Supplementary Report (No.3) documents the indicative nuclear deployment levels from adding new technology types to ESME enabled by low-cost carbon-free hydrogen. This informs the final scenario known as (4) Greater Nuclear Ambition. The project outputs to deliver the project objective are summarised in Table 1 below.

Table 1 – Sequence of project reports leading to nuclear deployment scenarios to deliver the project objective

Project	Report	Scope	Nuclear Deployment Scenarios
ESC NFNZ project	ESC project report	Overlap with majority of analysis detailed in NNL ITT	1 Constrained
NNL Energy System Modelling project	Supplementary report 1	Balance of analysis required by NNL ITT	2 Base case
	Supplementary report 2	Impact of revised inputs for nuclear technologies	3 Higher optimism
	Supplementary report 3	Additional technology added to and tested in ESME	4 Greater nuclear ambition

2.2.3. Purpose of Supplementary Report No.3

The purpose of Supplementary Report No.3 is to test the impact of two additional nuclear technologies proposed by LucidCatalyst through sensitivity testing using ESME to inform the analysis supporting the fourth nuclear deployment scenario known as "Greater Nuclear Ambition".

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2   Innovating to Net Zero. Energy Systems Catapult 10th March 2020.
    https://es.catapult.org.uk/reports/innovating-to-net-zero/

3   Nuclear for Net Zero – A UK Whole Energy System Appraisal.
    Project Technical Report dated 17th April 2020 by Energy Systems Catapult.

3. Approach to the Analysis for Supplementary Report No.3

3.1. Nuclear technologies and datasets available through LucidCatalyst

From its ongoing research and operational activities, LucidCatalyst is able to develop an expanded view of potential pathways to commercialisation and associated costs for advanced nuclear technologies, as well as learning from large reactor projects in development and deployment. The interest in this expanded set of nuclear technologies and associated datasets is not simply whether UK Net Zero can be achieved at lower net cost, and/or risk, but whether these datasets open up new insights regarding potential Market, Policy or Regulatory action by policymakers for introducing new technologies. In particular, these new technologies have the potential to introduce additional, and complementary, pathways in the transition to UK Net Zero.

For Supplementary Report No.3, the additional nuclear technologies comprise:

- The concept of a Hydrogen Gigafactory for dedicated production of high-volume low-cost hydrogen with a low carbon footprint

- A technology for the production of liquid synthetic hydrocarbon fuel, or Jet A, for "drop-in" application within the aviation sector as an alternative fuel with no net carbon emissions.

These technologies and associated datasets are described in more detail later in Section 4 and Annex 1.

3.2. Approach informed by the alternative datasets

The approach to the scope for Supplementary Report No.3 is illustrated in Figure 3.

The nuclear technology datasets carried forward from Supplementary Report No.2 comprise large Gen III+ and Light-Water nuclear Small Modular Reactors (LWSMRs). It is a feature within Supplementary Report No.2 that, based on an aggressive commercialisation programme, High Temperature Gas Reactors using proven TRISO coated particle fuel commercial deployment is assumed from 2030 with a NOAK cost profile comparable with that of low-cost LWSMRs. Therefore, in the ESME modelling in Supplementary Report No.3, the nuclear technology of LWSMR can actually be viewed as a proxy for low-cost modular nuclear either as HTGRs or light-water small modular reactors.

Techno-economic assumptions were provided by LucidCatalyst for the Hydrogen Gigafactory and the liquid synthetic fuel plant, as described below in Section 4 and Annex 1. Based on the process schematics detailed in Annex 1, the two new additional technologies were created within ESME, and ESME functionality was updated accordingly. The new technologies and functionality were tested with different parameters and scenarios to demonstrate that the system changes were operating and responding as expected.

The scenario analysis was then designed to explore the energy system impacts from the introduction of these new technologies with a comprehensive set of deterministic and probabilistic scenarios which examined:

- The Hydrogen Gigafactory with Gen III+ and LWSMR

- The liquid synthetic fuel plant with Gen III+ and LWSMR

- All nuclear technologies in combination

Results are considered and finally any learning relevant to markets, policy and regulation.

It should be remembered that NFNZ and Supplementary Reports Nos. 1 and 2 were based on nuclear technologies with supporting and documented techno-economic evidence. Supplementary Report No.3 is based on techno-economic assumptions, as described in Section 4 and Annex 1. This report documents these assumptions but does not deliver the underpinning techno-economic evidence to substantiate these assumptions.

Update datasets
- Use previous ESME nuclear technology datasets for Gen III+ and LWSMR from SR2 from LucidCatalyst
- Generate new datasets for hydrogen Giga factory and liquid synthetic fuel plant

Add new techs
- Introduce the Giga factory and the liquid synthetic fuel plant into ESME and test functionality to confirm their operation and system response as expected

Scenario analysis
- Combined assessment to test impact and value of all nuclear options together
- Sensitivity studies for both Gigafactory and liquid synthetic fuel plant
- Repeated probabilistic analysis to address uncertainties

Results
- Examine multi-vector impacts; power, heat and hydrogen production
- Identify tipping points and their consequences/opportunities
- System relationships with other non-nuclear technologies and overall emissions

MPR actions
- Identification of opportunities associated with each nuclear technology
- Decisions for each technology; little/no regret based on opportunity value
- Associated actions for policy and regulation to stimulate markets

Figure 3 – Schematic showing process flow to deliver analysis for Supplementary Report No.3

3.3. Updating ESME functionality to include the new technologies

ESME is a data-driven system modelling tool and therefore introducing these two new technologies is relatively straightforward for a system modelling engineer familiar with ESME. The necessary inputs are a collection of techno-economic parameters to characterise a technology such as capital and operating costs, efficiency (inputs/outputs) and deployment rates.

3.3.1. Incorporating the functionality of the hydrogen gigafactory

ESME already contains diverse technologies for hydrogen production including from fossil fuels, biomass and low temperature electrolysis. These technologies are well established in the current ESME standard release version 4.5.

The Nuclear for Net Zero project introduced a further technology option to flexibly convert nuclear energy to either electricity or hydrogen, or a combination of both. This technology is described in the NFNZ summary report and in greater detail in the NFNZ technical report. The Hydrogen Gigafactory technology represented in this report is essentially a simplification of the NFNZ advanced nuclear technology, where the flexibility is removed to create a single energy vector output (hydrogen only) and the rate of deployment is increased associated with a reduction in costs.

3.3.2. Incorporating the functionality of the liquid synthetic fuel plant

The concept of combining pre-processed carbon dioxide with hydrogen to produce a fossil fuel replacement is not new either in reality or within energy system models. ESME already includes a technology to produce synthetic natural gas from electricity and processed carbon dioxide.

The typical challenge is in representing the CO_2 processing step, or the collection of environmental carbon with oxygen and pre-preparing it into the process stream required for the conversion plant. As an example, the synthetic natural gas plant in ESME assumes that the CO_2 source is carbon dioxide captured from energy conversion plant such as industrial Carbon Capture and Storage (CCS) or Direct Air Capture of CO_2 (DACC) plant. This CO_2 is already removed from the atmosphere and thus utilising this CO_2 in the energy system is net neutral (and atmospheric extraction avoids the need to consume fossil fuels before capturing the emissions). The only techno-economic scenario for using such CO_2 in a further process is if the cost of transport and storage of this CO_2 is prohibitive.

The liquid synthetic fuel plant technology explored in this study is assumed to have its own environmental source of CO_2, such as biofuels or seawater, without recourse to a separate DACC plant (i.e. the processing of environmental carbon with oxygen is an intrinsic part of the synthetic fuel production plant). The CO_2 cannot be injected into networks for long-term storage and therefore within ESME the plant does offer the ability to decrease net emitted Greenhouse Gases (GHGs) when the resulting fuel is used in place of fossil fuel.

Within this report it has also been possible to disaggregate the different elements of the synthetic production plant, i.e. the production of hydrogen and high-temperature heat, processing of environmental CO_2 into a form ready for further combination, and then the final synthetic fuel production module. This enables assessment of the sensitivity of plant deployment to the techno-economic feasibility of the different modules within the plant.

If liquid synthetic fuels were to be widely available as a cost-competitive alternative to liquid fossil fuels, then there would be numerous potential applications to model within ESME to support multiple pathways towards the achievement of Net Zero. Within this project, there is a focus on the international aviation emissions which are recognised as a "hard to treat" category of residual emissions. The focus on aviation fuel within this project, which gives the potential to eliminate 31-36 Mt of aviation emissions, is intended to provide an indication of the system value of such a technology and demonstrate the benefit of developing further techno-economic evidence to support the assumptions used within Supplementary Report No.3.

4. Updated datasets for Supplementary Report No.3

4.1. Dataset for large Gen III+

Table 2 – Large Gen III+ selected key parameters applied for Supplementary Report No.3

Gen III+ Electricity Generation (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2025	2025	2030
Construction Duration (years)	4.5	5.5	7
Build Out Rate (GWe/year)	2.1	1.4	0.7
Overnight Capital Cost ($/KWe in 2017 dollars)	$4,000/KWe at 2025 reducing to $3,500/KWe by 2050	$4,500/KWe at 2025 reducing to $4,000/KWe by 2050	$5,500/KWe at 2030 reducing to $5,000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The dataset for large Gen III+ for Supplementary Report No.3 has been carried forward from Supplementary Report No.2. For ease of reference the key parameters are shown in Table 2. For brevity, the full dataset and associated supporting assumptions and related data are not detailed here but included in Annex 1 to Supplementary Report No.2.

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 2 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

4.2. Dataset for LWSMR

Table 3 – LWSMR cogen (flexible power and heat for district heating energisation) selected key parameters applied for Supplementary Report No.3

Cogen LWSMR Electricity and Heat (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2028	2030	2035
Construction Duration (years)	3	4	5
Build Out Rate (GWe/year)	2.7	1.2	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,000/KWe at 2028 reducing to $2,000/KWe by 2050	$4,000/KWe at 2030 reducing to $3,000/KWe by 2050	$5,000/KWe at 2035 reducing to $4,000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Capex is for cogeneration with heat rejected from power conversion system used for DH energisation with power downrate penalty. Costs include $500/kWe Capex increment for CHP which includes pipe runs circa 10 km to connect plant to city scale DH ring main (4) For electricity only plant remove the $500/KWe CHP increment included in the Capex (5) Full DH energisation across England and Wales equates to 22 GWe of LWSMR in England and Wales from ETI ANT project. (6) Site capacity limit for England and Wales at 2050 established from the ETI PPSS (7) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

The dataset for LWSMR for Supplementary Report No.3 has been carried forward from Supplementary Report No.2. For ease of reference the key parameters are shown in Table 3. For brevity, the full dataset and associated supporting assumptions and related data are not detailed here but included in Annex 1 to Supplementary Report No.2.

It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 3 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

4.3. Dataset for the hydrogen gigafactory

The Hydrogen Gigafactory technology is a refinery-scale hydrogen production facility, sized to produce one tenth of UK hydrogen demand in 2050. The Hydrogen Gigafactory delivery model with its integrated onsite manufacturing of key components and compact layout can deliver large quantities of very low-cost hydrogen. Almost all of the components are manufactured and assembled in two high productivity environments (pre-cast factory and reactor systems manufacturing facility) on-site. This results in a highly integrated manufacturing, assembly and installation process on one site. This enables high quality, repeatable processes, with quality assurance designed into every step of the process. At full production rate, the factory is designed to produce twelve 600MWTh reactors per year, equivalent to approximately 3GW of hydrogen production. Manufactured components can also be moved by barge to other coastal refinery sites. The Hydrogen produced by the Gigafactory is either supplied directly to the gas networks or is supplied to a synthetic fuels plant on an adjacent site.

The Hydrogen Gigafactory, sized to be equivalent to a medium-sized refinery in terms of output, enabled by storable, transportable commodities production, is large enough to justify the capital investment required for the factory. Annex 1 provides a representative image of the Gigafactory concept and further description. The Hydrogen Gigafactory technology is proposed as a next generation refinery to be located on brownfield sites, such as large coastal oil and gas refineries in the UK. LucidCatalyst's forthcoming reports: Clean and Scalable Synthetic Fuels for the Electric Power Research Institute presents the detailed techno-economic analysis for this concept; and Decarbonizing Prosperity: Hydrogen Enabled Synthetic Fuels in collaboration with the Nuclear Energy Institute describes the potential for market transformation and de-risking decarbonisation enabled by large quantities of clean and low-cost hydrogen.

4.3.1. Hydrogen gigafactory – Greater nuclear ambition baseline

The technical and economic parameters for the Hydrogen Gigafactory are not supported by underpinning evidence substantiated within the scope of this project or report. For ease of reference the assumptions regarding key parameters are shown in Table 4. It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 4 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

As discussed in more detail in Annex 1, LucidCatalyst developed these technical and economic parameters for the Hydrogen Gigafactory based on existing studies of high-temperature reactor designs combined with new cost reduction strategies, not examined in previous studies, to create the Hydrogen Gigafactory concept. Highly productive on-site manufacturing dramatically reduces the production and installation cost for the plant for reactor manufacturing and on-site operation of numerous reactors allows the facility to produce hydrogen at low-cost through significant economies of scale. The Operation and Maintenance (O&M) cost estimates derive from studies by the Japan Atomic Energy Agency on a high-temperature gas-cooled reactor.[4] Hydrogen produced from a Gigafactory at these cost profiles is delivered at the site fence at between 2.4p/kWh.H_2 and 2.6p/kWh.H_2 (1.2 $/kg to 1.3 $/kg). This undercuts all alternative low- or zero-carbon hydrogen production options within the ESME reference dataset, with only unabated fossil-based options offering a cheaper source of hydrogen (which would be inconsistent with stringent GHG targets).

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4   Japanese Atomic Energy Agency (Xing L. Yan), HTGR Brayton Cycle: Technology and Operations, 2017.
    https://energy.mit.edu/wp-content/uploads/2017/02/2-3.-HTGR-Brayton-Cycle-YAN-MIT-talk-r1-min.pdf

Table 4 – Hydrogen Gigafactory selected key parameters applied for Supplementary Report No.3

Hydrogen Gigafactory (NOAK)	Greater Nuclear Ambition Baseline
First Operations date	2030
Construction Duration (years)	2
Build Out Rate	5 GW/year initially ramping up to 10 GW*/year by 2040 * [where 1 GW represents instantaneous production of 1 GW of hydrogen]
Overnight Capital Cost	£1000/kW at 2030 reducing to £750/kW by 2050
Notes: (1) Economic life 60 years (2) Design capacity factor 92% (3) Data values reflect aspirational NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies	

4.3.2. Sensitivities

The cost and efficiency assumptions represent aspirational targets, reflective of successful global innovation and a supportive policy environment. From a techno-economic perspective, however, it is also important to understand how the degree of innovation success influences the chosen energy system designs rather than simply fixing on a single set of ambitious technology assumptions. Greater insight is obtained by determining how the energy system both reacts to availability of such an option and how the system design changes (if at all) if the aspirational costs are either not achieved or over-achieved.

Table 5 – Gigafactory hydrogen production cost as the variable parameter in sensitivity testing

Sensitivity	2050 H_2 Production Cost from Gigafactory
1	1.1 $/kg
2 (Base)	1.2 $/kg
3	1.6 $/kg
4	2.0 $/kg
5	2.4 $/kg
6	2.8 $/kg

To support this requirement, six technology cost sensitivities have been modelled as detailed in Table 5. To remove confounding effects from the simultaneous introduction of the synthetic fuel plant and the Gigafactory, these sensitivities are based around Run 301 (TECH100) as described in Section 5. No synthetic fuel production is assumed available within these sensitivity studies.

4.4. Dataset for the liquid synthetic fuel plant

The technology concept is that each liquid synthetic fuel plant would use heat and power from reactors to produce hydrogen, which would then be combined with carbon to produce 'drop-in' liquid synthetic aviation fuel ('Jet A'). The carbon could come from various source options, as discussed above in Section 3.3.2. Annex 1 provides a schematic diagram of the liquid synthetic fuel plant and discusses its techno-economic parameters.

4.4.1. Liquid synthetic fuel plant – Greater nuclear ambition baseline

Table 6 – Liquid synthetic fuel production plant: Selected key parameters applied for Supplementary Report No.3

Synthetic Aviation Fuel Plant (NOAK)	Greater Nuclear Ambition Baseline
First Operations date	2030
Construction Duration (years)	4
Build Out Rate	1 GW/year in 2030 ramping up to 10 GW*/year from 2040 onwards * [where 1 GW represents instantaneous production of 1 GW of synthetic liquid fuel]
Overnight Capital Cost	£1600/kW at 2030 reducing to £1200/kW by 2050: • Nuclear to hydrogen: £1,200/kW.H_2 in 2030 • Carbon treatment to process ready CO_2: £160/kW.*(synthetic fuel)* in 2030 • Hydrogen to aviation fuel: £240/kW.*(synthetic fuel)* in 2030 • Total plant: £1,600 in 2030 Capital costs decrease 25% by 2050 (total plant: £1,200/kW in 2050). Alternative representation for 2050 era plant: • Hydrogen and high-temperature heat production module: £900/kW.H_2 • CO_2 processing module: Equivalent to £13/tCO_2 • Aviation fuel synthesis module: £180/kW.*(synthetic fuel)*
Notes: (1) Economic life 60 years (2) Design capacity factor 92% (3) Data values reflect aspirational NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies	

While the technical and economic parameters for the liquid synthetic fuel plant are based on existing studies of the underlying technology, the development of a systematic evidence base for the innovative delivery model is still required, the scope for which is outlined in Annex 5. For ease of reference the assumptions regarding key parameters are shown in Table 6. It should be noted that, as with all other technology datasets within ESME, the parameter values in Table 6 are defined on the basis of Nth-of-a-Kind (NOAK) values, rather than for First-of-a-Kind (FOAK).

The total plant capex is £600/kWe higher than the Hydrogen Gigafactory because it includes the reformer and Fischer-Tropsch reactor for combining hydrogen and carbon to produce synthetic liquid fuel. The capex adder for this equipment derives from Idaho National Laboratory's report on a nuclear plant design for hydrogen production (which in the source report is combined with nitrogen to produce ammonia).[5] Opex estimates for the liquid synthetic fuel plant derive from the JAEA HTGR study cited above. Details on the capex and opex allocation across the plant's sub-systems appear in Annex 1. The synthetic fuel plant delivers aviation fuel at between 3.0p/kWh and 3.5 p/kWh. When available, this undercuts the cost of conventional fossil-based aviation fuel (circa 5p/kWh) throughout (and thus the implied marginal cost of abatement is negative).

4.3.2. Sensitivities

Sensitivities around synthetic fuel production cost detailed in Table 7 have been explored in a similar way to those outlined in Section 4.3.2. In this case, however, only sensitivities that increase cost have been explored: as noted above, the base case Greater Nuclear Ambition cost assumptions already undercut the cost of fossil fuel and thus limited value is expected from modelling even lower costs.

Table 7 – Liquid synthetic fuel production cost as the variable parameter in sensitivity testing sensitivity 2050 synthetic fuel production cost 1 (Base) 3.0 p/kWh

Sensitivity	2050 synthetic fuel production cost
1 (Base)	3.0 p/kWh
2	4.1 p/kWh
3	6.2 p/kWh
4	12.5 p/kWh
5	33.7 p/kWh

The cost sensitivities assumptions were chosen to be deliberately broad so that the tipping point at which no synthetic fuel was produced could be studied.

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5   Idaho National Laboratories, Nuclear-Integrated Ammonia Production Analysis. Technical Evaluation Study. Project No. 23843. Document ID: TEV-666. Revision 2. 2010. https://art.inl.gov/NGNP/INL%20Documents/Year%202010/Nuclear-Integrated%20Hydrogen%20Production%20Analysis%20rev%201.pdf

5. ESME analysis and results

The charts and tables shown in section 5 are intended to collate and summarise key information from the many ESME runs across relatively few pages. These results are then interpreted and discussed in Section 6. A listing of all new scenario runs is provided in Annex 2. All ESME Runs undertaken for Supplementary Report No.3 are numbered sequentially from 301 to distinguish them from earlier runs for NFNZ and Supplementary Reports Nos. 1 and 2. To provide a greater level of detail, all the relevant ESME core chart outputs for these Runs are included in Annex 3.

5.1. Electricity capacity and generation
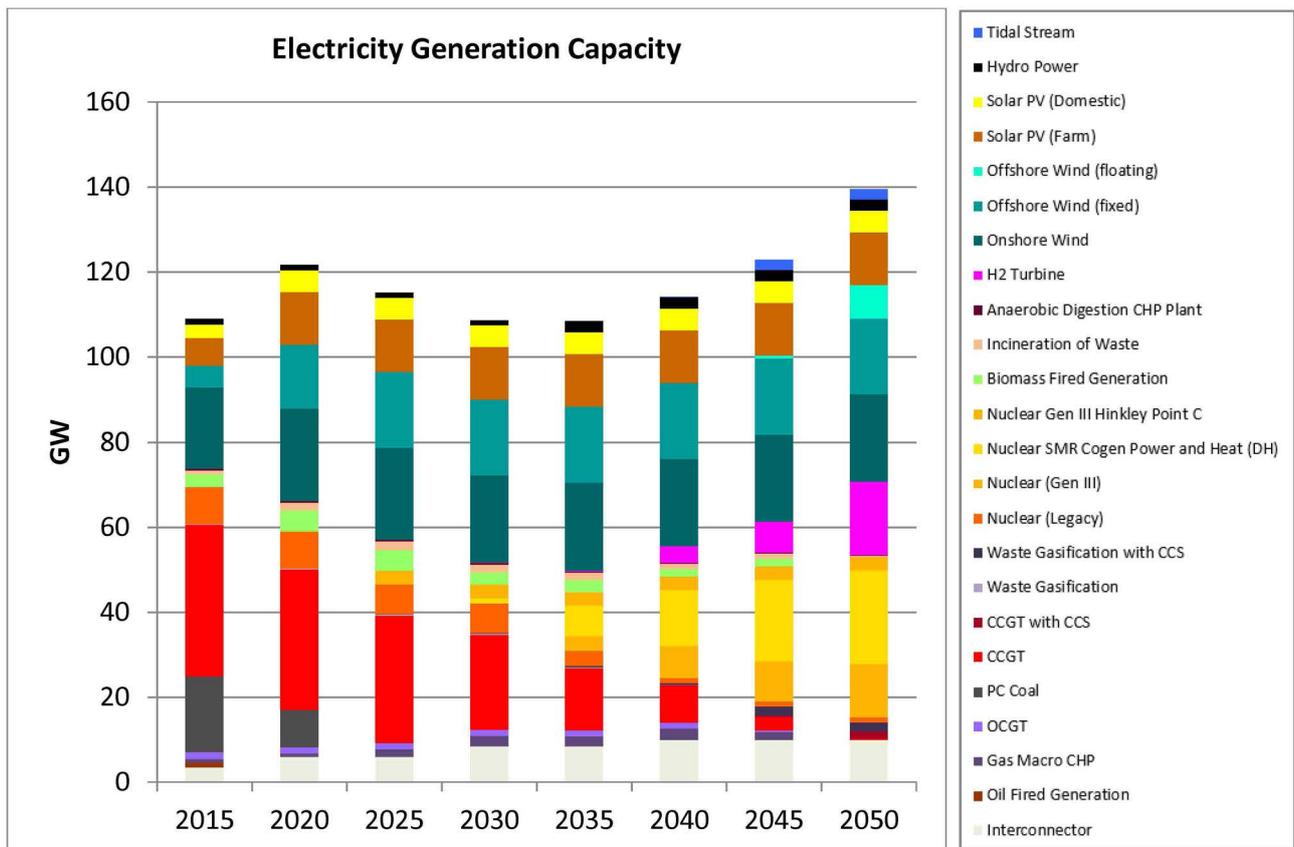
Figure 4 – Electricity generating capacity – Run 301 without hydrogen gigafactory or synthetic fuel plant (TECH100)
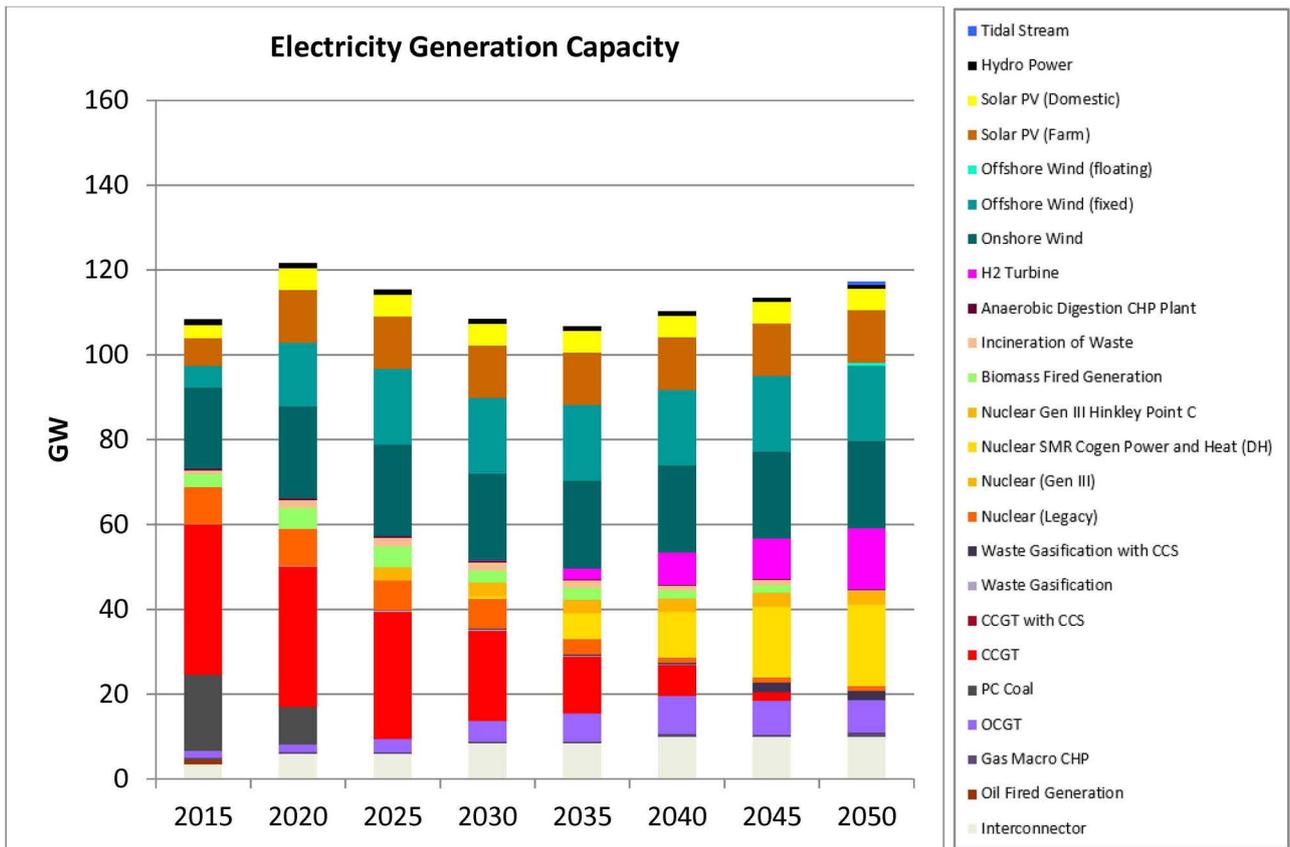
Figure 5 – Electricity generating capacity – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)
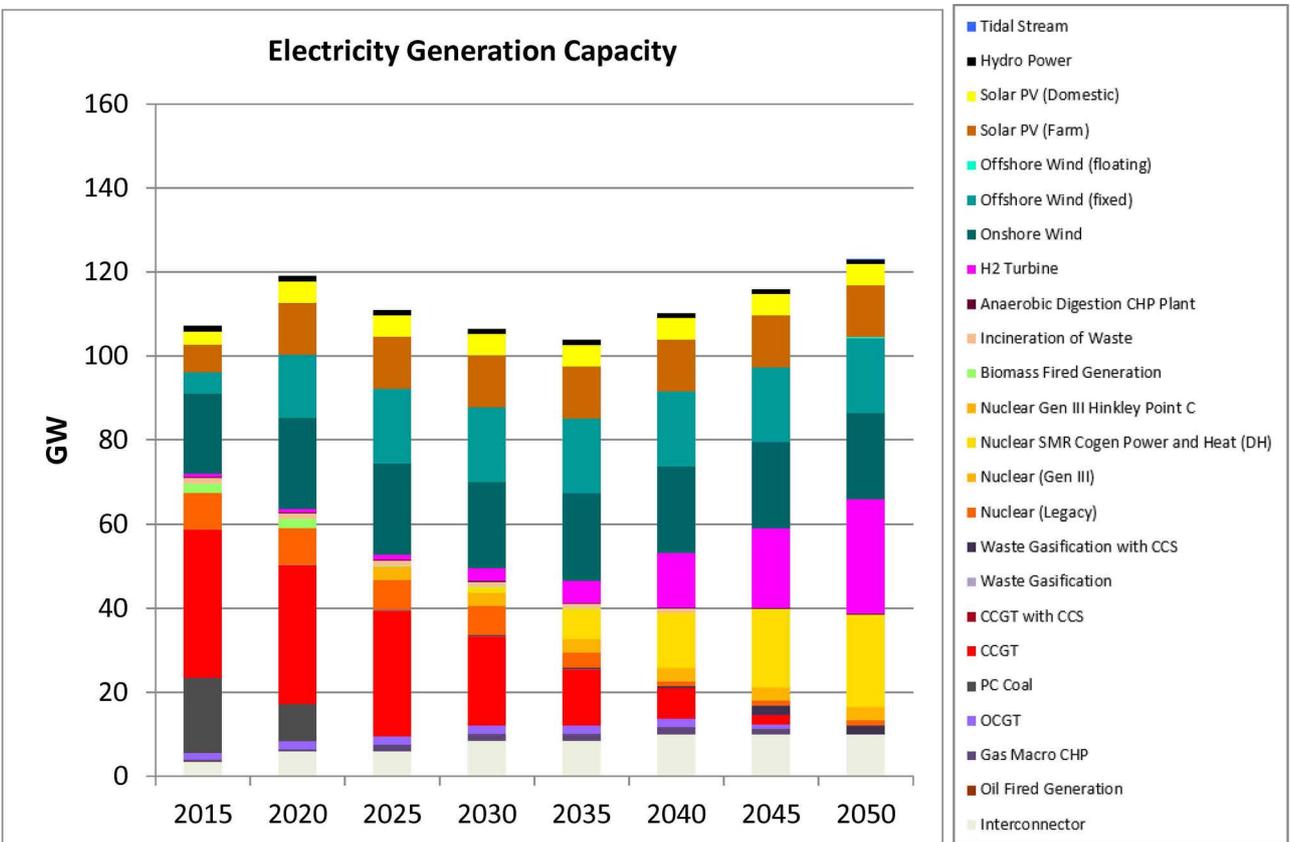
Figure 6 – Electricity generating capacity – Run 312 with hydrogen gigafactory and synthetic fuel plant (FA100)
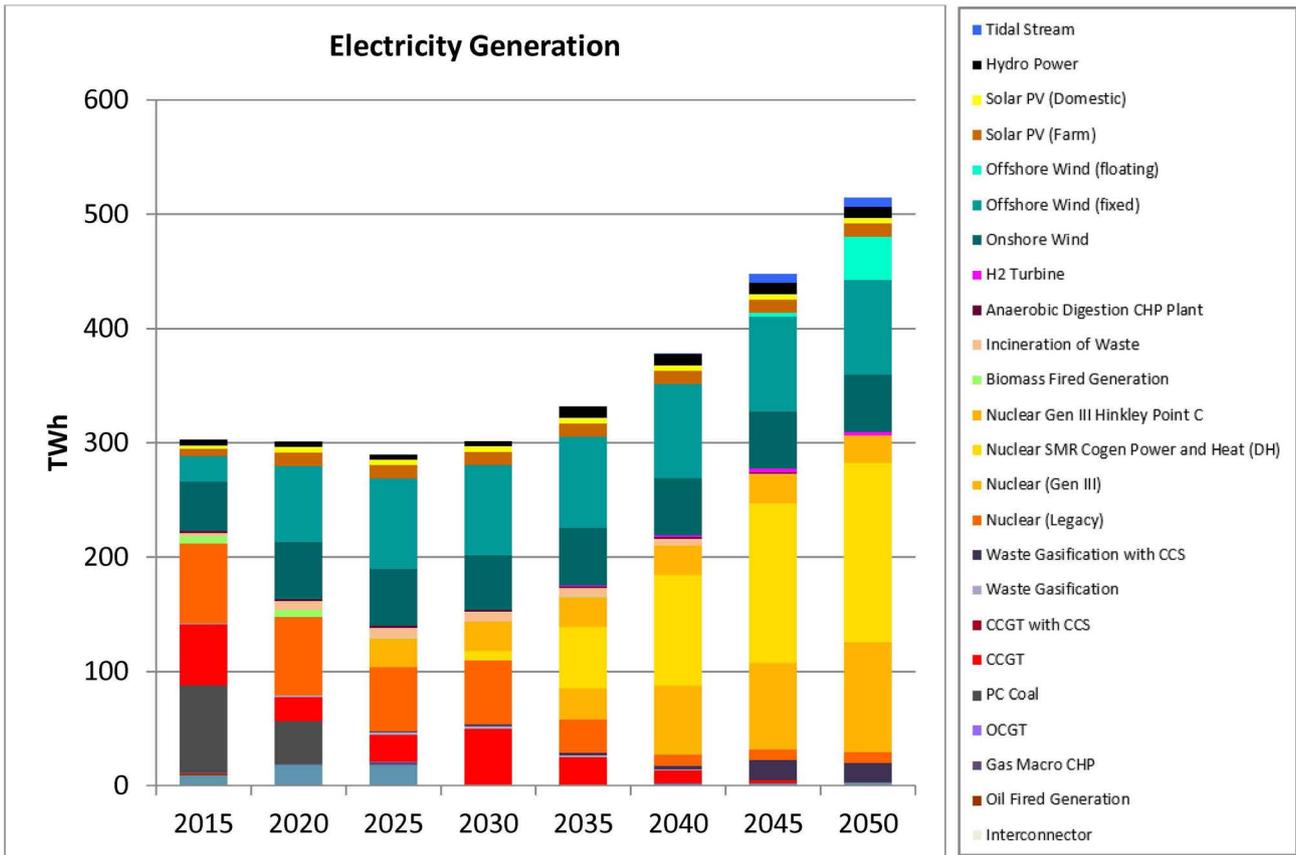
Figure 7 – Electricity generation – Run 301 without hydrogen gigafactory or synthetic fuel plant (TECH100)
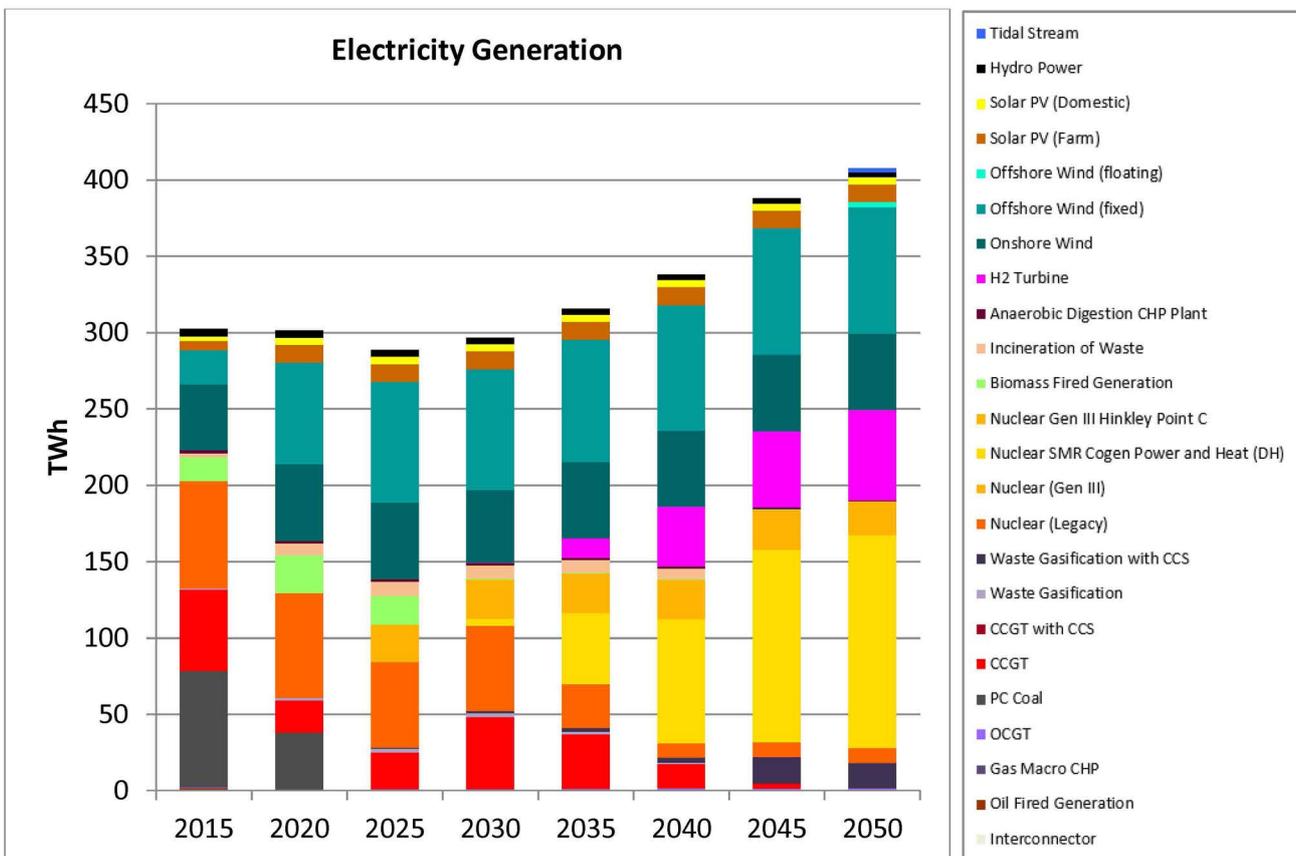
Figure 8 – Electricity generation – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)
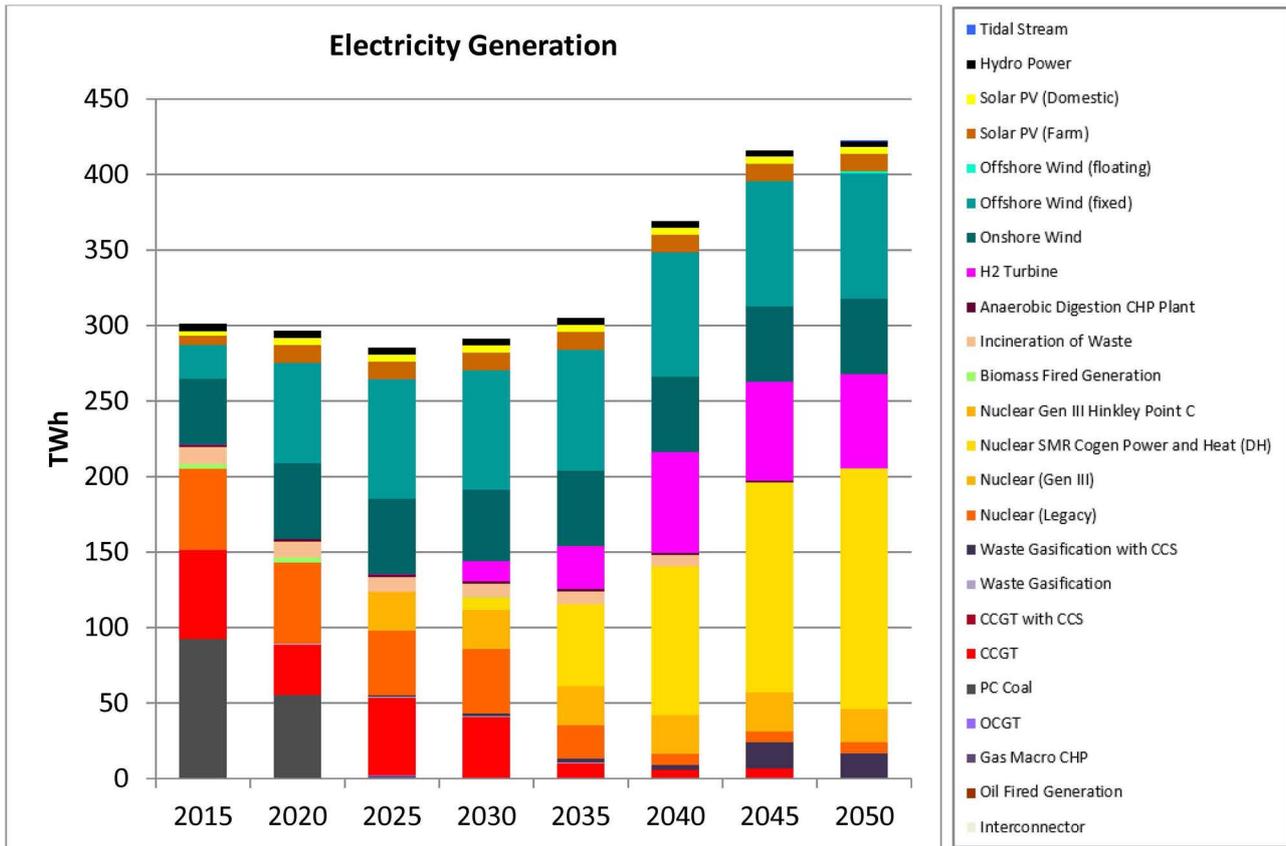
Figure 9 – Electricity generation – Run 312 with hydrogen gigafactory and synthetic fuel plant (FA100)

5.2. Hydrogen consumption and supply
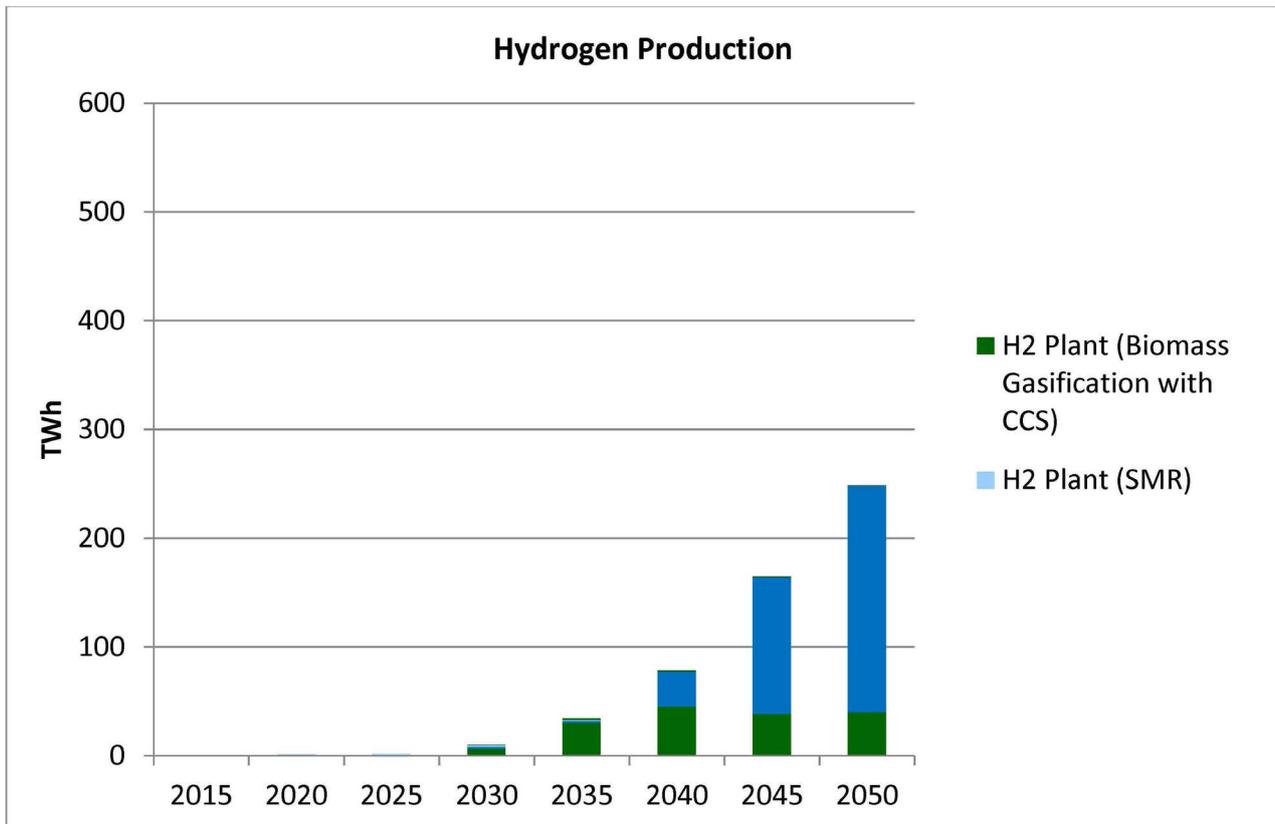
Figure 10 – Hydrogen production – Run 301 without hydrogen gigafactory or synthetic fuel plant (TECH100)
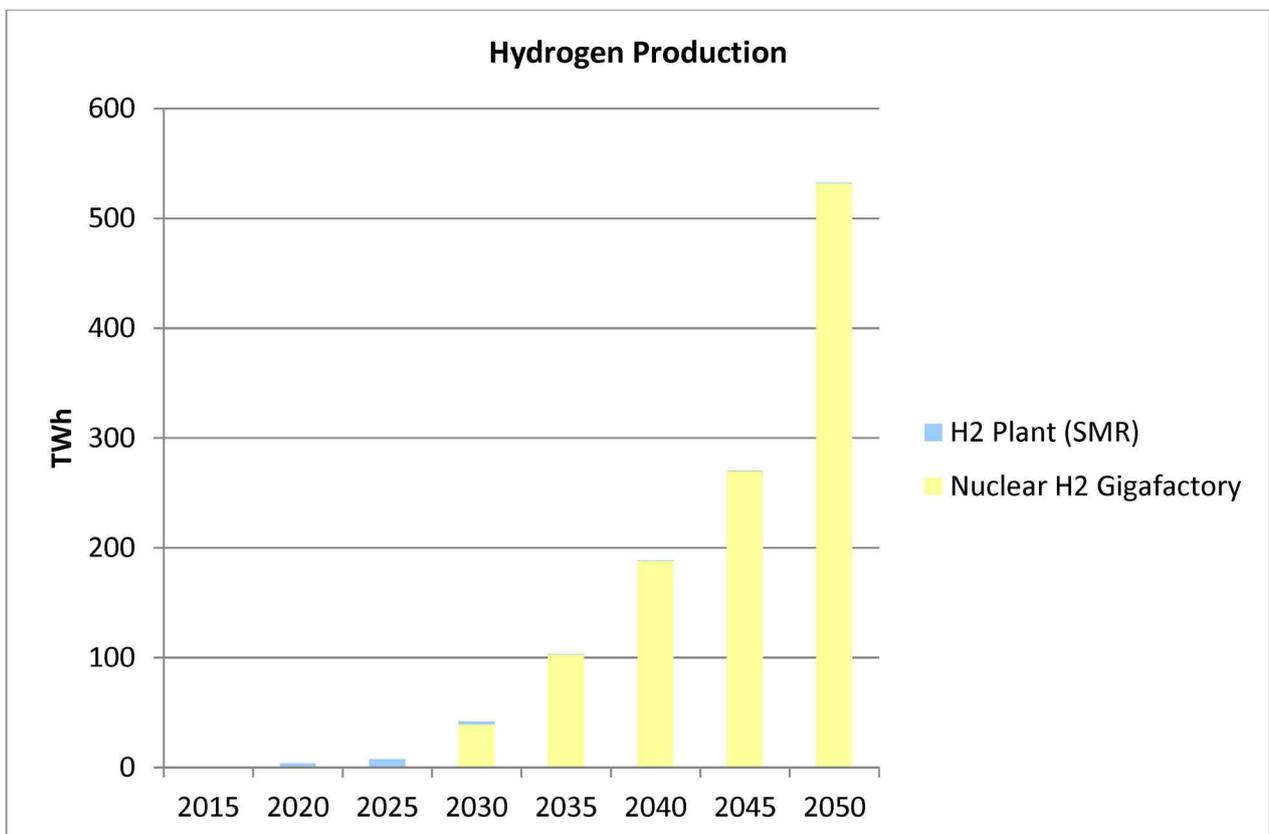
Figure 11 – Hydrogen production – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)
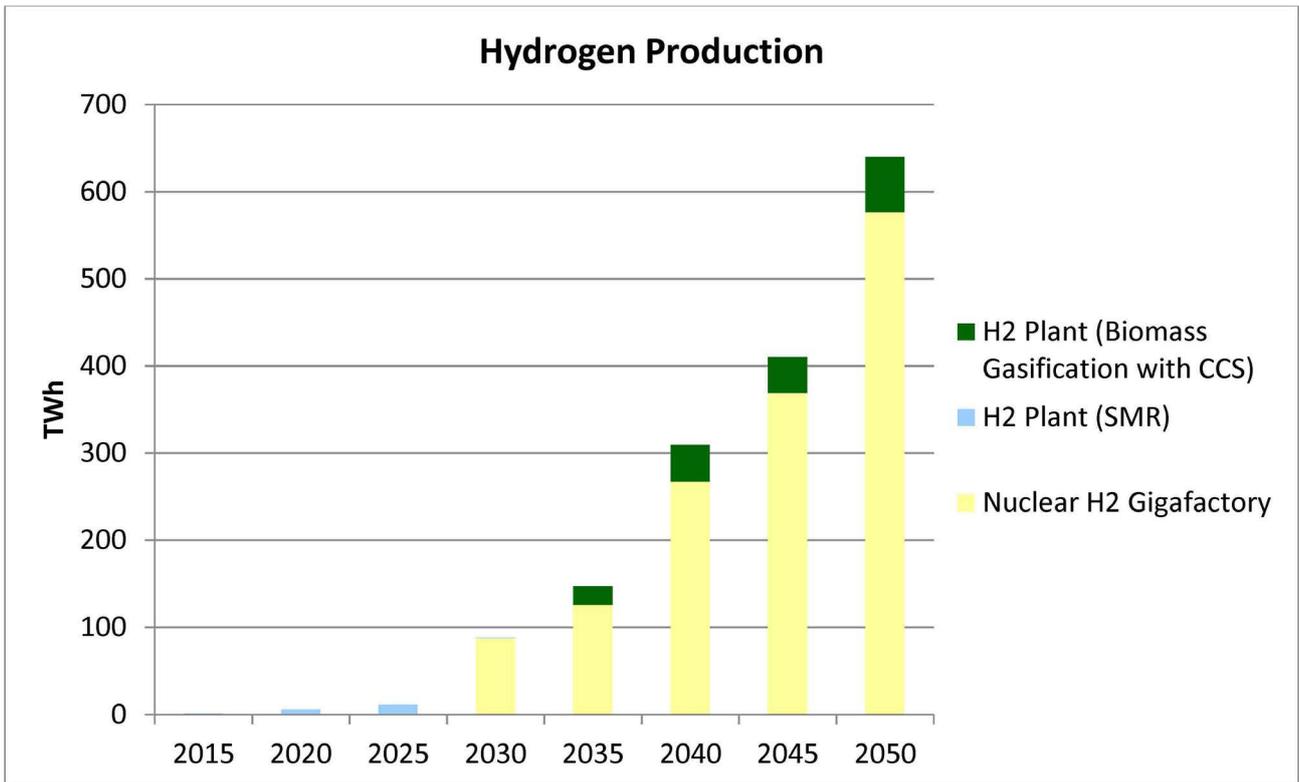
Figure 12 – Hydrogen production – Run 312 with hydrogen gigafactory and synthetic fuel plant (FA100)
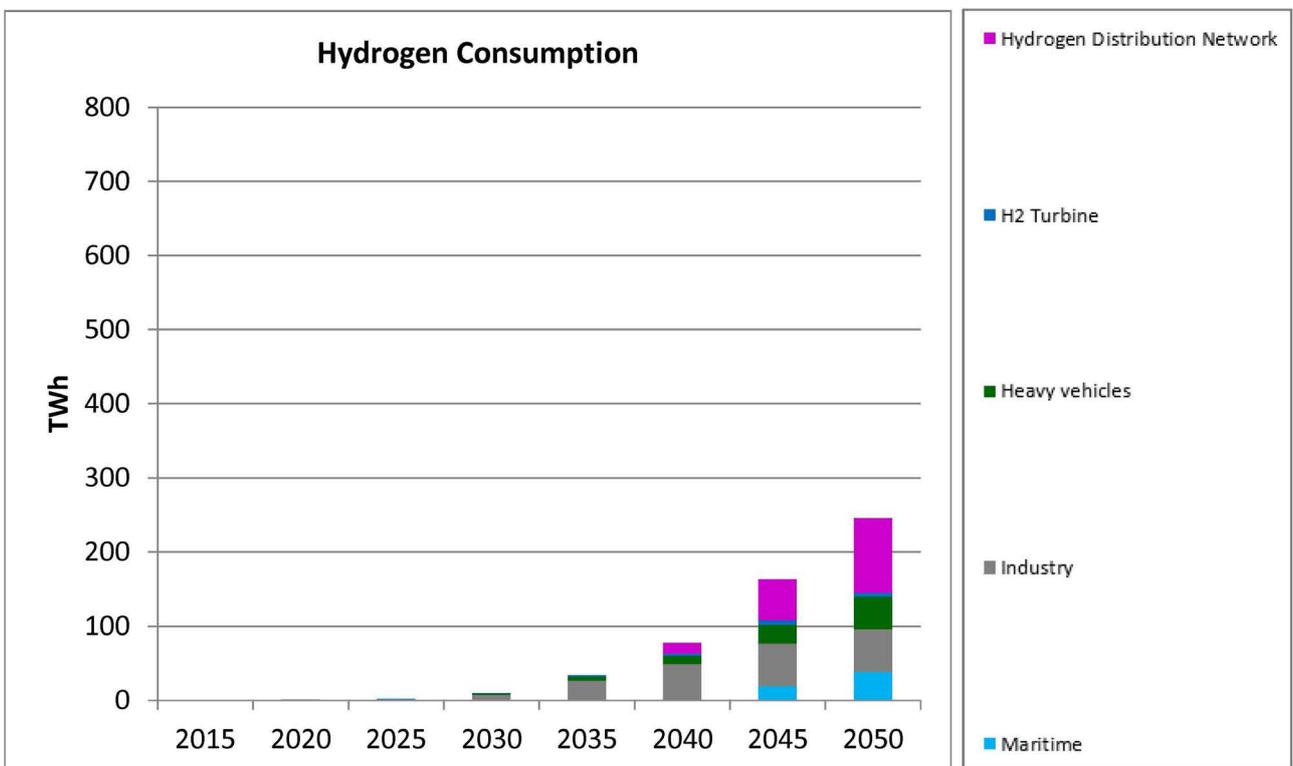
Figure 13 – Hydrogen production – Run 301 without hydrogen gigafactory or synthetic fuel plant (TECH100)
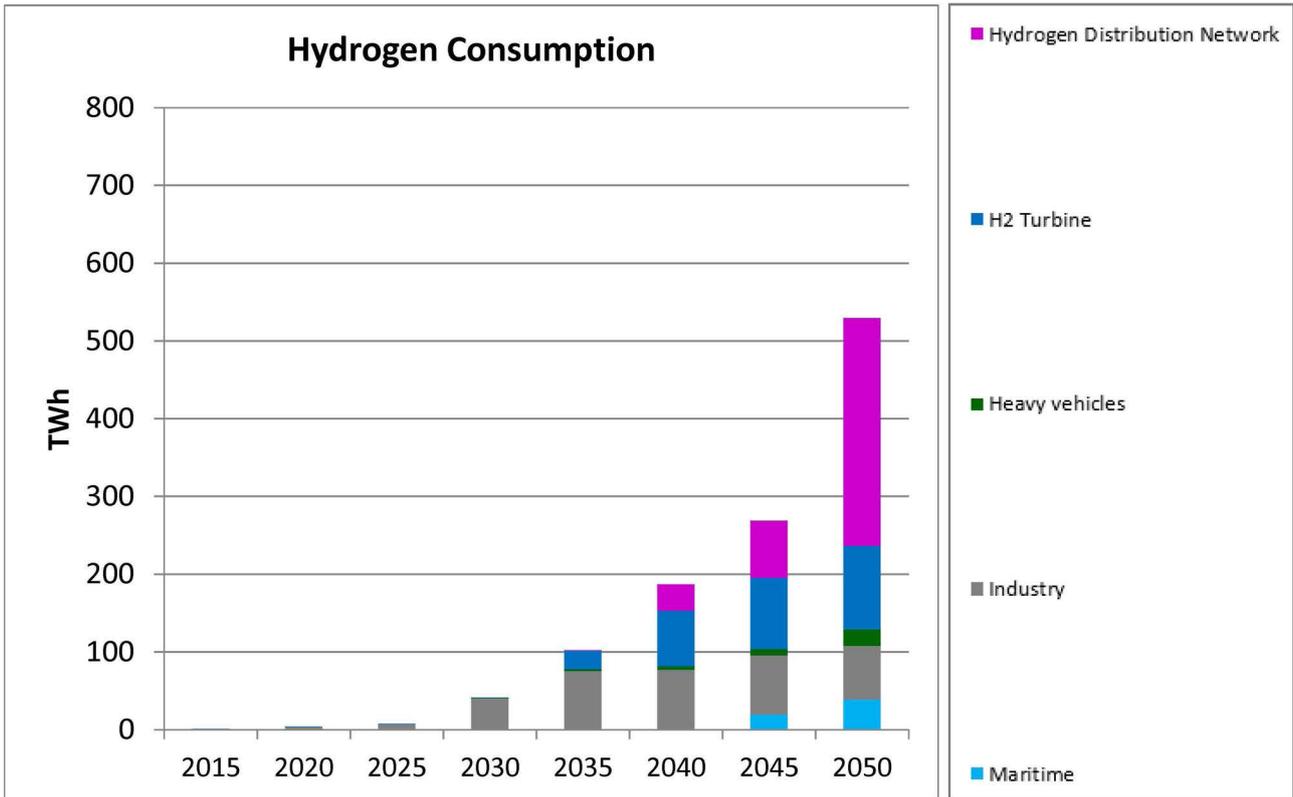
Figure 14 – Hydrogen consumption – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)
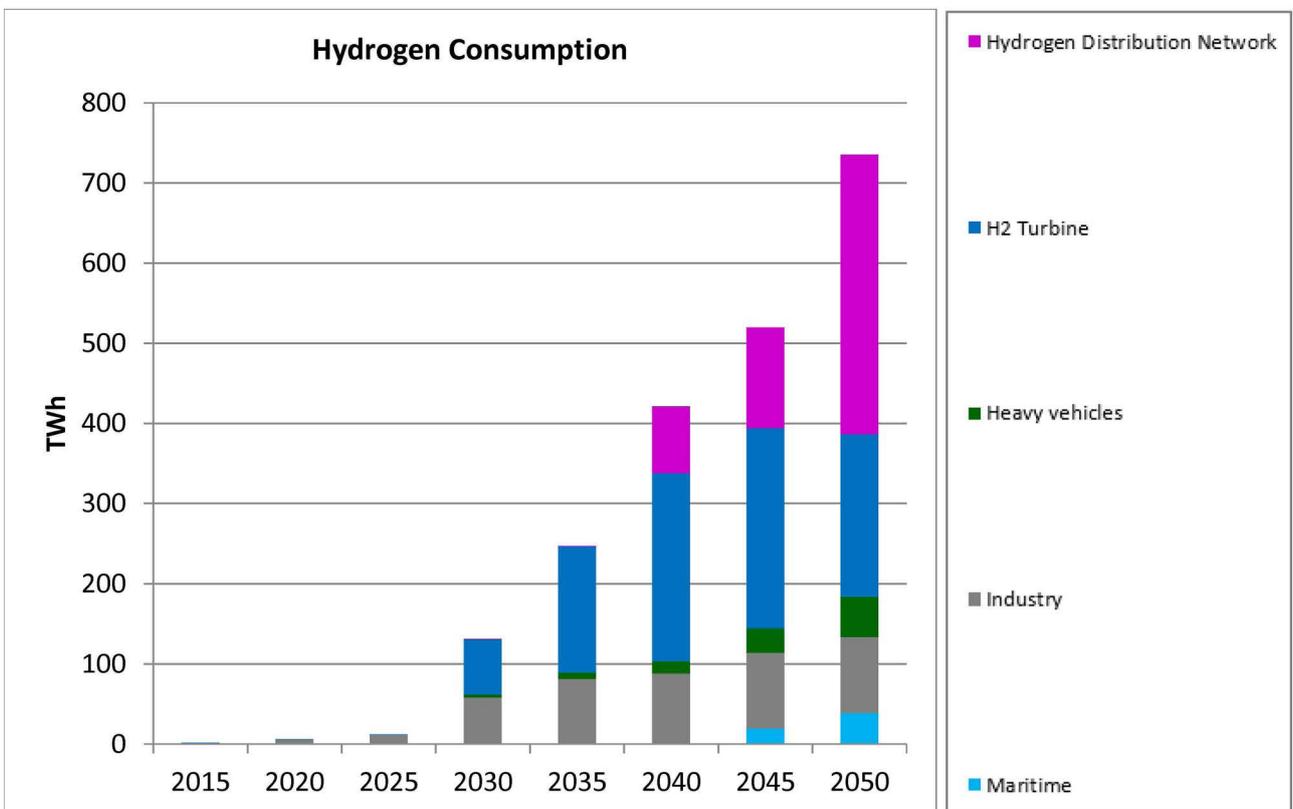
Figure 15 – Hydrogen consumption – Run 312 with hydrogen gigafactory and synthetic fuel plant (FA100)

5.3. Heat networks and energy supply from nuclear
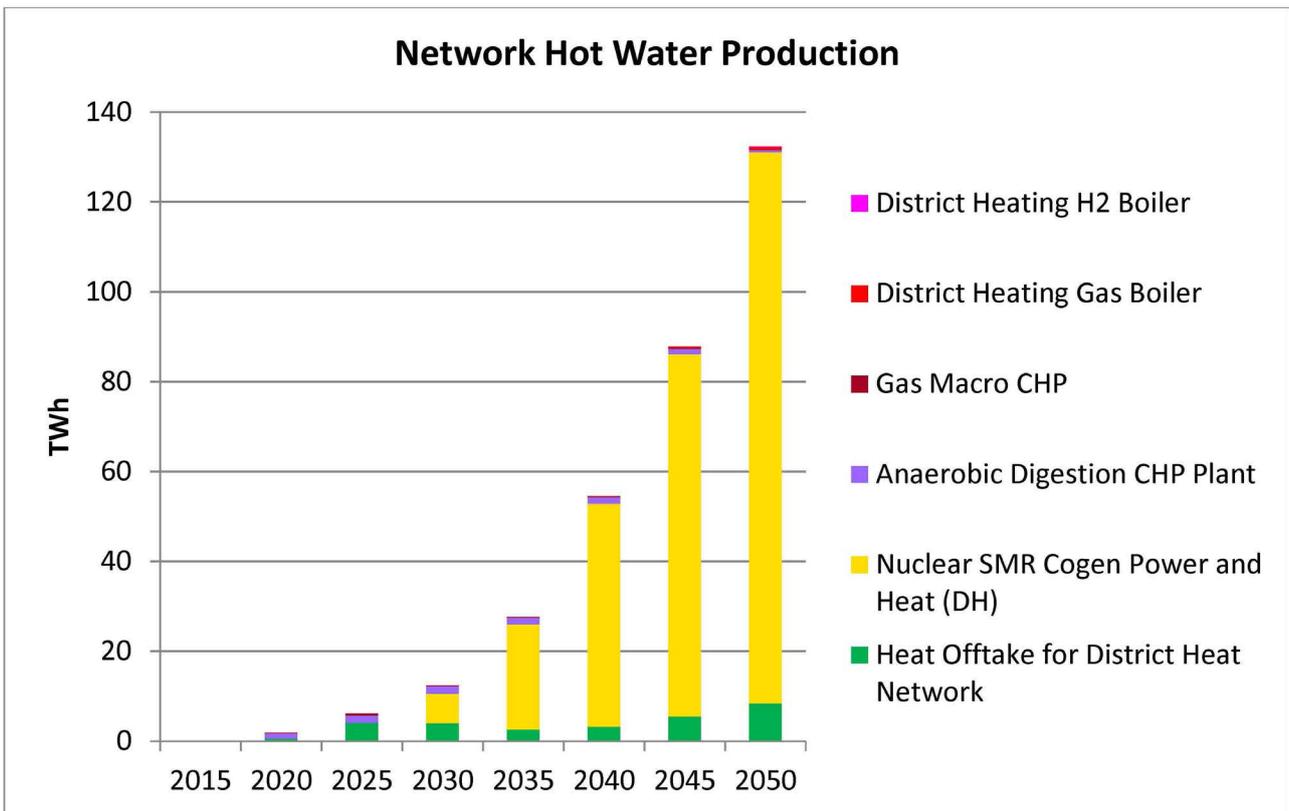
Figure 16 – Nuclear contribution to heat network energisation – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)

5.4. Synthetic fuel production
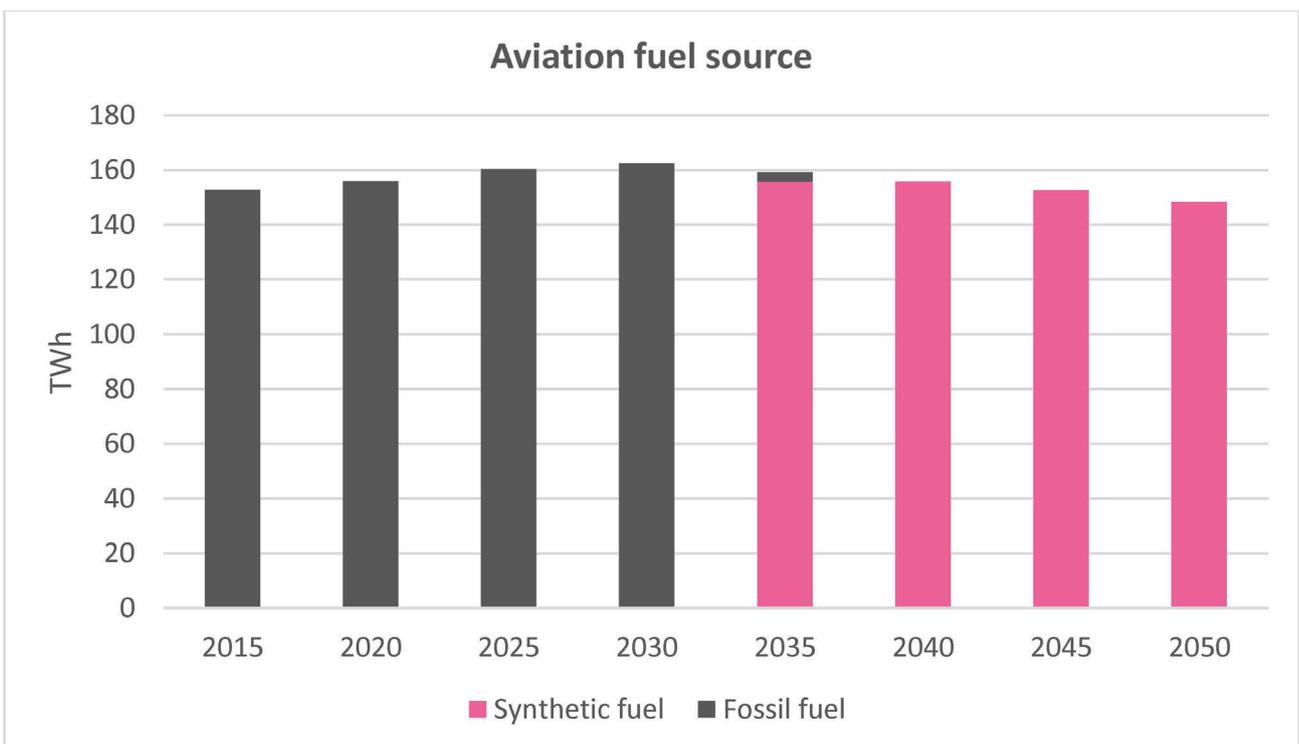
Figure 17 – Sourcing of aviation fuel – Run 310 with hydrogen gigafactory and synthetic fuel plant (TECH100)

5.5. Hydrogen production sensitivities
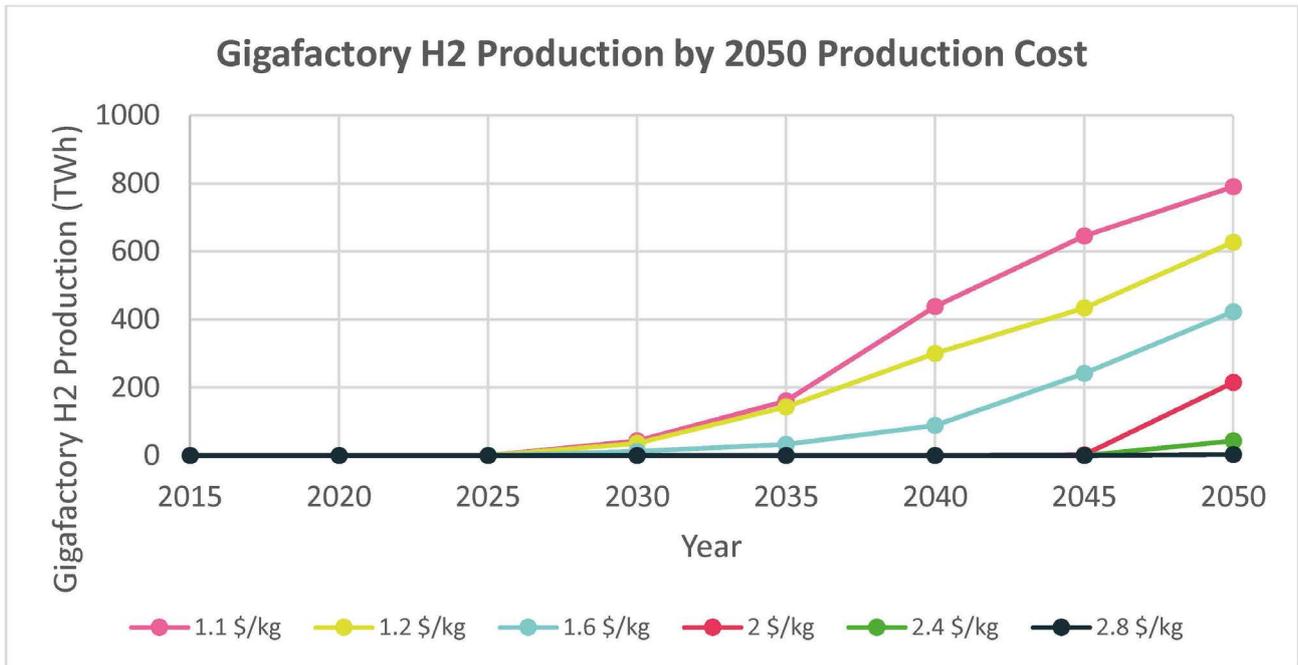
Figure 18 – Hydrogen production from gigafactory: sensitivity to production costs at site fence ($2017)
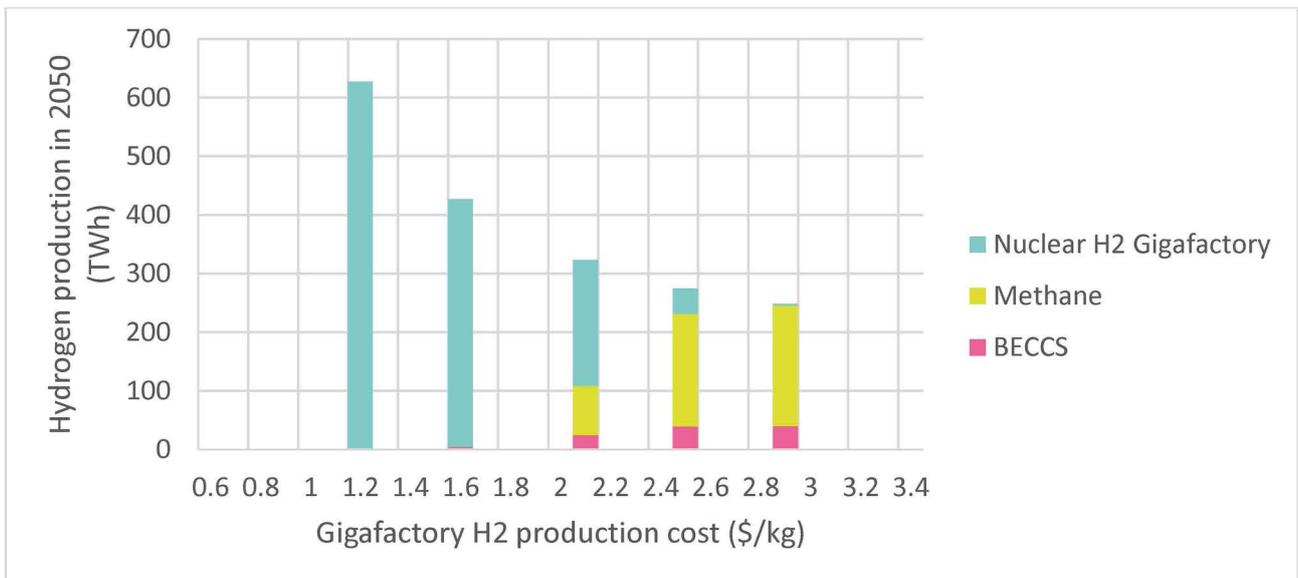
Figure 19 – Hydrogen production in 2050 by technology as a function of gigafactory H_2 production cost ($2017)
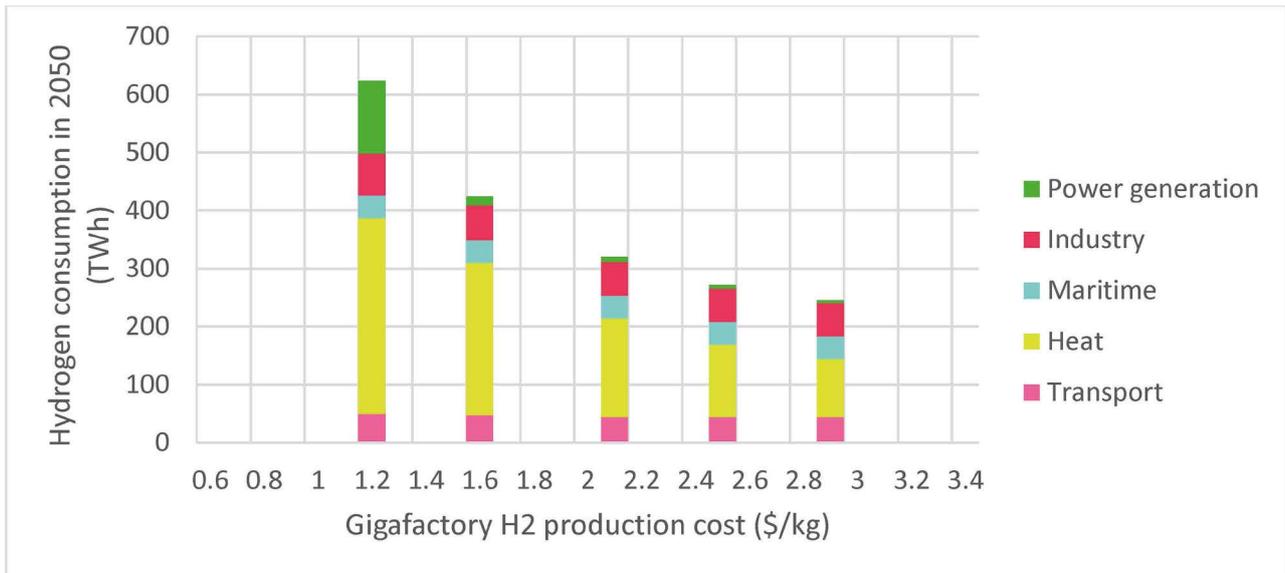
Figure 20 – Hydrogen consumption in 2050 by technology as a function of gigafactory H$_2$ production cost ($2017)

5.6. Synthetic fuel production sensitivities
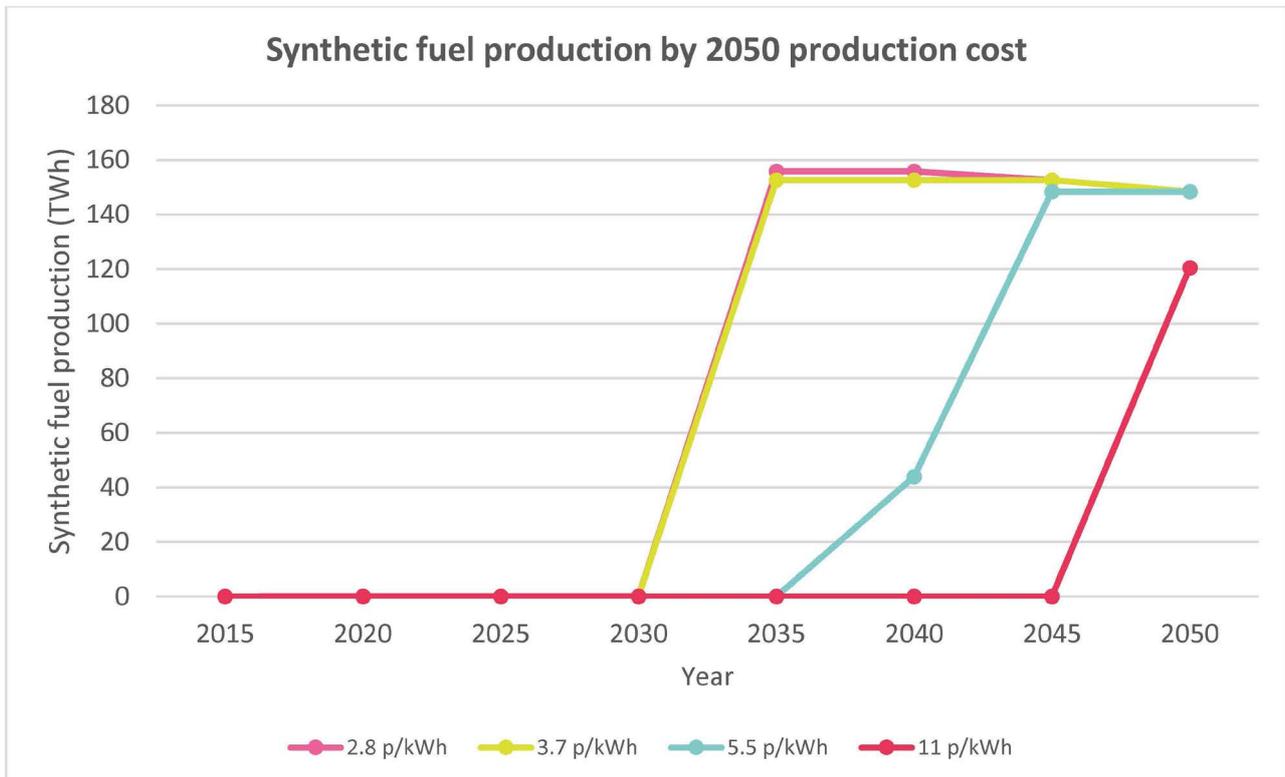
Figure 21 – Liquid synthetic aviation fuel production as a function of production cost (£2010p/kWh)

5.7. Net emissions

Figure 22 – 2050 CO$_2$ emissions with higher nuclear optimism (Run 202 TECH100), greater nuclear ambition without hydrogen gigafactory and synthetic fuel production (Run 301 TECH100,) and greater nuclear ambition with hydrogen gigafactory and synthetic fuel production (Run 310 TECH100)

5.7.1. Impact of synthetic fuel production
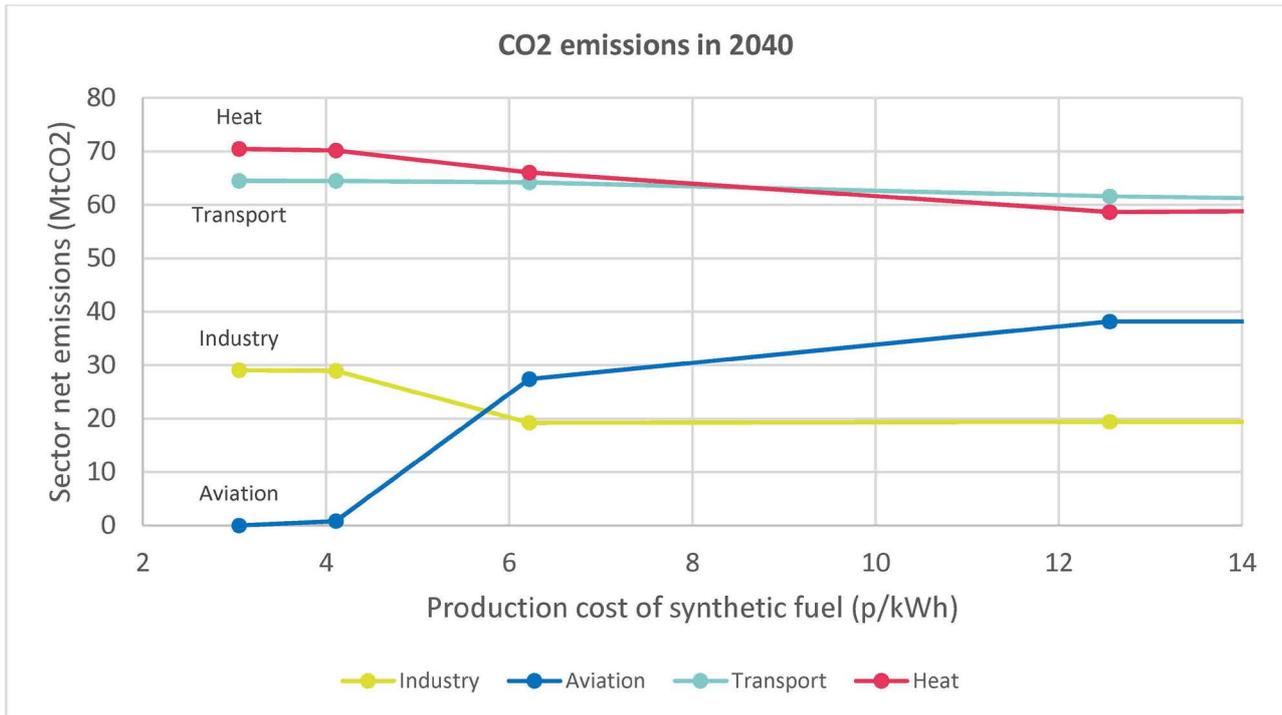
Figure 23 – Net CO_2 emissions in 2040 as function of liquid synthetic fuel production cost
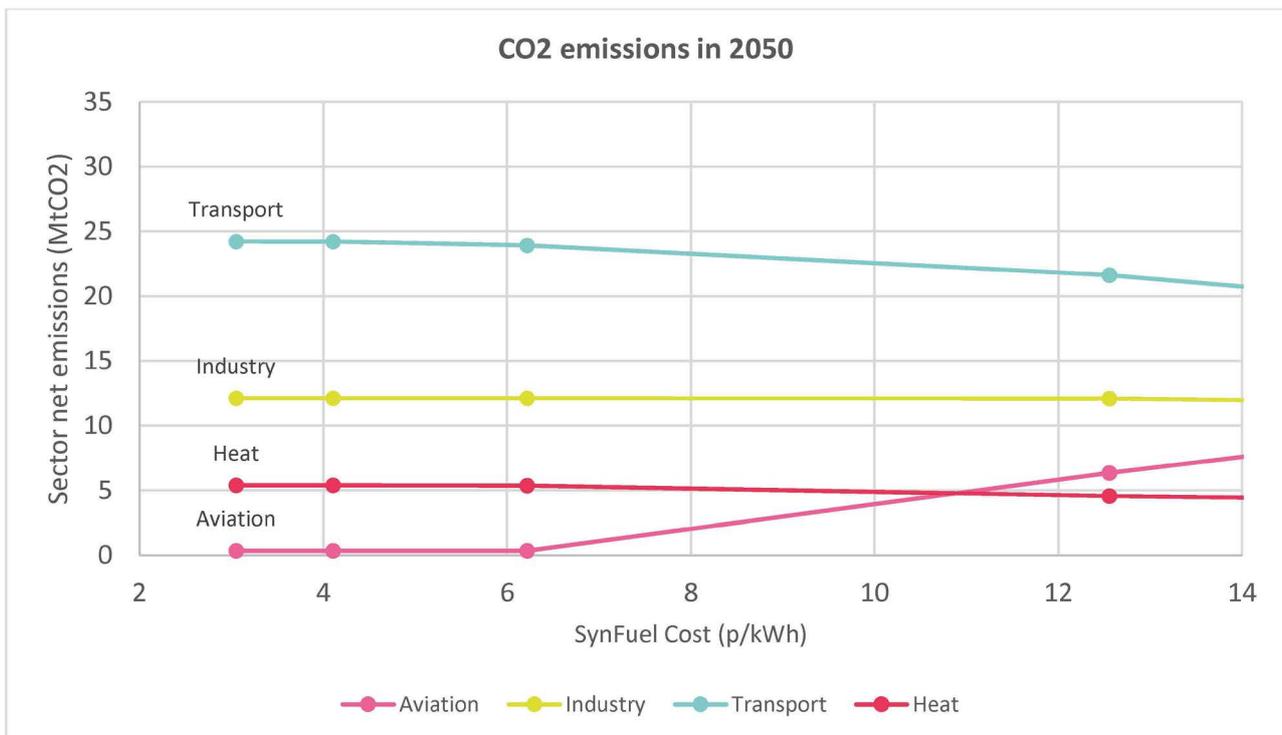
Figure 24 – Net CO_2 emissions in 2050 as function of liquid synthetic fuel production cost

5.8. Probabilistic (Monte Carlo) assessment

5.8.1. Selection of Run 310 as the basis for probabilistic (Monte Carlo) analysis

As with the sensitivities outlined earlier, the Monte Carlo modelling analysis undertaken for this report is a supplementary exploratory study intended to deepen understanding of the features that influence deployment of nuclear technologies. Generally, the philosophy adopted when carrying out probabilistic modelling using ESME is to permit many of the key uncertain system properties to vary. These include future technology costs, fuel prices and constrained energy resources such as biomass. Adopting a Monte Carlo modelling approach offers new insights by considering different relative levels of technology cost-competitiveness and allows the value of electricity, hydrogen and district heat to be assessed when features of the energy system change simultaneously. This method goes beyond a simple independent variation of the costs of the Gigafactory and synthetic fuel plant and thus complements the approach tested in the deterministic sensitivities.

It should be noted, however, that in general the availability of biomass can strongly influence the feasibility of delivering on a Net Zero target. Whereas the TECH100 scenarios have been hand-tuned[6] to ensure carbon targets are met, a typical probabilistic assessment produces an ensemble of simulations which may achieve differing levels of decarbonisation: lowering the biomass resource reduces the amount of negative emissions available to the system and thus affects the achievable greenhouse gas abatement target. In contrast to this, though, the availability in the current project of synthetic fuel to eliminate emissions from the aviation sector acts as a counter. Even the most challenging systems (i.e. with lowest levels of bioenergy resource) can draw on more than 30 Mt of greenhouse gas abatement to remove all remaining emissions. As the bioenergy resource assumed within TECH100 is at the upper end of the range of plausible levels, it is likely that most of the simulations would incorporate relatively high costs for decarbonisation via synthetic fuel production.

Selecting Run 310 as the basis of the Monte Carlo study is appropriate for the current analysis within Supplementary Report No.3. This permits some competition of emissions removal technologies (BECCS, DACC and synthetic fuels), which would not be present to the same extent in FA100. The inclusion of technologies with high carbon capture rates – particularly methane reformers – implies a level of technical optimism that is likely to be consistent with delivery of the advanced nuclear technologies studied within this report.

As already highlighted within the dataset descriptions, the greater nuclear ambition baseline costs for both the Gigafactory technology and the synthetic fuel production technology are sufficiently low that they are likely to deploy extensively assuming a modest (±30%) cost variation, as typically used within a probabilistic study using ESME. Such cost variation is unlikely to reveal fresh insights and therefore the 2050 cost ranges have been significantly enlarged to roughly align to the sensitivities outlined in the dataset descriptions. As with the deterministic sensitivities, tipping points and trends associated with deployment of advanced nuclear technologies are of greater value in the current exploratory project than adopting tight, robust cost ranges.

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6   Scenario descriptions can be found in the Energy System Catapult's Innovating to Net Zero report

5.8.2. Overall system design – Probabilistic analysis
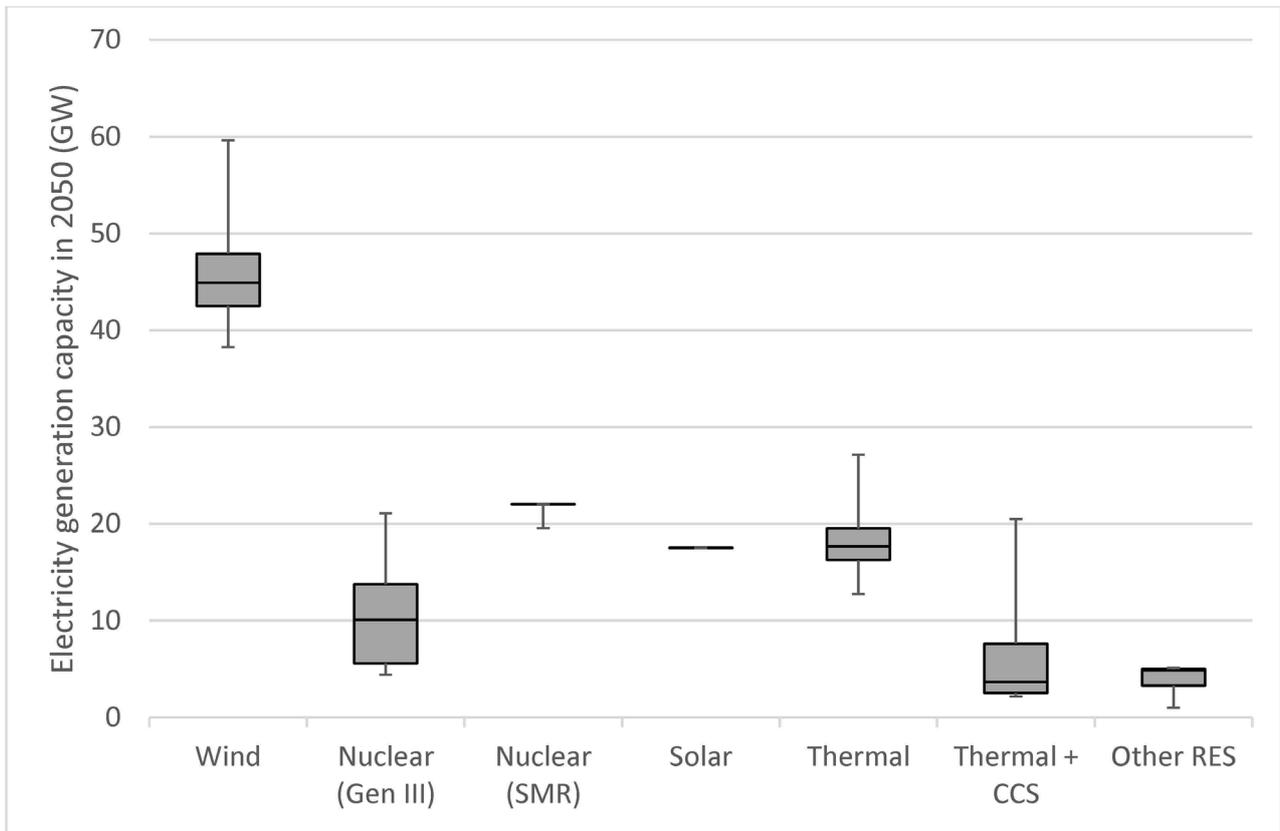
Figure 25 – 2050 electrical generation capacity by technology – Probabilistic (Monte Carlo) analysis based on deterministic Run 310 TECH with hydrogen gigafactory and liquid synthetic fuel plant
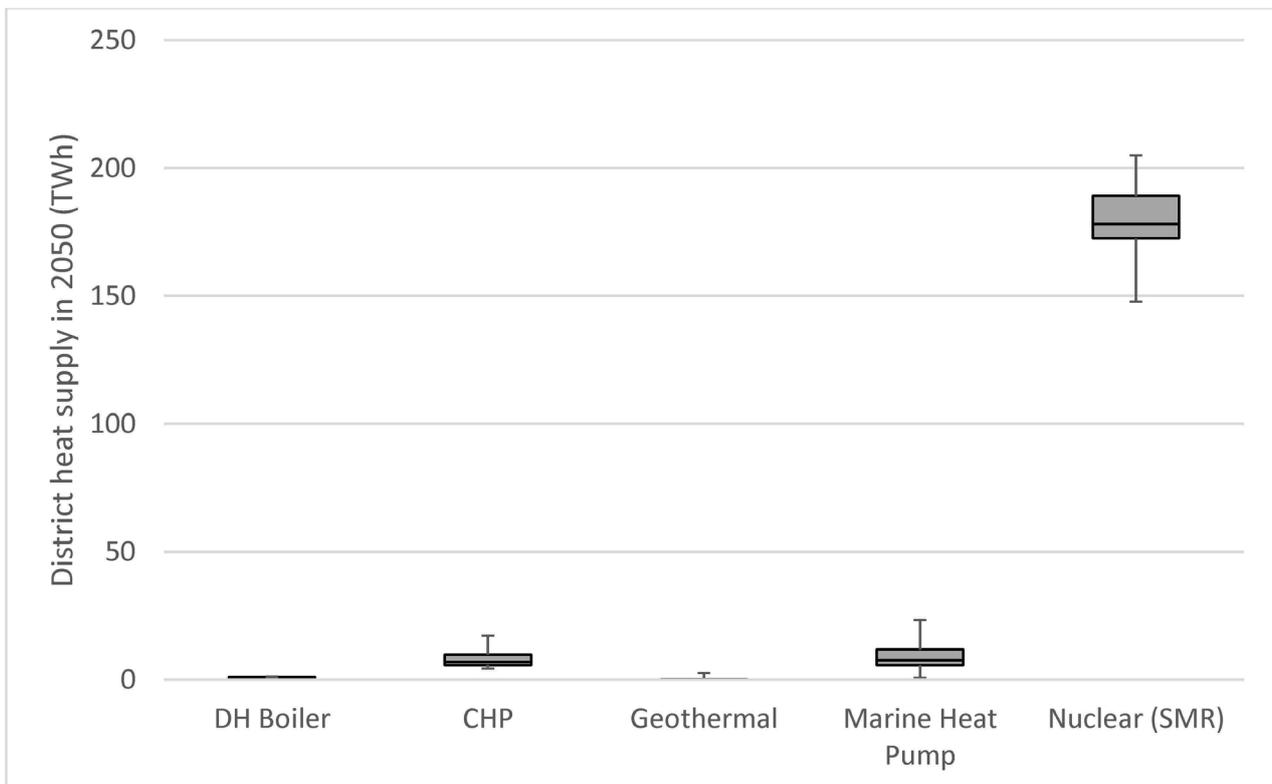
Figure 26 – 2050 district heat supply by technology – Probabilistic (Monte Carlo) analysis based on deterministic Run 310 TECH with hydrogen gigafactory and liquid synthetic fuel plant

5.8.3. Hydrogen gigafactory – Probabilistic analysis
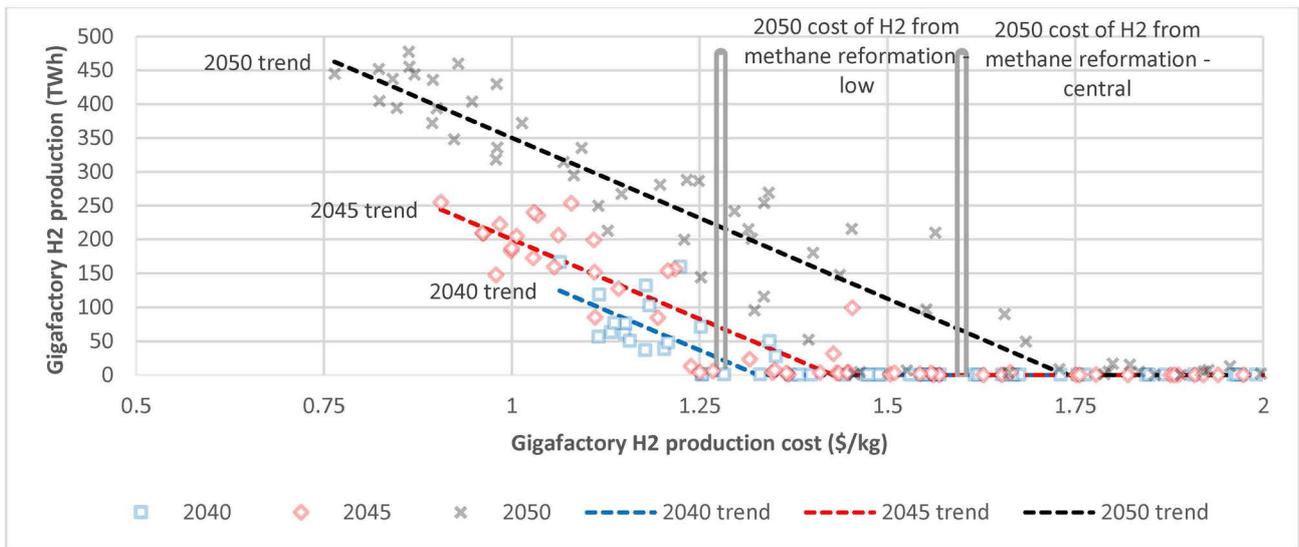
Figure 27 – SR No.3 Probabilistic (Monte Carlo) Run showing hydrogen production from the gigafactory as a function of production cost ($2017) – Decarbonisation scenario TECH100

5.8.4. Liquid synthetic fuel plant – Probabilistic analysis
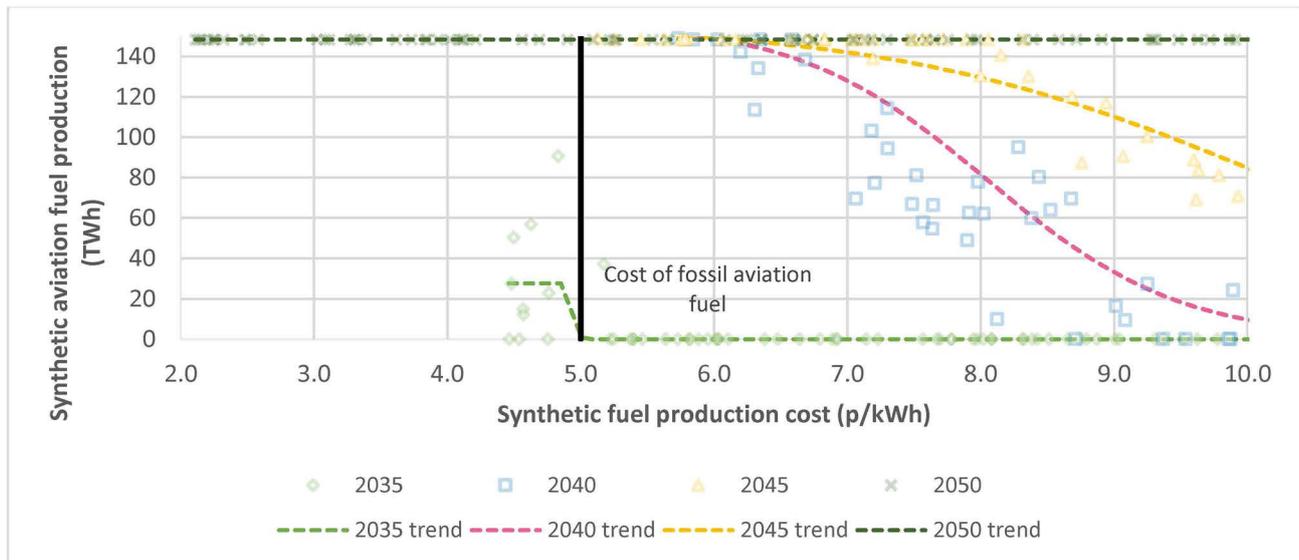
Figure 28 – SR No.3 Probabilistic (Monte Carlo) Run showing liquid synthetic fuel production as a function of production cost (£2010 p/kWh of aviation fuel) – Decarbonisation scenario TECH100

6. Discussion

6.1. System overview

The optimal system design is modified extensively upon introduction of the Hydrogen Gigafactory and synthetic liquid fuel plant options assuming that these are delivered at the ambitious cost levels described in Section 4. Key observations regarding energy systems incorporating these technologies include:

- In the electricity generation sector, a reduction in production from offshore wind and Gen III+ power generation plant (circa 20 GW total reduction) which is countered by an uplift in supply via hydrogen turbines and retention of some unabated gas plant (Figures 4 to 9)

- The key enabler of this change is the ability of synthetic fuel to provide a viable, large-scale decarbonisation option for the aviation sector. Without this option, the aviation sector's options are limited to injection of biofuels (making use of a constrained, in-demand resource) and improved aircraft efficiencies. If liquid synthetic aviation fuel is sufficiently cost-competitive, the aviation sector is wholly decarbonised (Figure 22), offering some 30+ $MtCO_2$ of additional emissions to be produced elsewhere

- This allows residual emissions to remain in other, costlier-to-decarbonise sectors of the energy system. In Runs 310-312, the impact is mostly on the transport sector (mostly affecting freight transport) and on the degree of deployment of direct air CO_2 capture (DACC)

- As synthetic fuel production costs at base case level undercut fossil aviation fuel throughout, full deployment of synthetic fuel technology takes place as soon as plant becomes available, i.e. in the 2030s

- The most notable feature of the new systems, however, is the change in source and quantity of hydrogen produced (Figures 10 to 15). Where hydrogen from nuclear sources is not available, production originates from a combination of biomass gasification, methane reformation and electrolysis. With low production costs via the Gigafactory, almost all hydrogen is generated via this technology

- Most strikingly, the lower hydrogen costs drive a dramatically different role for hydrogen as an energy carrier, system wide. Hydrogen production to supply heat to buildings and support the power generation system is significantly uplifted (from < 300 TWh in Run 301 and previous studies, to > 500 TWh in runs with a cost competitive Gigafactory)

- The mixed group of deployed space heating technologies changes in response to a lower-cost source of hydrogen. The hybrid heat pump systems firing hydrogen mostly in cold periods (typically observed in NFNZ and Run 301) are supplemented by conventional boiler systems firing hydrogen throughout the year. One key driver behind this choice is the disconnection of power and hydrogen production costs, with the Gigafactory being optimised to produce bulk hydrogen it is likely that a portion of this need would be better served by deploying either flexible or dedicated electricity-producing plant, or diverting the electricity generated within the Hydrogen Gigafactories at peak demand periods direct to the grid rather than for hydrogen production

- Differences between runs 310, 311 and 312 are fairly modest. Due to the absence of additional decarbonisation options such as high CO_2 capture rates and DACC, Run 312 demonstrates a slightly more challenging system to decarbonise in 2050 than the simulations based on TECH100 and BOB100 (hence the removal of unabated natural gas-fired peaking plant), but the broad system features remain similar. There is little difference in the supply of district heat, with nuclear LWSMRs forming the main source of heat in all scenarios.

6.2. Hydrogen consumption and supply

As outlined above, Runs 310, 311 and 312 demonstrate that the availability of low-cost synthetic fuel production plant and of hydrogen production have the potential to transform system designs and to affect the plausibility of achieving a Net Zero target. To better understand the system impacts in response to changes in hydrogen and synthetic fuel production cost, a suite of sensitivities has been developed. For sensitivities focused on the cost of the Hydrogen Gigafactory (without availability of synthetic fuel), key observations are:

- The total Gigafactory hydrogen supply reduces fairly smoothly as the cost of hydrogen production is increased. For the sensitivities derived from the TECH100 scenario, Gigafactory hydrogen supply is almost completely eliminated at a delivered hydrogen cost of around $2.5/kg. This delivered cost would still be achieved if Gigafactory capex was roughly quadrupled compared with the ambitious cost data assumptions used within this report

- Parity with methane reformation with carbon capture – the main cost-competitive alternative for bulk hydrogen supply – occurs at around $1.7/kg[7]. This tipping point is demonstrated within Figure 19, where methane as a hydrogen source is not utilised until the Gigafactory production costs are lifted beyond $2/kg

- The use of hydrogen is bounded by two extreme cases. Low-cost nuclear-derived hydrogen enables system-wide hydrogen deployment throughout power generation, heating, industry and transport. At higher costs, where methane reformation is used preferentially, heat (to support hybrid systems rather than gas-fired boiler replacements), industry and transport remain the preferred uses for hydrogen

- As the cost of Gigafactory hydrogen reduces below the tipping point, the main response is within the heat sector, with a gradual uplift in supply for heat (implying greater deployment of boiler replacements or greater use of hydrogen within hybrid heat pumps). Industry and transport use respond weakly to this cheaper source of fuel, as they already utilise hydrogen to a level deemed "optimal" for decarbonisation

- Approaching the ambitious costs assumed in this study, hydrogen utilisation within the heat sector accelerates. In parallel, this cost indicates a second tipping point, at which point hydrogen production for bulk electricity supply is initiated. At this point the cost of electricity production from this route drops below 5p/kWh, which undercuts all other non-intermittent electricity generation sources. As noted earlier, within the ethos of these system designs a preferred route may be to employ a mixture of electricity-producing, hydrogen-producing and flexible nuclear plant rather than explicitly adopt this approach modelled herein.

Underpinning the observations made in NFNZ and Supplementary Reports 1 and 2 of this project, it is clear that the ability to deploy nuclear plant to generate hydrogen at competitive prices has the potential to significantly affect the potential options for system designs which can achieve UK Net Zero. At modestly ambitious cost assumptions, this provides an alternative source of hydrogen to complement methane and electrolysis-derived systems, but with more successful innovation driving further reductions, a potential role as an enabler of economy-wide hydrogen consumption may be envisioned.

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7 Natural gas prices – and therefore the cost of hydrogen produced via reformation – vary according to source and season

6.3. Switch to synthetic liquid fuel for aviation use

At the most ambitious costs outlined within this report, synthetic fuel is delivered at a cost below that of fossil aviation fuel. As a result, the switchover of the aviation sector to use synthetic fuel is as rapid as technology deployment will permit. The sensitivity analysis carried out to supplement this initial case has brought to bear another few key observations:

- It is to be expected that for all plant production costs associated with a synthetic fuel cost below the fossil fuel alternative, fossil fuel is marginalised as rapidly as possible. The marginal abatement cost of such options is negative and thus such plant will deploy ahead of most other decarbonisation interventions

- When the cost of synthetic fuel production increases above 5p/kWh, the decision to deploy depends on the overall system challenge to decarbonise at any given point in time. In the 2030s the carbon target is less onerous than the 2050 Net Zero target, and thus there is less overall system benefit in electing to decarbonise aviation. Synthetic fuel production is thus required to be fairly competitive with fossil systems for it to be deployed – indeed, even at 5.5p/kWh the potential savings from carbon only lead to partial decarbonisation of aviation from 2040

- By far the starkest effect noted within this analysis is the challenge of meeting the 2050 target. Even at a synthetic fuel cost double that of fossil fuel, significant production of synthetic aviation fuel is observed. Indeed, this effect persists at even higher costs than those visualised in Figure 21: some synthetic aviation fuel is produced even if costs are more than six times the fossil fuel counterfactual

- This notable effect at 2050 is driven by the tightness of the modelled energy system in these periods. To achieve Net Zero emissions, some extremely costly interventions must be taken up, and this leads to a very high implied carbon price in this year. A high carbon price heavily penalises fossil-based systems: a cost of £500/t, for example, would be sufficient to support aviation fuel deployment even with costs reaching 17p/kWh

- Carbon prices at or above this level are entirely feasible within techno-economic models. In reality, however, carbon markets and pricing may not be designed to support this level of penalty. The interim years, 2030 to 2045, are reflective of more modest carbon pricing wherein synthetic fuel must be delivered at a cost competitive with fossil fuel, as the carbon penalty is insufficient to drive this excessively.

6.4. Probabilistic (Monte Carlo) assessment

Deterministic Run 310 was selected as the basis for the probabilistic (Monte Carlo) analysis. Run 310 comprises the following elements:

- Legacy, new Gen III+, LWSMR and Gen IV (Gigafactory and synthetic fuel production) plant availability

- Large Gen III+ key parameters as defined in Table 2

- LWSMR key parameters as defined in Table 3

- Hydrogen Gigafactory parameters as defined in Table 4

- Nuclear synthetic fuel production parameters as defined in Table 6

6.4.1. System design – Probabilistic analysis

The overall mixture of system designs is broadly similar to those observed within typical probabilistic Net Zero modelling, including the results within NFNZ. Wind power remains the key contributor to electricity nameplate capacity (although slightly reduced from simulations in support of NFNZ and Supplementary Report No.2, to an average deployment of around 45 GW), and district heat, predominantly from LWSMR plant, is also exploited extensively. With an absence of Gen IV electricity production technologies, Gen III+ plant is more frequently deployed, but usually alongside LWSMR rather than instead.

Typically, there is greater deployed capacity of thermal plant and Carbon Capture and Storage (CCS) here than in the previous work. Part of the reason for this is that within simulations where synthetic fuel plant is delivered at low-cost, the usual pressure to eliminate residual emissions elsewhere is alleviated, and this permits a greater operational role for low-carbon power generation options such as CCS. In parallel, simulations with a very low-cost Gigafactory technology still offer a route for nuclear power generation via hydrogen turbines.

6.4.2. Hydrogen gigafactory – Probabilistic analysis

Within TECH100 runs the choice for hydrogen production is typically between Gigafactory and methane reformation. Dedicated electrolysis plant is available but absent the challenging CO_2 target within the FA scenarios (heavily penalising any emissions from hydrogen production) it does not deploy. The choice between these two options is essentially controlled by the relative cost of the Gigafactory and reformer technologies (with a small correction to allow for residual CO_2 emissions associated with reformation).

Figure 27 indicates that deployment of the Gigafactory technology early in the pathway (i.e. in the 2030s) requires it to achieve very low production costs. At this time there is no significant CO_2 penalty for reformers so the cost comparison to make between nuclear and methane-based systems is simply that of the basic production cost. The variation of energy resource costs, along with a modest seasonal variability of gas costs, complicates the choice slightly. When entering the 2040s, however, the carbon constraint becomes more onerous. The effective penalty applied to reformer plant is notable even with high carbon capture rates; at first this penalty is modest but approaching 2050 it becomes severe. In the 2040s the tipping point at which the Gigafactory is the preferred source of hydrogen ramps up to about 2.7p/kWh ($1.3/kg). In 2050, system optimisation accepts an even greater cost for carbon-free hydrogen production – over 3p/kWh ($1.5/kg).

As noted within the deterministic sensitivity studies, low-cost hydrogen production as an enabler of system-wide change remains a clear effect – driving down costs sufficiently pushes up the levels of total hydrogen production.

6.4.3. Liquid synthetic fuel plant – Probabilistic analysis

As with the Gigafactory plant deployment profile, synthetic fuel deployment differs throughout the pathway. The deployment in 2050, in particular, is rather different to the preceding years.

In the early pathway years as shown in Figure 28, the decision to deploy synthetic fuel is based on a fairly strict cost comparison (although note that the Monte Carlo simulation involves variation in aviation fuel cost so a strict cut-off is not appropriate). The carbon target is not onerous at this point, and a gradual system-wide transition introducing wind and nuclear as low carbon power generation sources, alongside the beginnings of a transition of the transport and heating systems towards electric solutions, enables the emissions to reduce sufficiently to meet carbon budgets.

In the late 2030s/early 2040s a switch-over effect is notable in many simulations. As before, when synthetic fuel production costs drop below the price of fossil fuel, a complete switch-over is observed. However, even at costs above that of the fossil counterfactual, we see partial decarbonisation of the aviation sector. Even at relatively high synthetic fuel production costs, this technology is a more cost-effective option than employing decarbonisation options elsewhere. This observation is in line with the deterministic runs where emissions are left in the transport sector when aviation decarbonisation is deployed. In later years in the pathway, this trend continues with an even greater decarbonisation of aviation as the carbon target tightens.

The 2050 case is stark. All simulations adopt a complete decarbonisation of aviation at this time. The probabilistic range of production costs considered is relatively wide (although not quite as wide as the range considered within the deterministic sensitivities), and this suggests a robust role for synthetic fuel production even at costs some way higher than the Greater Nuclear Ambition baseline. However, comments around carbon pricing made in reference to the deterministic run apply here too: for a system with little GHG emission headroom, the implied carbon price is lifted significantly and thus a strong economic incentive to reduce emissions within aviation emerges. The highest synthetic fuel production cost considered within the Monte Carlo study – around 10p/kWh in 2050 – would necessitate a carbon price of greater than £300/tCO_2 to be chosen instead of fossil fuel. This scale of implied carbon price is entirely normal for a modelled scenario with a Net Zero GHG target.

Rather than following strict cost-deployment trends as illustrated in the deterministic modelling, noise within the cost/deployment curves provided here is to be expected. The nature of the Monte Carlo methodology means that other characteristics of the energy system, such as costs and bioenergy resource, vary probabilistically at the same time as the synthetic fuel production costs. Each of the simulated system designs contains a different mix of deployed technologies and implies a different cost to decarbonise; thus, the economic case for deployment of synthetic fuel systems can differ across simulations even if they have very similar synthetic fuel production costs.

6.5. Nuclear deployment scenario 4 – Greater nuclear ambition

Run 310 from Supplementary Report No.3 is used as the central case to define a high-level energy supply mix for the scenario known as "Greater Nuclear Ambition". This is shown in Table 6 along with the nuclear deployment scenarios defined through NFNZ and Supplementary Report No.2.

The data in Table 6 suggests that, at the level of cost and technical performance assumed in the analysis for Supplementary Report No.3, the dominant market for nuclear energy is in hydrogen production. The traditional market for electricity generation continues to be important alongside electricity supply from wind. The potential for liquid synthetic aviation fuel produced from new nuclear with no net carbon footprint could be a third important market, and a potential game-changing technology enabling new options and pathways for the achievement of Net Zero. Finally, lower grade heat supply from nuclear remains a significant opportunity for decarbonising space heating, which is an application demonstrated with many decades of experience.

Table 6 – Potential nuclear deployment scenarios with values shown at 2050

Nuclear Deployment Scenario (TECH100)	Overall Grid Capacity GWe	Gen III+ Installed Capacity GWe	LWSMR Cogen Power and Heat GWe	Gen IV Cogen Power & H_2 GWe	Nuclear Electricity Generation TWh	Nuclear Heat to DH Network TWh	H_2 Supply from Gen IV TWh	Liquid Synthetic Fuel Jet A TWh	Total Nuclear Energy Supply TWh
No Nuclear (Run 3a)	203	0	0	0	0	0	0	0	0
Constrained (Run 5)	177	14	0	0	154	0	0	0	154
Base Case (Run 26a)	144	4	19	22	298	167	33	0	498
Higher Optimism (Run 228)	148	4	13	49	399	131	87	0	617
Greater Nuclear Ambition (Run 310)	117	4	19	0	171	123	532	148	974

Excluding the "no nuclear" scenario defined by Run 3a, the other 4 nuclear scenarios defined by their respective ESME runs are defined in more detail in Annex 4. The nuclear energy elements of each run are detailed at five yearly intervals with associated load factors to be used as inputs to the various fuel cycle models operated by NNL.

7. Implications for markets, policy and regulation

7.1. Potential impact from aviation with no net emissions

One of the barriers to achievement of Net Zero is societal acceptance of the need to restrict growth in aviation due to residual emissions from the consumption of Jet A derived from fossil fuel. The decarbonisation scenario SOC100 assumes changes in societal behaviour at individual and collective levels including restrictions in the growth of aviation use, but the realism of such a scenario is uncertain.

The aviation sector is striving to reduce emissions through more efficient jet engines and other innovations such as hybrid propulsion. But the energy density of fossil fuel makes it an almost inevitable choice for long haul aviation.

This report provides no substantiation for the consideration of action with respect to aviation markets, policy and regulation. But this report does demonstrate the merit in further research on concepts for liquid synthetic aviation fuels because:

- The market value is high for solutions which are potentially viable

- Such solutions are likely to be important for consumers in removing potential barriers to continued use and growth of long-haul aviation

- The removal of the long-established system requirement to mitigate aviation emissions is potentially transformative in opening up new pathways to the achievement of Net Zero.

7.2. Potential impact from high-volume, low-cost hydrogen supply

A second social barrier to the achievement of Net Zero is the challenge in providing attractive and affordable low carbon options to space heating and domestic hot water production in homes. As the production cost of hydrogen reduces below $3/kg towards $1/kg the impact on the hydrogen economy is potentially transformative. Widespread replacement of natural gas domestic boilers with replacement units burning hydrogen at comparable cost would be an attractive proposition to policymakers and consumers. Such a possibility requires hydrogen production costs to reduce towards $1/kg. This report does not deliver the evidence that such costs can be delivered, but it does demonstrate the energy system value if such costs can be achieved. Options should be kept open for hydrogen production from nuclear energy and further evidence provided regarding the feasibility of high-volume, low-cost hydrogen production.

7.3. Requirement to generate further techno-economic evidence

The scope of this project and Supplementary Report No.3 was not designed to deliver the techno-economic substantiation that nuclear energy can be used to deliver high-volume, low-cost hydrogen, or that nuclear derived "drop-in" synthetic aviation fuels can be cost effectively supplied to decarbonise the aviation sector.

However, this report does indicate the market value associated with delivery of these "no-net-emissions" fuels at their respective target prices. The economic analysis in this report should be used to frame market requirements for hydrogen and liquid synthetic fuel. Technical innovation and associated evidence in these areas should be focussed against such requirements.

7.4. Further ESME modelling if evidence supports credible assumptions

The ESME functionality added to undertake this project is limited. If further techno-economic evidence becomes available, then the ESME functionality should be revisited and developed further:

- The Hydrogen Gigafactory can divert power into the grid when generation margins are low and prices high. This makes more sense than making hydrogen and building peaking plants elsewhere to burn it. This functionality is currently not provided in the analysis described in this report

- Liquid fuels used in industry, agriculture and transport can be displaced by liquid synthetic fuel, but the ESME functionality must be updated to be able to model this

More detail is provided in Annex 4 on the scope of a potential project to generate additional techno-economic evidence regarding the credibility of the techno-economic assumptions used in this analysis. The scope of this potential project includes some further energy system analysis to explore potential system wide benefits.

7.5. Existing MPR recommendations from NFNZ and Supplementary Report No.2

The scope of this project and Supplementary Report No.3 was not designed to deliver the techno-economic evidence to support the assumptions used in the analysis. Therefore, it is inappropriate to recommend further MPR action based on the analysis in this report. However, this report does deliver further information supporting recommendations already made through ESC's Nuclear for Net Zero report and Supplementary Report No.2.

One of these previous recommendations relates to the stage-gated development, demonstration and deployment of light-water small modular reactor and advanced nuclear technologies.

Earlier in Section 3.2, the nuclear technology datasets carried forward from Supplementary Report 2 were described as large Gen III+ and Light-Water nuclear Small Modular Reactors (LWSMRs). It was also identified within Supplementary Report No.2 that, based on an aggressive commercialisation programme, High Temperature Gas Reactors using proven Tristructural-isotropic (TRISO) coated particle fuel could be deployed from 2030 with a NOAK cost profile comparable with that of low-cost LWSMRs. Therefore, in the ESME modelling in Supplementary Report No.3, the LWSMR technology can actually be viewed as a proxy for low-cost modular nuclear either as HTGRs or light-water small modular reactors. This is relevant in that the parallel stage-gated development of LWSMR and advanced nuclear should focus on benefits including:

- Lowest cost in deployment and operation

- Lowest costs for hydrogen production when deployed with the best compromise technology for higher temperature hydrogen production available for commercial deployment from 2030

- Potential deployment at brownfield industrial sites not traditionally associated with nuclear energy

8. Conclusions

This report is the third in a series of three Supplementary Reports to build on the analysis reported previously in ESC's Nuclear for Net Zero report.

NFNZ and previous two Supplementary Reports each applied documented techno-economic evidence to explain and underpin the associated nuclear datasets used in the ESME sensitivity analyses examining a range of new nuclear technologies.

This third Supplementary Report uses techno-economic assumptions to define the nuclear datasets for a Hydrogen Gigafactory for the high-volume production of low-cost hydrogen, and also a plant for the low-cost production of liquid synthetic fuel for aviation use with no net emissions. This report does not provide underpinning substantiation of these assumptions, but references are provided to such concepts described elsewhere. The scope of a potential subsequent project is described to further establish the credibility of such techno-economic assumptions.

The conclusions from the analysis reported in Supplementary Report No.3 are:

Conclusion 1 – At the baseline cost level assumptions for the Hydrogen Gigafactory, this technology delivers high-volume, low-cost hydrogen into the hydrogen economy modelled in ESME. Sensitivity testing was undertaken by widely varying the cost assumptions. As hydrogen production cost reduces from $4/kg or more, then there is a clear sequence in the take-up of hydrogen to support decarbonisation across multiple sectors. Industry, transport and hybrid-heating technologies are established applications for hydrogen as a decarbonisation vector for hydrogen cost around $2 to $3/kg. As hydrogen production costs reduce below $2/kg, hydrogen is more widely used through domestic boilers for space heating and hot water production. Continued reduction in cost towards $1/kg shows increasing hydrogen use for power generation.

Conclusion 2 – At the baseline cost level assumptions for the liquid synthetic fuel plant, this technology delivers a "drop-in" replacement fuel for Jet A for aviation use with no net emissions. Sensitivity testing in ESME comprised increasing the assumed production costs by many multiples to a level at which the technology was not deployed. This technology appears to be so useful that even when it is ten times more expensive than the baseline cost assumption, it is still deployed. Aviation emissions are hard to decarbonise, therefore driving additional effort to reduce residual carbon emissions elsewhere in the system. The learning is that at a system level, the value of decarbonising aviation emissions is defined by avoiding the need to decarbonise other "hard to treat" technologies with their associated residual emissions.

Conclusion 3 – At a system level, the combined deployment of the Gigafactory and the liquid synthetic fuel plant has a significant impact on the overall system characteristics of a typical 2050 energy system. Growth of electricity generating capacity through to 2050 is less dramatic compared with previous scenarios and much of the space heating demand is delivered through the use of hydrogen rather than greater application of electrification via heat pumps as seen with previous scenarios. The decarbonisation of aviation emissions relieves some of the pressure on remaining Greenhouse Gas emissions which is more usually associated with the necessary deployment of more expensive technologies and system solutions for the elimination of hard to treat residual emissions.

Conclusion 4 – While the technical and economic parameters for nuclear hydrogen production are based on existing studies of the underlying technology, the development of a systematic evidence base for the innovative delivery model is still required to substantiate the techno-economic assumption that nuclear energy can be used to deliver high-volume, low-cost hydrogen

in a Gigafactory, or that nuclear derived "drop-in" synthetic aviation fuels can be cost effectively supplied to decarbonise the aviation sector. Reference is made to such concepts defined elsewhere in forthcoming reports. Analysis within this report does indicate the market value associated with delivery of these fuels at their respective target prices. The economic analysis in this report should be used to frame market requirements for hydrogen and liquid synthetic fuels and the low-cost technologies used to produce them. Technical innovation and associated evidence in these areas should be focussed against such future market requirements.

Conclusion 5 – Detail is provided on the scope of a potential subsequent project to generate additional techno-economic evidence to substantiate the techno-economic assumptions used in this analysis. The scope of this potential subsequent project includes some further energy system analysis to explore potential system wide benefits.

Conclusion 6 – Because the scope of this report is based on techno-economic assumptions not yet adequately substantiated, it is inappropriate to make new recommendations regarding markets, policy and regulation based on the analysis in this report. But the analysis in this report does further support previous MPR recommendations in ESC's Nuclear for Net Zero report and Supplementary Report No.2.

Conclusion 7 – The nuclear technology datasets used in the analysis for this report were carried forward from Supplementary Report 2. It is a feature within these datasets that with the assumption of an aggressive commercialisation programme, High Temperature Gas Reactors using proven TRISO coated particle fuel could be deployed from 2030 with a NOAK cost profile comparable with that of low-cost LWSMRs. Therefore, in the ESME modelling in Supplementary Report No.3, the LWSMR technology deployment shown in the various charts and data outputs could actually be viewed as a proxy for low-cost modular nuclear either as HTGRs or light-water small modular reactors, when deployed for the cogeneration of electricity and lower grade heat supply for the energisation of district heating systems. This is relevant in that the parallel stage-gated development of LWSMR and advanced nuclear should focus on the realisation of the most important benefits including; lowest costs in deployment and operation for hydrogen production or electricity production (or both); compatibility with best compromise technology for higher temperature hydrogen production available for commercial deployment from 2030, and; potential deployment at brownfield industrial sites not traditionally associated with nuclear energy.

Conclusion 8 – The analysis in this report is used to define the final nuclear deployment scenario defined as "Greater Nuclear Ambition". Alongside previous scenarios developed from NFNZ and Supplementary Reports Nos. 1 and 2, these potential scenarios are provided for consideration of potential 2050 nuclear energy production within NNL's Advanced Fuel Cycle Programme:

- No new nuclear – zero

- Constrained – 154 TWh

- Base Case – 498 TWh

- Higher Optimism – 617 TWh

- Greater Nuclear Ambition – 974 TWh

Acronyms

AFCP	Advanced Fuel Cycle Programme
ANT	Alternative Nuclear technologies (Project)
BECCS	Bio-energy with Carbon, Capture and Storage
BOB100	Best of Both ESME Scenario designed to achieve 100% decarbonisation based on the combination of TECH100 and SOC100
CCR	Carbon Capture Rate – typically associated with CCS
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DH	District Heat (system)
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment (a whole energy system model)
ETI	Energy Technologies Institute
FA96	Further Ambition 96 (% decarbonisation scenario)
FOAK	First of a Kind
Gen III+	Generation III+ nuclear reactor
Gen IV	Generation IV nuclear reactor
GHG	Greenhouse Gas
GWe	Giga-Watt electric
HPC	Hinkley Point C Project
HTGR	High Temperature Gas Reactor
IUK WP7	Innovate UK Work Package 7 (of the Energy Technologies Benchmarking Project)
JAEA	Japan Atomic Energy Agency
LWR	Light-Water Reactor
LWSMR	Light-Water (Nuclear) Small Modular Reactor
MWe	Mega Watt electrical
NCD	ETI's Nuclear Cost Drivers project
NFNZ	Nuclear for Net Zero
NNL	National Nuclear Laboratory
NOAK	N'th of a Kind
NPS	National Policy Statement
O&M	Operations and Maintenance
PPSS	The ETI's Power Plant Siting Study
SOC100	ESME scenario designed to achieve 100% decarbonisation using speculative changes in societal behaviour which reduce or restrict the growth of emissions
SZB	Sizewell B nuclear power station
TECH100	ESME Scenario designed to achieve 100% decarbonisation using speculative Technologies
TWh	Terra Watt hour

Annexes

Annex 1 – Additional technologies for Supplementary Report No.3

1. Introduction

This Annex describes the two innovative nuclear concepts that LucidCatalyst identified as highly promising for this Energy Systems Modelling project: (1) a Hydrogen Gigafactory for dedicated production of high-volume, low-cost hydrogen with a low-carbon footprint; and (2) production of liquid synthetic fuel for 'drop-in' application in the aviation sector with no net carbon emissions. Each of the following two sections on these concepts begins with an overview and then discusses the modelling parameters that LucidCatalyst provided to ESC. Section briefly describes additional concepts that were outside the current modelling scope but could be examined in subsequent modelling, as discussed in detail in Annex 4.

2. Hydrogen gigafactory

2.1. Overview

The Hydrogen Gigafactory would manufacture and operate nuclear reactors as high-temperature heat sources to create large quantities of low-cost, carbon-free hydrogen (H_2). The following image shows a Hydrogen Gigafactory with space for 36 reactors. The buildings on the left include the heat source manufacturing facility (larger building) and precast facility (smaller building). At the top in the middle is the finished bank of 12 reactors installed below grade with blue hatches, along with their heat exchanger 'pods' with green hatches. Preparation and installation are underway in the other two banks in the middle. Each reactor is 600 MWt and 250 MWe (42% efficiency).

Figure A1.1 – Conceptual illustration with modular manufacturing and assembly building at rear, hydrogen gigafactory under construction beneath the yellow cranes, adjacent hydrogen manufacturing plant and liquid synthetic fuel manufacturing plant in the foreground

LucidCatalyst describes the Hydrogen Gigafactory concept in the forthcoming report for the Electric Power Research Institute titled Clean and Scalable Synthetic Fuels as follows:

- The 'factory' configuration is a highly productive, dedicated manufacturing facility where the high-temperature heat sources are fabricated and installed on site. Hydrogen production is also on the same site. The heat sources are small modular 600 MWt units with a complementary modular heat exchanger unit which transfers the heat to the molten-salt heat-supply network for the thermochemical hydrogen plant. Rail and port access is adjacent to the manufacturing facility, allowing the manufacturing plant to transport high-value components that are not necessarily used at the facility when the construction of the plant is complete.

- The US-based Gas Technologies Institute (GTI) has several RD&D initiatives that include testing components within the US natural gas transport and distribution infrastructure for various hydrogen blends.[8] They are also developing standards for hydrogen use on existing infrastructure equipment, which can help determine how much hydrogen can be used within existing natural gas systems and how much can be used with equipment modification. Several similar efforts are underway in the UK, such as H21 and HyDeploy.

As LucidCatalyst describes in the forthcoming report titled Decarbonizing Prosperity: Hydrogen Enabled Synthetic Fuels in collaboration with the Nuclear Energy Institute, the Hydrogen Gigafactory would ideally be located at brownfield sites, such as locations of large coastal oil and gas refineries in the UK.

For this modelling project, the earliest potential operation year for the Hydrogen Gigafactory in the UK is 2030, and the construction period is 2 years. Nuclear reactors are then manufactured and installed after construction at the factory site. The maximum potential build rate for the Gigafactory ramps up from 5 GWe in 2030 to 10 GWe per year from 2040 onwards. The economic and technical life is 60 years. The technology has a peak contribution factor of 95% and annual availability factor of 92%. It has a flexibility factor of 50%, which reflects the facility's capacity to sell power from the nuclear reactors directly to the UK grid if necessary, based on ESME's simulation of power market conditions.

2.2. Inputs and outputs

The Hydrogen Gigafactory uses 1.923 kWh of nuclear fuel energy as input to produce each kWh of hydrogen output (52% efficiency). This operational conversion efficiency comes from a 2003 report on the use of high-temperature nuclear heat for hydrogen production from General Atomics.[9]

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8   Gas Technologies Institute (2020). Hydrogen.
    https://www.gti.energy/focus-areas/hydrogen/

9   General Atomics, High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, 2003, p. vii
    https://www.osti.gov/biblio/814014

The following figure provides a process schematic of the Hydrogen Gigafactory.
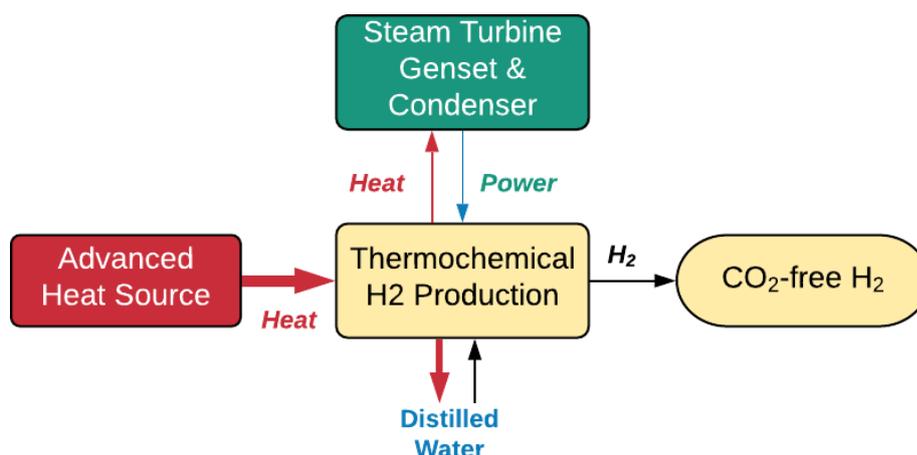
Figure A1.2 – Schematic of hydrogen gigafactory

2.3. Costs

LucidCatalyst provided the following cost parameters to ESC for the Hydrogen Gigafactory.

- Capex: £1,000/kW in 2030, decreasing to £750/kW in 2050
- Fixed O&M: £31/kW-year (constant for all modelling years)
- Variable O&M: £4/MWh (constant for all modelling years)

LucidCatalyst describes the cost efficiencies of the Hydrogen Gigafactory in the forthcoming Clean and Scalable Synthetic Fuels report as follows:

- Due to the electron beam welding, and other highly automated processes in the reactor component factory, the marginal cost of components used in the plant is very low compared with traditional manufacturing and supply methods. The thermochemical plant is 9-times the unit size of the plant in the 2003 study by General Atomics [cited above]. As with many chemical engineering studies for one-off plants, the designers accept very high quotations for specialty components, and in this case, approximately 10 of the 60 components account for 2/3 of the cost. Furthermore, the total quoted cost of these specialty components is 12-times the cost of the conventional components on which the design was based. These would yield dramatic cost reduction benefits both from re-engineering and volume production. This estimate uses a component cost that is 5-times the cost of the conventional component cost build-up. Although building the precast concrete and reactor manufacturing factories is a substantial investment, it represents a relatively minor proportion of the plant's cost when amortized over the number of units installed.

The cost estimates shown above reflect the efficiencies in numerous direct and indirect cost categories (equipment, materials, labour, engineering design, construction supervision and inspection, etc) from the economies of scale for the Hydrogen Gigafactory. The cost estimates also account for learning effects that allow for reductions over time to these NOAK levels. The O&Mcost estimates derive from studies by the Japan Atomic Energy Agency on a high-temperature gas-cooled reactor.[10]

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10 Japanese Atomic Energy Agency (Xing L. Yan), HTGR Brayton Cycle: Technology and Operations, 2017.
    https://energy.mit.edu/wp-content/uploads/2017/02/2-3.-HTGR-Brayton-Cycle-YAN-MIT-talk-r1-min.pdf

3. Liquid synthetic fuel plant

3.1. Overview

Each liquid synthetic fuel plant would use heat and power from a nuclear reactor to produce hydrogen, which would then be combined with carbon to produce 'drop-in' liquid synthetic aviation fuel ('Jet A'). The carbon could come from various source options. Biogenic carbon from biofuels or the air or sea would provide the full potential climate mitigation benefit, because in this case the carbon extraction would reduce the carbon concentration in the environment leading to climate change. Alternatively, the carbon for synthetic fuel production could come from capture and storage of emissions from fossil fuel use (such as coal plants), but this would provide only half the climate benefit of using biogenic carbon because the fossil fuel carbon has been brought up from geological deposits.

The earliest potential operation year for the liquid synthetic fuels plant in the UK is 2030, and the construction period is 4 years. The maximum potential build rate ramps up from 5 GWe in 2030 to 10 GWe per year from 2040 onwards. The economic and technical life is 60 years. The technology has a peak contribution factor of 95% and annual availability factor of 92%.

3.2. Inputs and outputs

The following figure provides a process schematic of the liquid synthetic fuels plant.
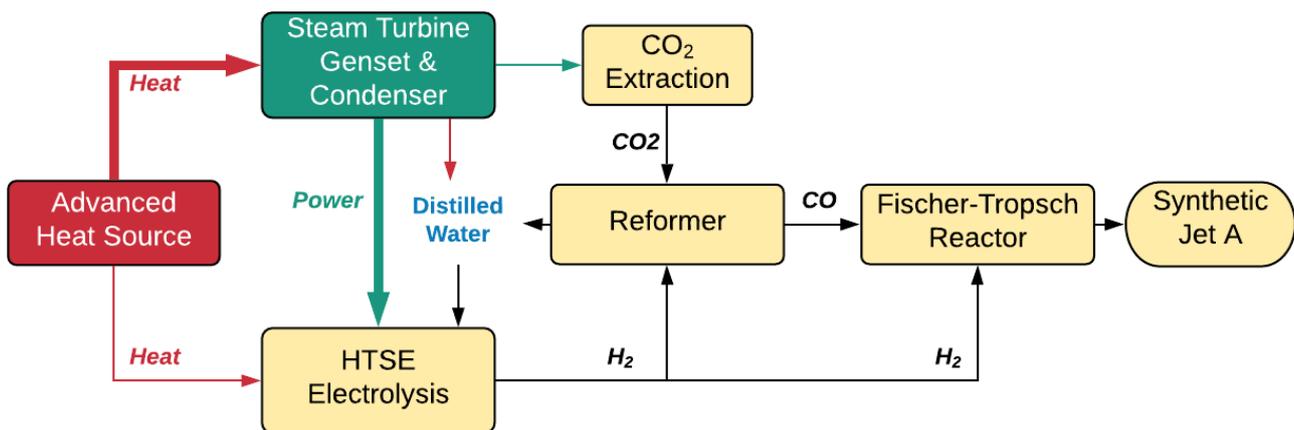
Figure A1.2 – Schematic of liquid synthetic fuels plant

LucidCatalyst divided the liquid synthetic fuels plant into three systems for the ESME modelling: (1) nuclear to hydrogen; (2) hydrogen to Jet A; and (3) carbon processing. The nuclear-to-hydrogen system uses 2.5 kWh of nuclear fuel energy to produce 1.326 kWh of hydrogen output (52% system efficiency) as well as 0.250 kWh of high-temperature heat. The second system uses the hydrogen and heat output from the first system to produce each kWh of Jet A (40% overall efficiency relative to nuclear fuel energy input). The operating efficiencies for the synthetic liquid fuel plant derive from analysis in LucidCatalyst's forthcoming report on Clean and Scalable Synthetic Fuels. As described above, each tonne of carbon embedded in the Jet A from the plant must come from a biogenic source for maximum climate benefit, or from carbon captured and stored from fossil fuel use for half as much climate benefit.

3.3. Costs

LucidCatalyst provided the following capex parameters to ESC for the liquid synthetic fuels plant.

- Nuclear to hydrogen: £1,200/kW in 2030, decreasing to £900/kW in 2050

- Hydrogen to Jet A: £240/kW in 2030, decreasing to £180/kW in 2050

- Carbon: £160/kW in 2030, decreasing to £120/kW in 2050

- Total plant: £1,600/kW in 2030, decreasing to £1,200/kW in 2050

The total plant capex is £600/kWe higher than the Hydrogen Gigafactory because it includes the reformer and Fischer-Tropsch reactor for combining hydrogen and carbon to produce synthetic liquid fuel. The capex adder for this equipment derives from Idaho National Laboratory's report on a nuclear plant design for hydrogen production (which in the source report is combined with nitrogen to produce ammonia).[11], LucidCatalyst's forthcoming report on Clean and Scalable Synthetic Fuels contains further cost information on this concept. The capex parameter for the nuclear-to-hydrogen system represents 75% of the plant total, whilst the hydrogen-to-Jet A system represents 15% and the carbon processing represents the remaining 10%.

LucidCatalyst provided the following opex cost parameters to ESC for the liquid synthetic fuels plant. As with the Hydrogen Gigafactory opex parameters, they are constant for all modelling years.

- Nuclear to hydrogen fixed O&M: £16/kW-year

- Nuclear to hydrogen variable O&M: £2/MWh

- Hydrogen to Jet A fixed O&M: £8/kW-year

- Hydrogen to Jet A variable O&M: £1/MWh

- Carbon fixed O&M: £8/kW-year

- Carbon variable O&M: £1/MWh

- Total plant fixed O&M: £32/kW-year

- Total plant variable O&M: £4/MWh

The synthetic liquid fuel plant has the same total fixed and variable opex values derived from the JAEA HTGR study cited above as the Hydrogen Gigafactory, because additional opex for combining hydrogen and carbon are negligible. Opex parameters for the nuclear-to-fuel system represents 50% of the plant total, whilst each of the parameters for the hydrogen-to Jet A and carbon processing systems represents 25% of the plant total.

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11   Idaho National Laboratories, Nuclear-Integrated Ammonia Production Analysis. Technical Evaluation Study. Project No. 23843. Document ID: TEV-666. Revision 2. 2010, https://art.inl.gov/NGNP/NEAC%202010/INL_NGNP%20References/TEV-666%20Nuclear-Integrated%20Ammonia%20Prod.pdf

4. Additional concepts outside current modelling scope

This section describes two additional innovative nuclear concepts for low-carbon energy outside the current scope for this Energy Systems Modelling project: Small Modular Reactors (SMRs) and nuclear-enabled ammonia. Further details on steps and deliverables for including these concepts in UK energy transitions modelling are provided in Annex 4.

4.1. Shipyard small modular reactors

Small modular reactors (SMRs) could be deployed at numerous locations in the UK to produce electricity, heat (co-generation), and/or hydrogen. LucidCatalyst describes the advantages of SMRs in the forthcoming report Decarbonizing Prosperity: Hydrogen Enabled Synthetic Fuels:

- Over the past 20 years, studies comparing shipyard construction of naval vessels and construction of commercial nuclear plants have focused on use of modular construction as a path to more economical builds. While this opportunity is worthwhile, shipyard construction goes beyond the limits of just modules to be transported for final assembly and construction at a site.

  Since the 1970s, shipyards have evolved into some of the most productive manufacturing environments across all industries—particularly when it comes to large-scale fabrication. Decades of fierce competition and a large and growing demand for ships, offshore platforms and offshore production facilities have fostered world-class design capabilities, manufacturing, and quality assurance programs in the world's leading commercial shipyards. The goals of the shipyards and their owners are not unlike of those of future manufacturers of nuclear plants—produce a high-quality, cost-competitive product on schedule, and in high volumes.

  These high-tech, large-scale shipyards are now being considered as well suited for fabricating advanced reactor systems. They could also make large-scale hydrogen production systems, and design and build ships or offshore platforms to house them. Some studies have already concluded the scale of the manufacturing systems at shipyards means that it is possible today to build an entire nuclear plant in a shipyard and float the finished product to its final location. The final location may be onshore at a coastal site or offshore.

  The main advantage of shipyard manufacturing comes from high productivity, which leads to lower costs and faster projects. Shipyard productivity is among the highest in the world. Labor costs constitute only 10 – 15% of the final assembly and delivery cost. By contrast, labor constitutes up to 35% of the costs in best-in-class conventional nuclear construction. The most productive shipyards in Korea and Japan have been able to sustain 10 – 15% per year improvements in productivity over multiple years. This productivity is made possible through for example:

- Innovation – Shipyards are leading innovators in design and build processes, having adopted the most advanced 3D design and simulation tools, as well as implementation of advanced cost-reduction technologies such as robotics/automation in fabrication and inspection.

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12 United Nations conference on Trade and Development Review of Maritime Transport (2019)

- Scale – The largest shipyards in the world are in Korea, China, and Japan. The gross tonnage produced by these three countries in their recent peak year (2008) was 25 million, 25 million, and 14 million, respectively, for a total gross tonnage of 64 million.[12] A recent study by a company that is planning to have its plants made in a shipyard in Korea suggested that a single large shipyard, without any investments to expand production, would be able to make as many as 40 power-plant-sized ships (at 500MW each) per year—20GW per year. This shipyard represents less than 5% of global capacity.[13]

- Production capacity – Currently most of the world's shipyards do not produce at their maximum rate, and there is considerable excess capacity.[14] To provide an idea of production capacity, the world's shipyards produce the equivalent of around 700 ships per year and are operating at approximately 50 per cent capacity. If they were operating at full capacity, they could produce twice that number of ships. Many of the products currently being made in these shipyards are Floating Production Storage and Offloading (FPSO) vessels for the oil and gas industry. It is also likely that in addition to the excess capacity, that production of existing fossil fuel-oriented products would be substituted for new clean synthetic fuels production facilities.

- Training and skilled labor – Unlike construction workers, who are temporarily onsite for any given project, the workers at a shipyard are all local residents, and view working at the shipyard as their long-term career. This provides strong alignment for deep development of skills and a culture of quality that is built around the production processes executed every day. The largest shipyards employ 25,000 or more personnel, with extensive cross training and skill sets.

- Infrastructure – Shipyards invest extensively in supplies, tools, support systems, and transportation systems. Together these investments provide for an extremely efficient and productive work environment compared with even the most efficiently organized construction site.

- Quality – Shipyards develop, maintain, and follow strict quality control and quality assurance programs not unlike the nuclear and aerospace industries. These programs must satisfy national and international standards to ensure safe transport of volatile commodities such as LNG and other chemicals. They have tight tracking of parts and status, with barcodes and/or Radio Frequency Identification (RFID) tags, throughout the facility and the broader supply chain.

    High productivity leads to lower costs – The cost of building large ships in world-class shipyards is extremely low relative to construction of major equipment and facilities in other industrial sectors. Besides high productivity, costs are affected by the following:

- Lower risk – Deliveries are on a fixed price basis, with the yard taking schedule risk and often providing performance guarantees. Multi-unit orders often have a cost reduction curve reflected in the pricing, based on the experience of the shipyard in reducing costs when manufacturing multiple units of the same design.

- Schedule – Shipyards routinely operate around tight schedules—a 399-meter, 165,000 ton, $230m[15] large container ship can be built in as little as 18 months. Late deliveries are unusual. Highly-skilled assembly line-style manufacturing in shipyards is very different to nuclear construction projects under an engineering procurement contractor (EPC) approach.[16]

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13 Thorcon (2018). http://thorconpower.com/docs/domsr20180119.pdf

14 This excess capacity is even before Covid-19 has had its full impact on cruise companies' new ship orders or on the demand for new offshore oil-drilling platforms.

15 In 2011, Maersk entered into a contract with DSME in Korea to build ten Triple-E Class container ships, each capable of carrying 20,000 TEU (or 10,000 40-foot containers), for $1.9B or $190m per ship ($230m in 2019). https://www.ship-technology.com/projects/triple-e-class/

16 Atomic Insights Jack Devanney Who will be ThorCon's EPC contractor? (2017)

- Business model – Shipyards routinely rely on long-term collaborative relationships with buyers, which encourages significant investment in the shipyards by their owners to increase productivity and quality, and reduces cost in exchange for commitments from buyers for future orders.

4.2. Ammonia

The following figure provides a schematic of a nuclear plant concept to produce carbon-free ammonia (NH_3).
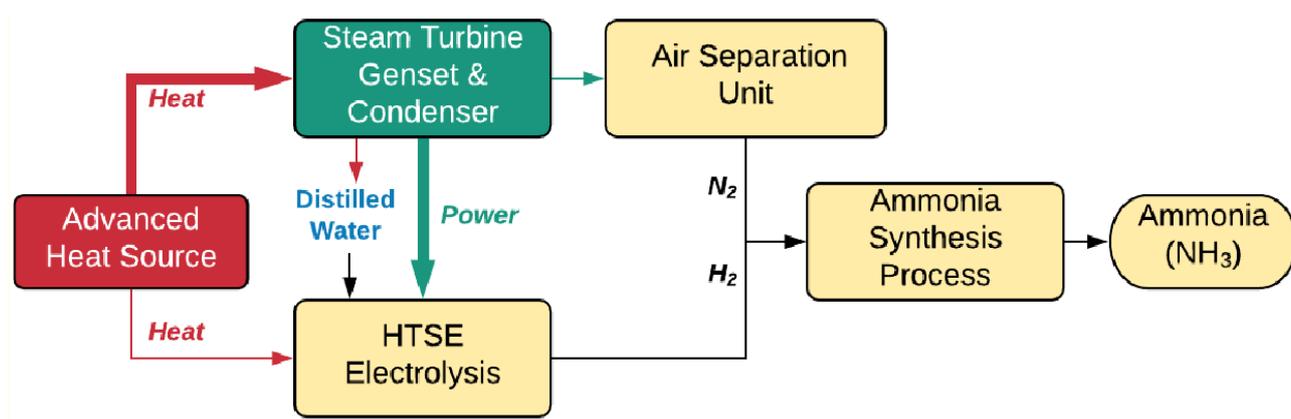
Figure A1.3 – Schematic of nuclear-enabled ammonia plant

As LucidCatalyst discusses in the forthcoming report on Clean and Scalable Synthetic Fuels, ammonia has been traditionally used in fuel refinement and as a fertilizer feedstock; however, it has become increasing recognized as a stable hydrogen (energy) carrier and viable liquid fuel for applications like marine shipping.[17,18] Producing ammonia requires combining hydrogen and nitrogen streams, and often (but not always) occurs through the Haber-Bosch process. The hydrogen is produced via high-temperature steam electrolysis (HTSE) and the nitrogen is pulled from the air using an air separation unit (or ASU). The Haber-Bosch process uses high heat, pressure, and a metal catalyst to combine hydrogen and nitrogen to make ammonia.

Nuclear-enabled ammonia could be highly cost-competitive with other conventional ammonia production because of the high capacity factor of nuclear plants and other economic factors, as LucidCatalyst explains in the forthcoming report on Decarbonizing Prosperity: Hydrogen Enabled Synthetic Fuels. With low hydrogen costs from nuclear and low resulting ammonia product costs, this innovative energy pathway could be cost-competitive with conventional oil products even when oil market prices are relatively low.

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17   The Royal Society. 'Ammonia key to reducing shipping's carbon emissions.' February 19, 2020.
https://royalsociety.org/news/2020/02/green-ammonia-report/

18   Katherine Palmer, Halving GHG emissions by 2050, Lloyd's Register, 2019.
https://www.lr.org/en-us/insights/articles/decarbonisation-no-time-to-lose/

Annex 2 – List of ESME sensitivity runs for Supplementary Report No.3

For Base, Lower and Higher values refer to the datasets for Supplementary Report No.2 listed in Annex 1.

The list below uses the same scenario definitions as introduced in the main body of this report:

- FA96 – using core technologies for 80% decarbonisation and stretched to deliver 96%
- TECH100 – introduction of additional speculative technologies to deliver 100% decarbonisation
- SOC100 – introduction of speculative changes to societal behaviours for 100% decarbonisation
- BOB100 – combination of both TECH100 and SOC100

Table A2-1 – Run Summary from Previous SR No.2 Sensitivity Studies

Run	Scenario	Sensitivity Criteria Applied	Notes
		Nuclear Technologies deployed in combination from SR No.2 Gen IV deployment only; no Large Gen III+ deployment up to 35 GWe, light-water SMRs for cogeneration up to 22 GWe and Gen IV cogeneration up to 55 GWe; all other parameters at base case values. No hydrogen Gigafactory or liquid synthetic fuel plants	
228	TECH100	All nuclear technologies available for deployment in combination. Base case data.	

For Base, Lower and Higher values refer to the datasets for Supplementary Report No.3 listed in Annex 1.

Table A2-2 – Run Summary from SR No.3 Sensitivity Studies

Run	Scenario	Sensitivity Criteria Applied	Notes
		New Baseline for Supplementary Report No.3	
301	TECH100	Gen III+ and LWSMR cogeneration data as per base case values from SR No.2. LucidCatalyst base case values applied for the hydrogen Gigafactory and the liquid synthetic fuel plant. For this and all other SR No.3 scenarios, utilisation of hydrogen boilers in winter period increased to 35% and no new internal combustion engine and hybrid vehicles permitted after 2040. For Run 301, both Gigafactory and synthetic fuel plant unavailable for deployment.	
310	TECH100	Gen III+ and LWSMR cogeneration data as per base case values from SR No.2. LucidCatalyst base case values applied for the hydrogen Gigafactory and the liquid synthetic fuel plant. For this and all other SR No.3 scenarios, utilisation of hydrogen boilers in winter period increased to 35% and no new internal combustion engine and hybrid vehicles permitted after 2040.	
311	BOB100	Technologies and parameters as per Run 301 with BOB scenario.	

312	FA96	Technologies and parameters as per Run 301 with FA96 scenario but with	Availability of decarbonisation of aviation sector permits upgrade to Net Zero ("FA100")
		Sensitivity Runs for the Hydrogen Gigafactory (without the liquid synthetic fuel plant)	
320	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory as defined by LucidCatalyst (LC)	
321	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory 2 x LC CAPEX.	
322	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory 3 x LC CAPEX.	
323	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory 4 x LC CAPEX.	
324	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory 5 x LC CAPEX.	
325	TECH100	As Run 301 without the liquid synthetic fuel plant. Costs for hydrogen Gigafactory 0.66 x LC CAPEX.	
		Sensitivity Runs for the liquid synthetic fuel plant (without the Hydrogen Gigafactory)	
350	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant as defined by LucidCatalyst (LC)	
351	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 2 x LC CAPEX.	
352	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 4 x LC CAPEX.	
353	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 10 x LC CAPEX.	
354	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 30 x LC CAPEX.	
355	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 40 x LC CAPEX.	
356	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 50 x LC CAPEX.	
357	TECH100	As Run 301 without the hydrogen Gigafactory. Costs for the liquid synthetic fuel plant 60 x LC CAPEX.	
		Monte Carlo Run to Recognise Uncertainties	
	M/C	Probabilistic Run with the inputs as per deterministic Run 301.	Cost spread for Gen III+ and LWSMR nuclear technologies is -30% to +40% of Base Case. Broader spread for Gigafactory and fuel plant as defined in sections 4.3.2 and 4.4.2

Annex 3 – Selected ESME outputs for Supplementary Report No.3

The columns below are the colour coded legends for the respective ESME generic output core charts which follow.

Primary Resource Consumption

- Wave
- Tidal Stream
- Tidal Range
- Hydro
- Solar
- Wind (deep offshore)
- Wind (shallow offshore)
- Wind (onshore)
- Nuclear
- Geothermal Heat
- Wet Waste
- Dry Waste Resource
- Dry Waste
- Biomass
- UK Biomass
- Biomass Imports
- Coal
- Gas
- GasTS
- GasLDN
- Gas_Zeb_Import
- Gas_UKCS_Import
- Gas_TTF_Import
- Gas_NCS_Import
- Gas_LNG_Import
- Biofuel Imports
- Liquid Fuel
- Diesel
- Petrol
- Aviation Fuel
- Hydrogen
- Electricity_DX_LV
- Electricity_DX_HV
- Electricity_TX

Net CO2 Emissions

- GasTS
- Biomass
- Hydrogen
- Electricity
- CapturedCO2
- Retroplus
- Retrofix
- PC Coal CCS Retrofit
- PC Coal Biomass Retrofit
- IGCC Coal CCS Retrofit
- CCGT CCS Retrofit
- Energy Storage
- Industry
- International A & S
- Transport Sector
- Buildings Sector
- Power Sector
- Other Conversion Sector
- Industry Sector (combustion)
- Industry Sector (process CO2)
- Other CO2
- Biogenic credits
- Wood in Construction
- Waste incineration
- Settlements
- Peatland
- LULUCF Other
- Industry
- IGCC Coal with CCS - 99pct CCR
- H2 Plant (SMR with CCS) - 99pct CCR
- H2 Plant (Biomass Gasificn. with CCS) - 99pct CCR
- Forest land
- Energy crops, agroforestry, hedges
- Converted Biomass Plant (Drax)
- CCGT with CCS - 99pct CCR
- CO2 Processing for synfuel
- Biopetrol Production with CCS - 99pct CCR
- Biokerosine Production with CCS - 99pct CCR

Electricity Generation Cap. & Annual Generation

- Geothermal Plant (HSA) Electricity & Heat
- Geothermal Plant (EGS) Electricity & Heat
- Wave Power
- Tidal Stream
- Tidal Range
- Severn Barrage
- Hydro Power
- Solar PV (Domestic)
- Solar PV (Farm)
- Offshore Wind (floating)
- Offshore Wind (fixed)
- Onshore Wind
- Micro Wind
- Micro CHP - Space Heat
- Micro CHP - Hot Water
- H2 Turbine
- ATC of Waste
- Anaerobic Digestion CHP Plant
- Incineration of Waste
- IGCC Biomass with CCS
- Biomass Fired Generation with CCS
- Biomass Macro CHP
- IGCC Biomass
- Converted Biomass Plant
- Biomass Fired Generation
- Nuclear Gen III Hinkley Point C
- Nuclear Gen IV Hydrogen only
- Nuclear Gen IV Elec only
- Nuclear SMR Elec only
- Nuclear (SMR)
- Nuclear (Gen IV)
- Nuclear SMR Cogen Power and Heat (DH)
- Nuclear Gen IV Cogen Power and H2
- Nuclear (Gen III)
- Nuclear (Legacy)
- Waste Gasification with CCS
- Waste Gasification
- CCGT with CCS
- CCGT
- IGCC Coal with CCS
- IGCC Coal
- PC Coal with CCS
- PC Coal
- OCGT
- Gas Macro CHP
- Oil Fired Generation
- Interconnector Nordel (Electricity)
- Interconnector Ireland (Electricity)
- Interconnector France (Electricity)
- Interconnector Benelux-Germany (Electricity)
- CCGT with CCS - 99pct CCR
- Converted Biomass Plant (Drax)
- IGCC Coal with CCS - 99pct CCR

Space Heat Capacity & Space Heat Generation

H2 Micro CHP - Space Heat
H2 Boiler - Space Heat
Heat Pump (Ground Source, Space Heat)
Heat Pump (Air Source, Space Heat)
Electric Resistive Heating - Space Heat
Biomass Boiler - Space Heat
Micro CHP - Space Heat
Gas Boiler - Space Heat
Oil Boiler - Space Heat
DH for Dwelling (LD, ThP)
DH for Dwelling (LD, ThP with Retroplus)
DH for Dwelling (LD, ThP with Retrofix)
DH for Dwelling (LD, ThM)
DH for Dwelling (LD, ThM with Retroplus)
DH for Dwelling (LD, ThM with Retrofix)
DH for Dwelling (LD, ThG)
DH for Dwelling (LD, ThE)
DH for Dwelling (MD, ThP)
DH for Dwelling (MD, ThP with Retroplus)
DH for Dwelling (MD, ThP with Retrofix)
DH for Dwelling (MD, ThM)
DH for Dwelling (MD, ThM with Retroplus)
DH for Dwelling (MD, ThM with Retrofix)
DH for Dwelling (MD, ThG)
DH for Dwelling (MD, ThE)
DH for Dwelling (HD, ThP)
DH for Dwelling (HD, ThP with Retroplus)
DH for Dwelling (HD, ThP with Retrofix)
DH for Dwelling (HD, ThM)
DH for Dwelling (HD, ThM with Retroplus)
DH for Dwelling (HD, ThM with Retrofix)
DH for Dwelling (HD, ThG)
DH for Dwelling (HD, ThE)
District Heating (Public floorspace)
District Heating (Commercial floorspace)
Solid Fuel Boiler - Space Heat

Hydrogen Production

Nuclear Gen IV Hydrogen only
Nuclear Gen IV Cogen Power and H2
H2 Plant (Biomass Gasification with CCS)
H2 Plant (Biomass Gasification)
H2 Plant (SMR with CCS)
H2 Plant (SMR)
H2 Plant (Coal Gasification with CCS)
H2 Plant (Electrolysis)
H2 Plant (Biomass Gasification with CCS) - 99pct CCR
H2 Plant (SMR with CCS) - 99pct CCR
Nuclear H2 Gigafactory

Network Hot Water Production

District Heating H2 Boiler
Heat Pump (Large Scale Marine)
Geothermal Plant (EGS) Electricity & Heat
Geothermal Plant (HSA) Electricity & Heat
Geothermal Plant (HSA) Heat Only
District Heating Gas Boiler
Gas Macro CHP
District Heating Biomass Boiler
Biomass Macro CHP
Anaerobic Digestion CHP Plant
Nuclear SMR Cogen Power and Heat (DH)
Nuclear (SMR)
Heat Offtake for District Heat Network

Industry Fuel Consumption

Industry - Liquid Fuel
Industry - Hydrogen
Industry - GasTS
Industry - Electricity
Industry - Coal
Industry - Biomass

Hydrogen Consumption

Hydrogen Distribution Network
H2 Turbine
Bus (Hydrogen FCV)
MGV
HGV
LGV (Hydrogen ICE)
Car Hydrogen ICE (C/D Segment)
Car Hydrogen ICE (A/B Segment)
LGV (Hydrogen FCV)
Car Hydrogen FCV (C/D Segment)
Car Hydrogen FCV (A/B Segment)
Industry
Wheeled Excavator (H2)
Medium Wheel Loader (H2)
Medium Articulated Truck (H2)
Maritime (Ammonia International)
Maritime (Ammonia Domestic)
Large Articulated Truck (H2)
Industry I8 SpH Hyd Sw
Industry I7 SpH Hyd Sw
Industry I7 DaS Hyd Sw
Industry I6 SpH Hyd Sw
Industry I6 DaS Hyd Sw
Industry I5 SpH Hyd Sw
Industry I5 DaS Hyd Sw
Industry I4 LTP Hyd Sw
Industry I4 DaS Hyd Sw
Industry I3 SpH Hyd Sw
Industry I2 SpH Hyd Sw
Crawler Excavator (H2)
Agricultural Vehicle (H2)

Run 228 FA96 From Supplementary Report No.2 – DH deployment enabled; all nuclear technologies with LWSMR as cogen power and heat; Gen IV site capacity limit raised to 55 GWe and build-out raised to match; base case data
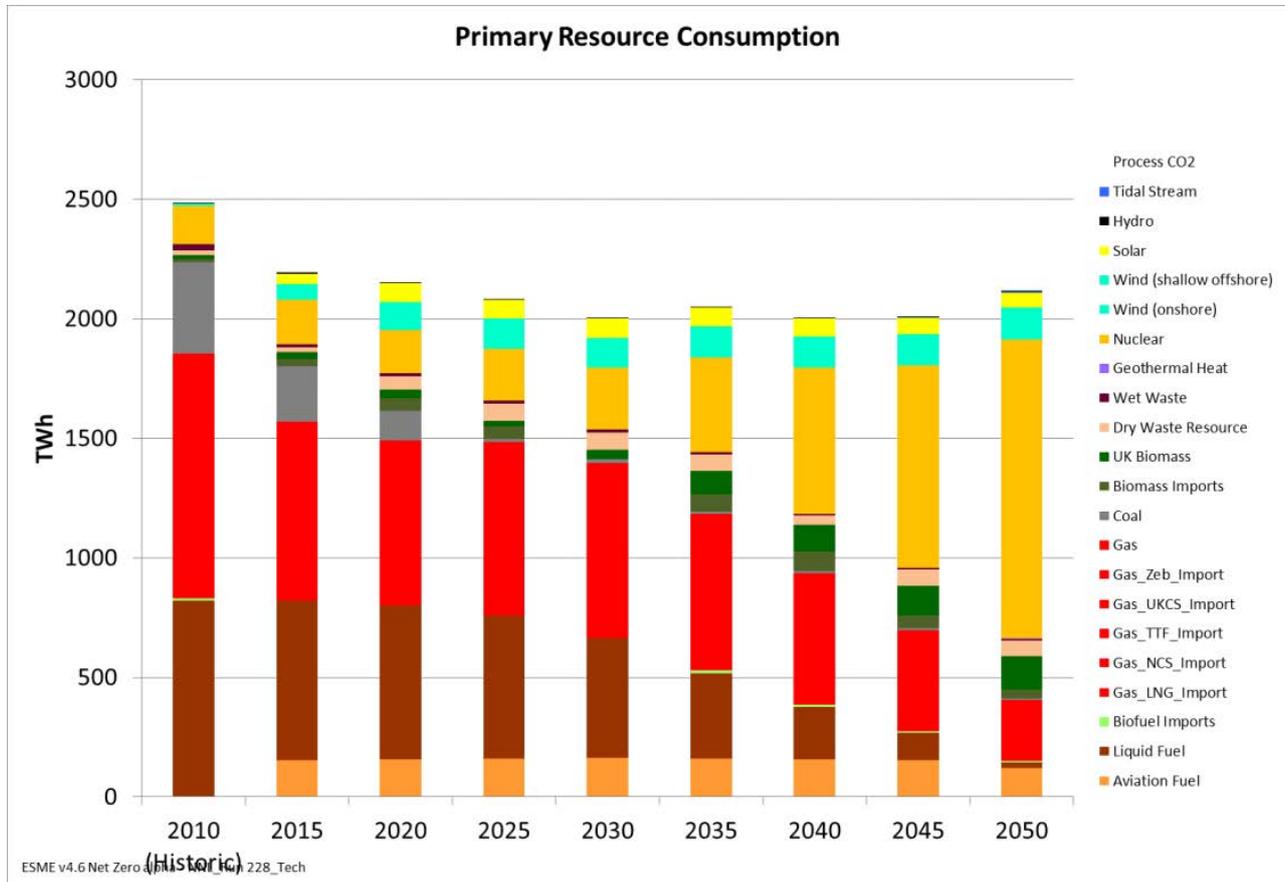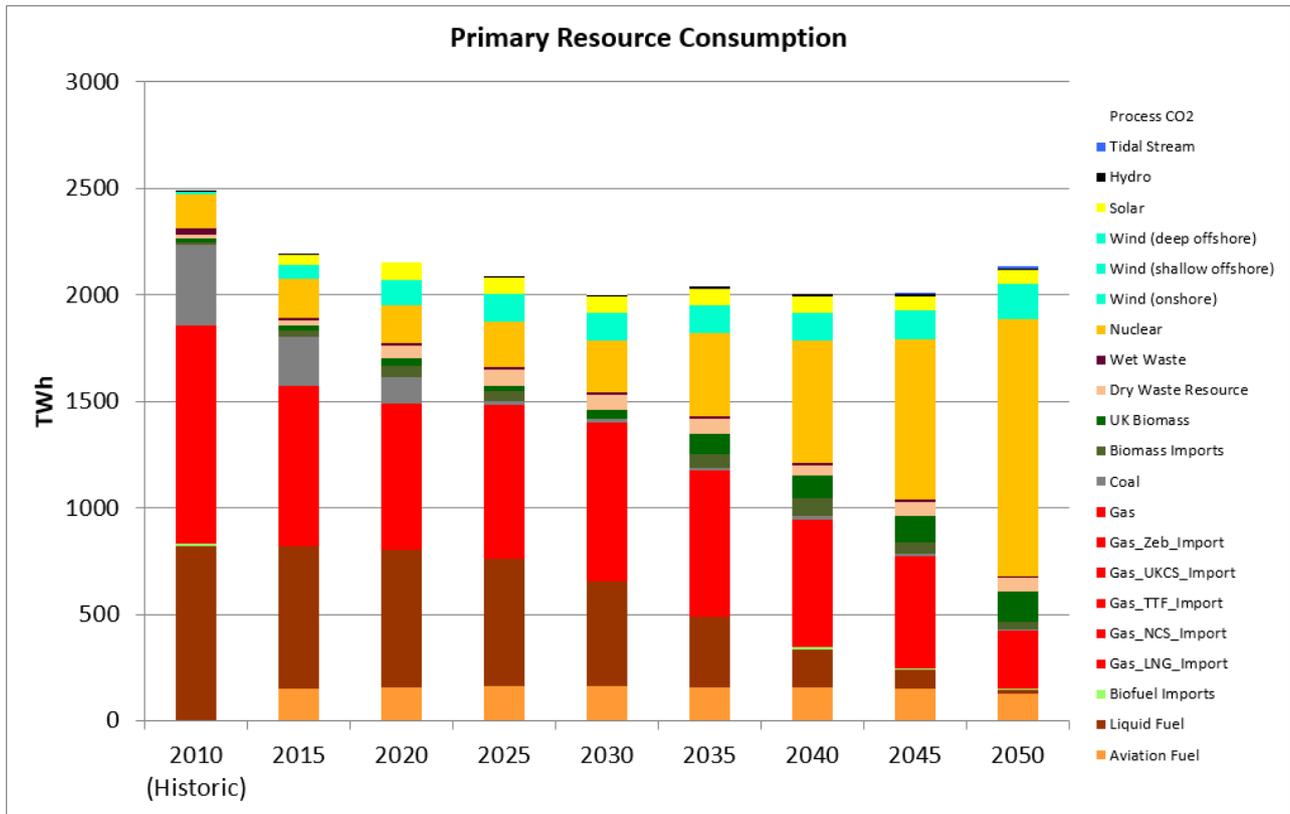

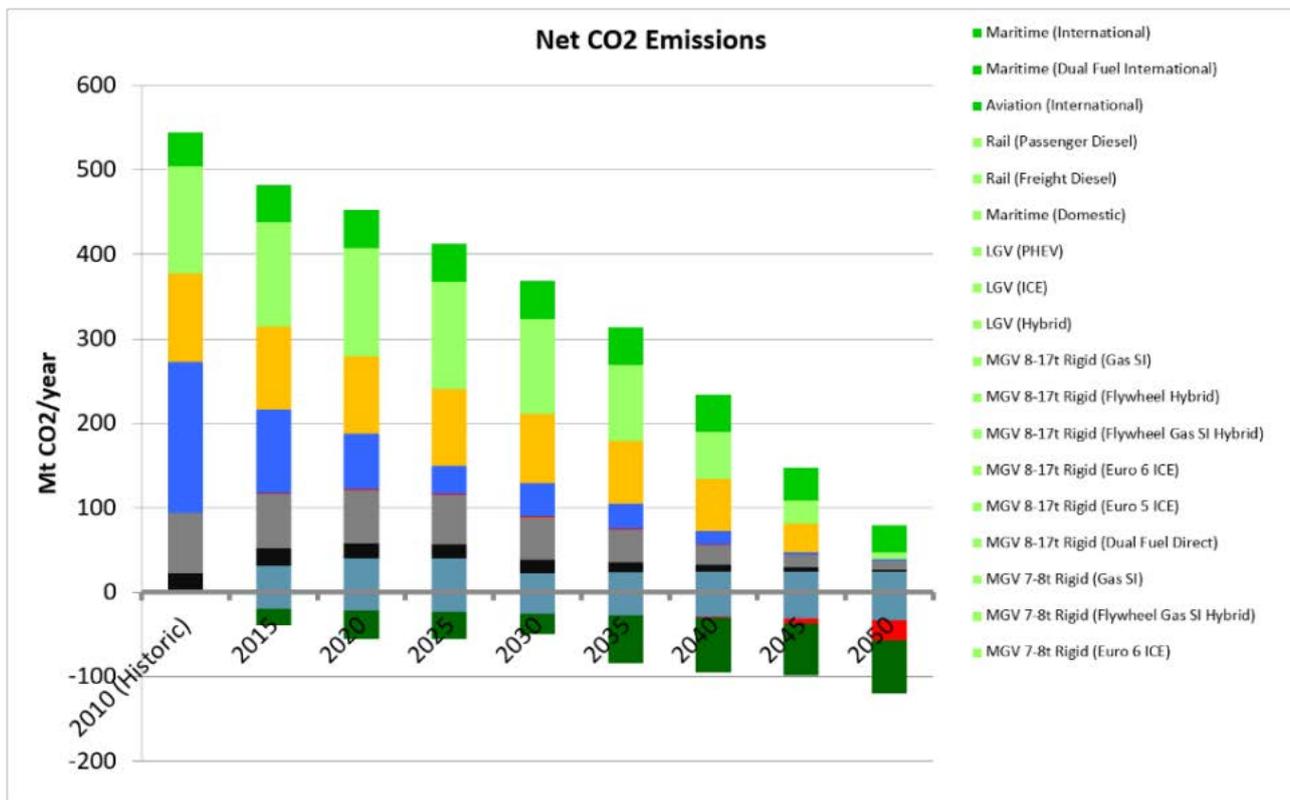Figure A3-1 – Run 228 Primary Resource Consumption
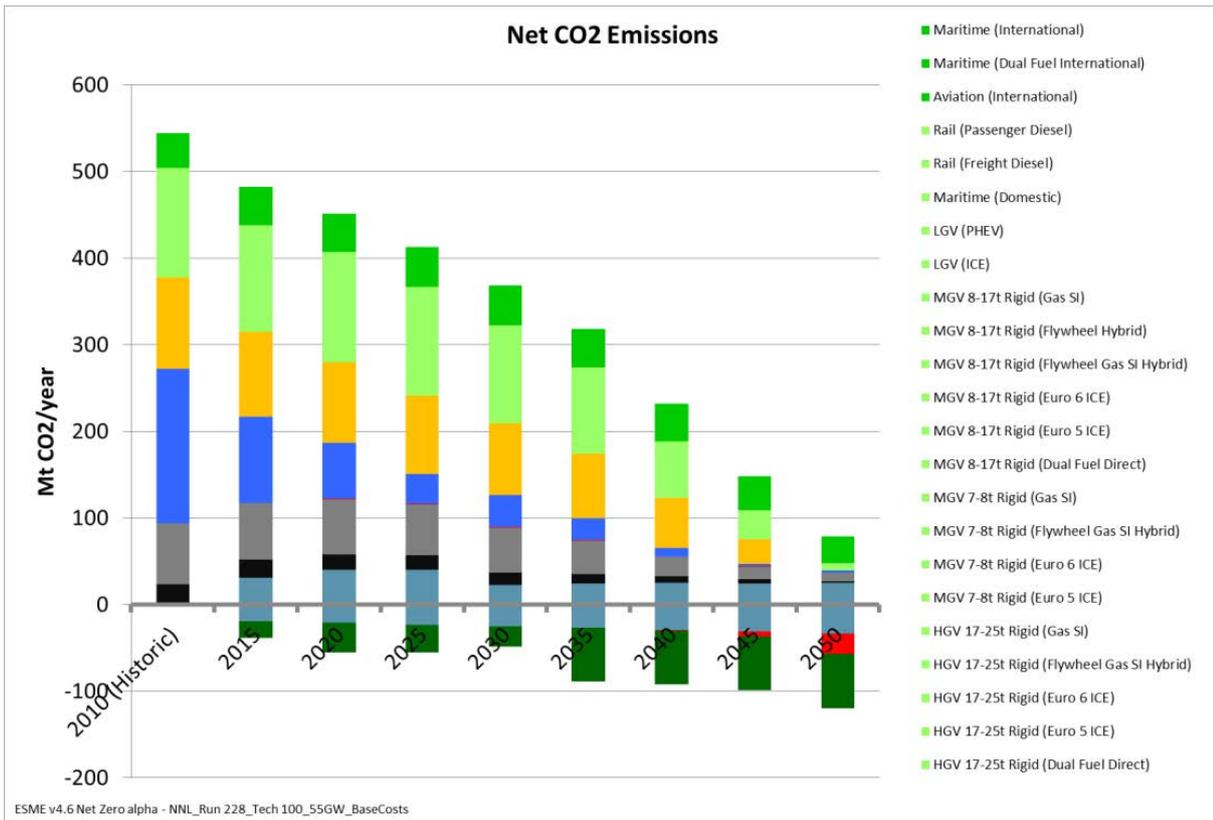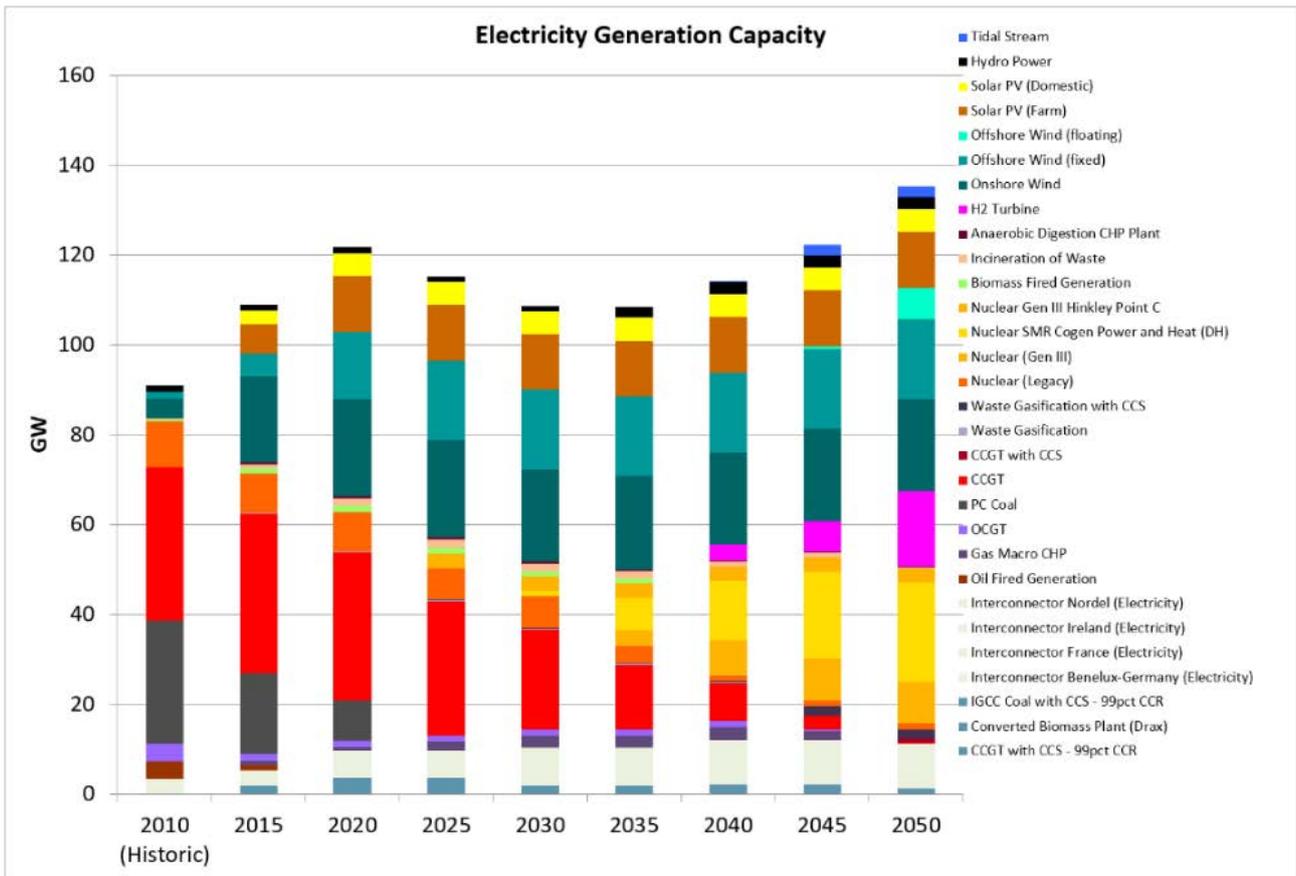
Figure A3-2 – Run 228 Net CO$_2$ Emissions
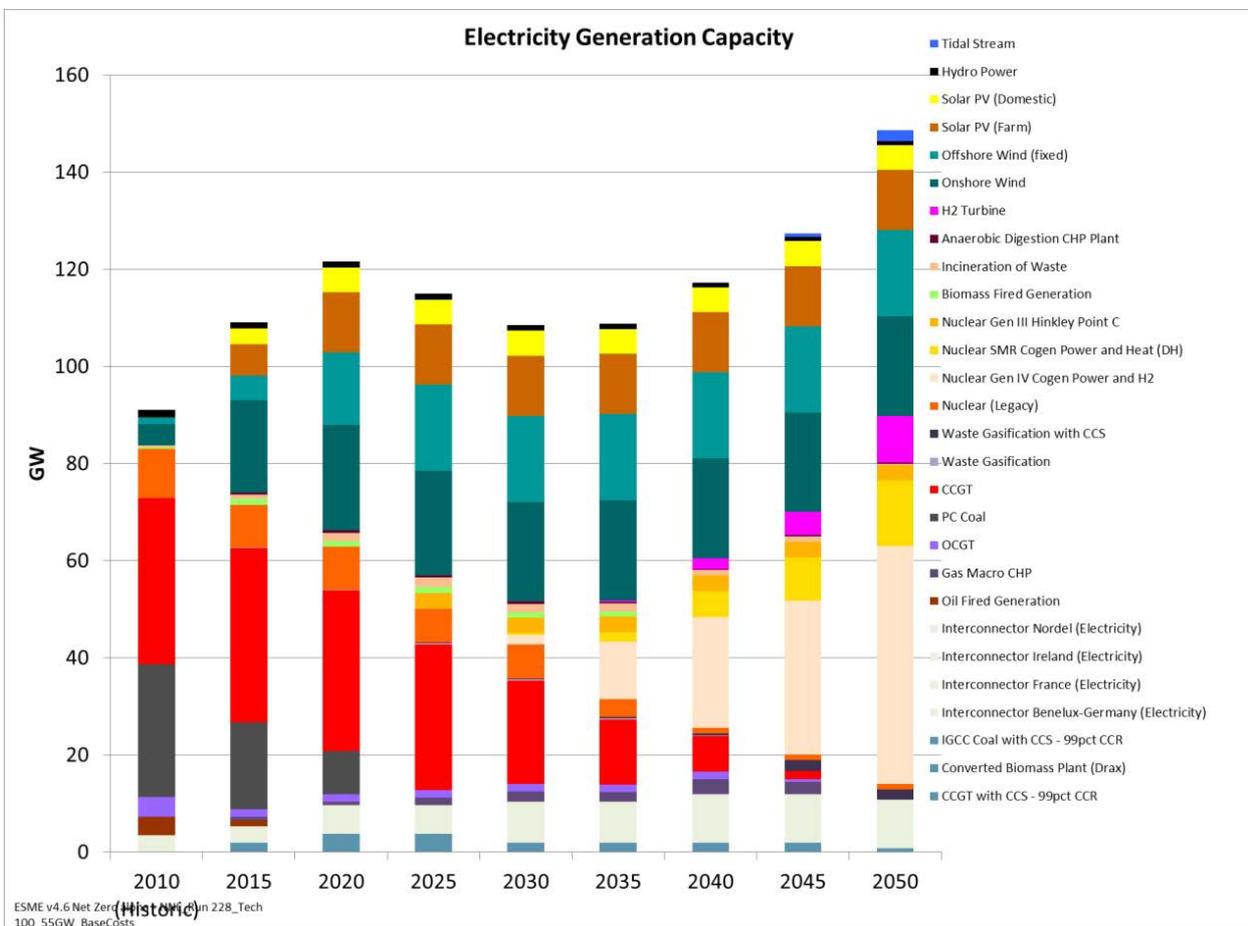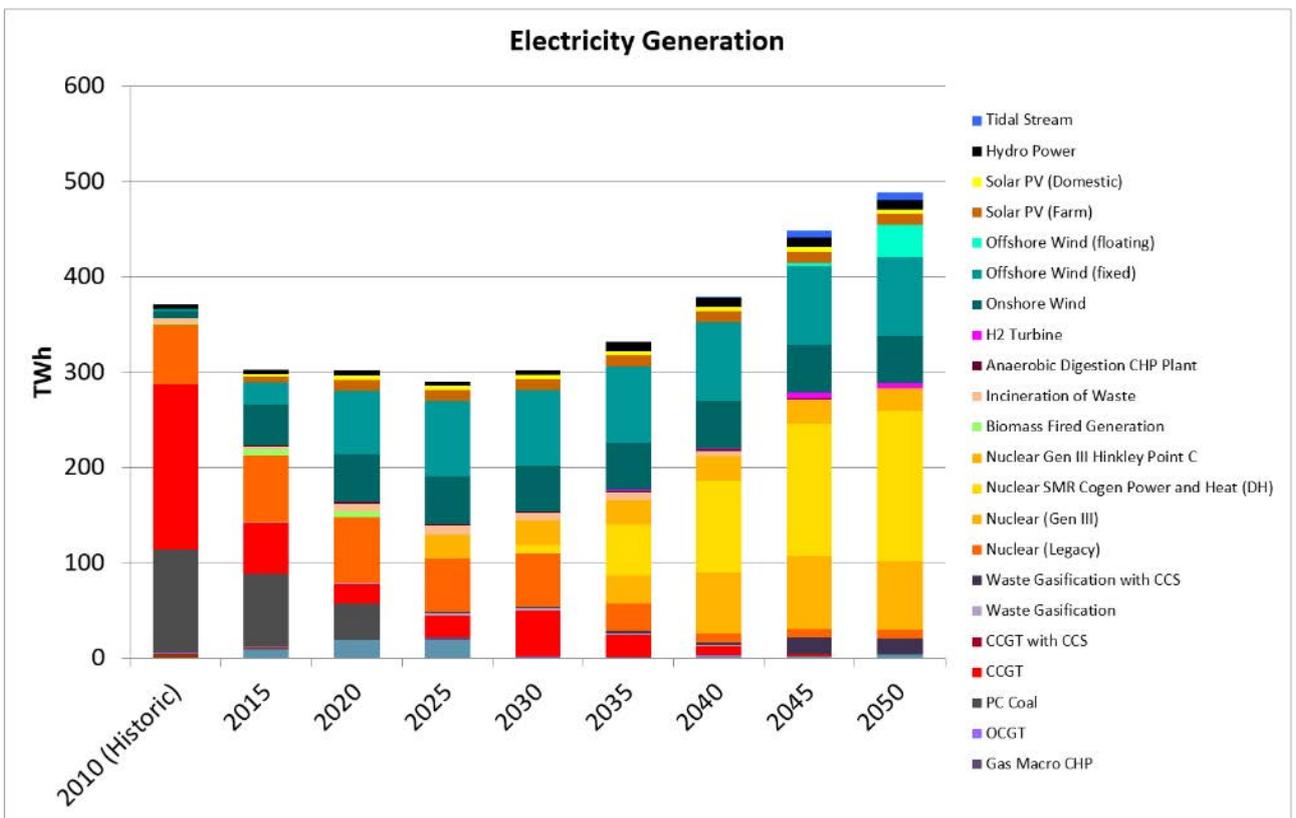

Figure A3-3 – Run 228 Electricity Generation Capacity
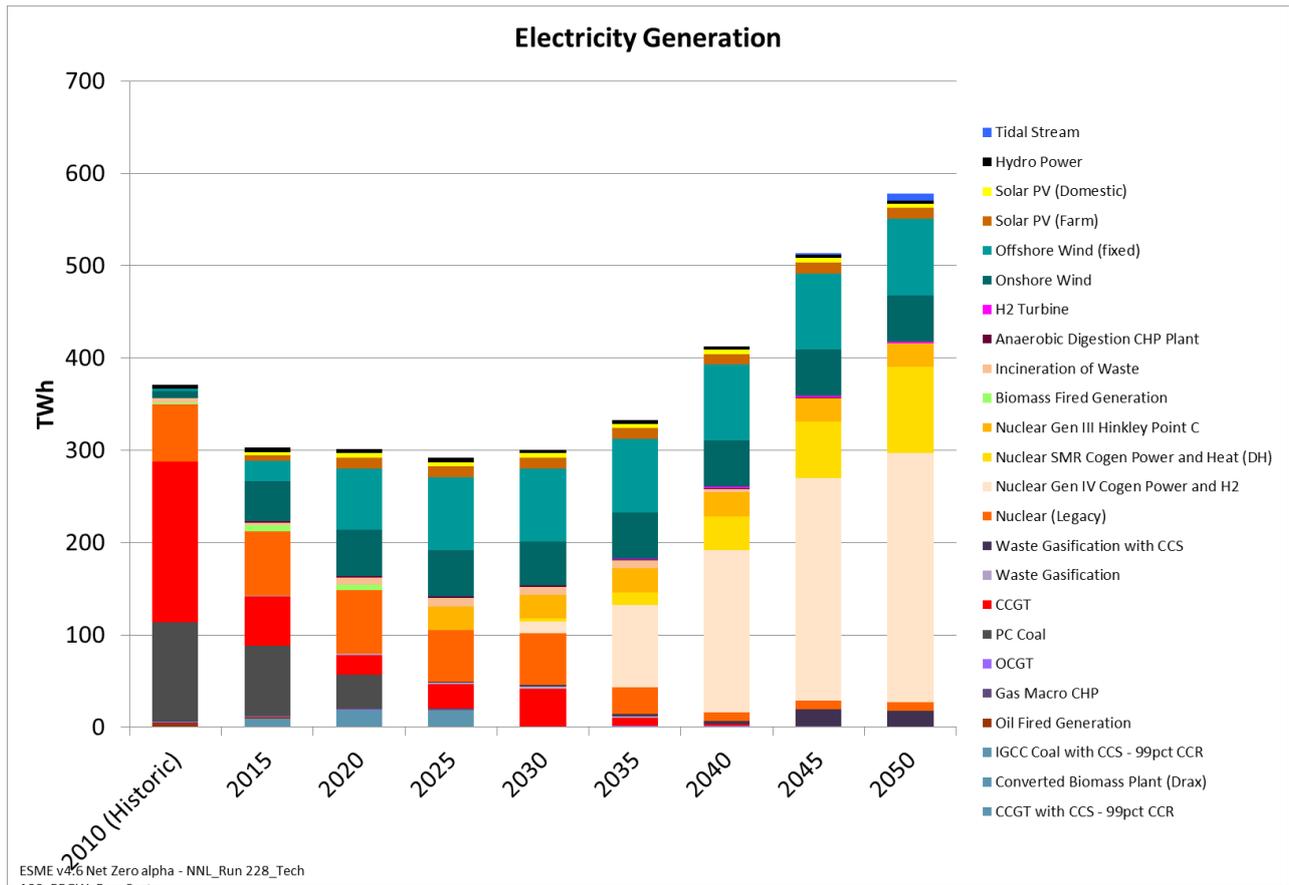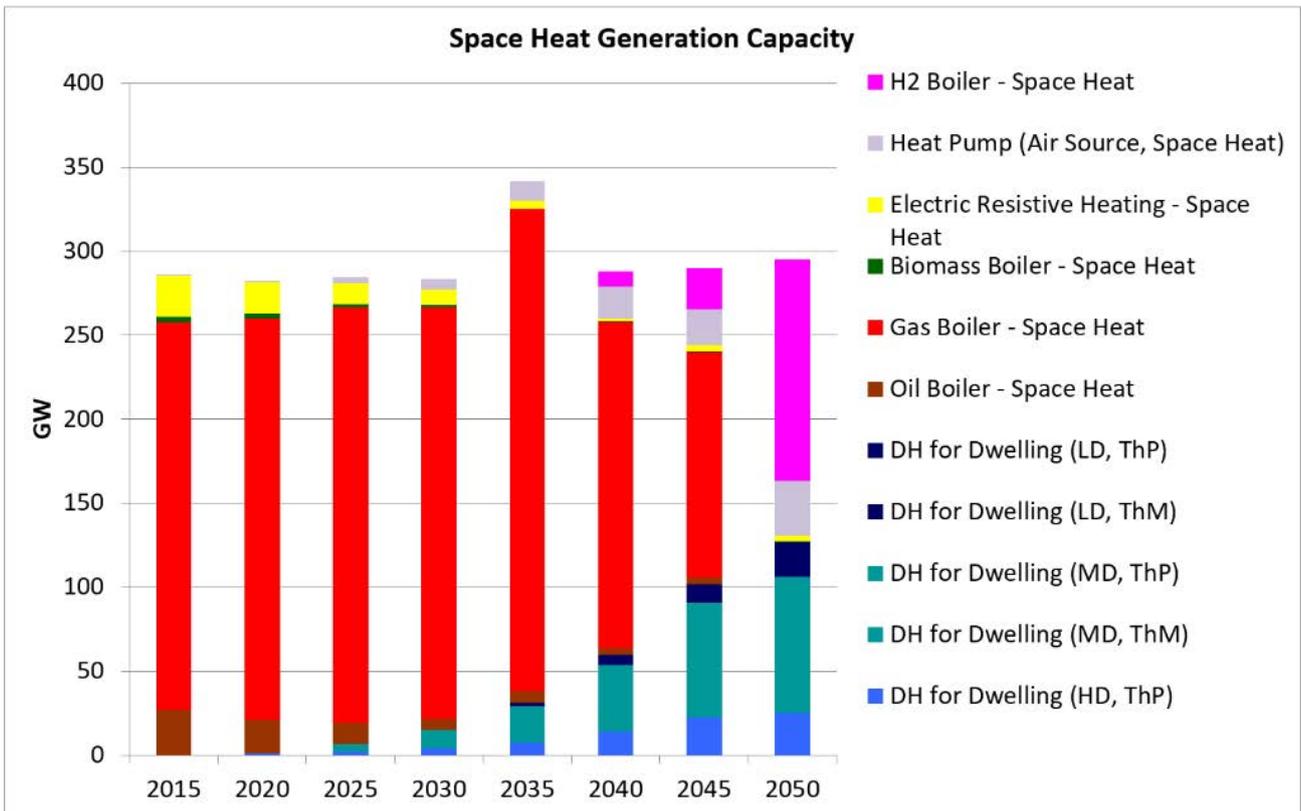
Figure A3-4 – Run 228 Electricity Generation
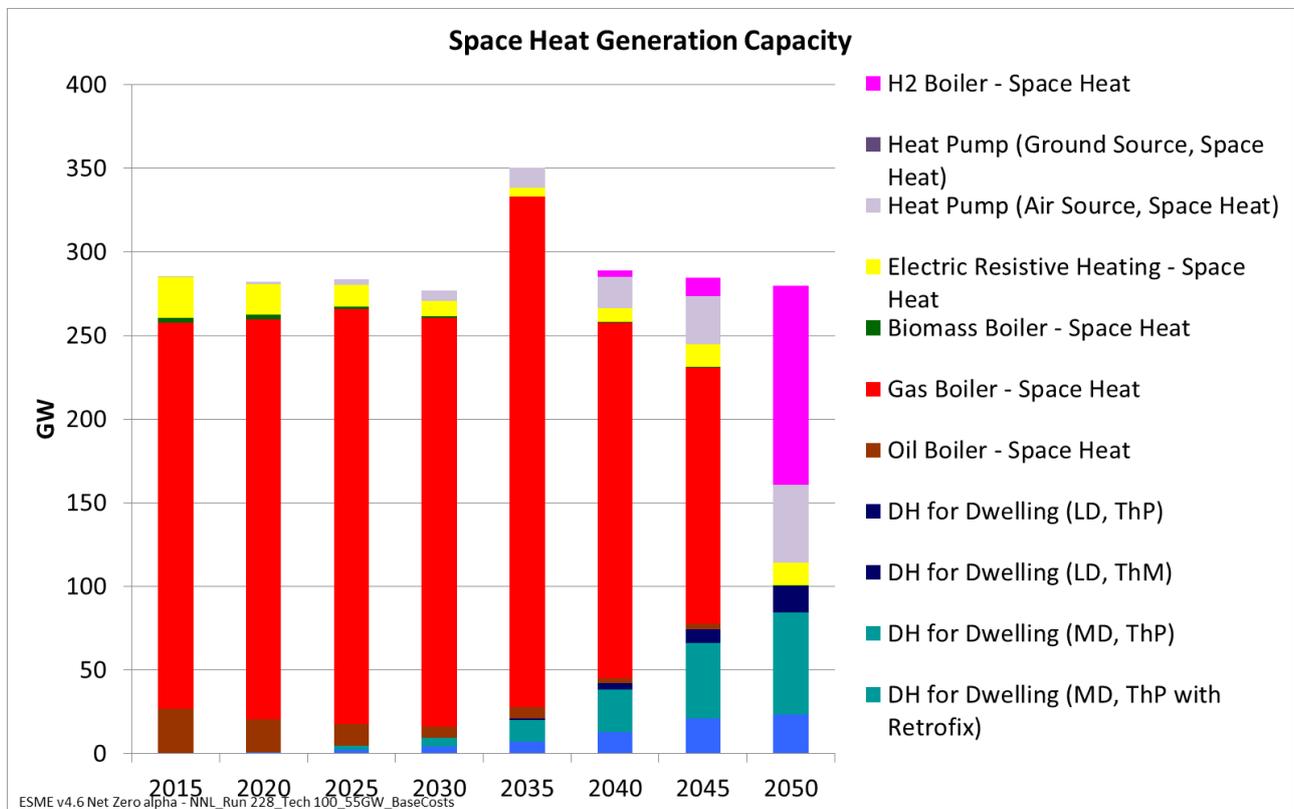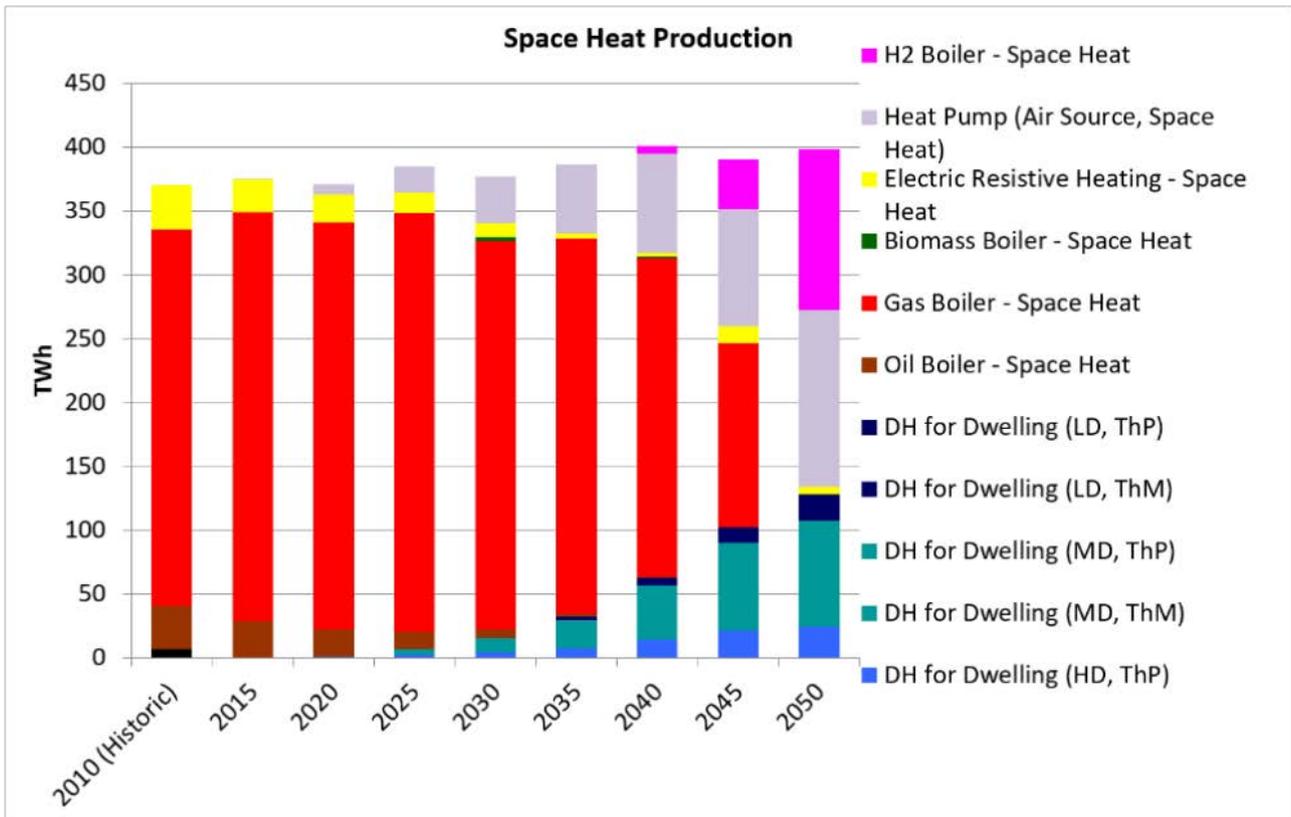

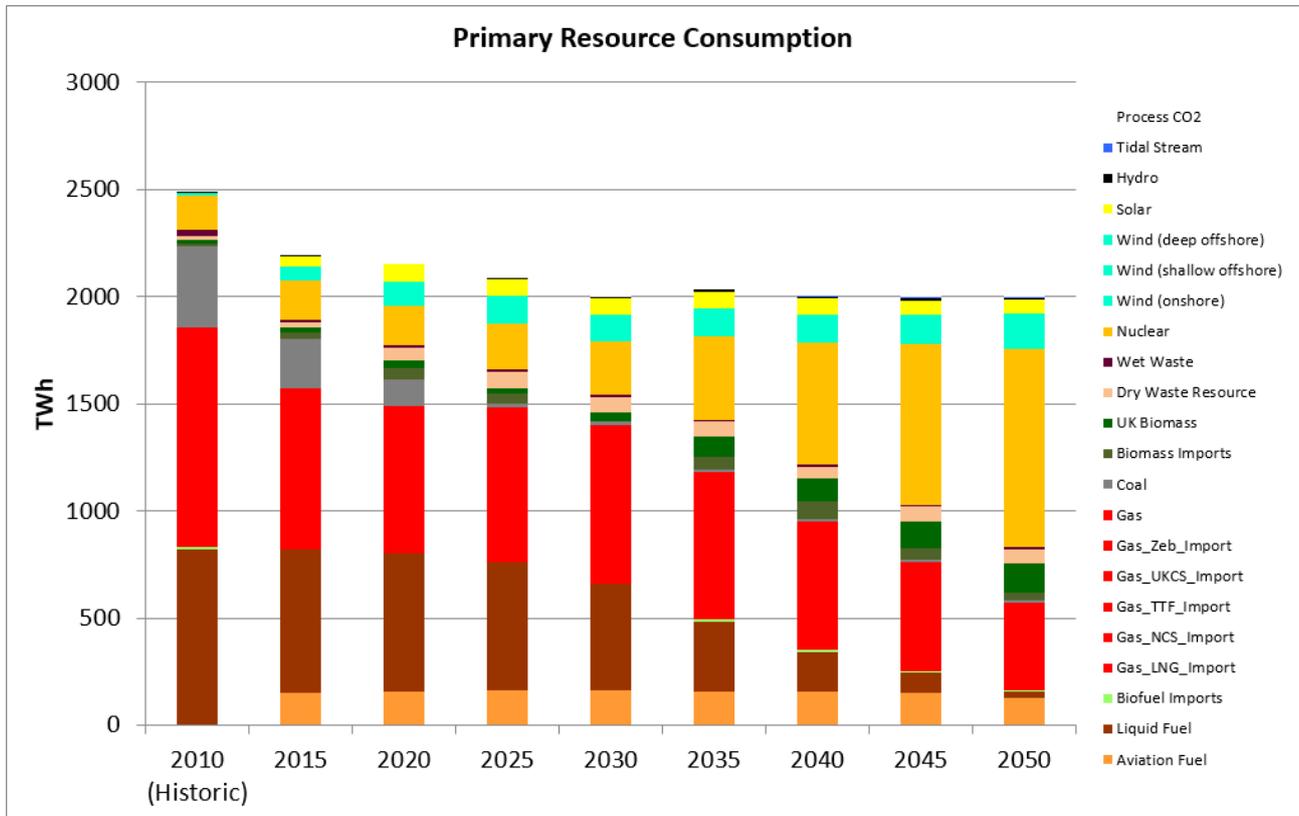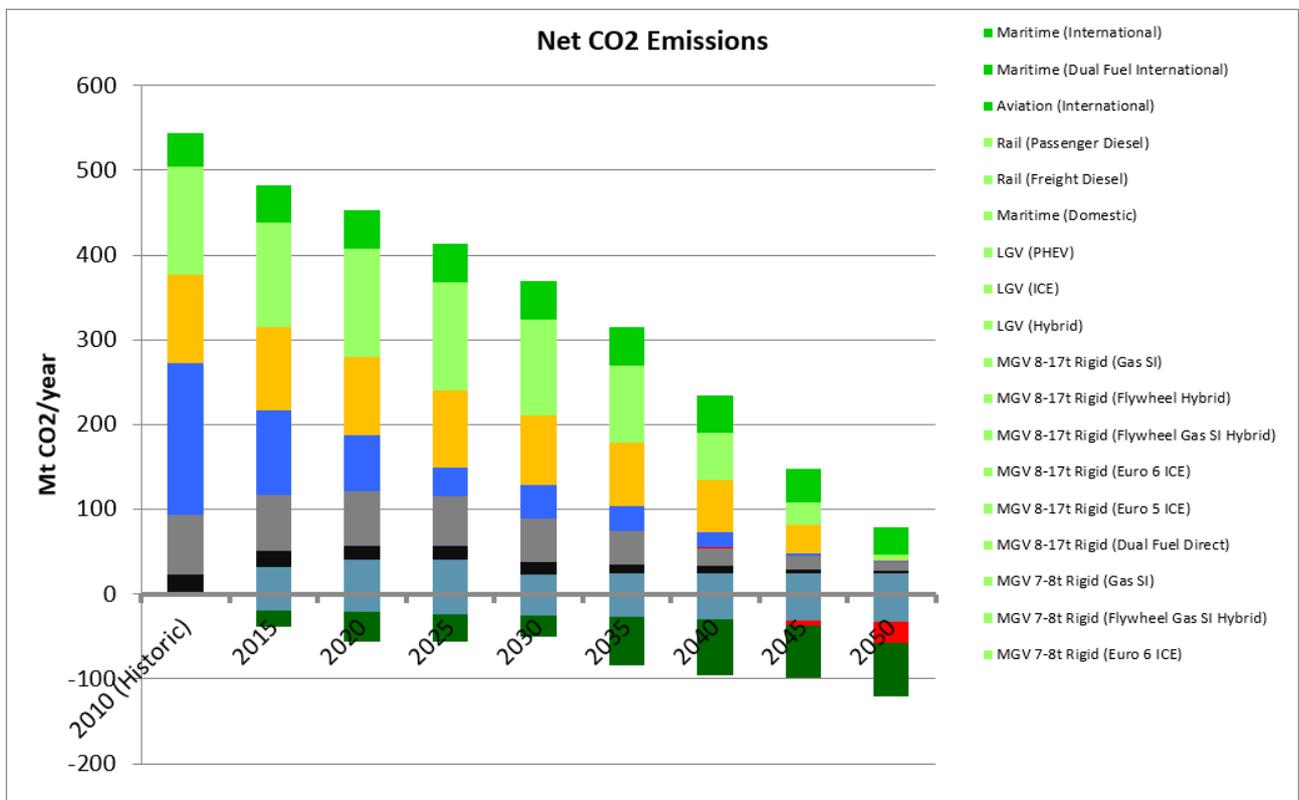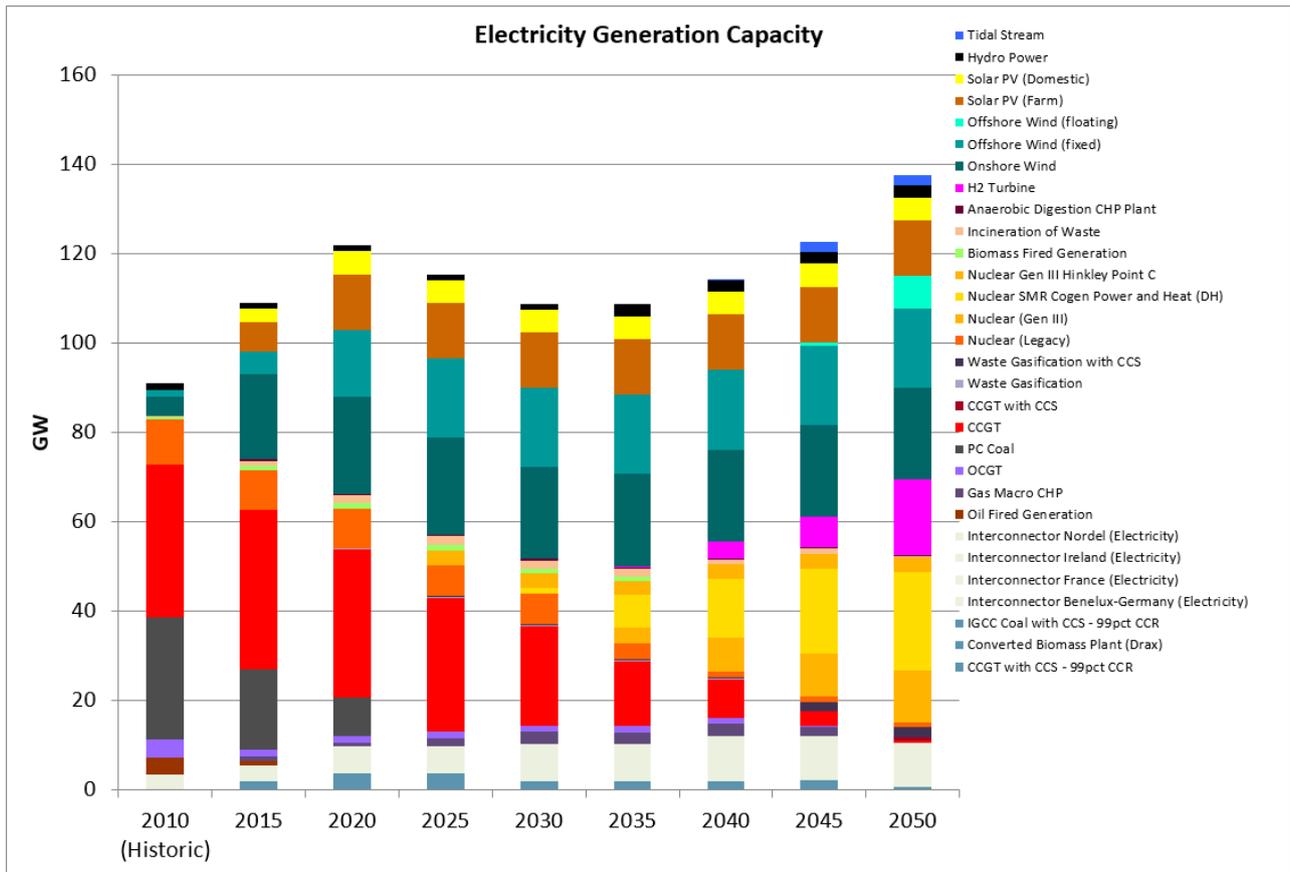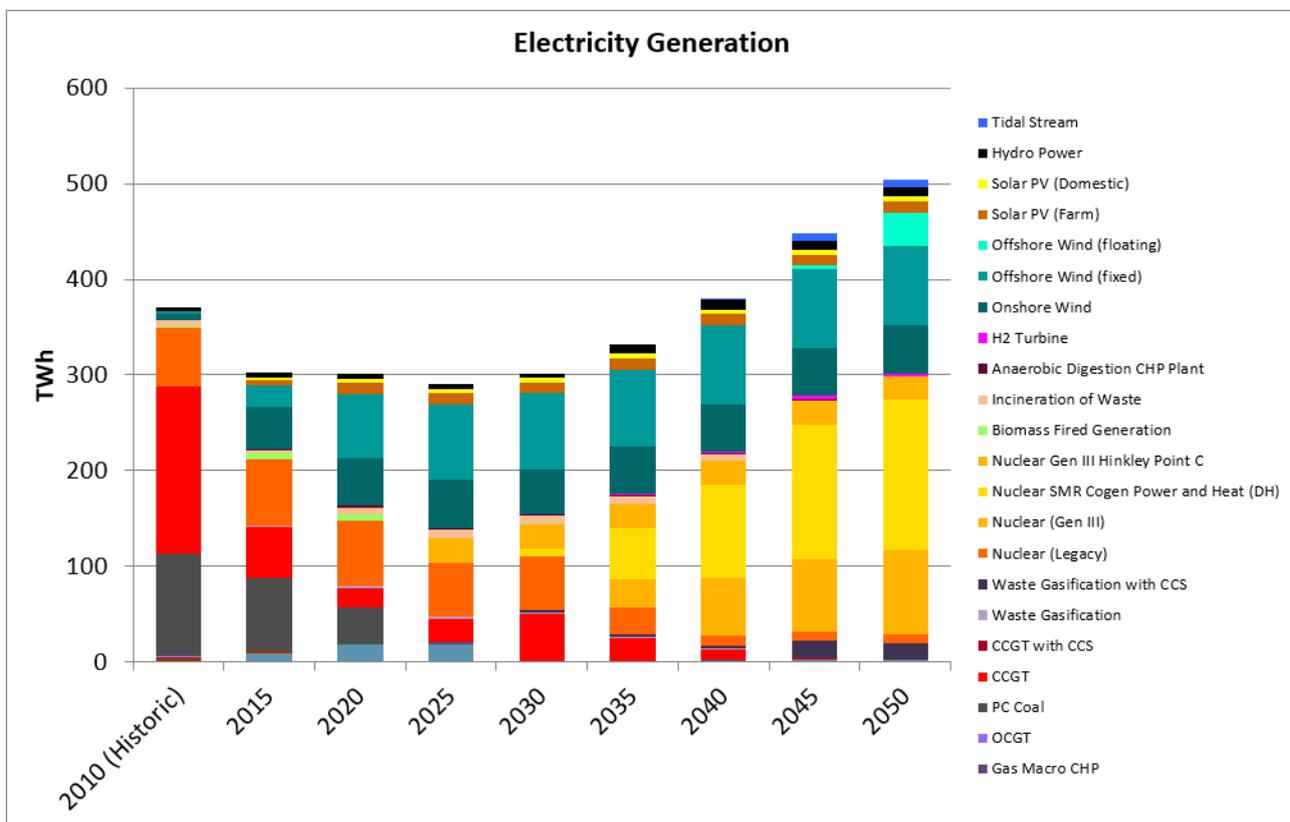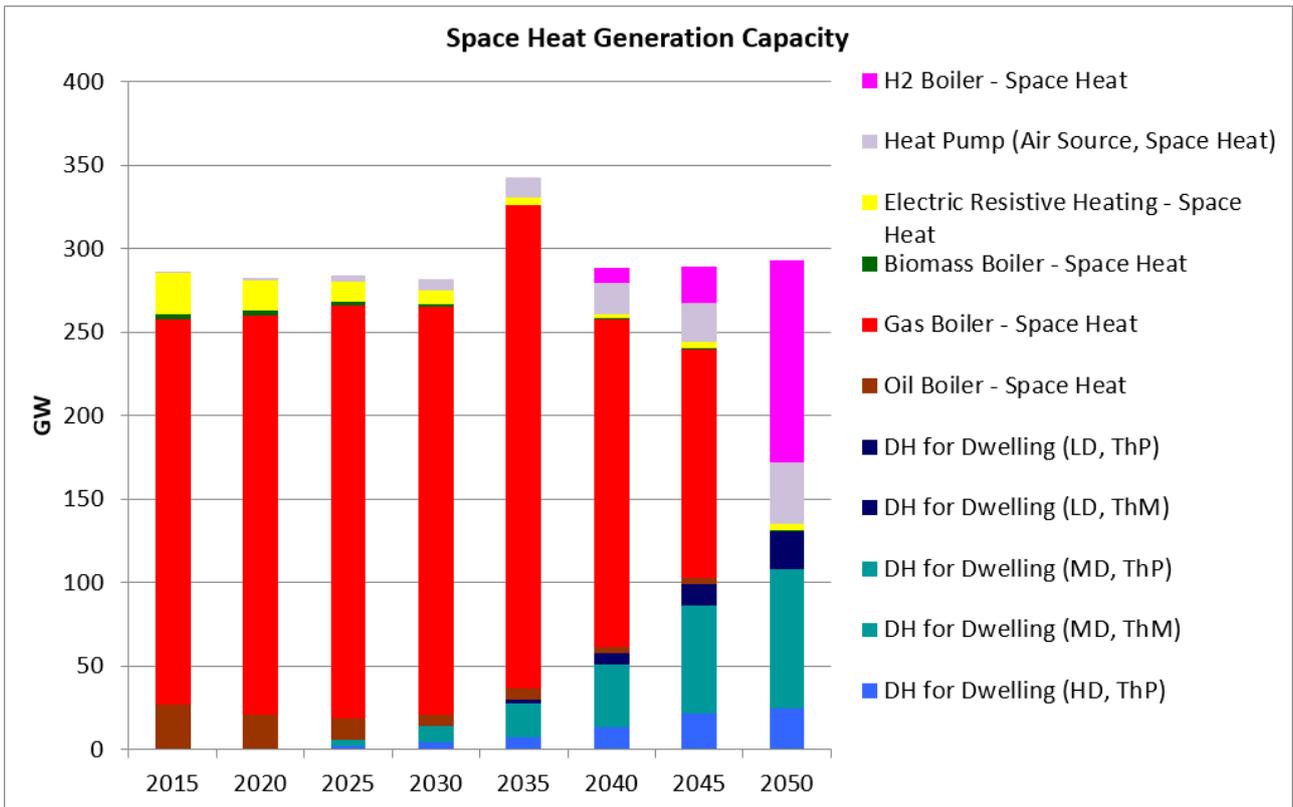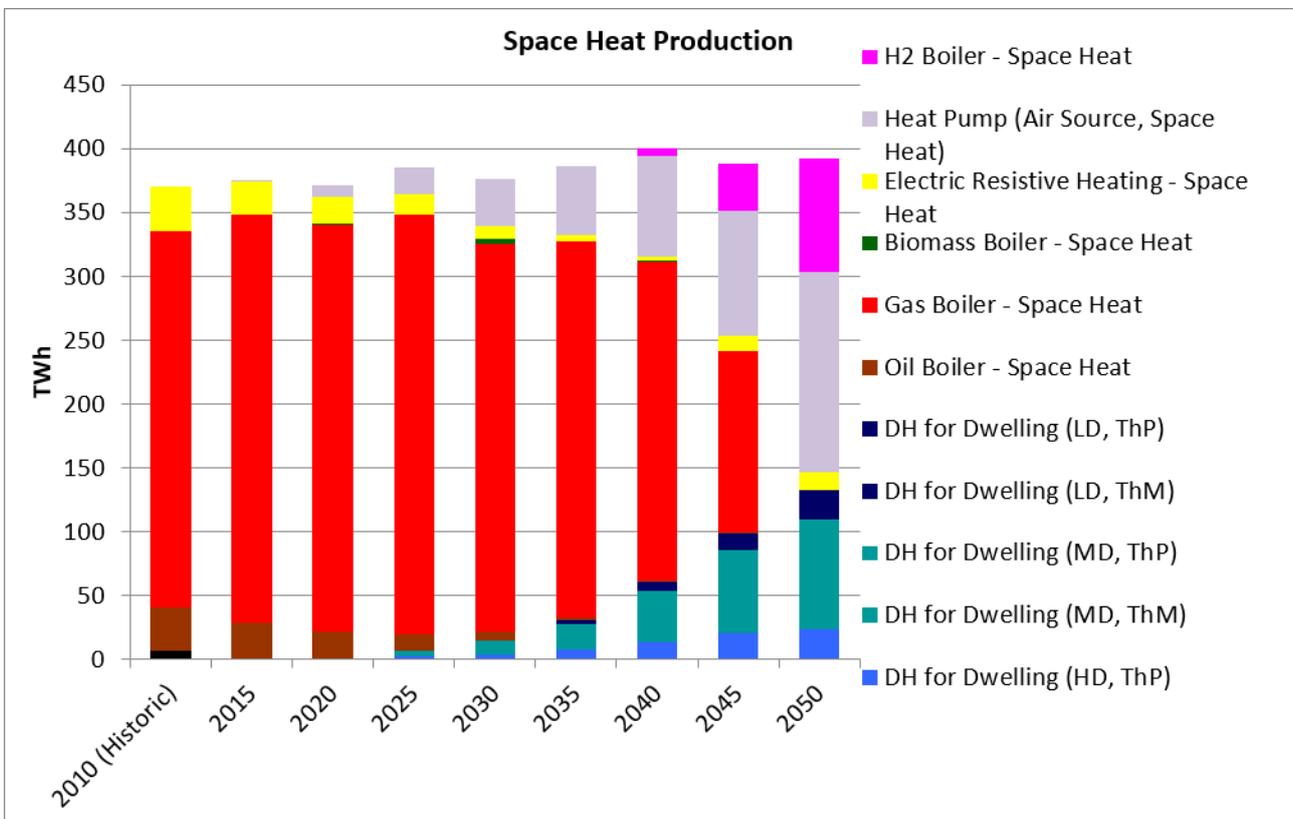Figure A3-5 – Run 228 Space Heat Generation Capacity
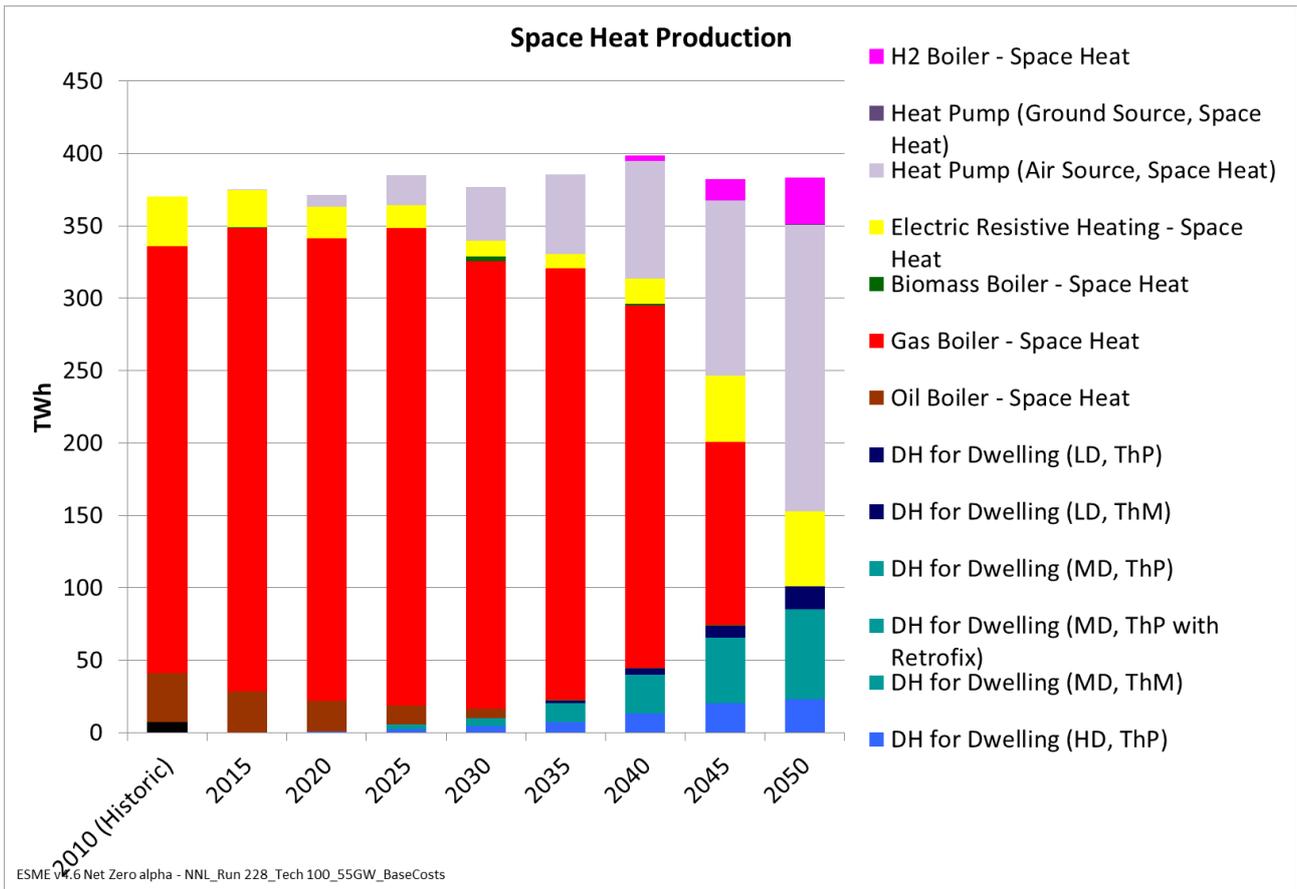
Figure A3-6 – Run 228 Space Heat Production
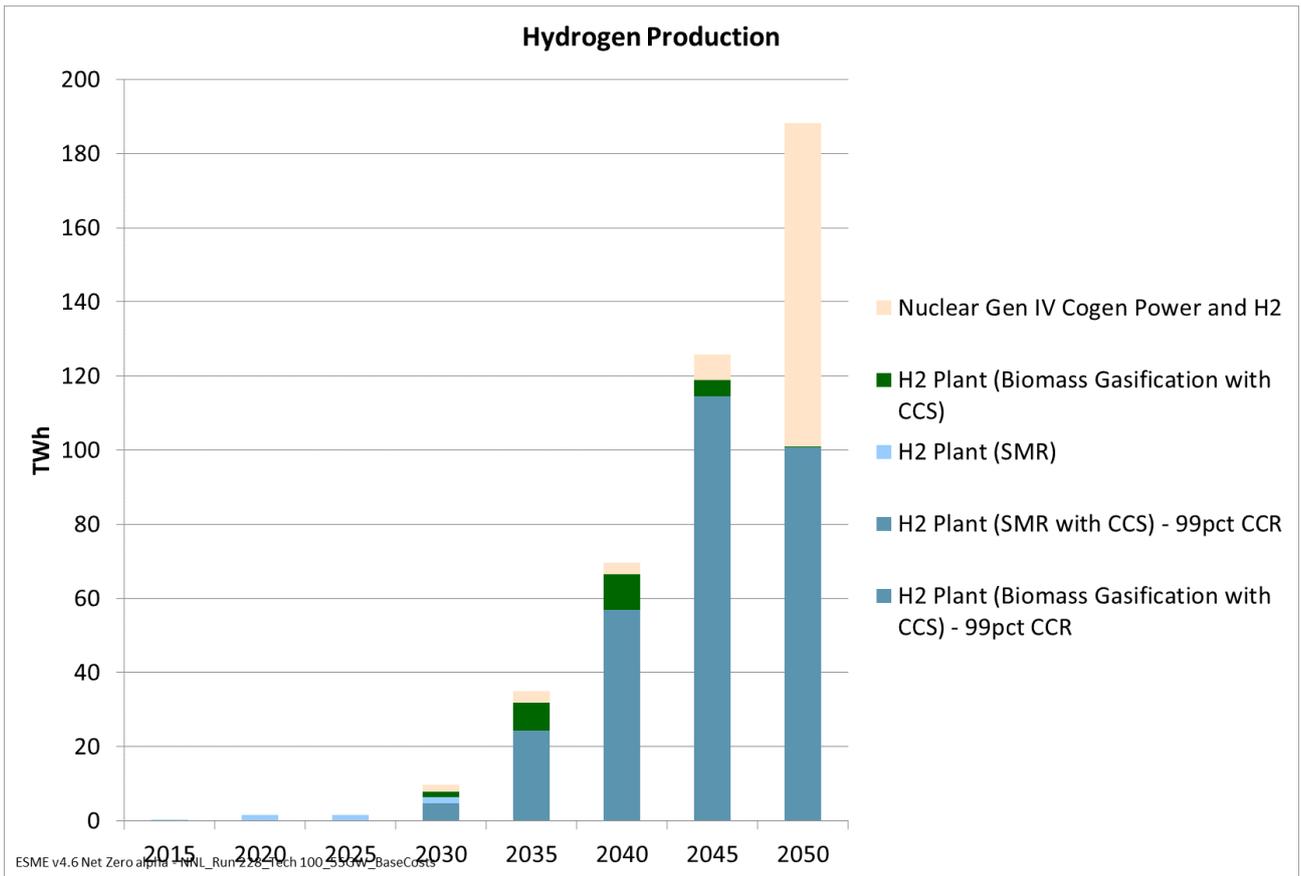
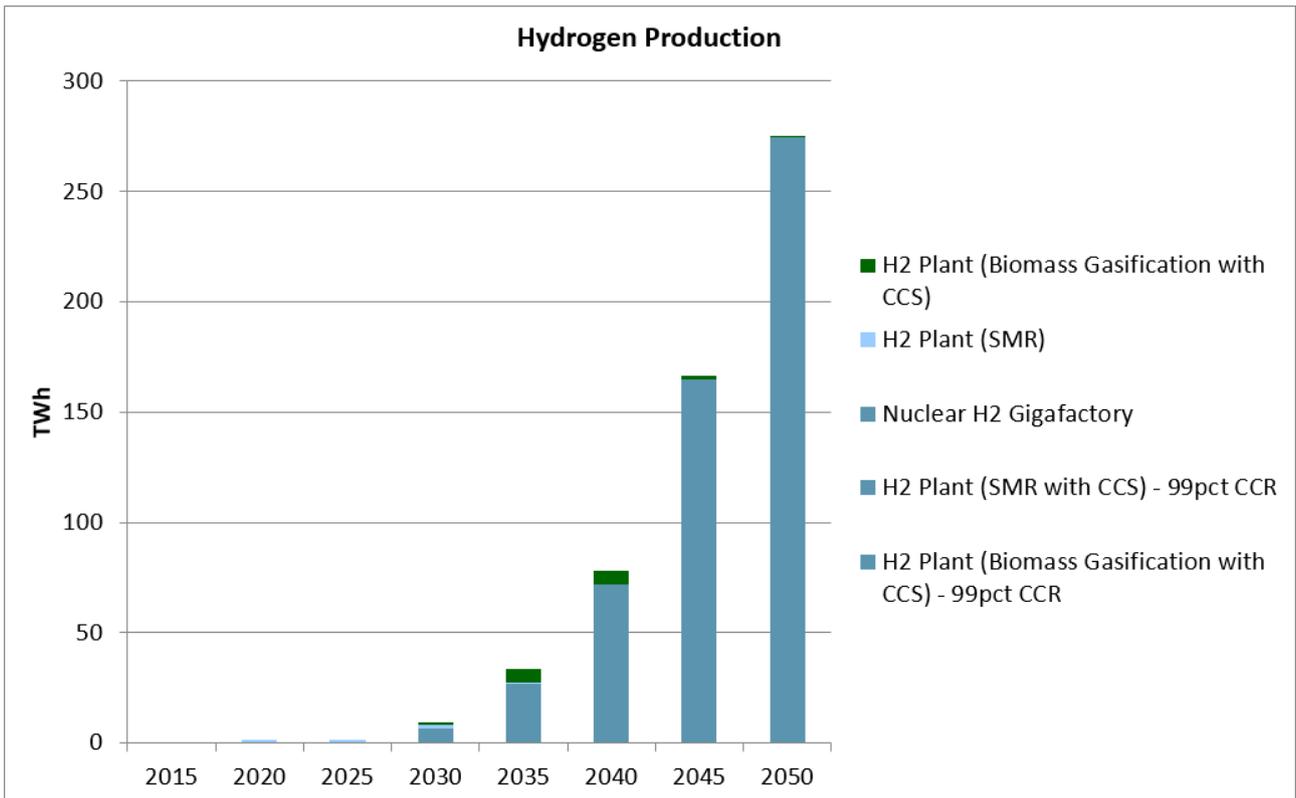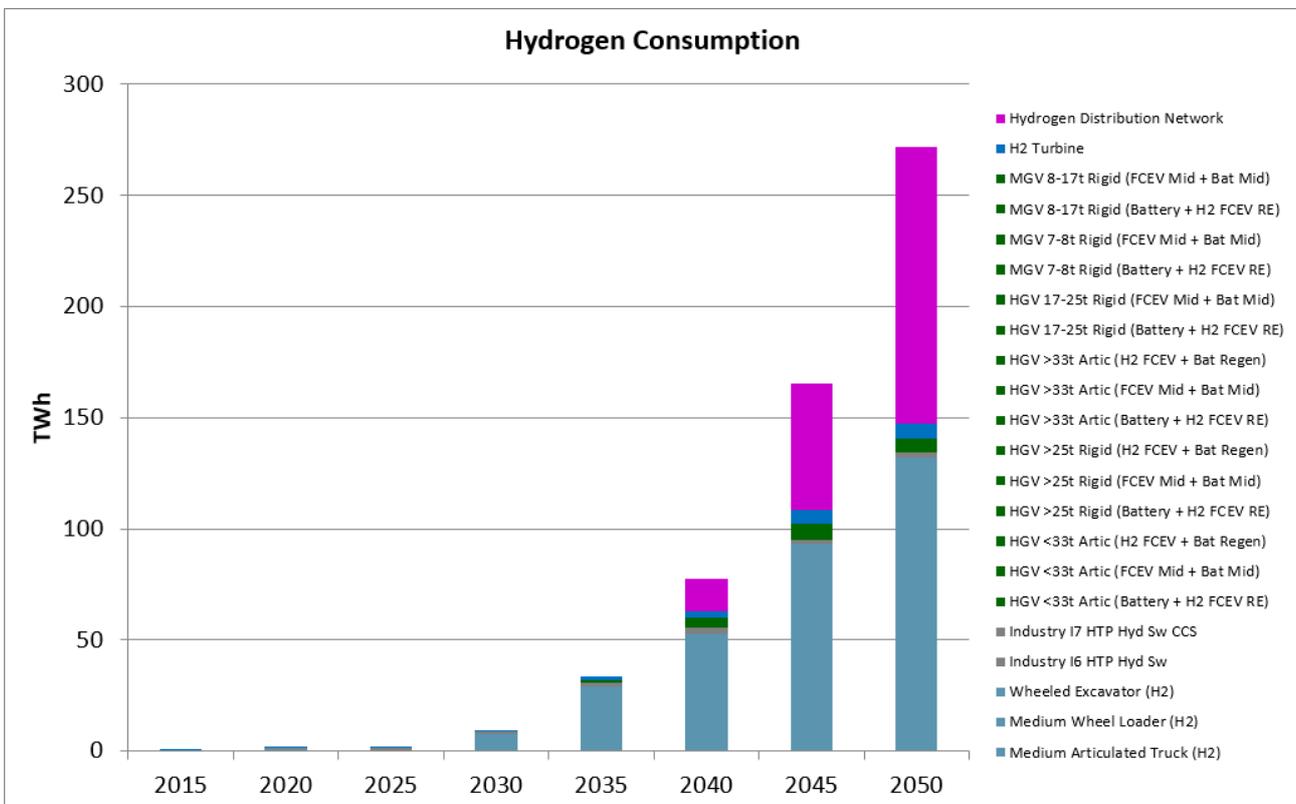Figure A3-7 – Run 228 Hydrogen Production
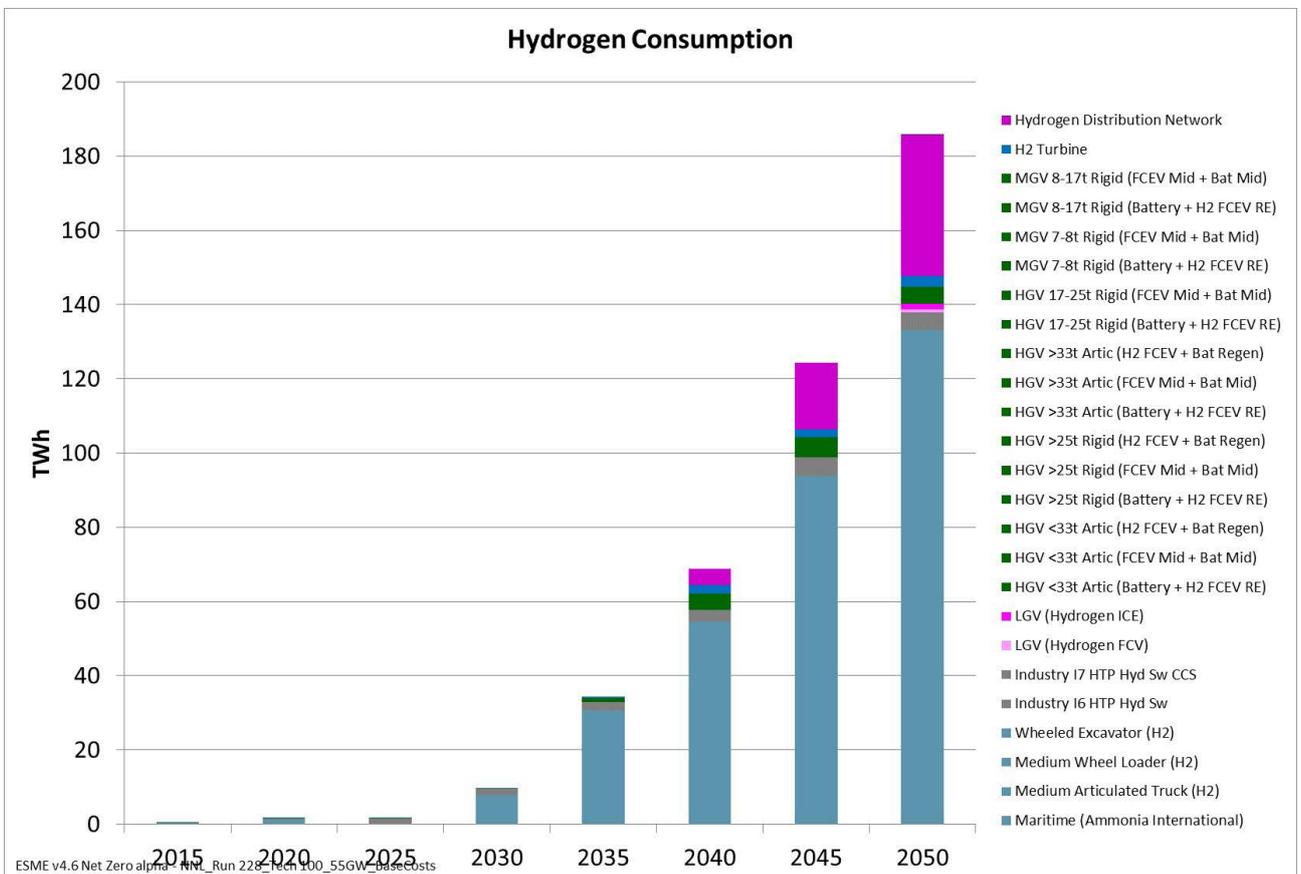
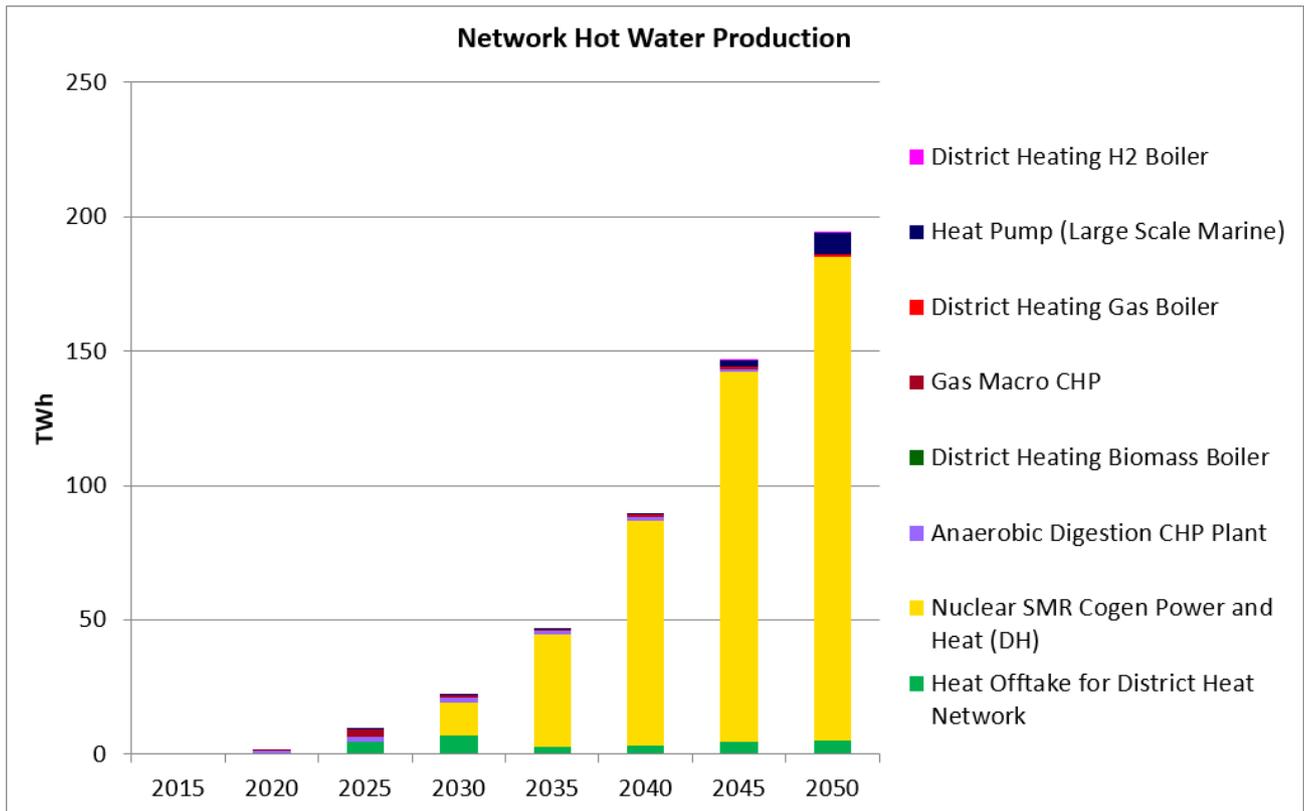Figure A3-8 – Run 228 Hydrogen consumption
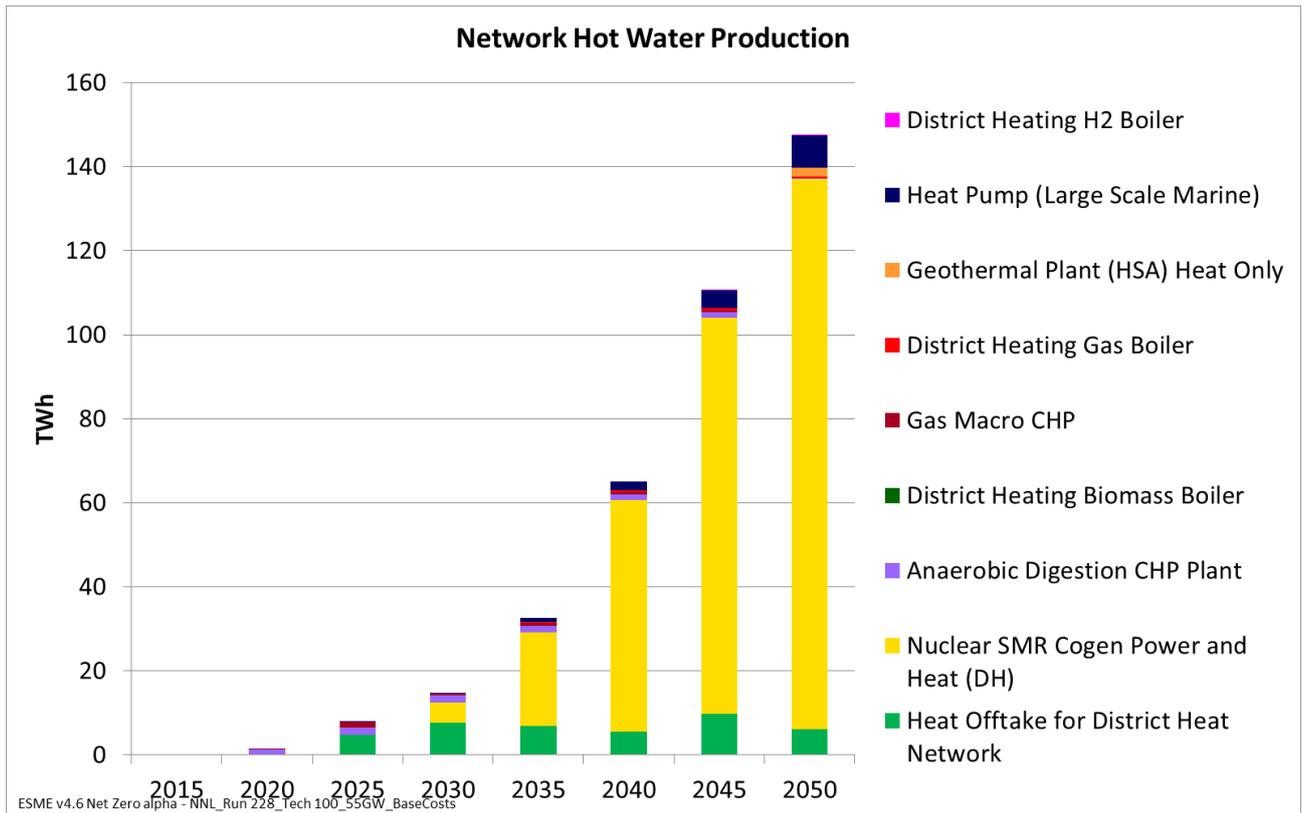
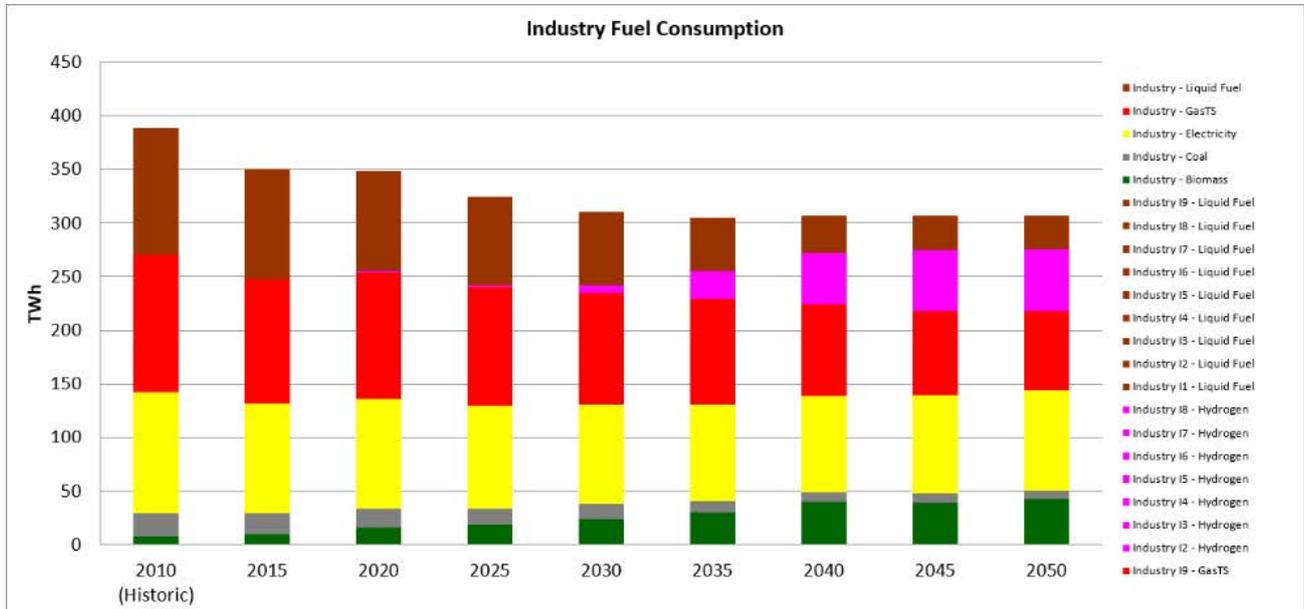**Figure A3-9 – Run 228 Network Hot Water Production**
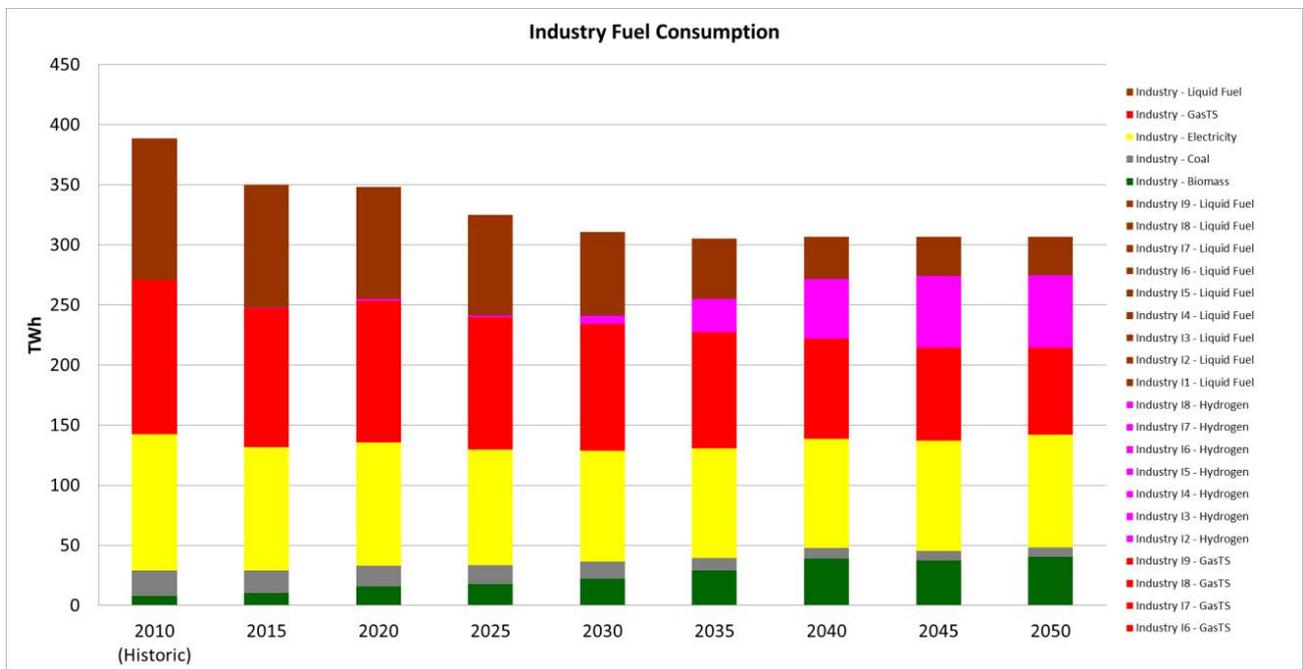
Figure A3-10 – Run 228 Industry Fuel Consumption

Run 301 TECH100 – Gen III+, LWSMR cogen, no gigafactory or synthetic fuel plant; base case data
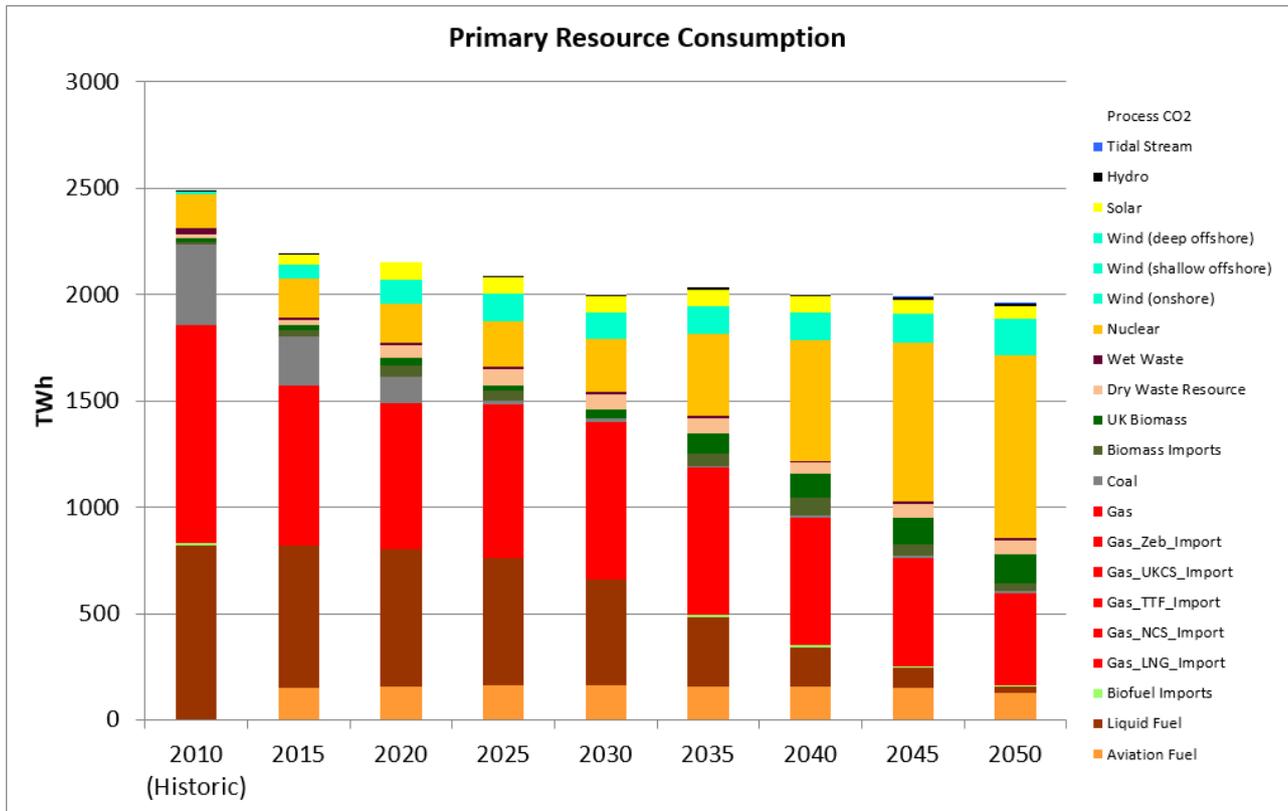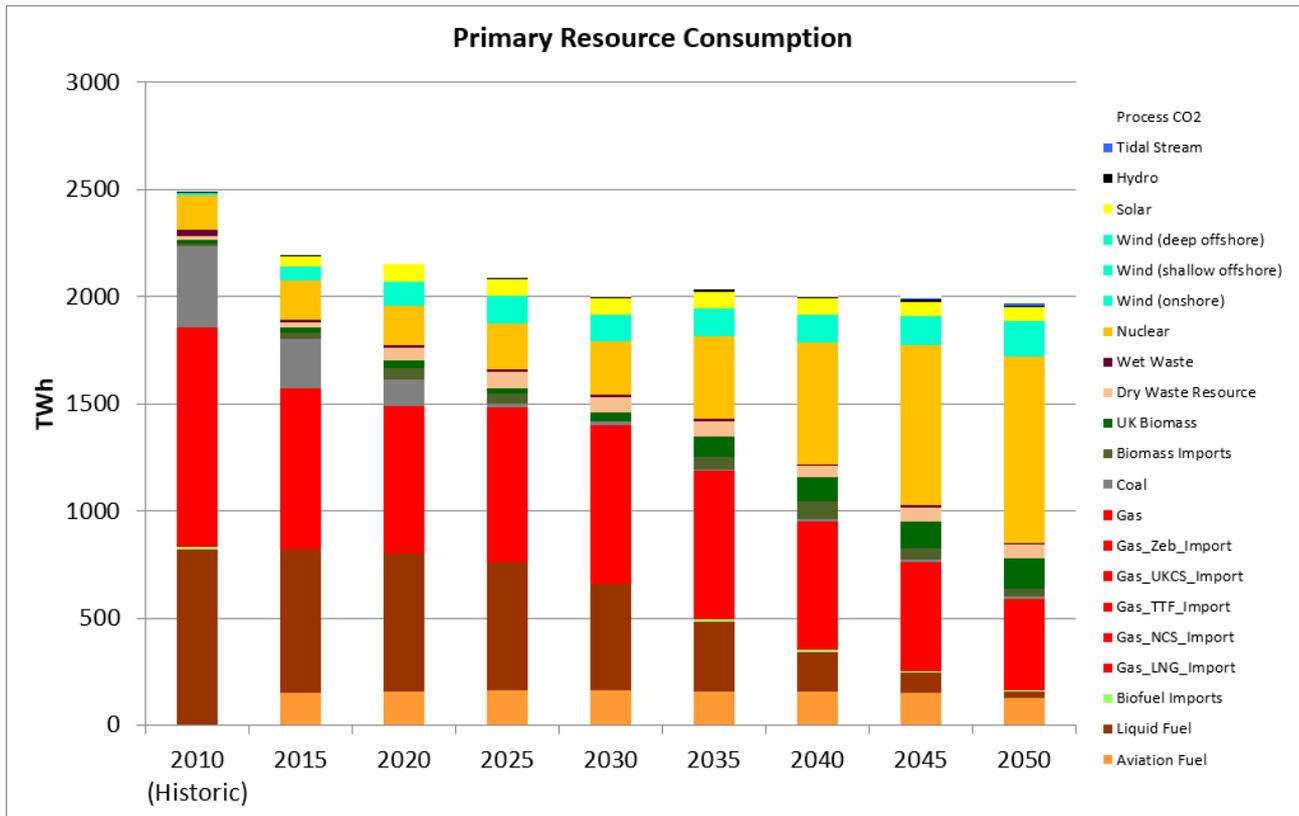

Figure A3-11 – Run 301 Primary Resource Consumption
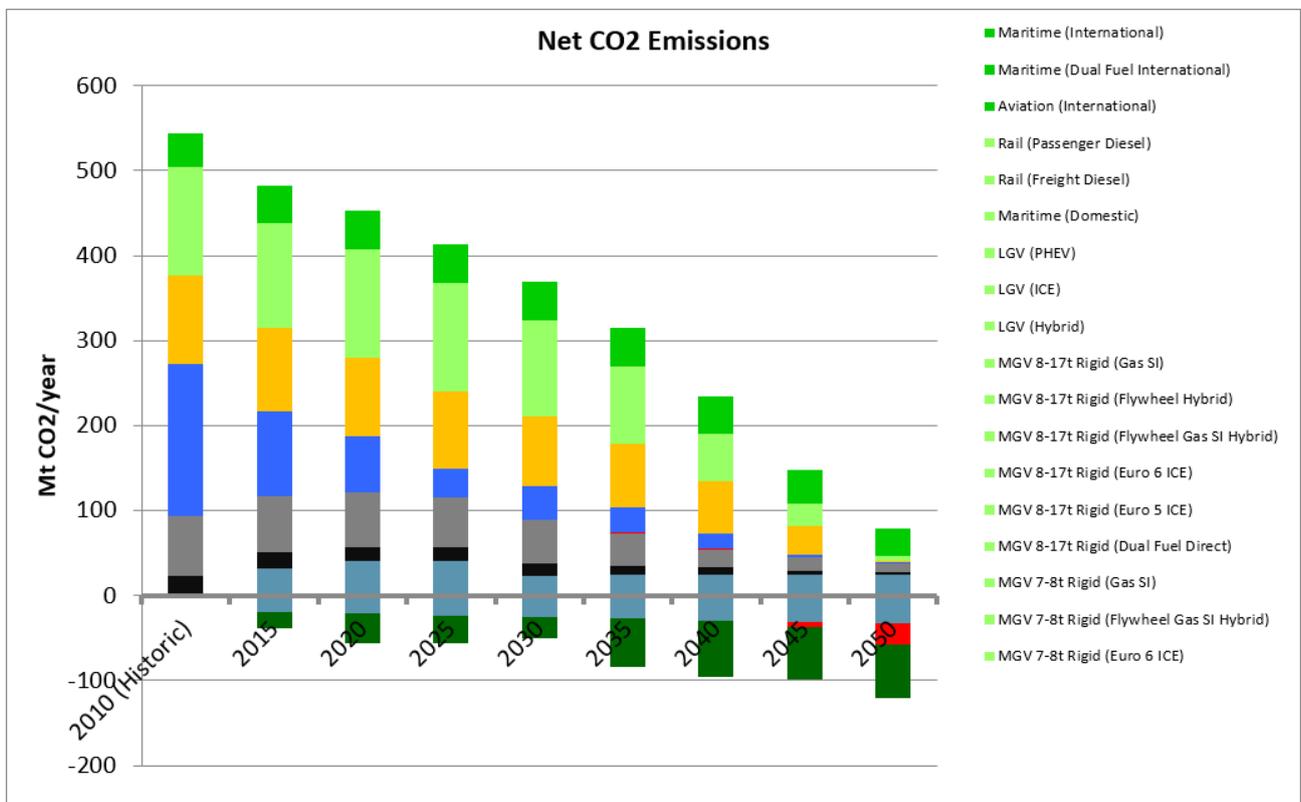
Figure A3-12 – Run 301 Net CO$_2$ Emissions
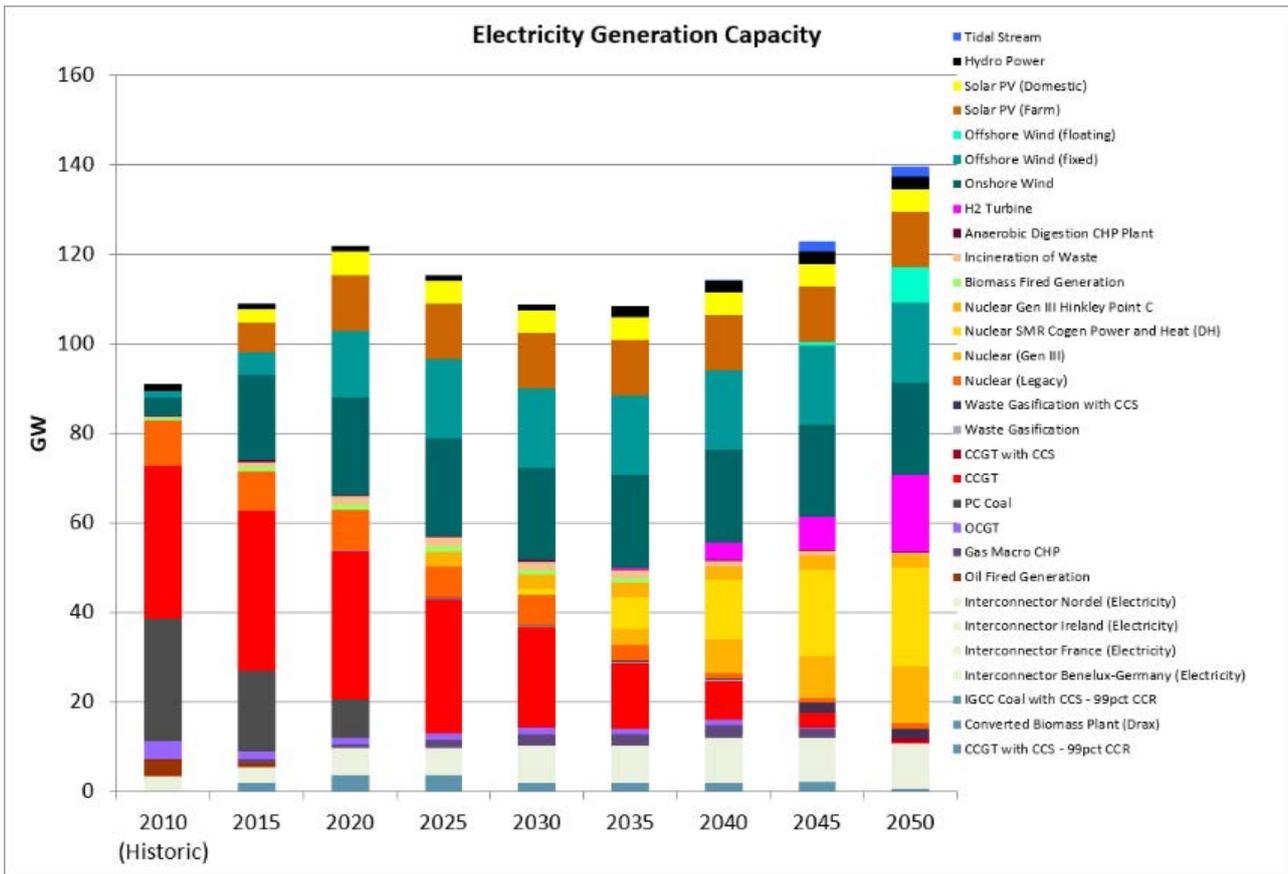
Figure A3-13 – Run 301 Electricity Generation Capacity
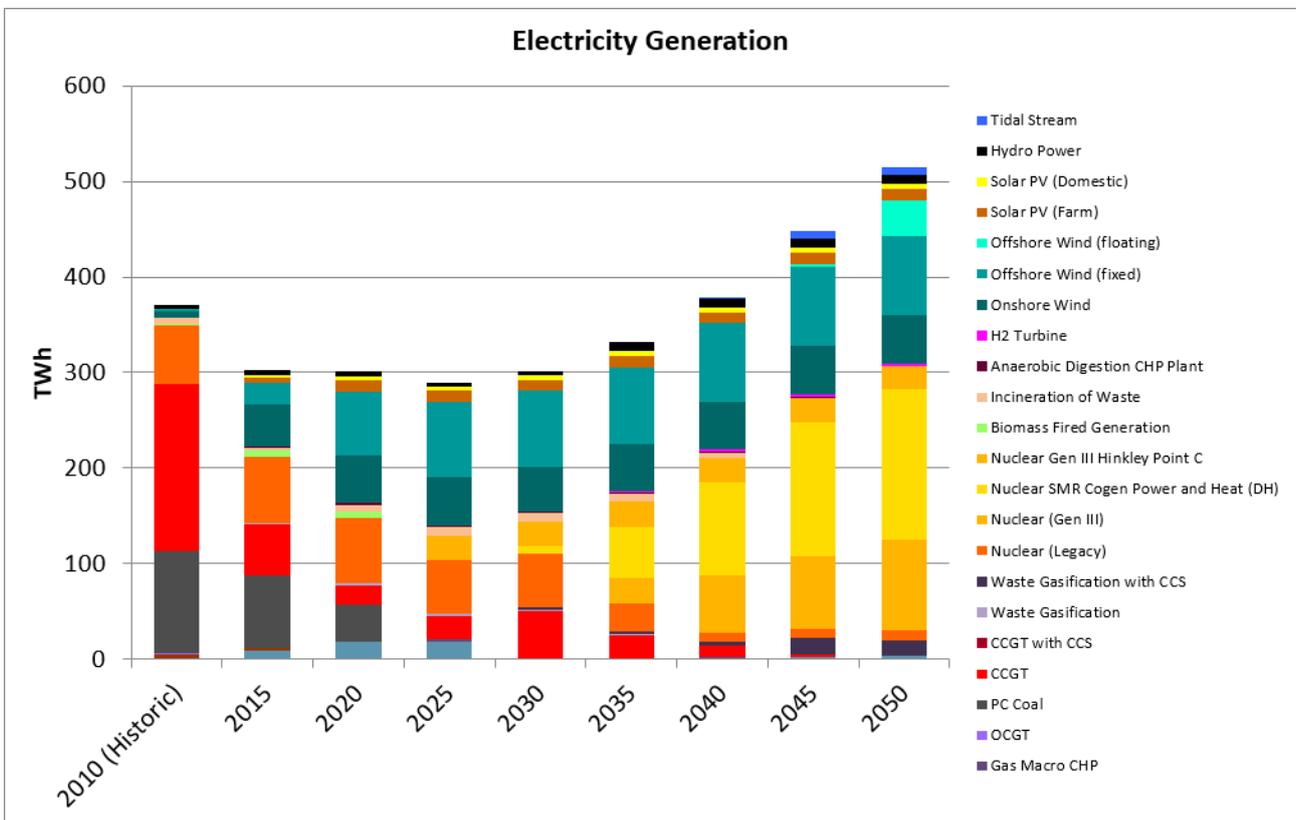
Figure A3-14 – Run 301 Electricity Generation
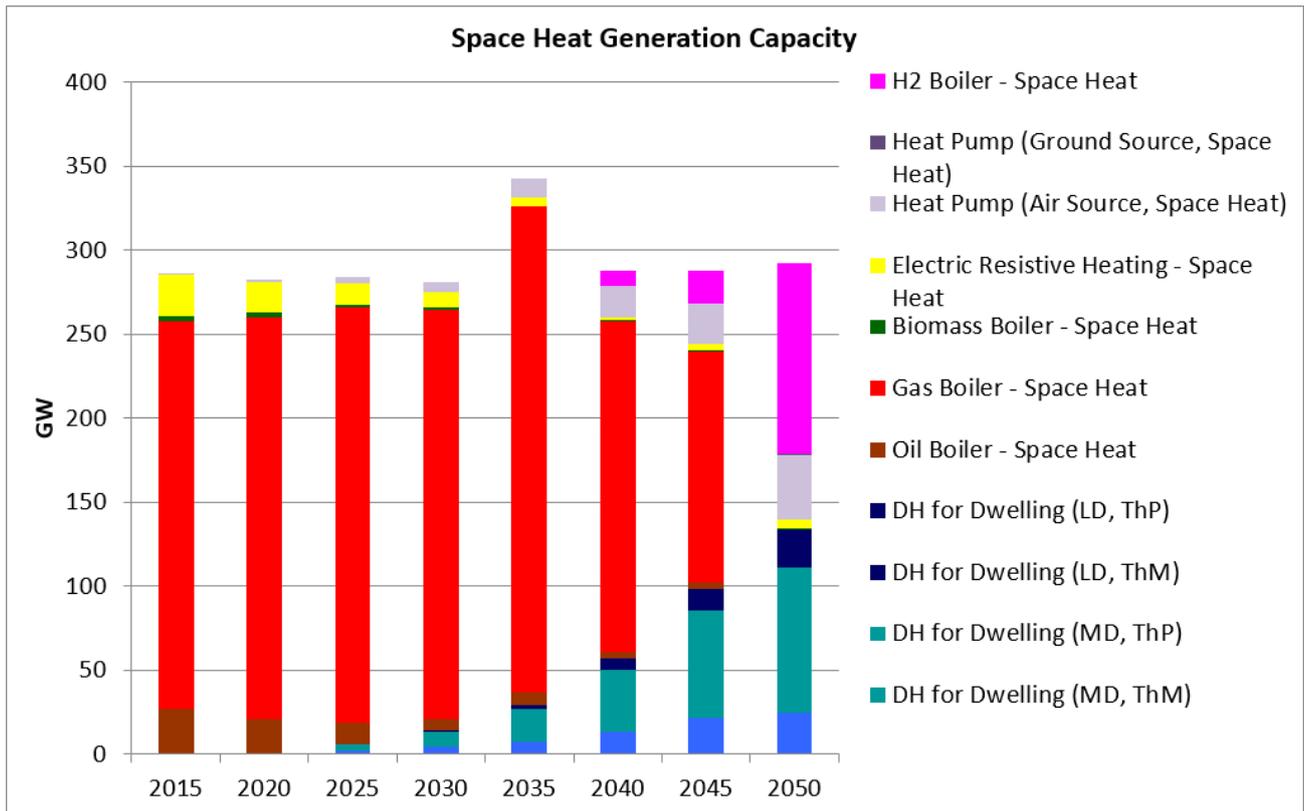
Figure A3-15 – Run 301 Space Heat Generation Capacity
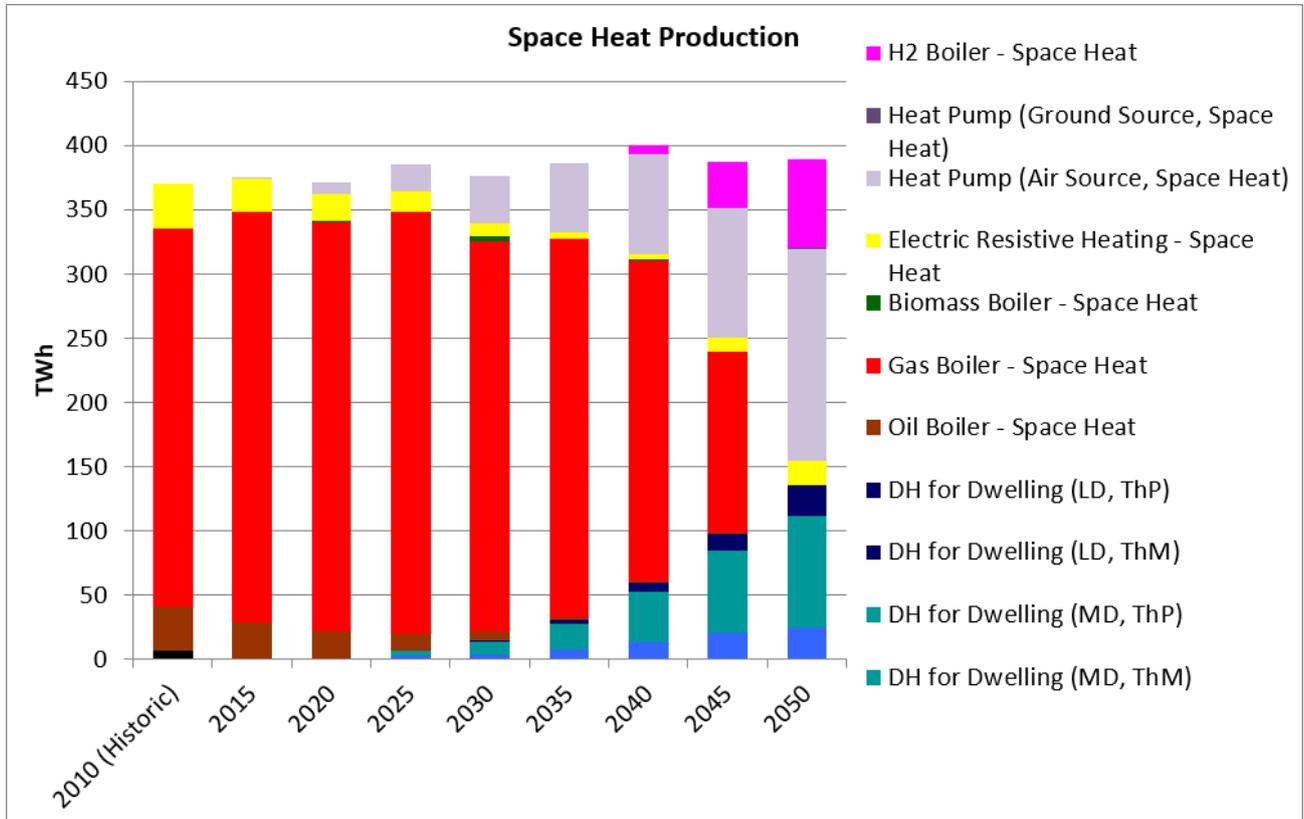
Figure A3-16 – Run 301 Space Heat Production
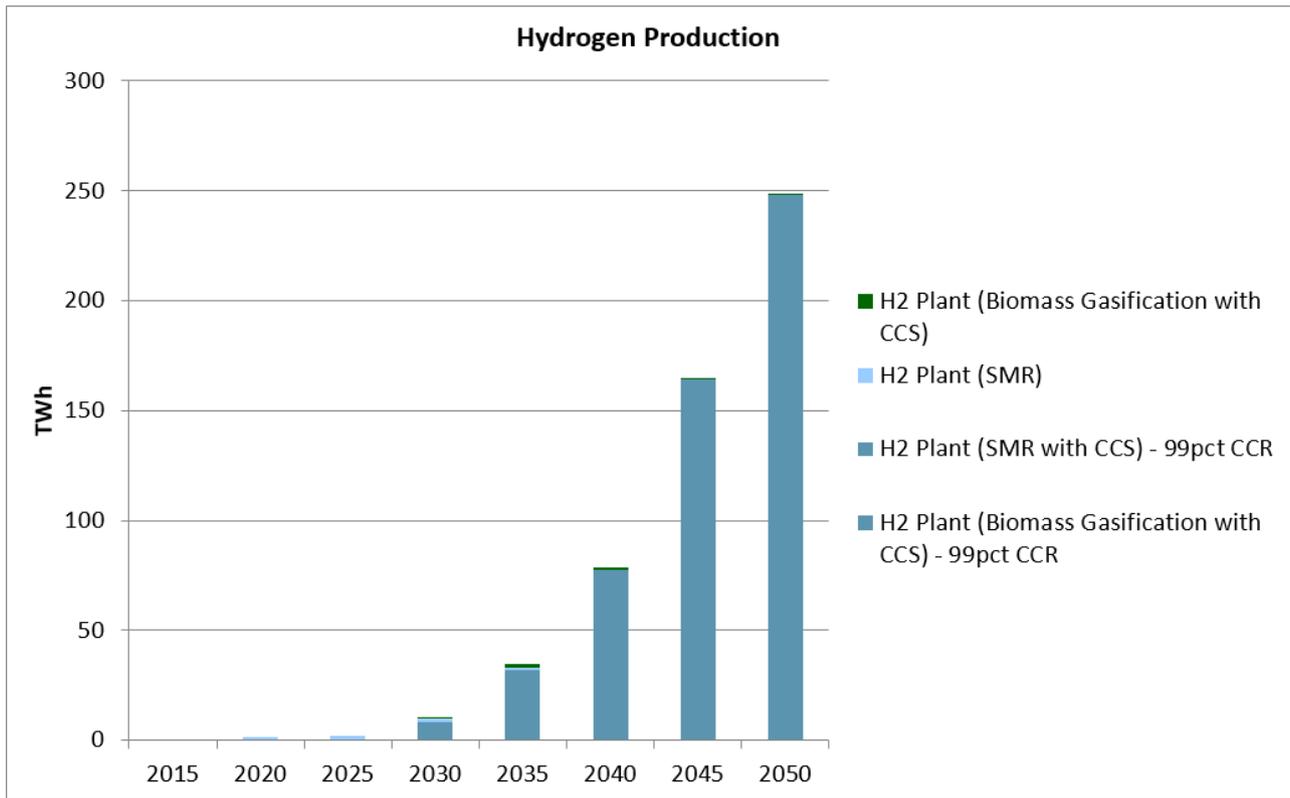
Figure A3-17 – Run 301 Hydrogen Production
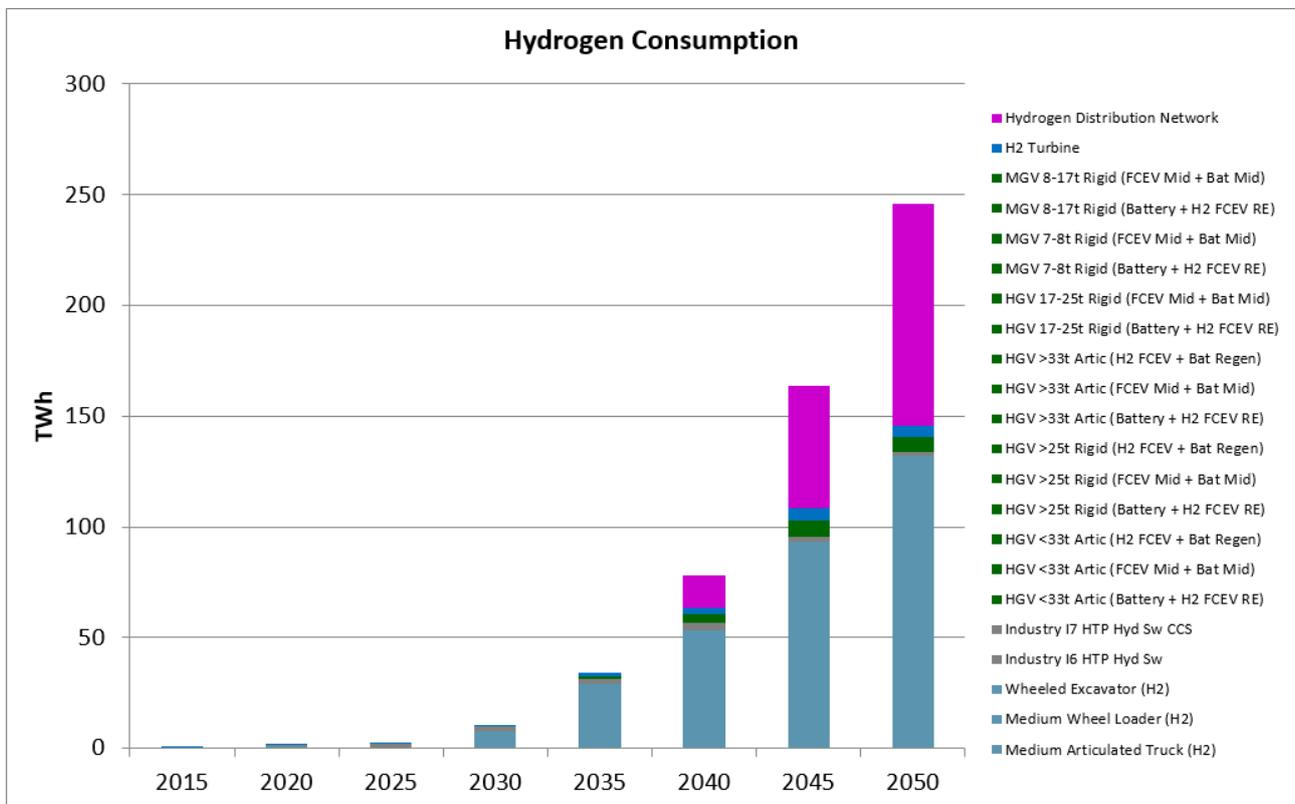
Figure A3-18 – Run 301 Hydrogen consumption
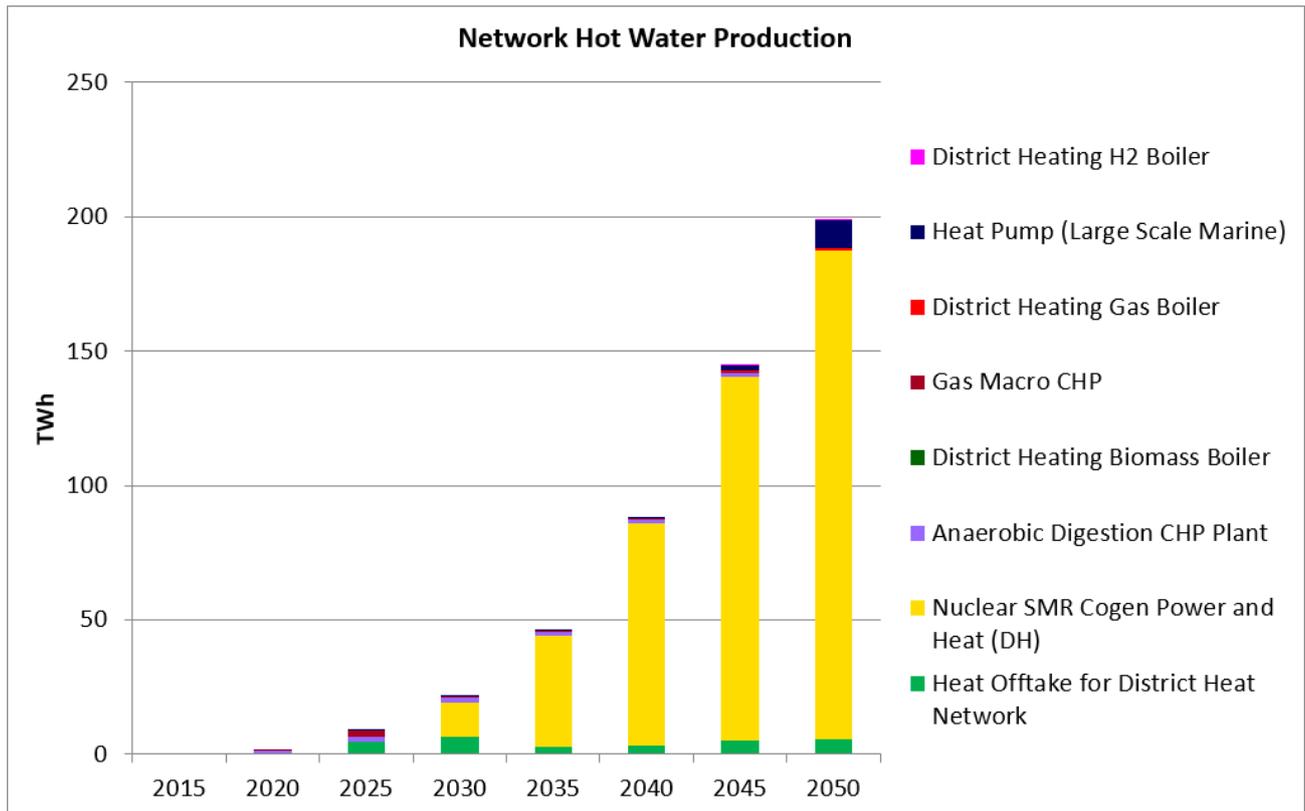
Figure A3-19 – Run 301 Network Hot Water Production
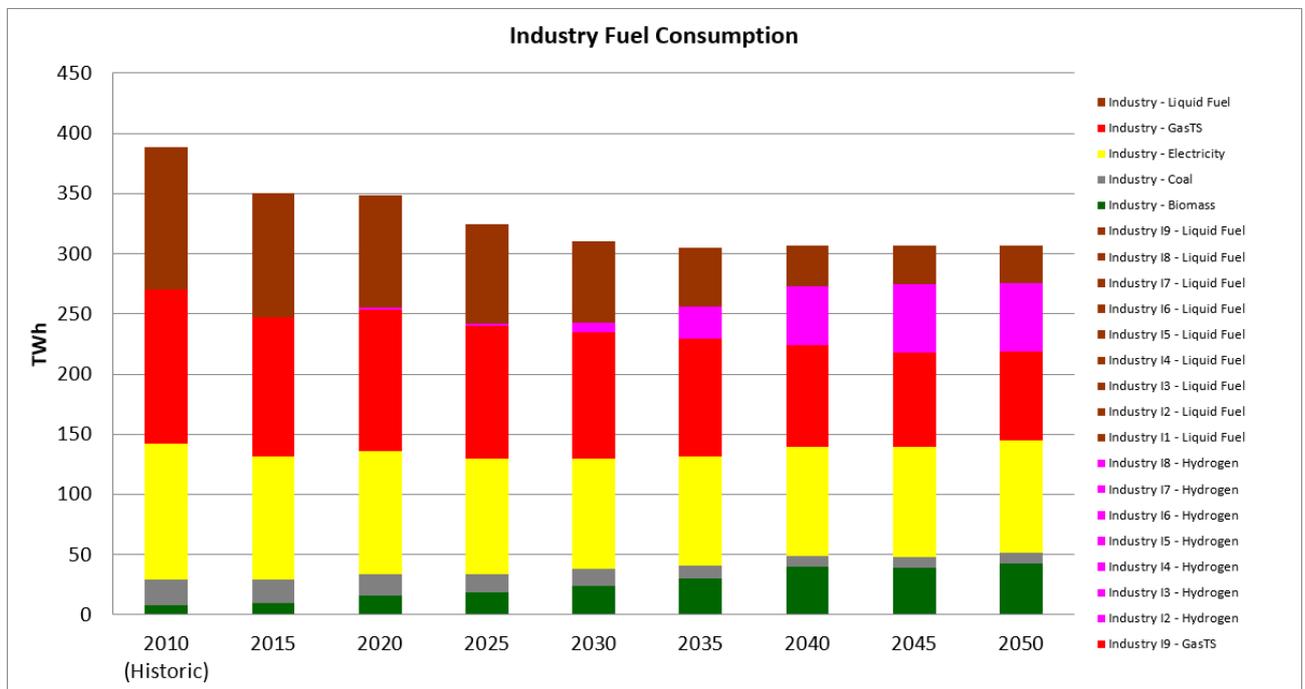
Figure A3-20 – Run 301 Industry Fuel Consumption

Run 310 TECH100 – Gen III+, LWSMR cogen, gigafactory and synthetic fuel plant; all nuclear technologies; base case data
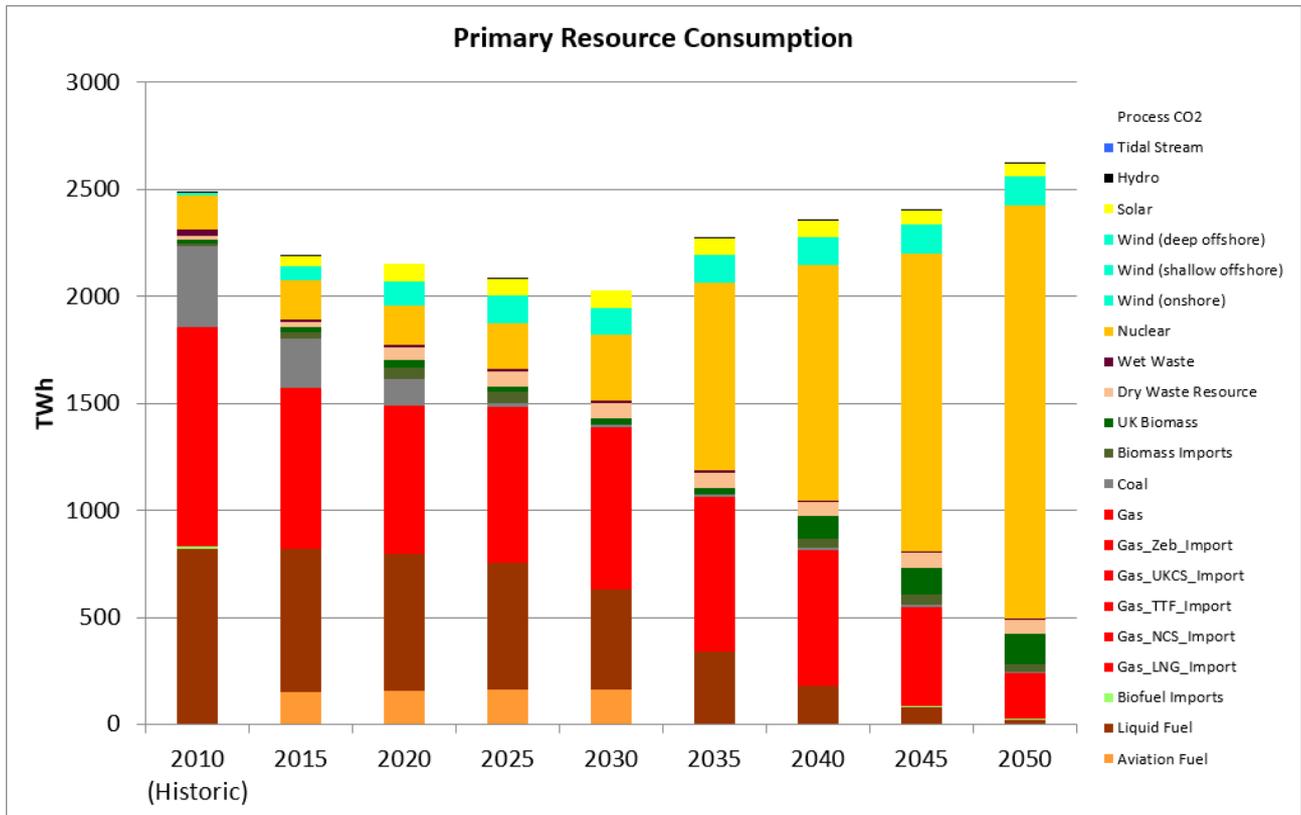
Figure A3-21 – Run 310 Primary Resource Consumption
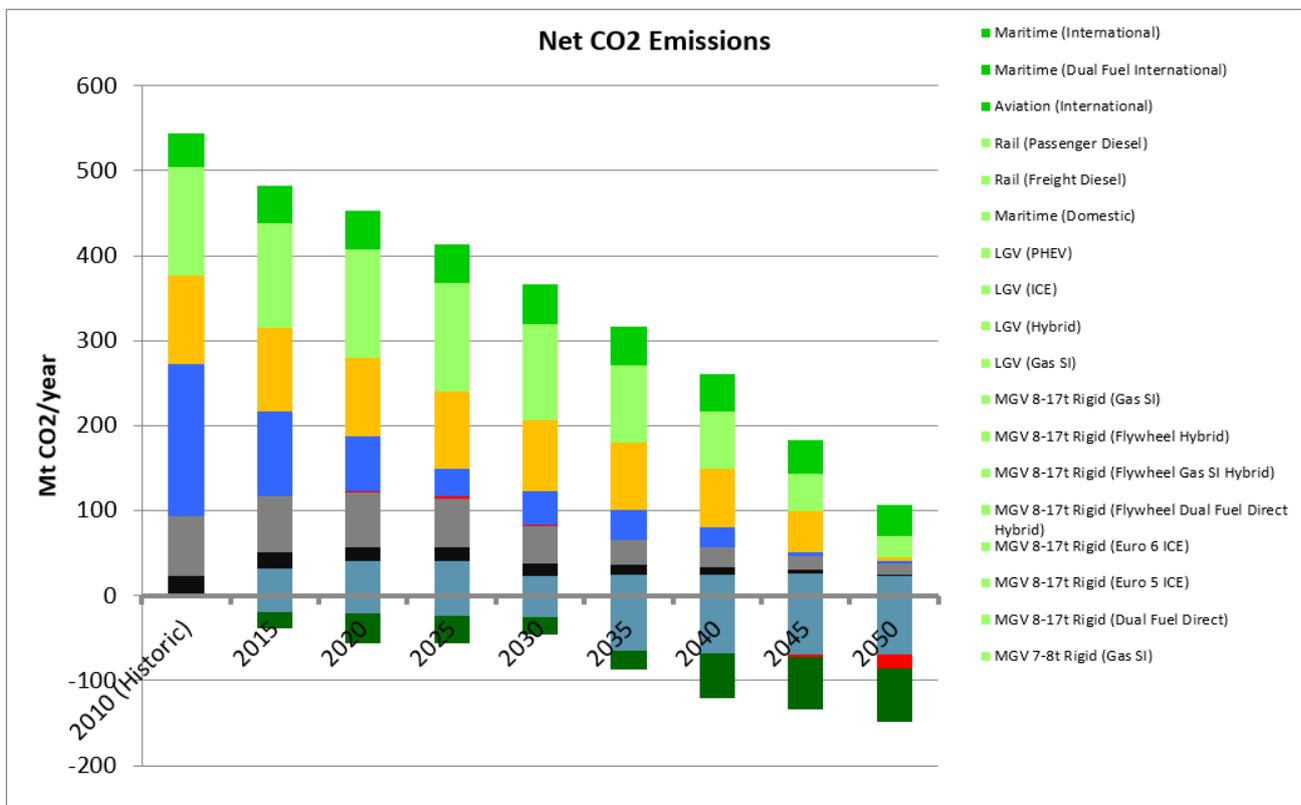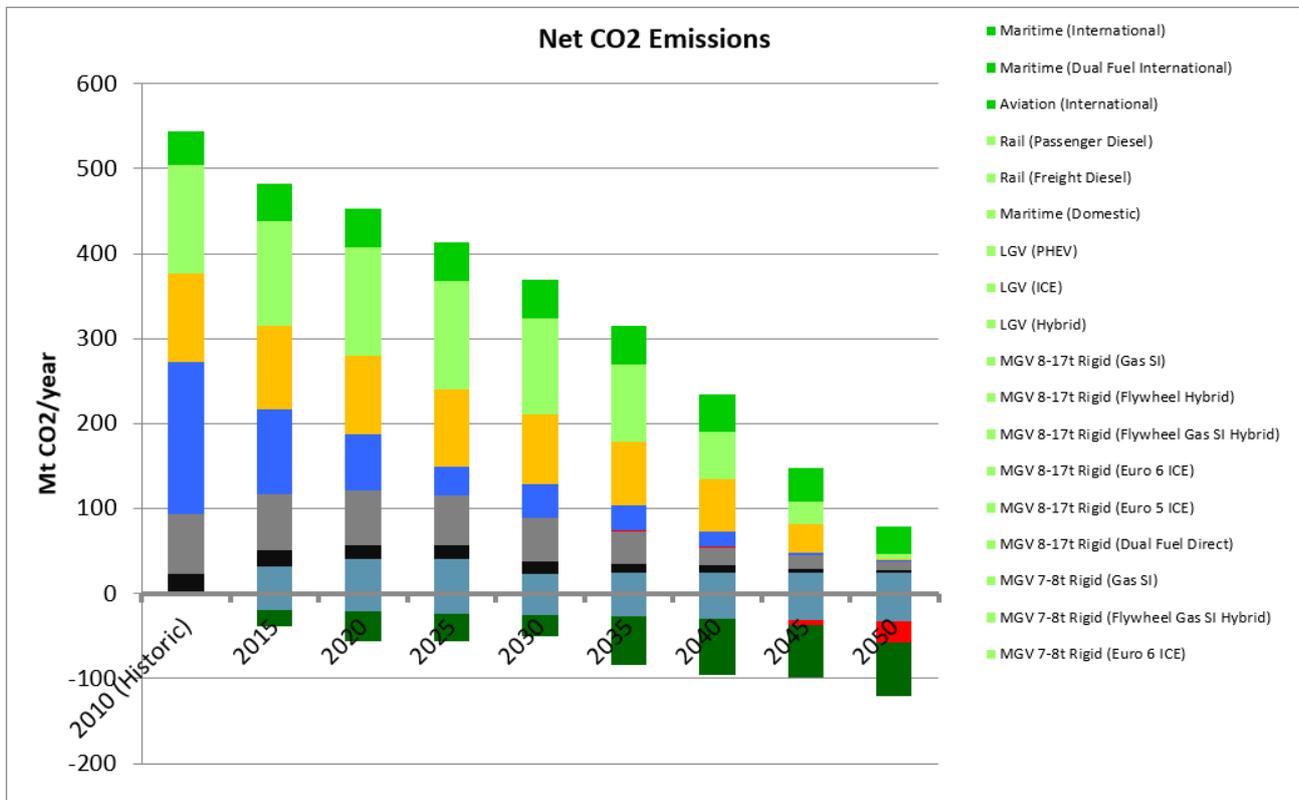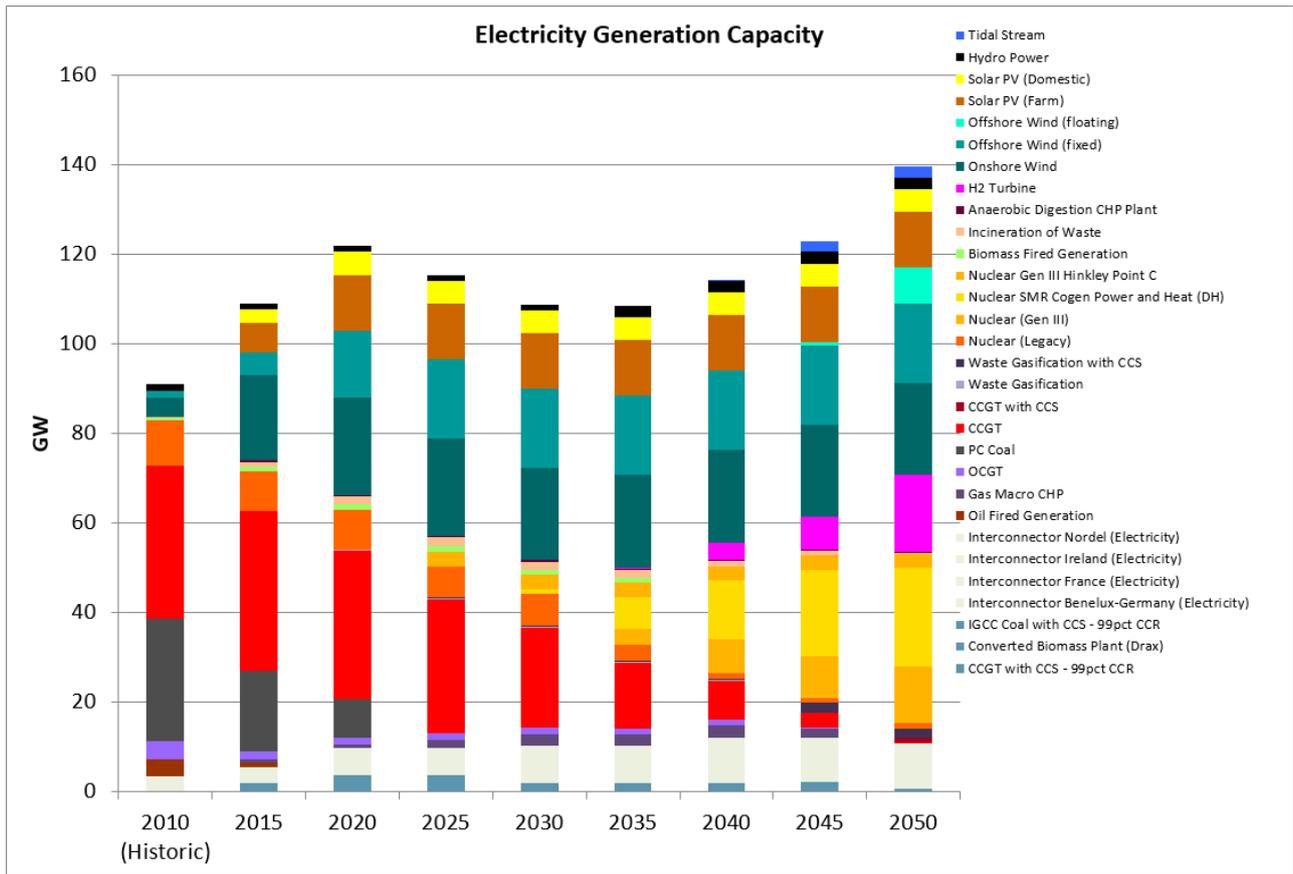

Figure A3-22 – Run 310 Net CO$_2$ Emissions
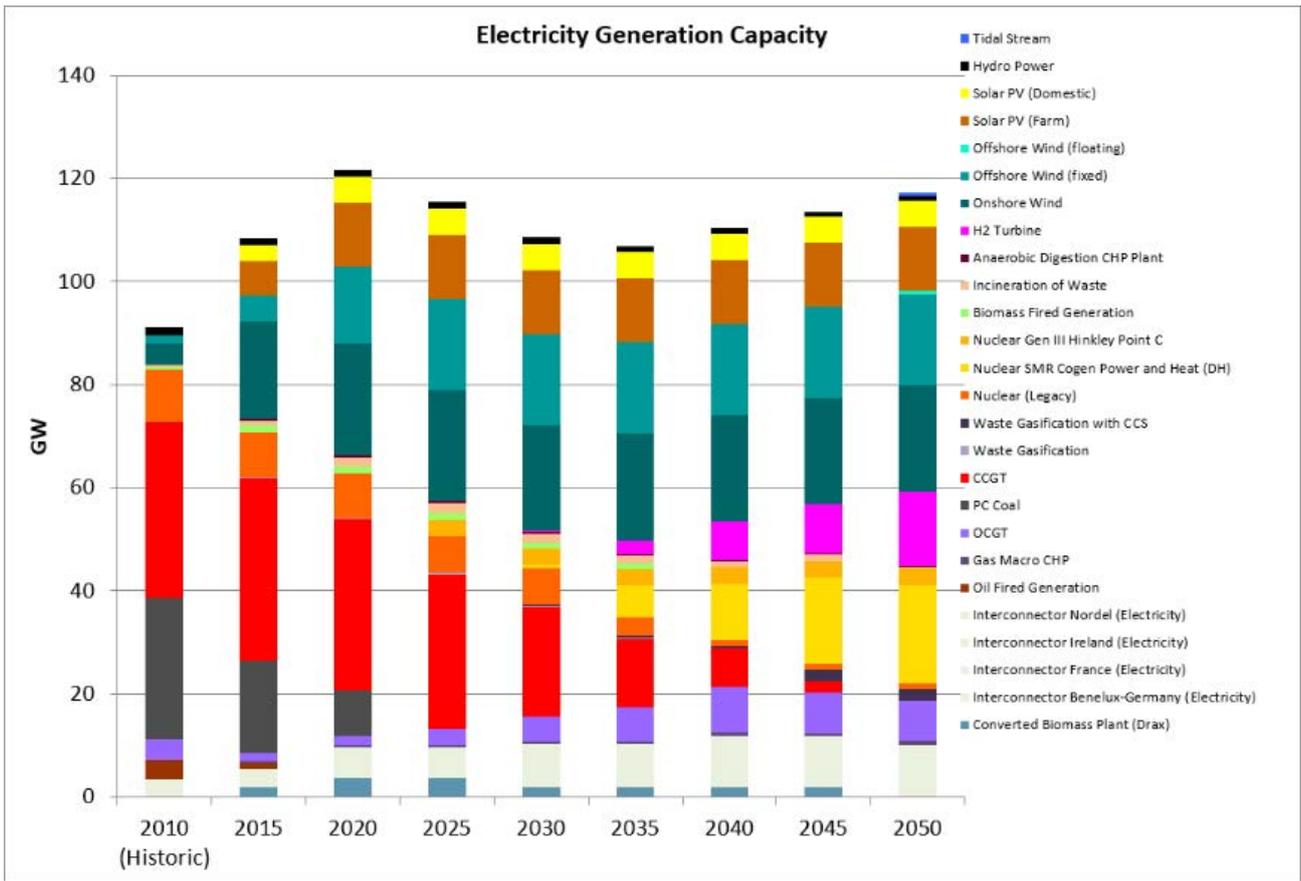
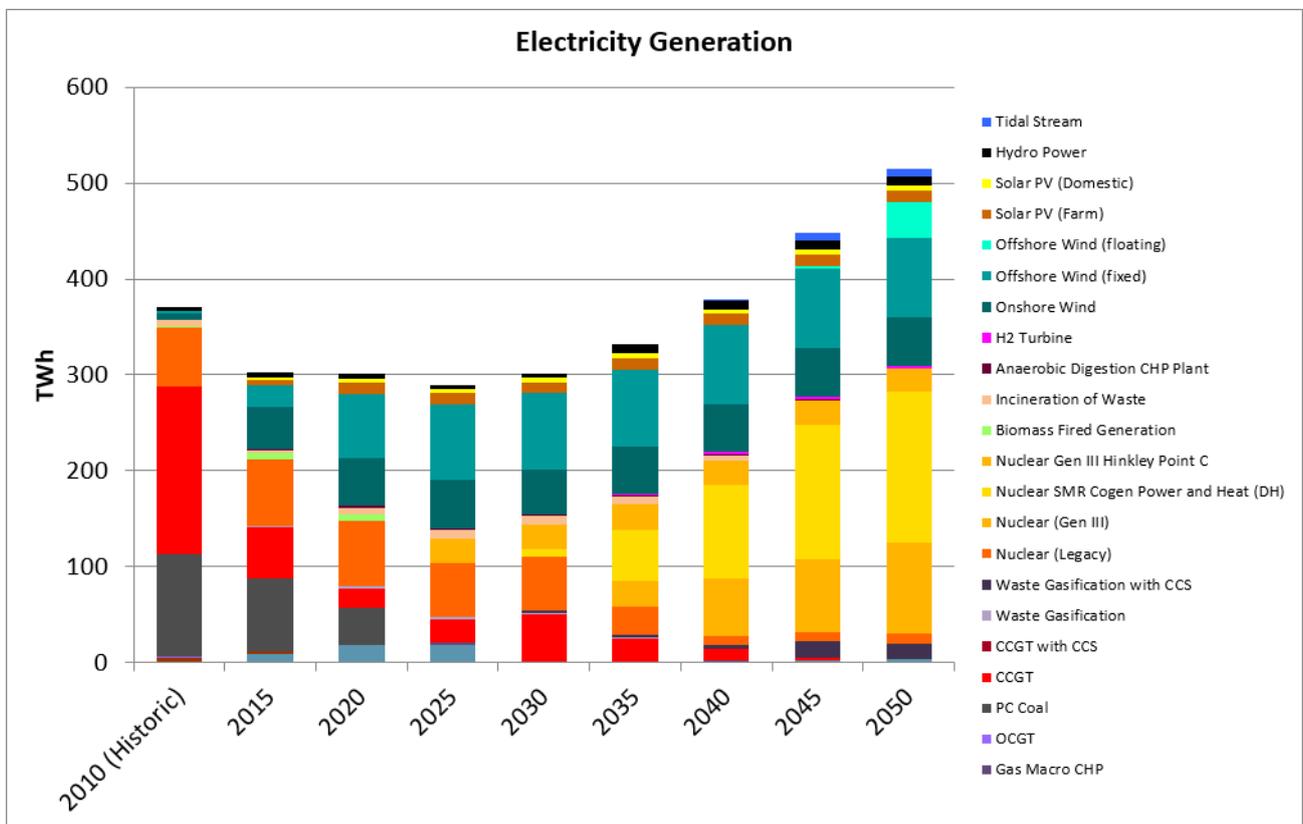Figure A3-23 – Run 310 Electricity Generation Capacity
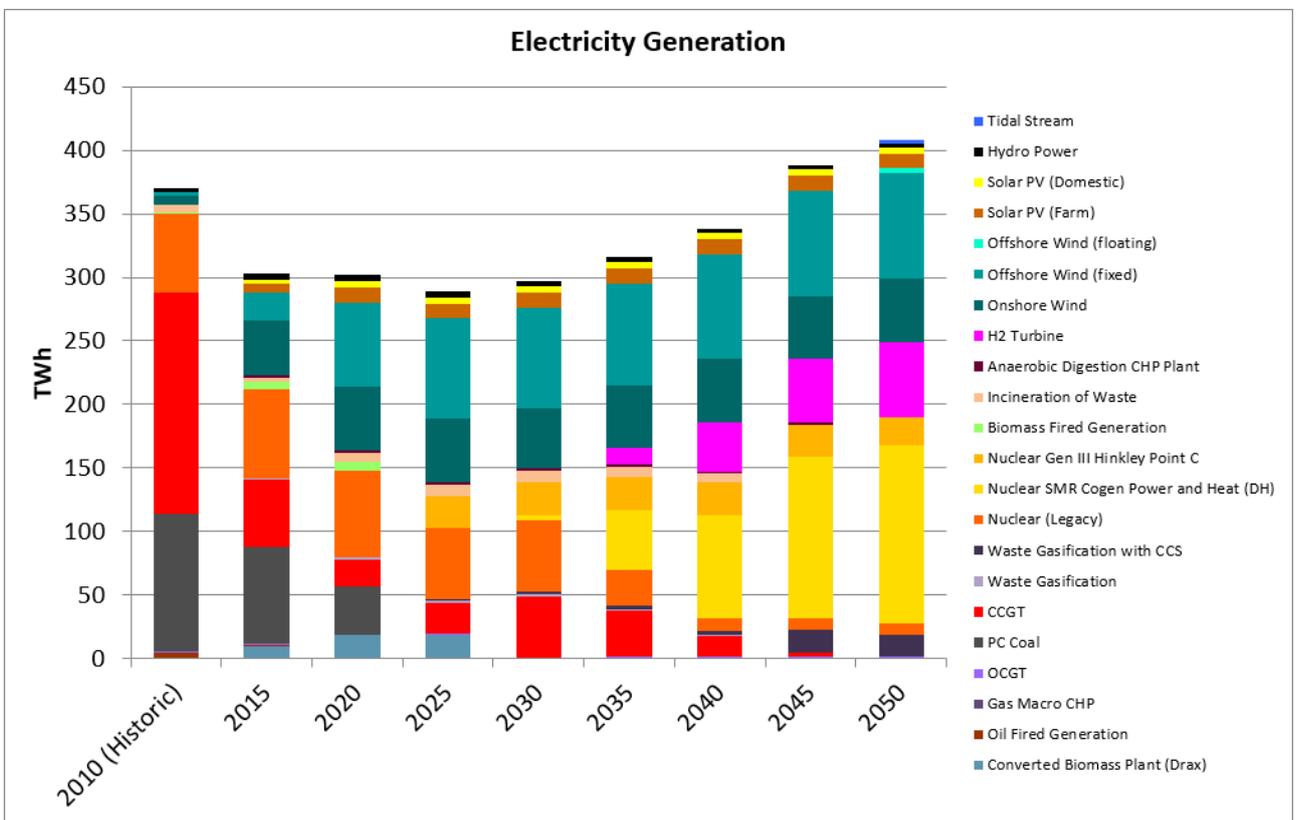
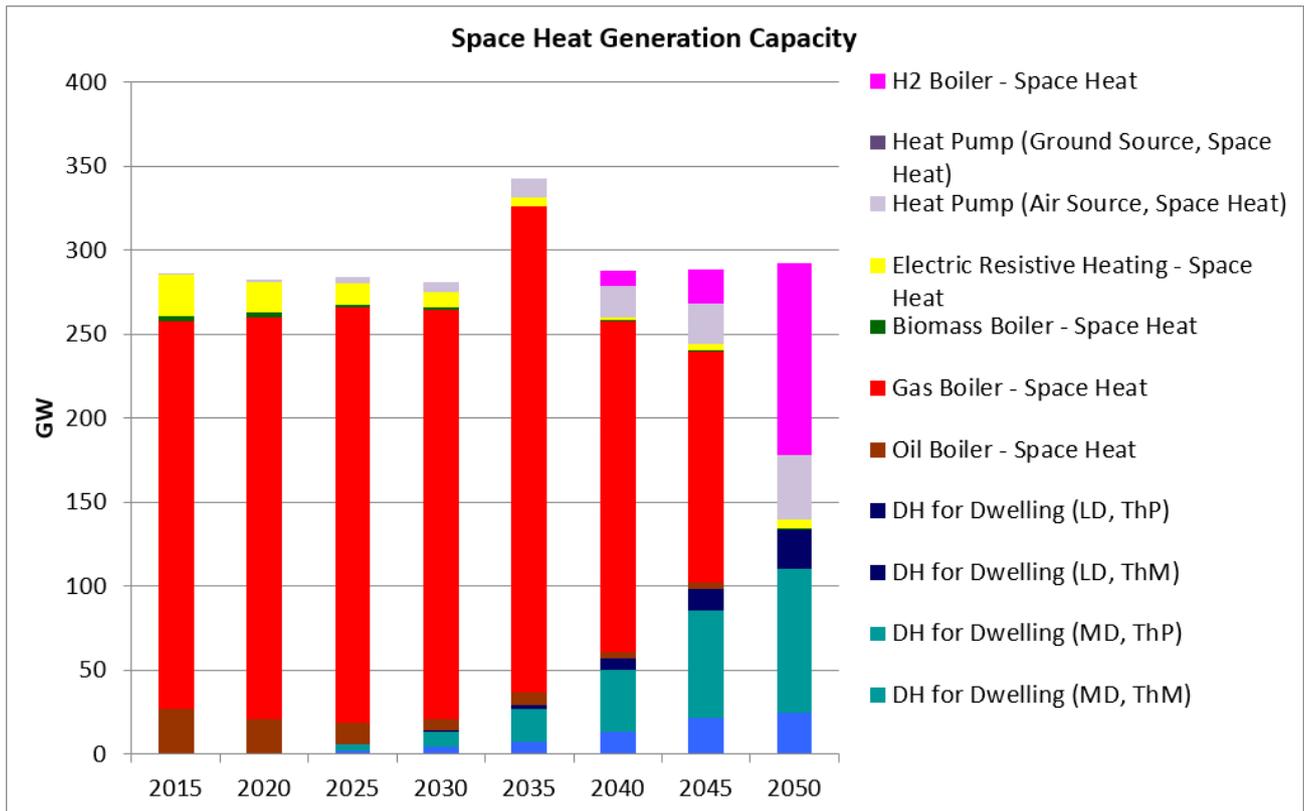Figure A3-24 – Run 310 Electricity Generation
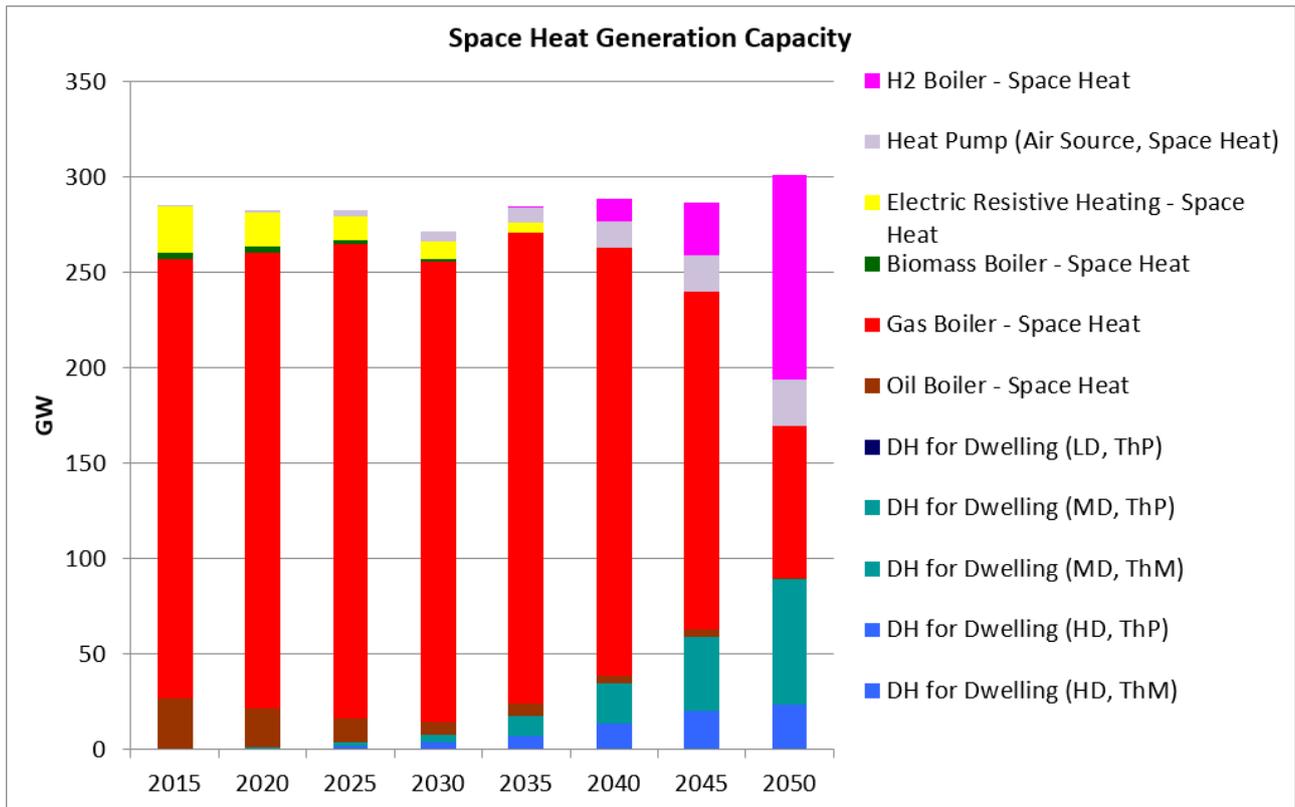
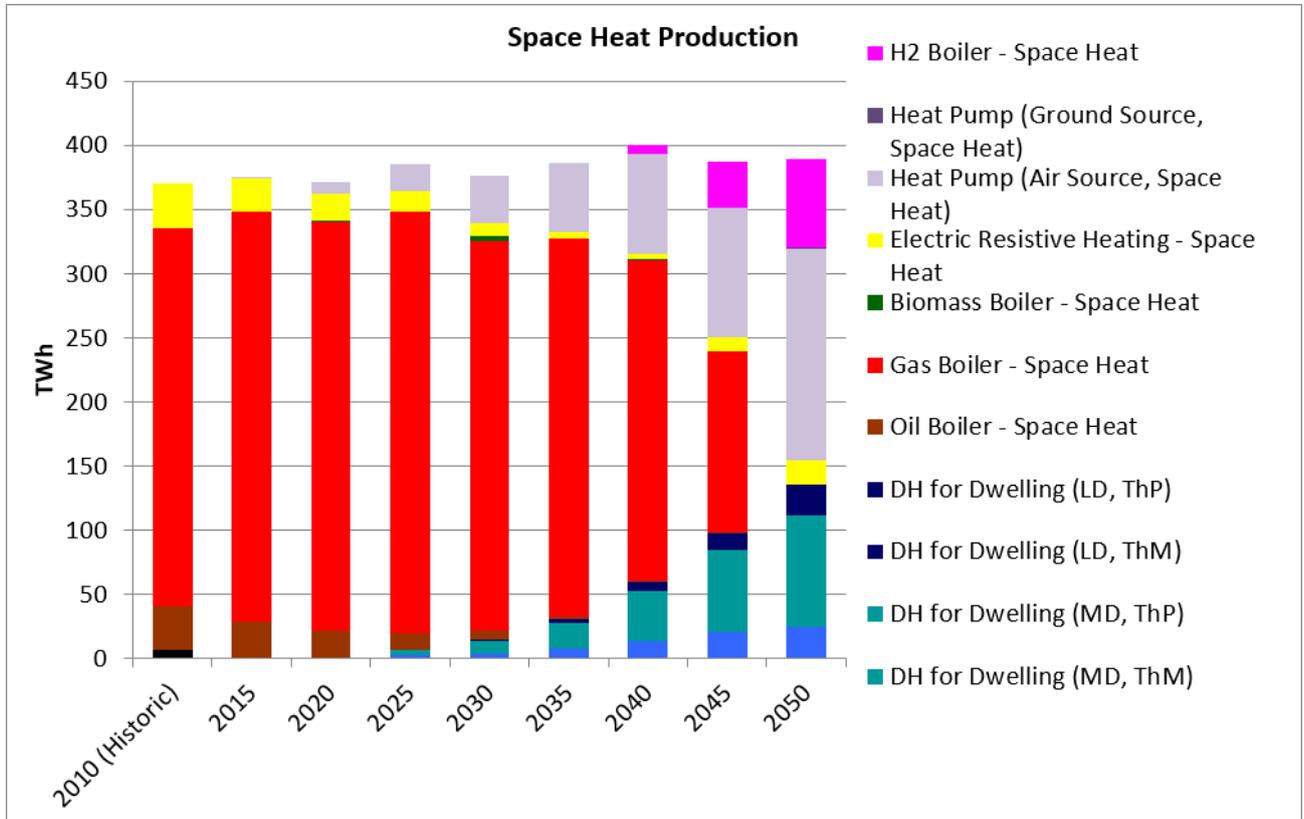Figure A3-25 – Run 310 Space Heat Generation Capacity
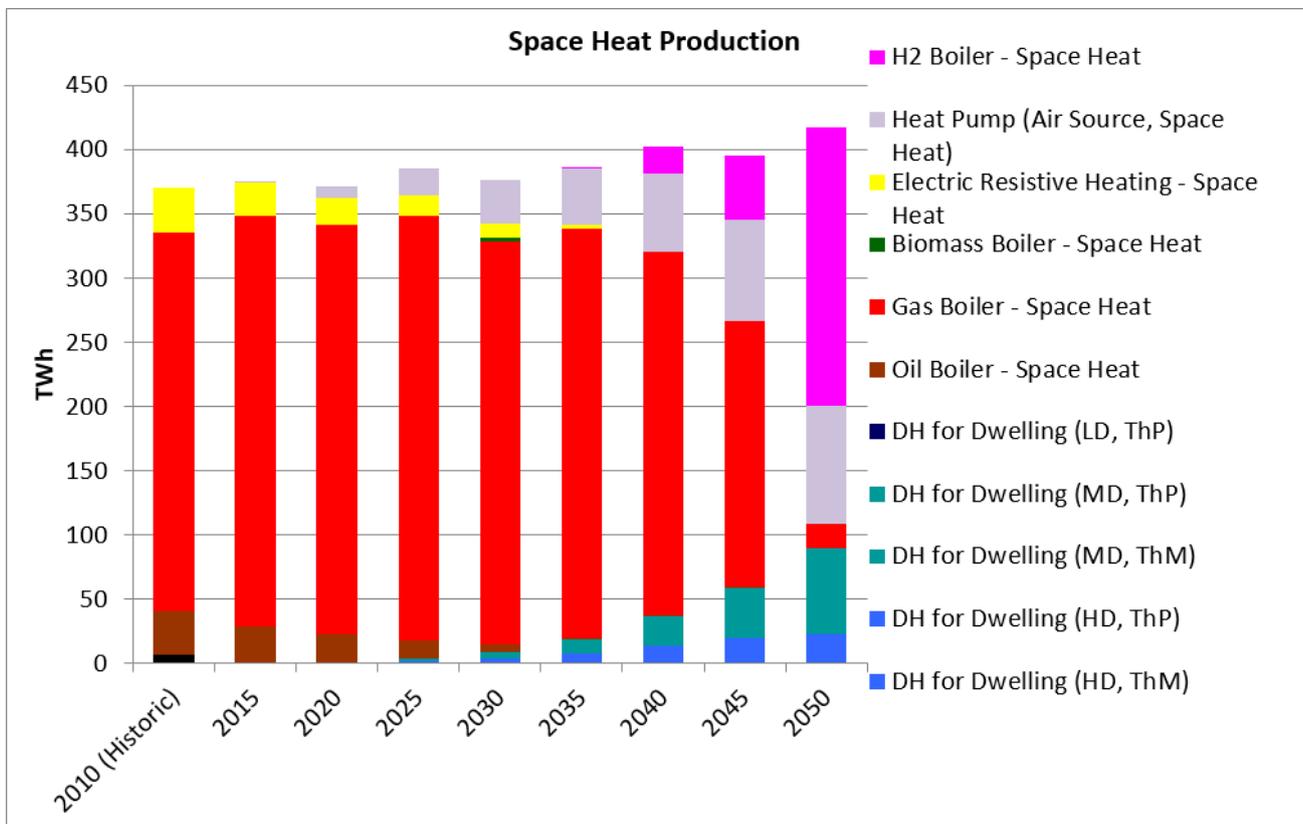
Figure A3-26 – Run 310 Space Heat Production
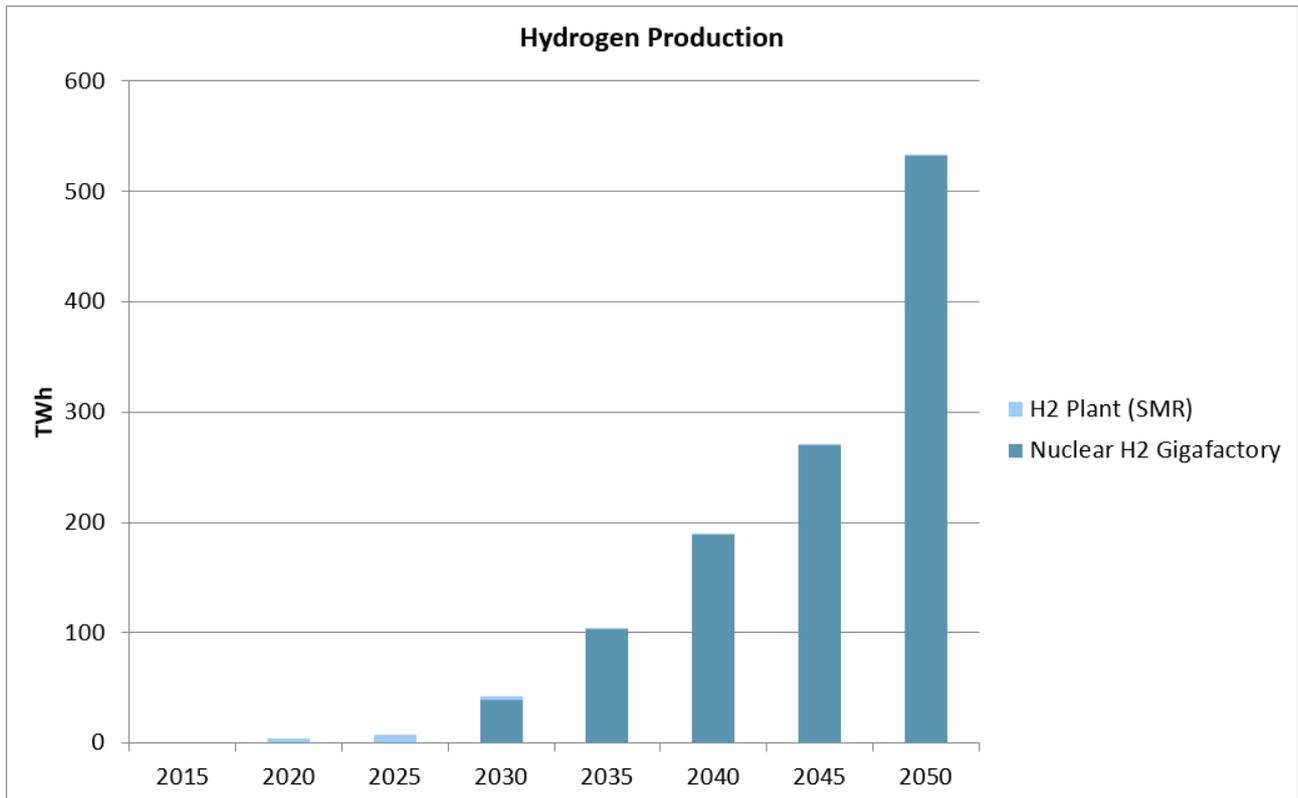
Figure A3-27 – Run 310 Hydrogen Production
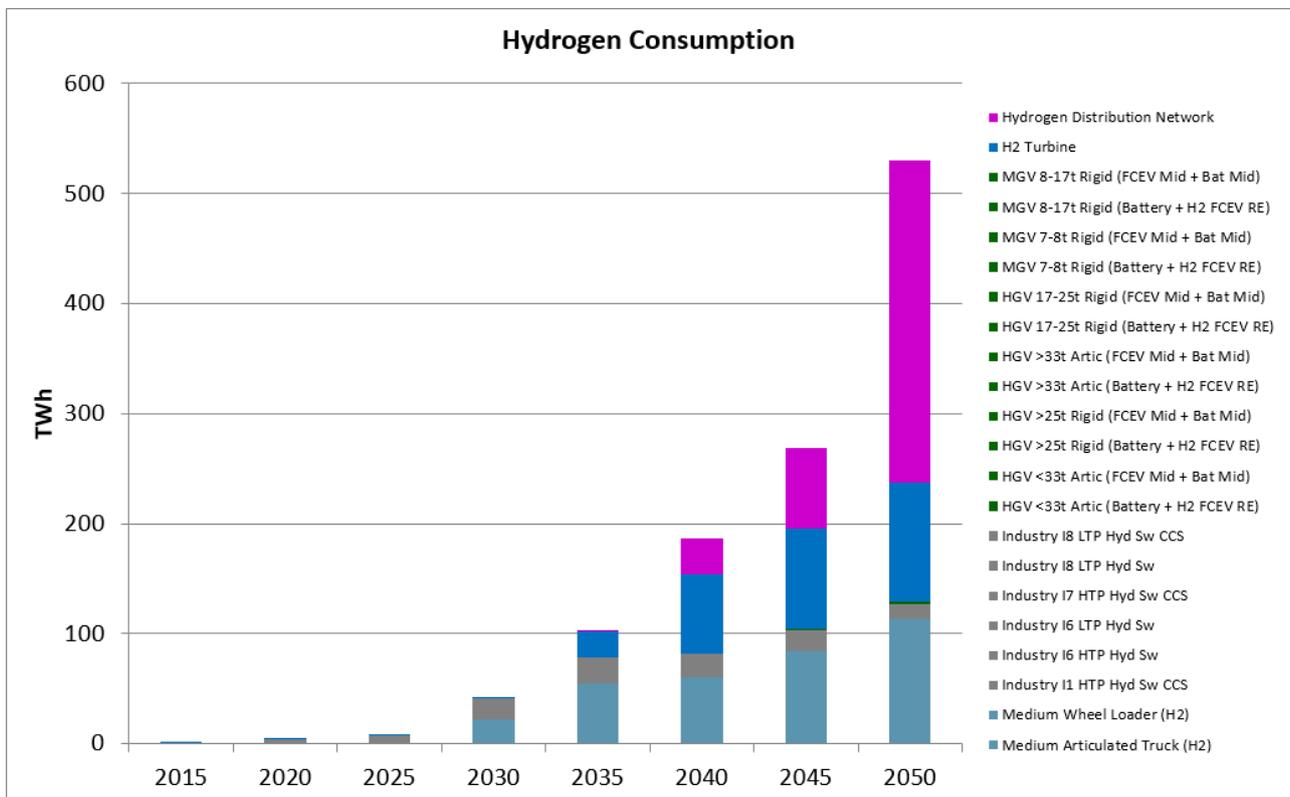
Figure A3-28 – Run 310 Hydrogen consumption
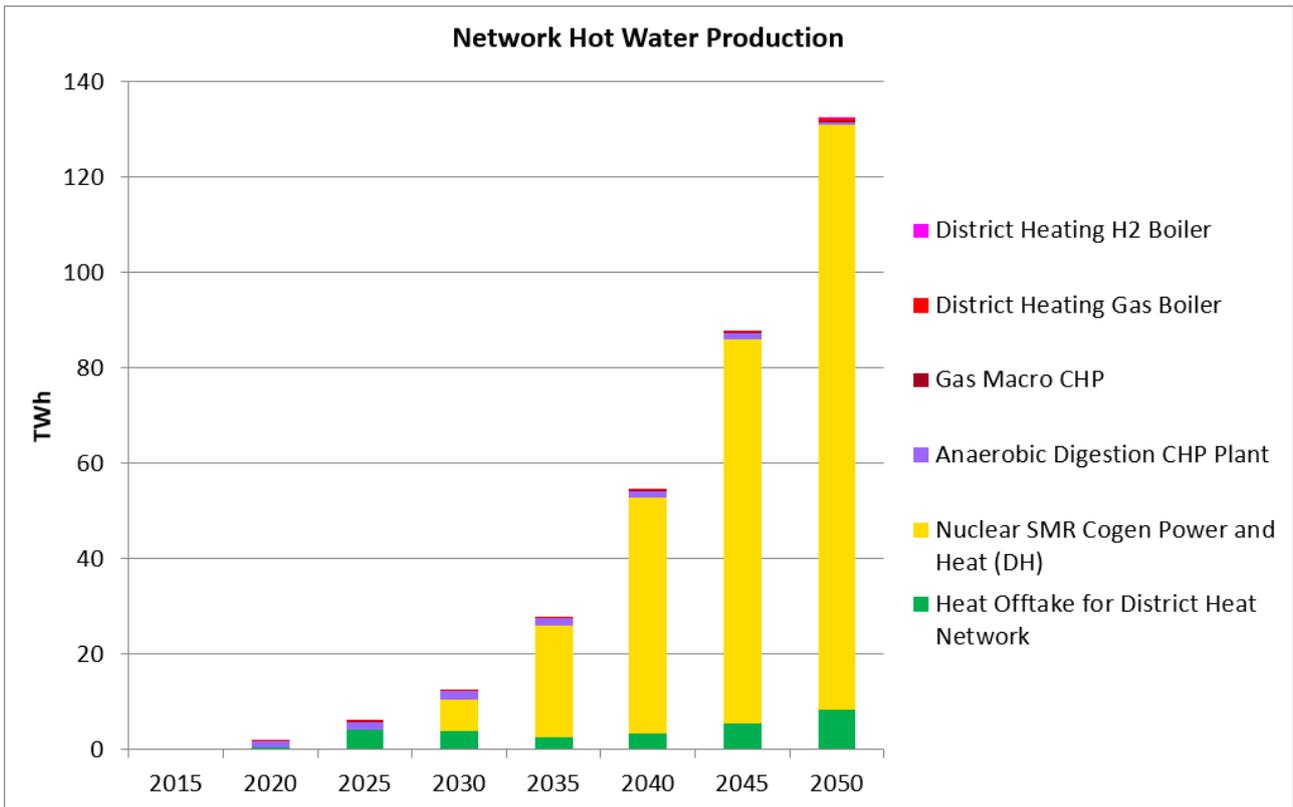
Figure A3-29 – Run 310 Network Hot Water Production
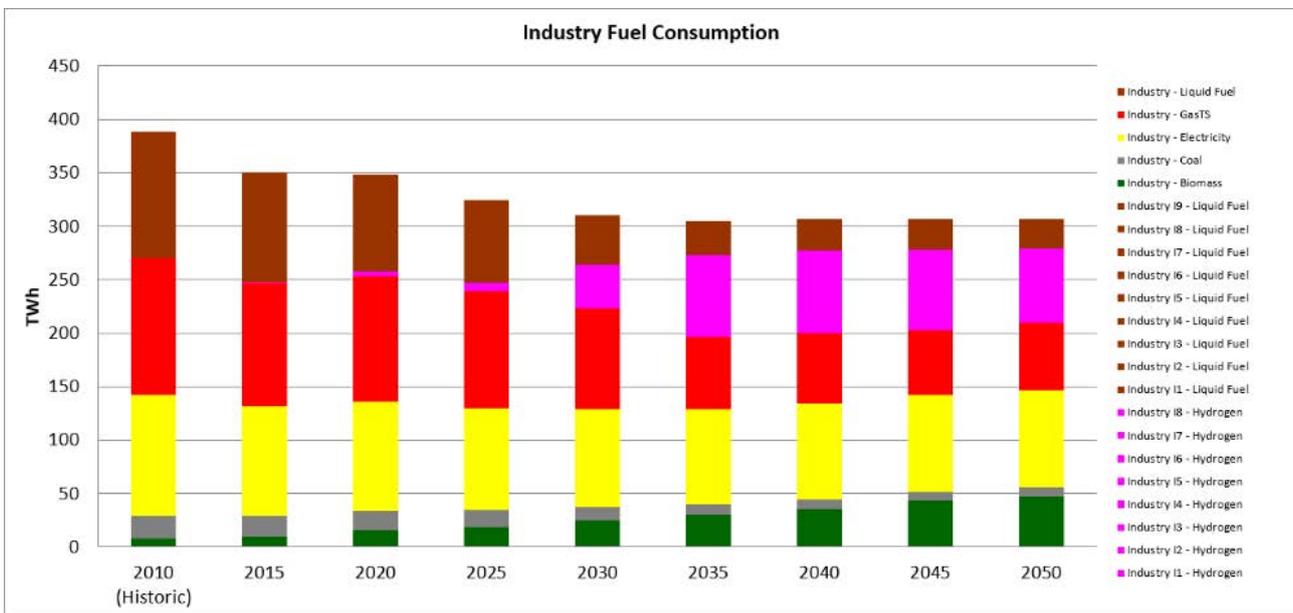
Figure A3-30 – Run 310 Industry Fuel Consumption

Run 311 BOB100 – Gen III+, LWSMR cogen, gigafactory and synthetic fuel plant; all nuclear technologies; base case data
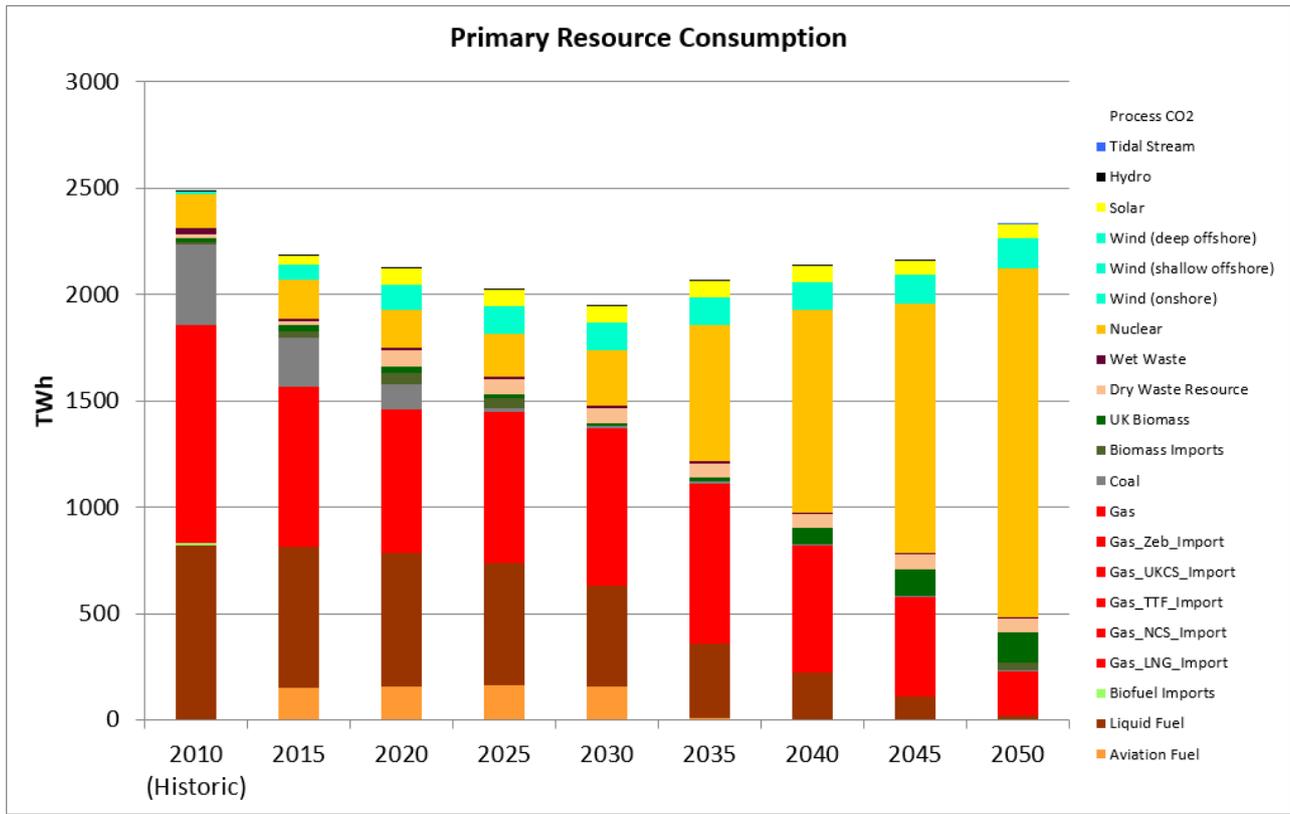
Figure A3-31 – Run 311 Primary Resource Consumption
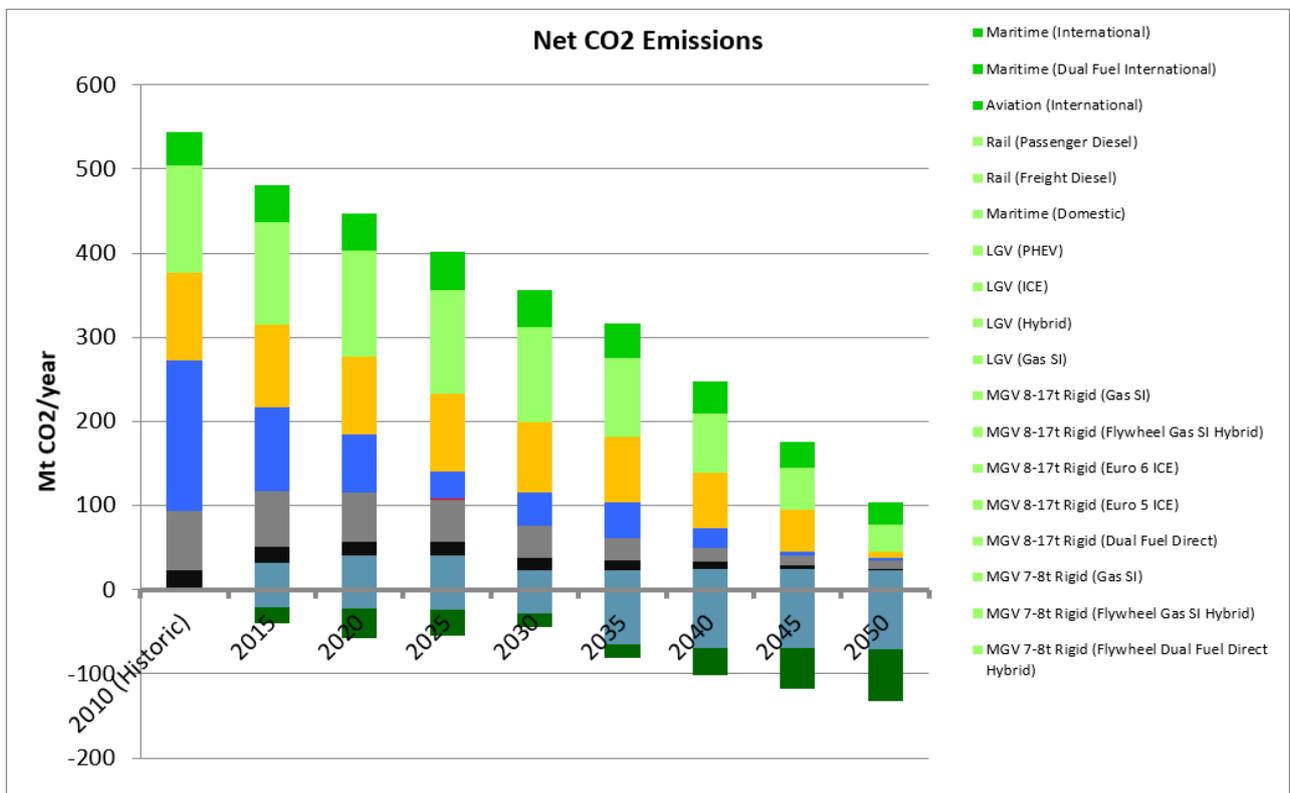
Figure A3-32 – Run 311 Net CO₂ Emissions
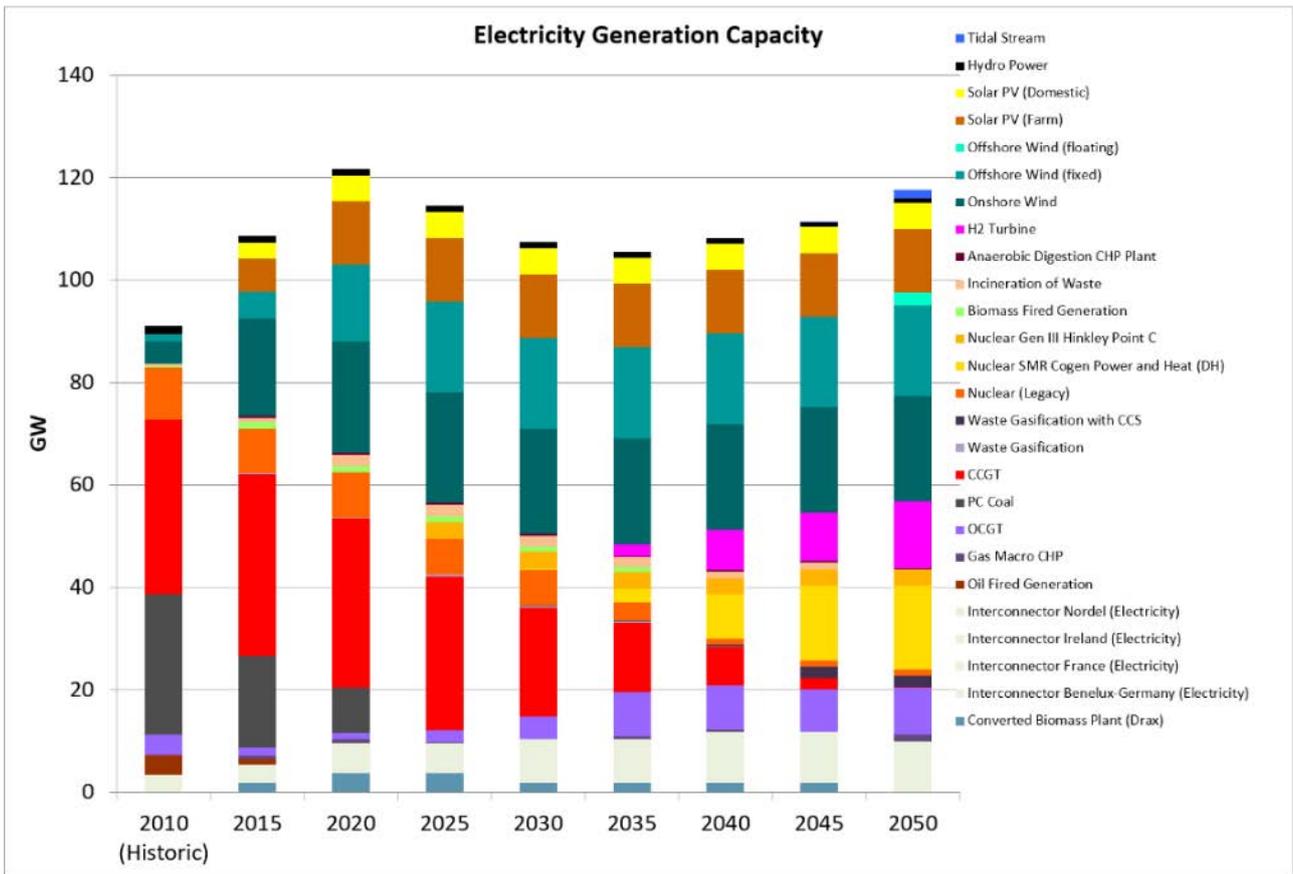
Figure A3-33 – Run 311 Electricity Generation Capacity
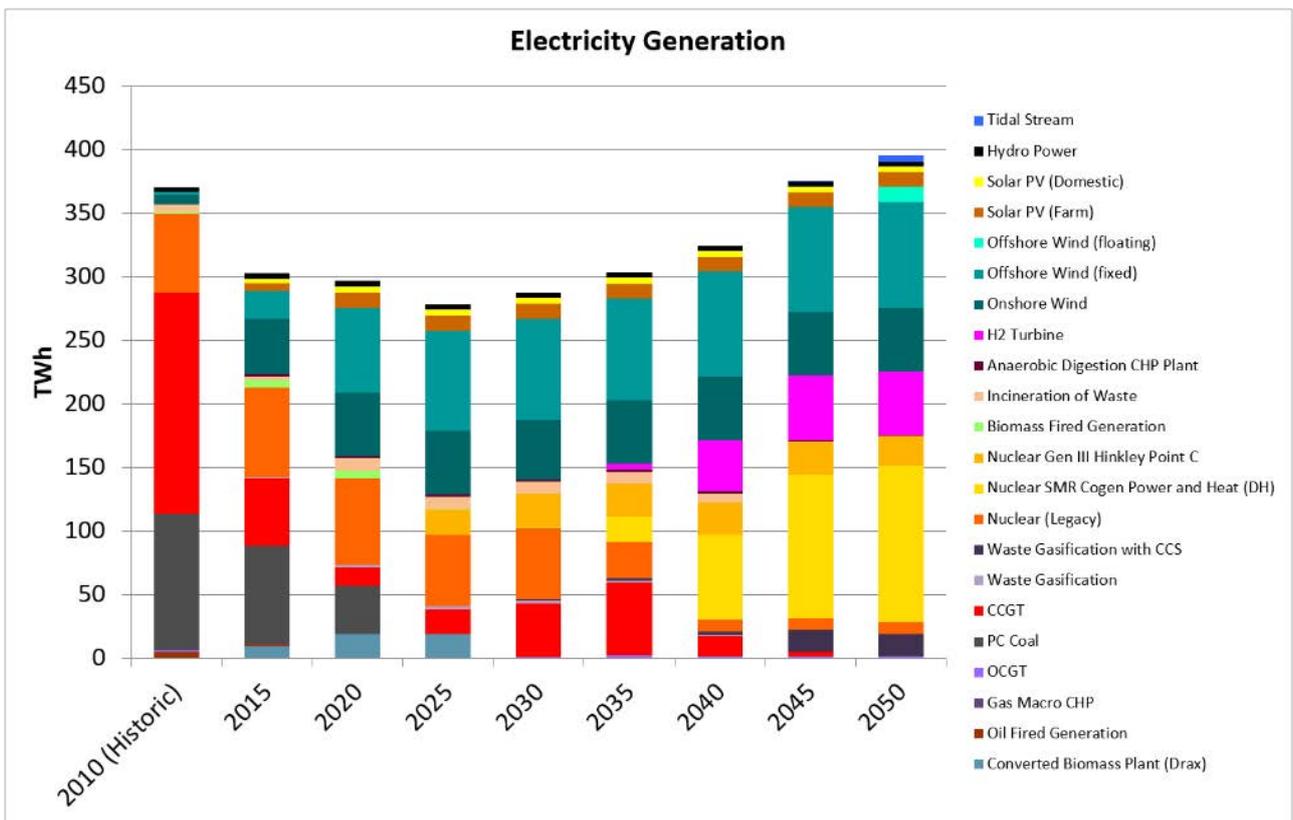
Figure A3-34 – Run 311 Electricity Generation
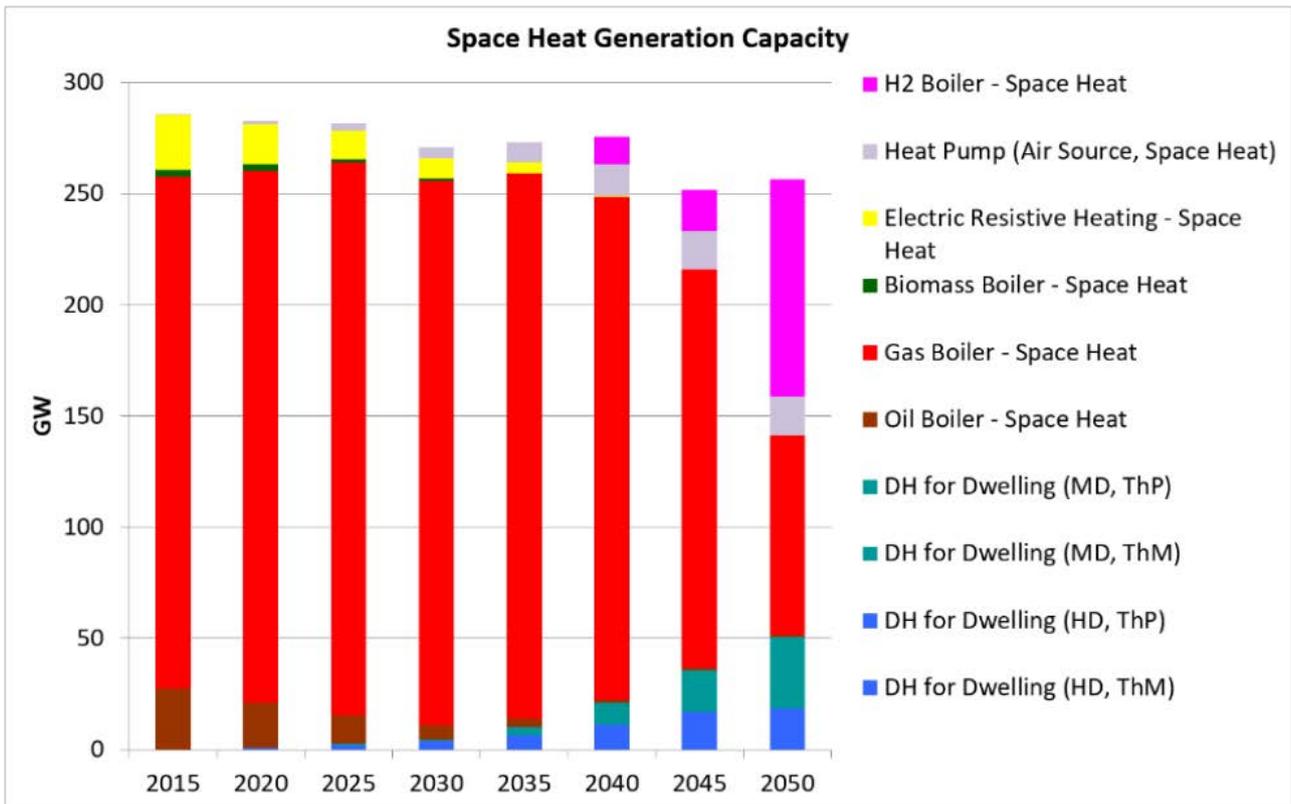
Figure A3-35 – Run 311 Space Heat Generation Capacity
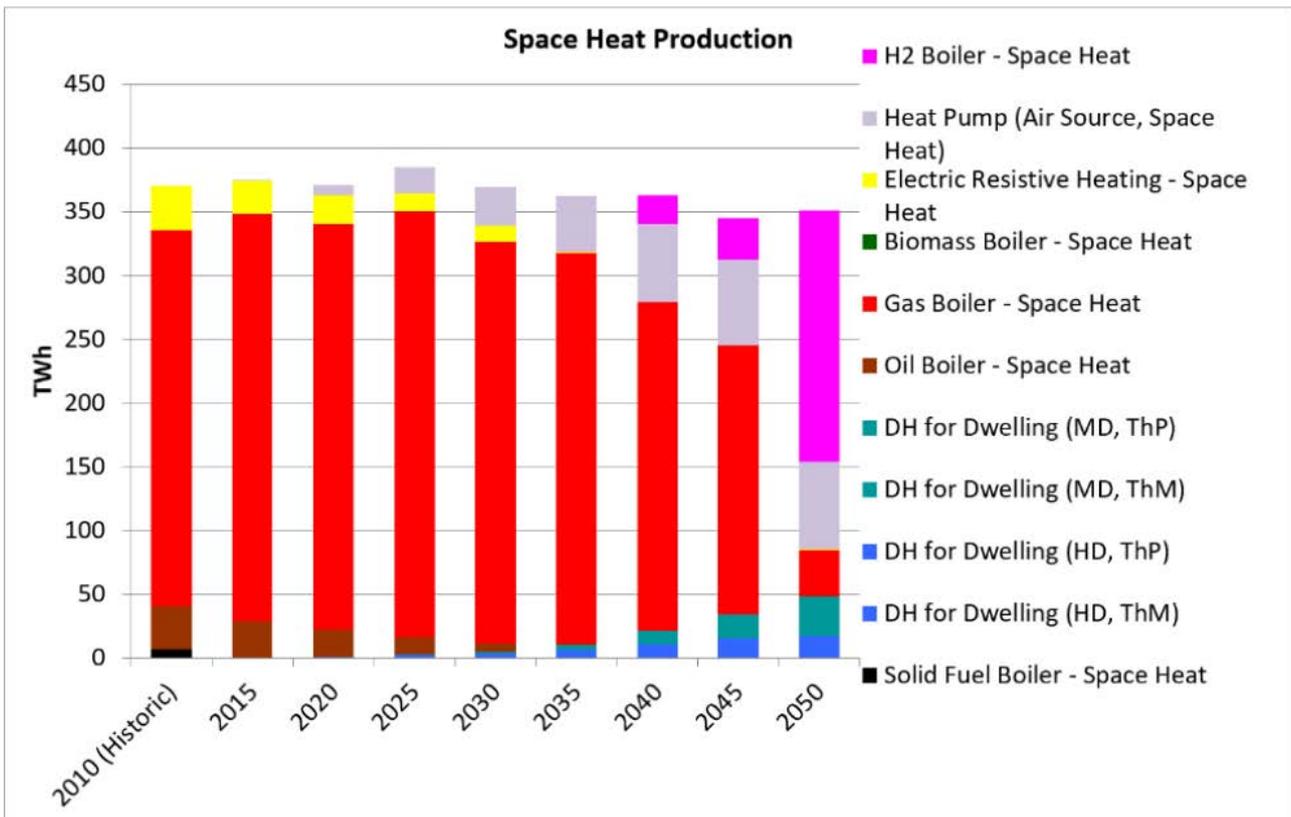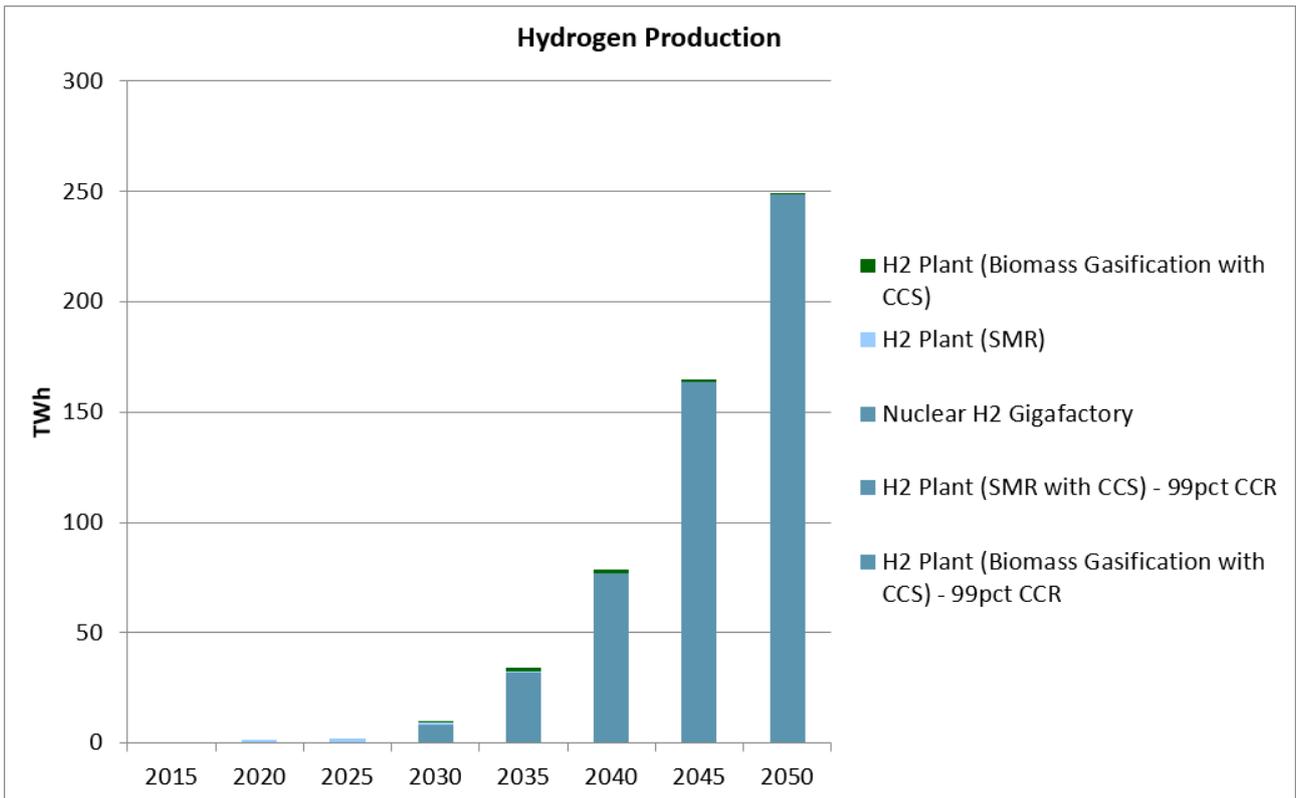

Figure A3-36 – Run 311 Space Heat Production
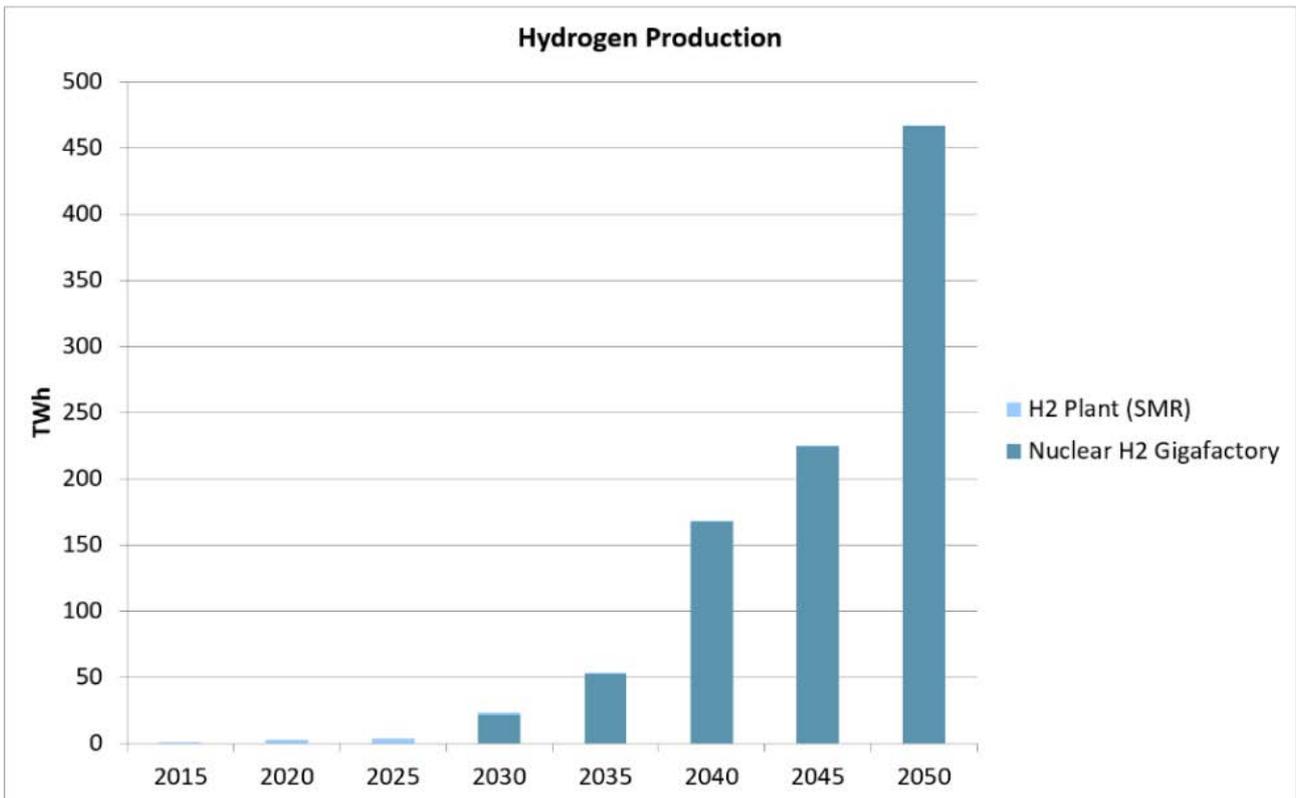
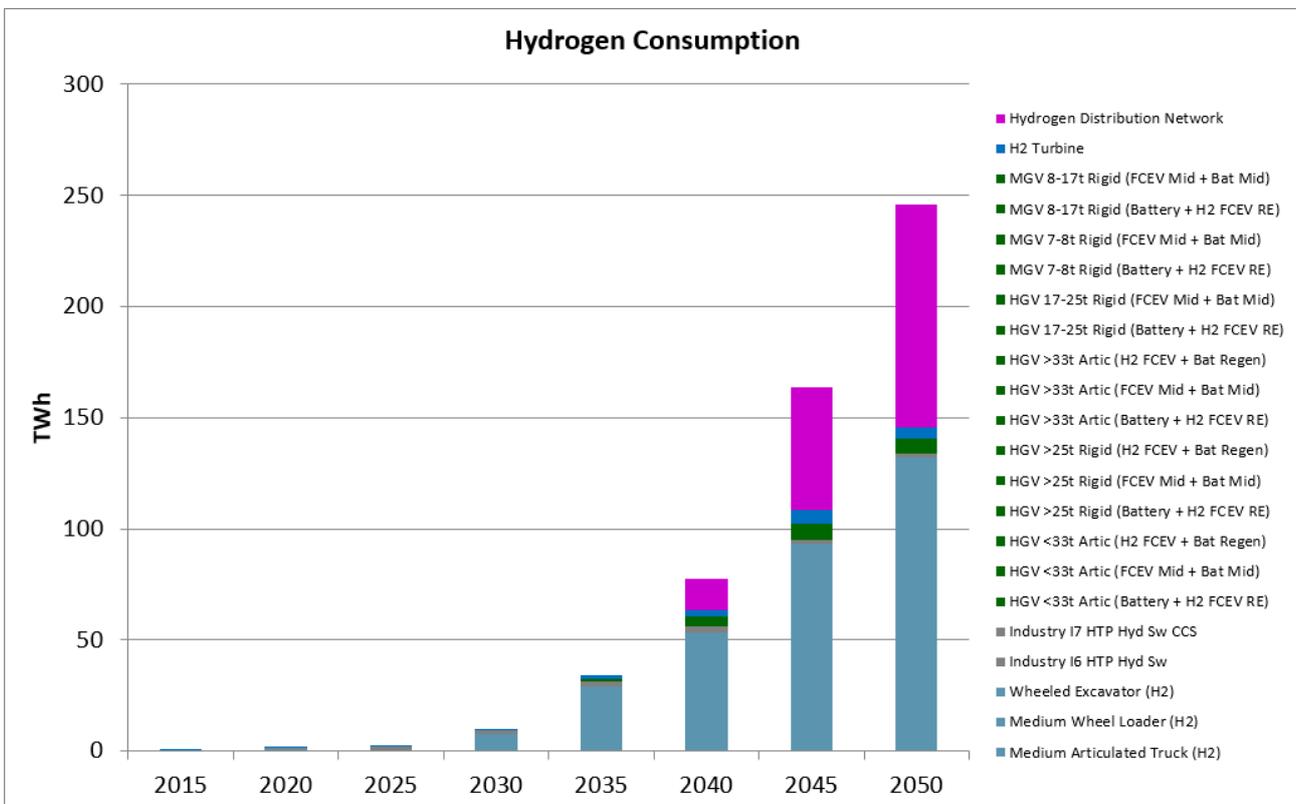Figure A3-37 – Run 311 Hydrogen Production
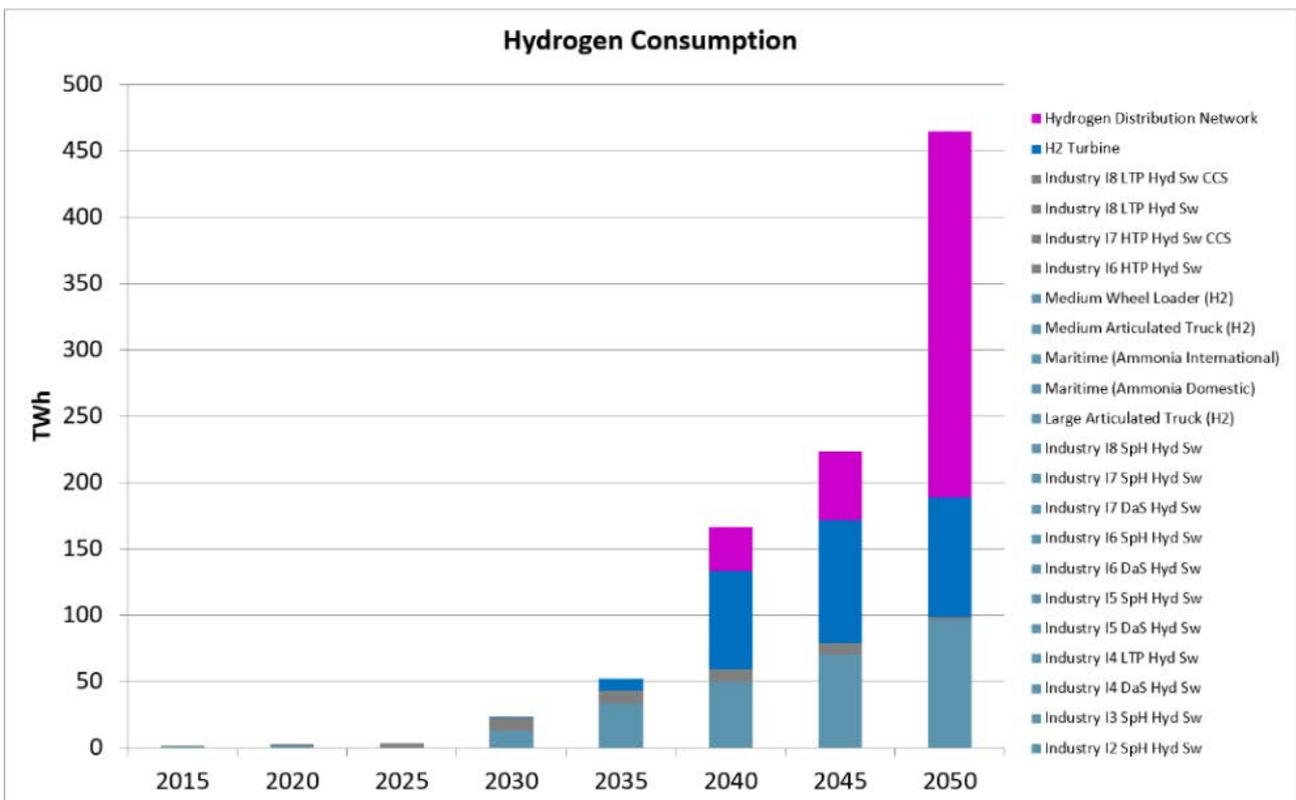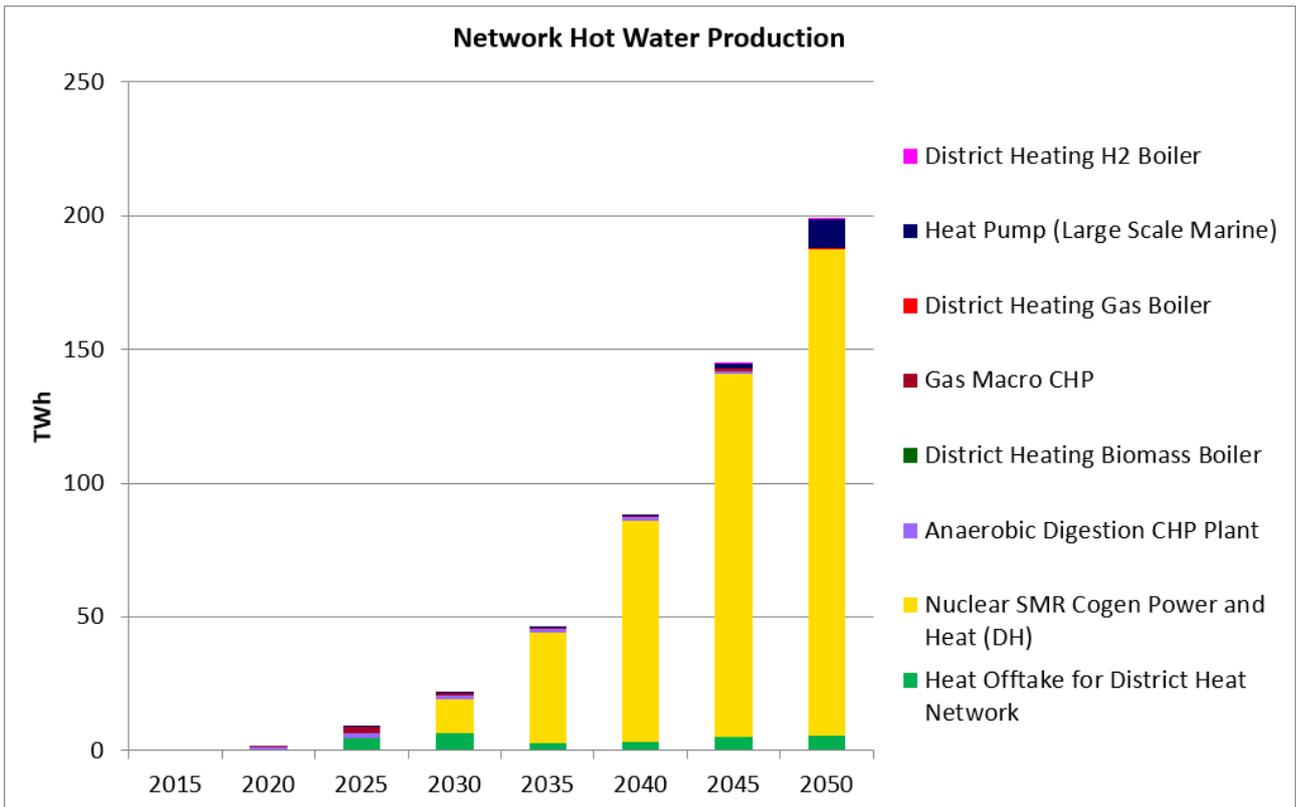

Figure A3-38 – Run 311 Hydrogen consumption
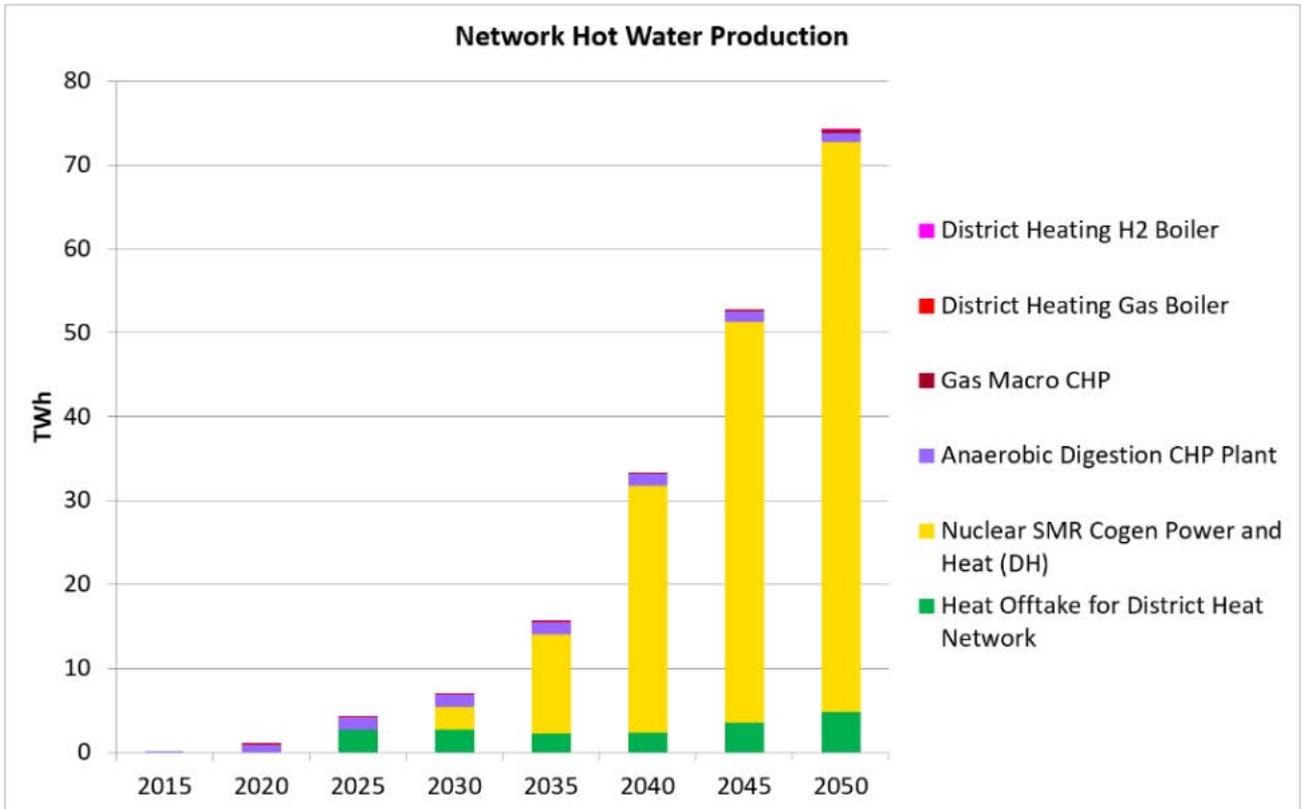
Figure A3-39 – Run 311 Network Hot Water Production
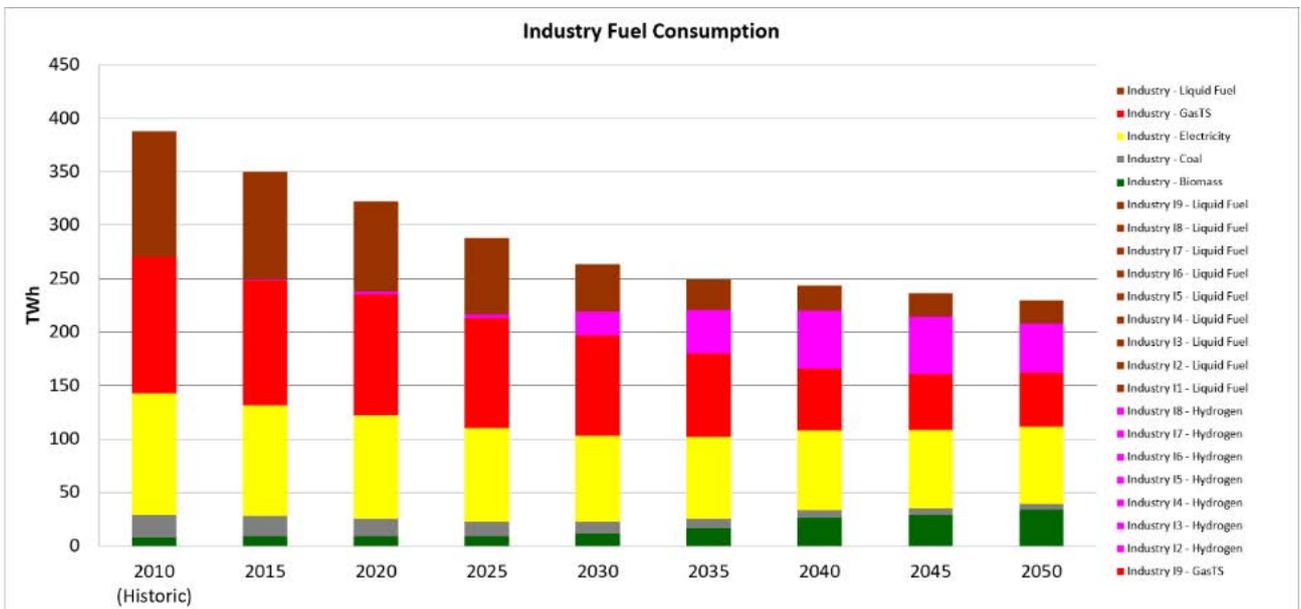
Figure A3-40 – Run 311 Industry Fuel Consumption

Run 312 FA96 – Gen III+, LWSMR cogen, gigafactory and synthetic fuel plant; all nuclear technologies; base case data
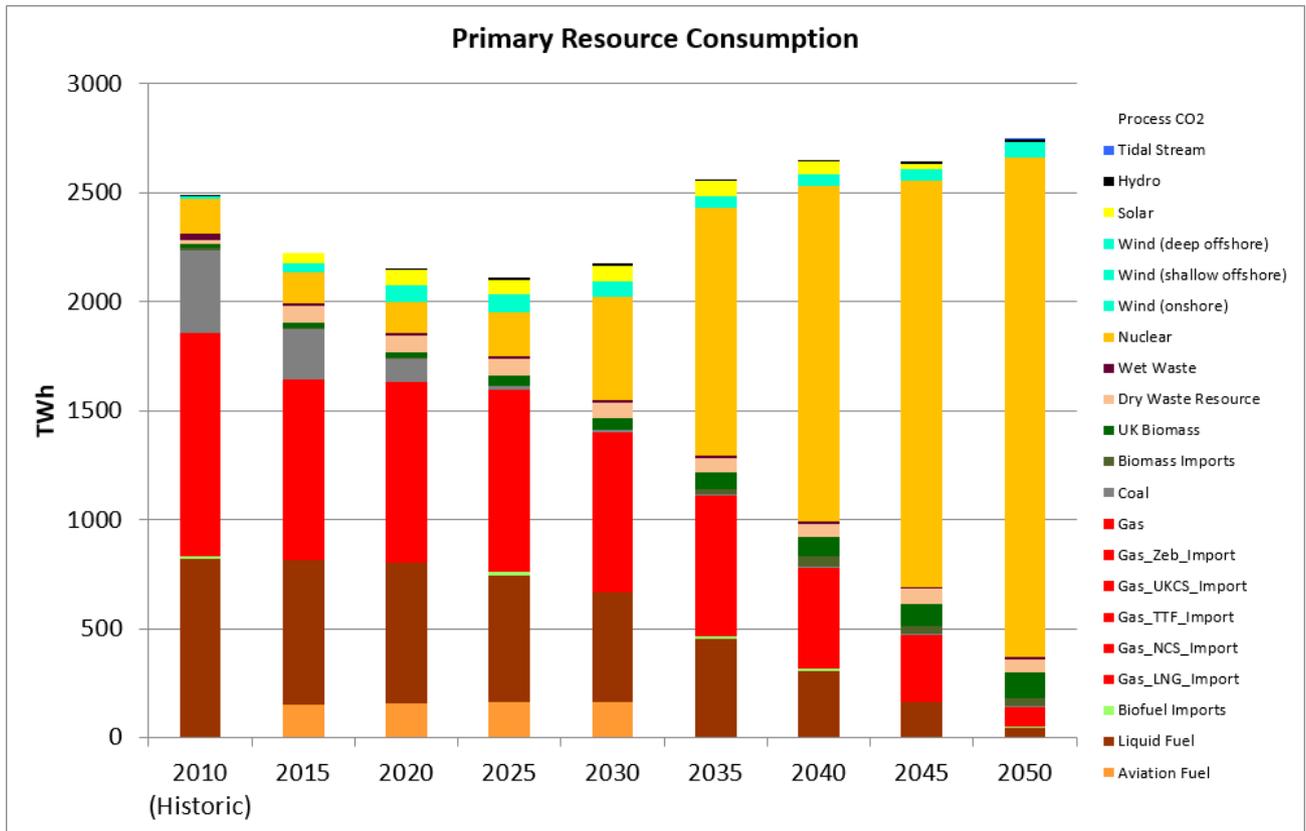
Figure A3-41 – Run 312 Primary Resource Consumption
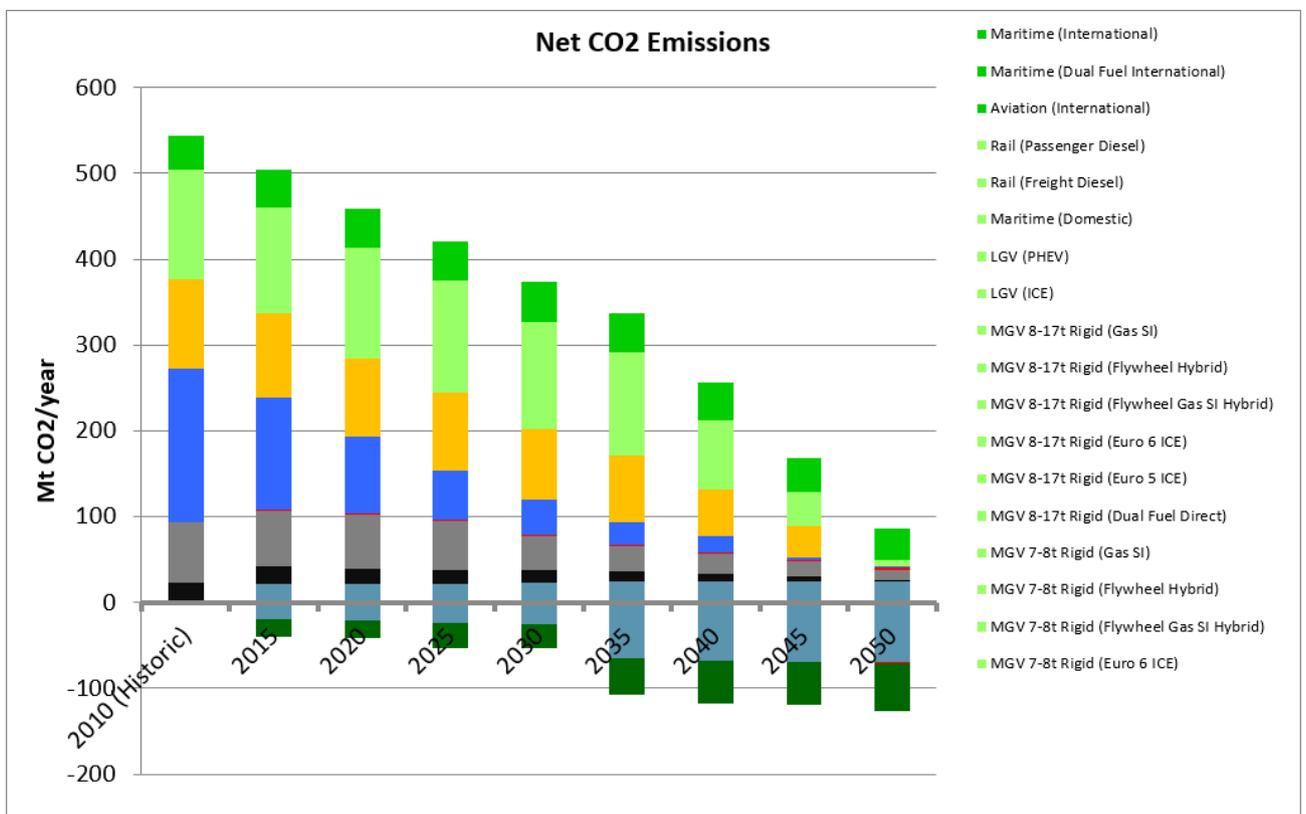
Figure A3-42 – Run 312 Net CO$_2$ Emissions
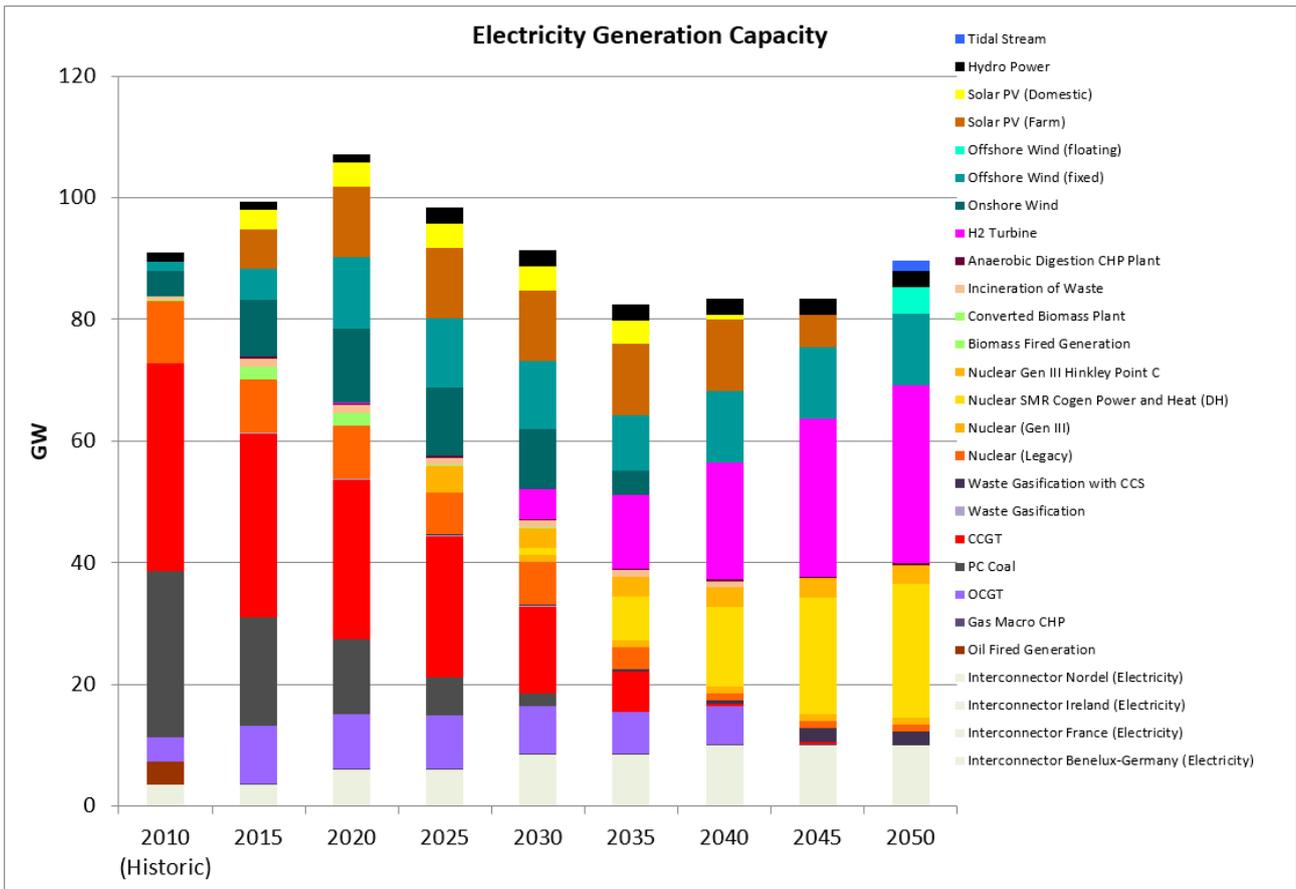
Figure A3-43 – Run 312 Electricity Generation Capacity
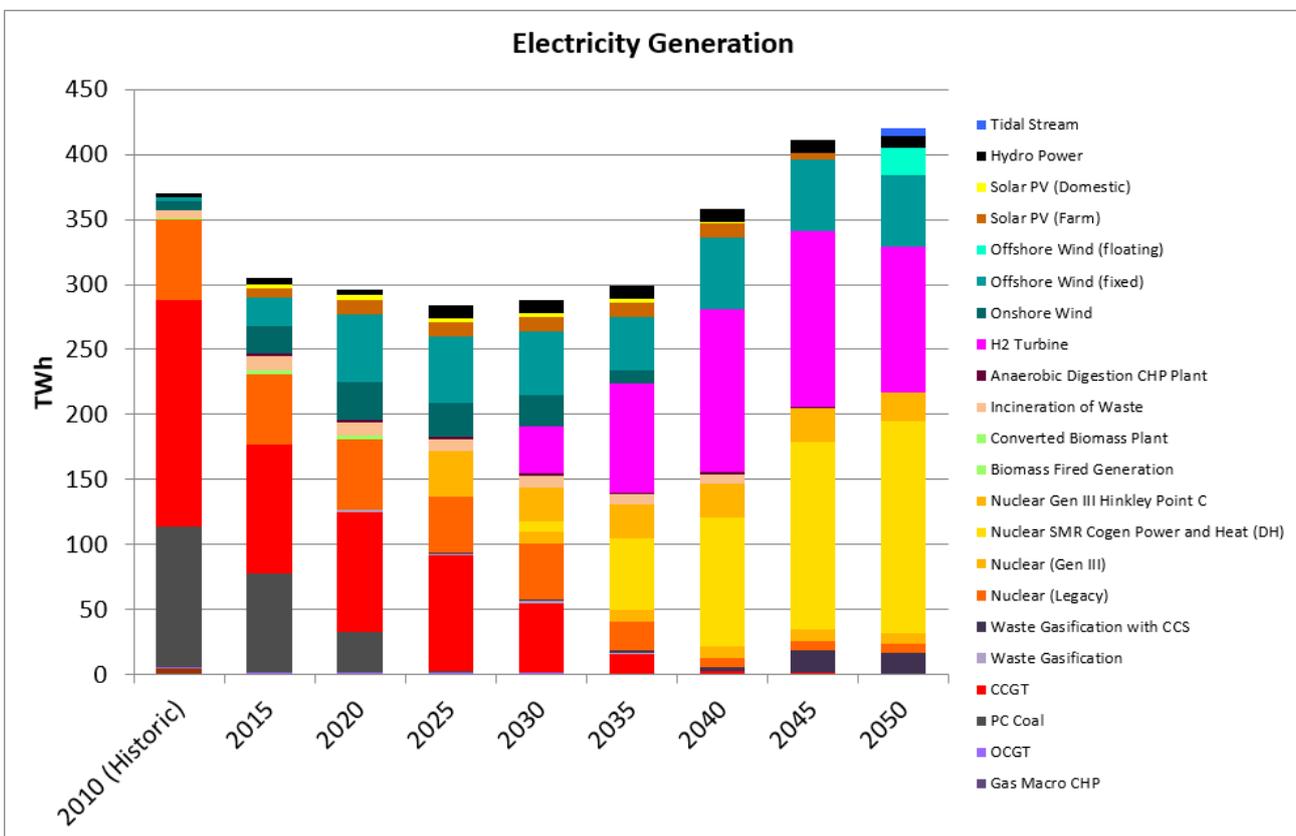
Figure A3-44 – Run 312 Electricity Generation
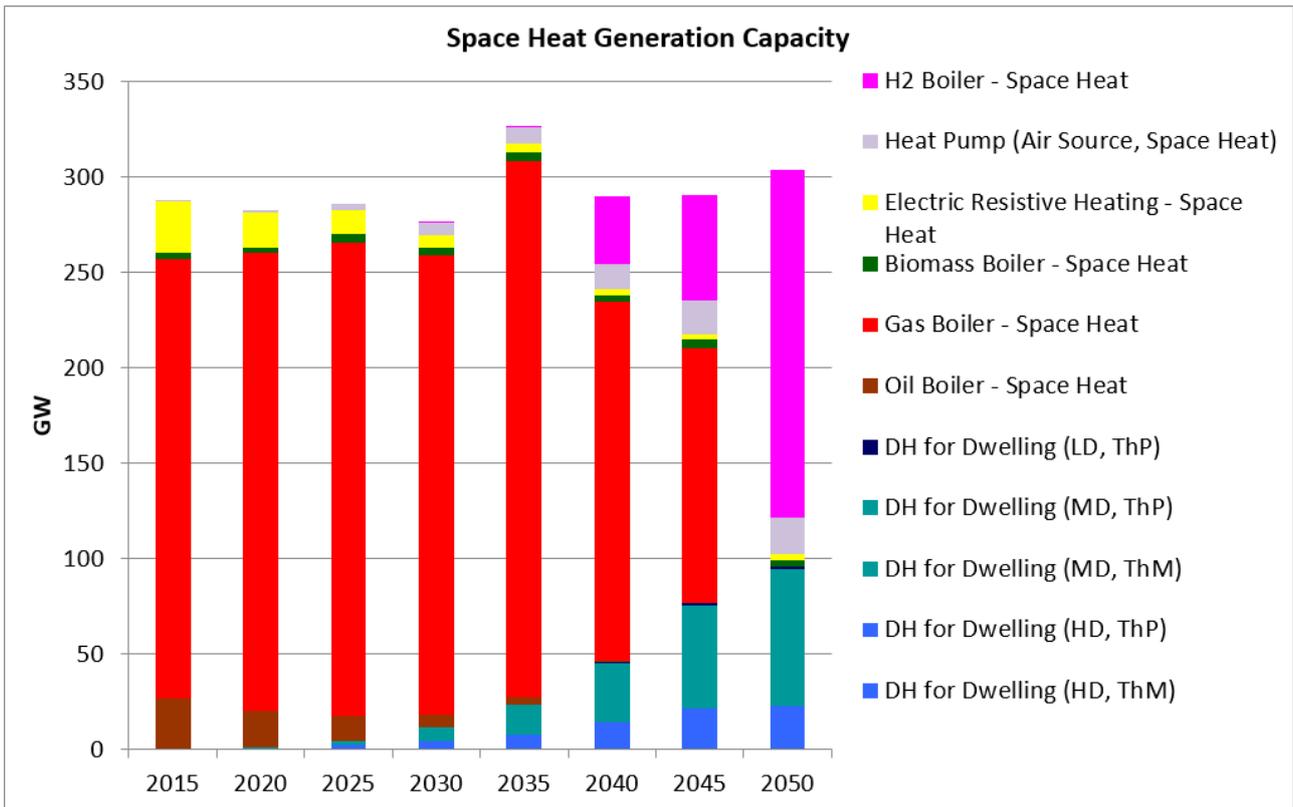
Figure A3-45 – Run 312 Space Heat Generation Capacity
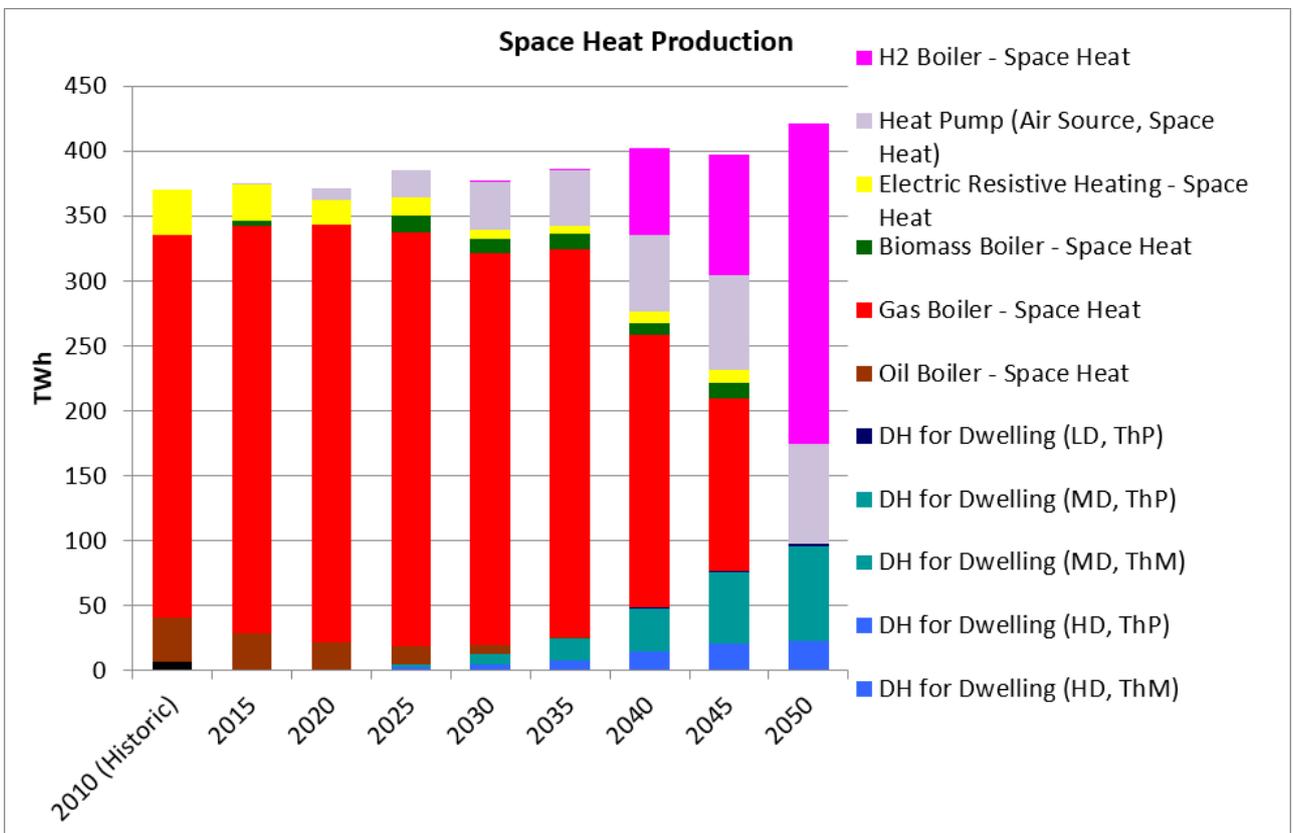
Figure A3-46 – Run 312 Space Heat Production
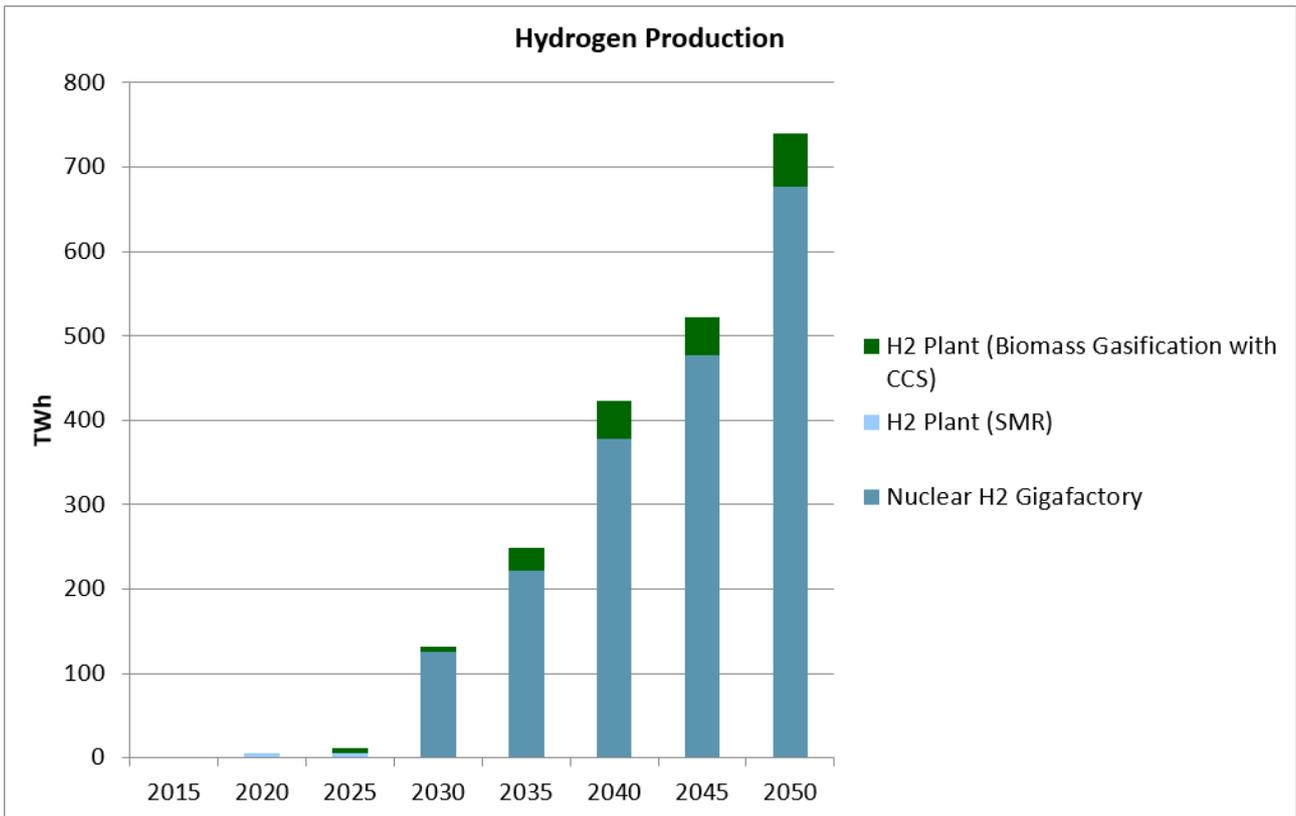
Figure A3-47 – Run 312 Hydrogen Production
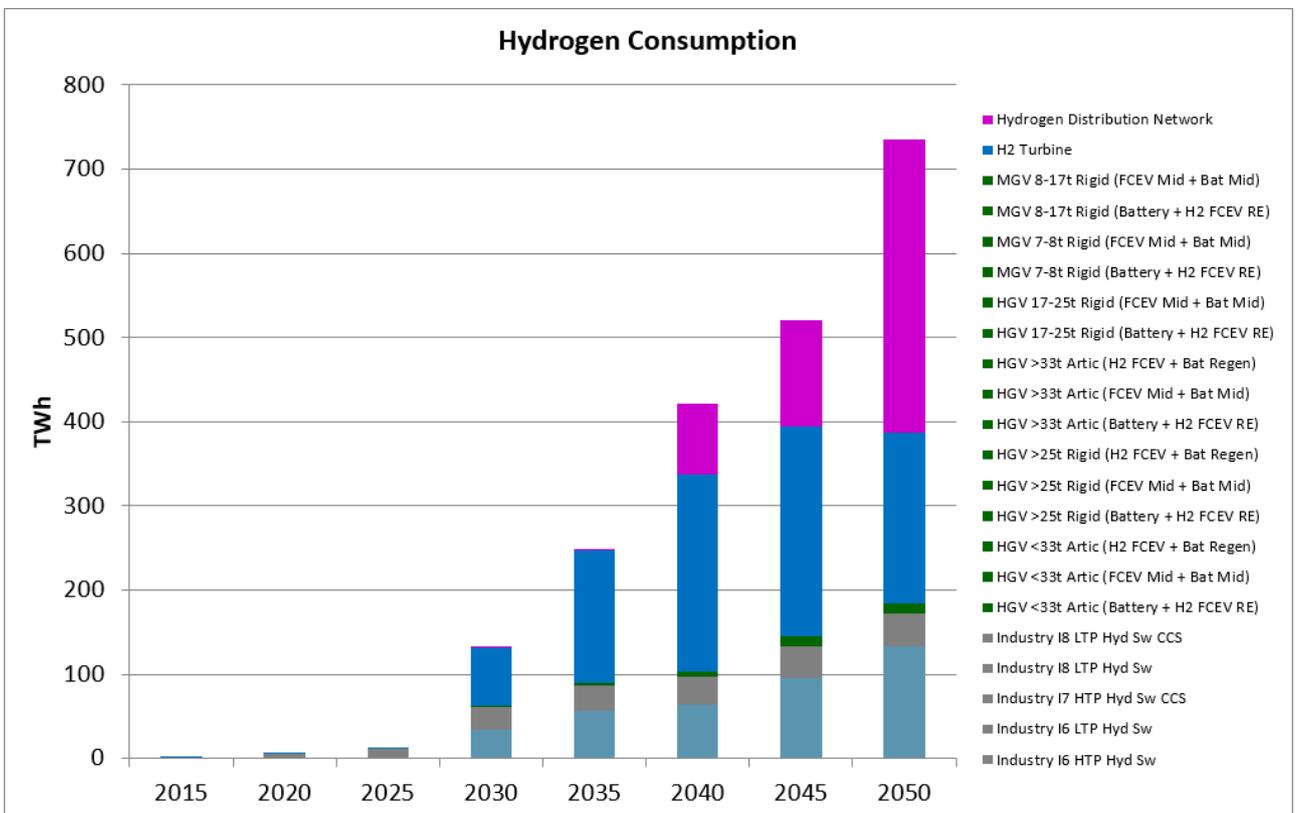
Figure A3-48 – Run 312 Hydrogen consumption
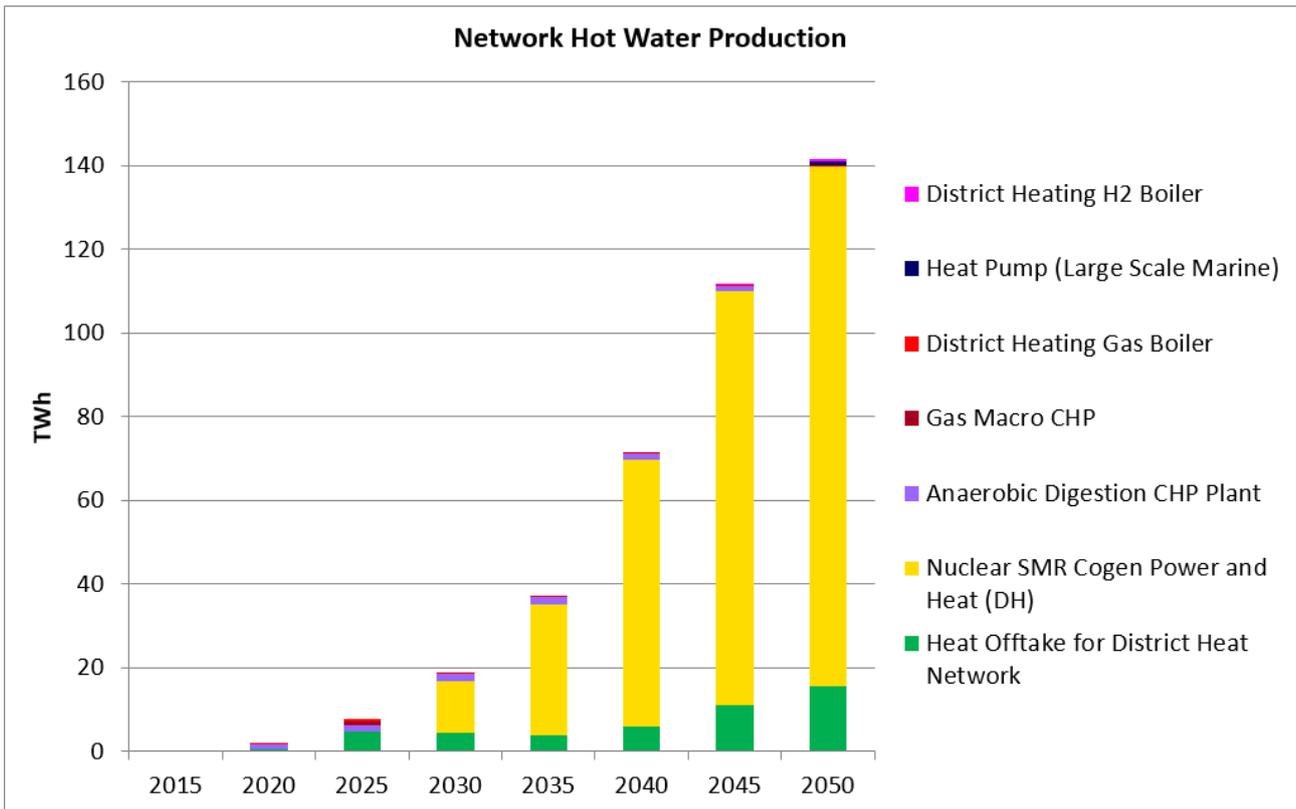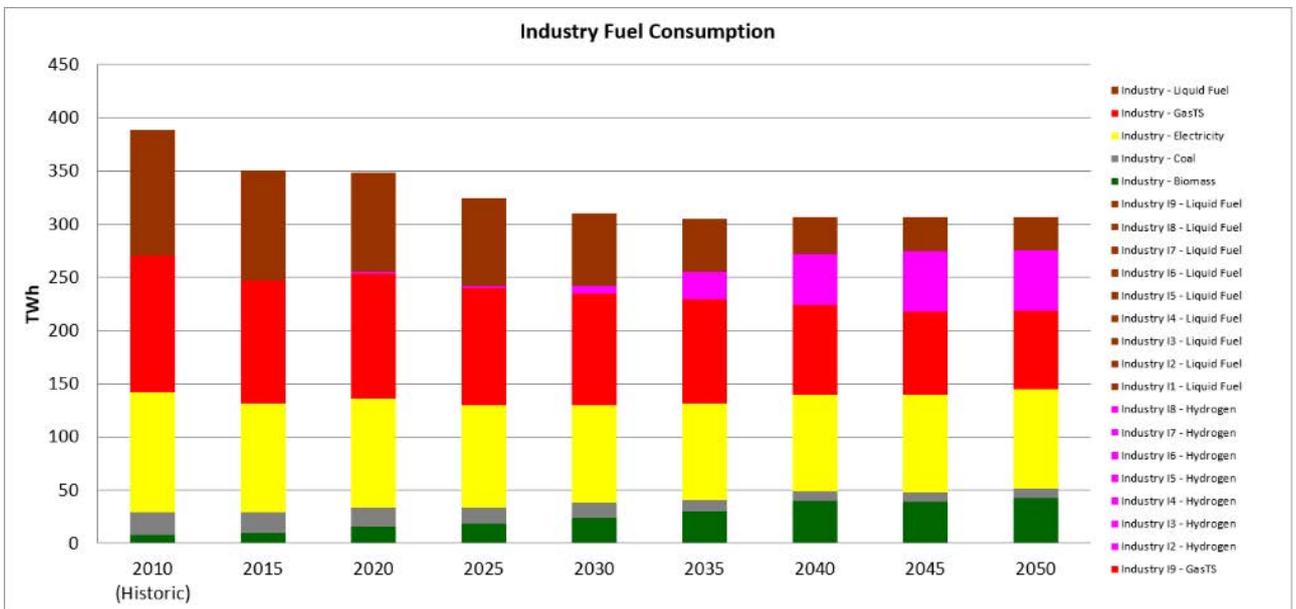
Figure A3-49 – Run 312 Network Hot Water Production
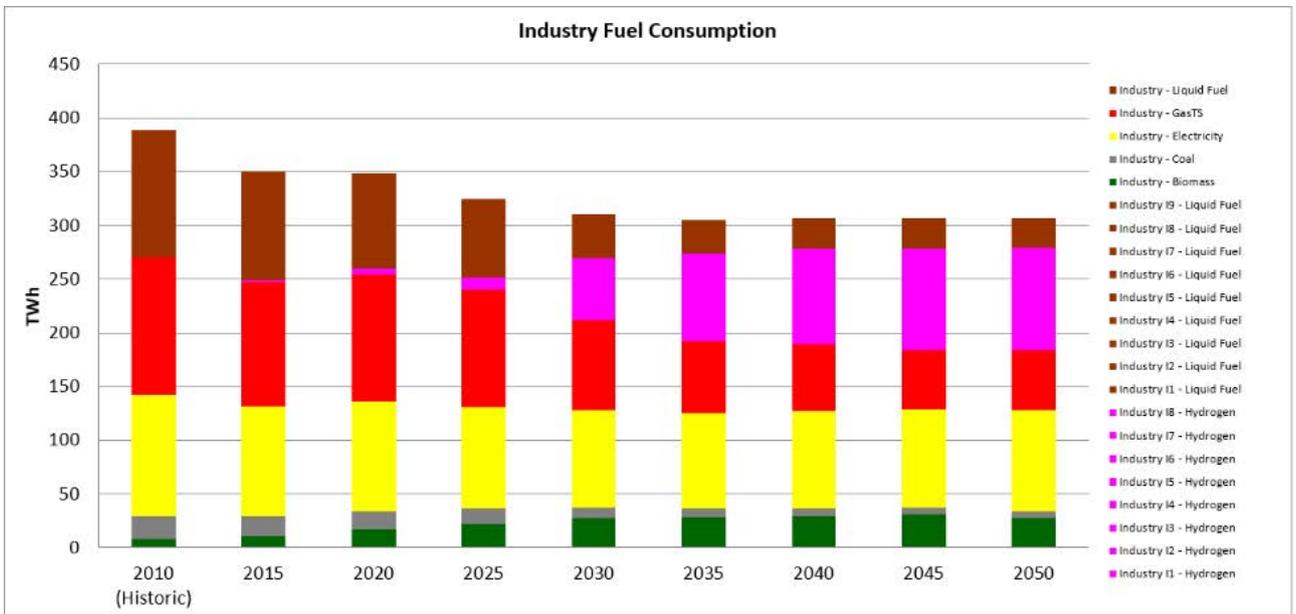
Figure A3-50 – Run 312 Industry Fuel Consumption

Run 320 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 1 x LC values
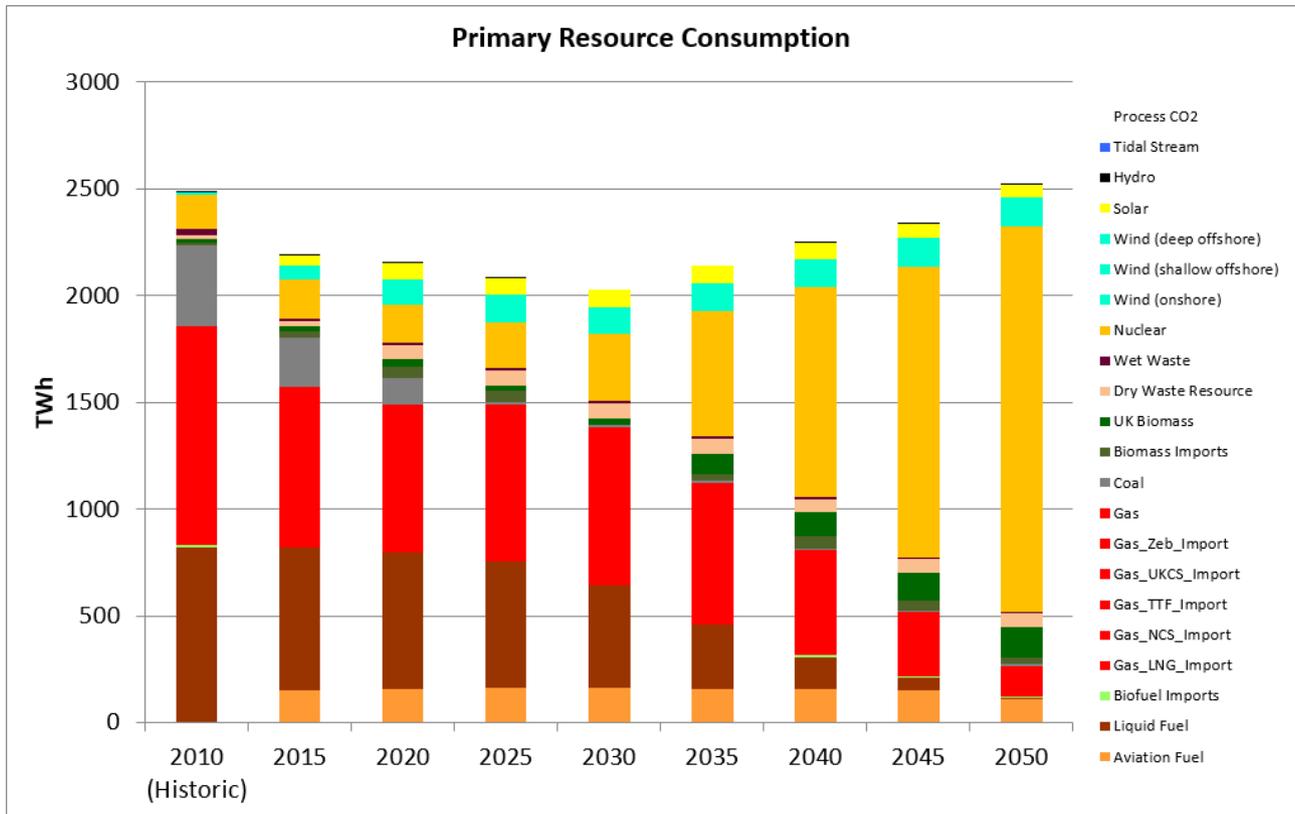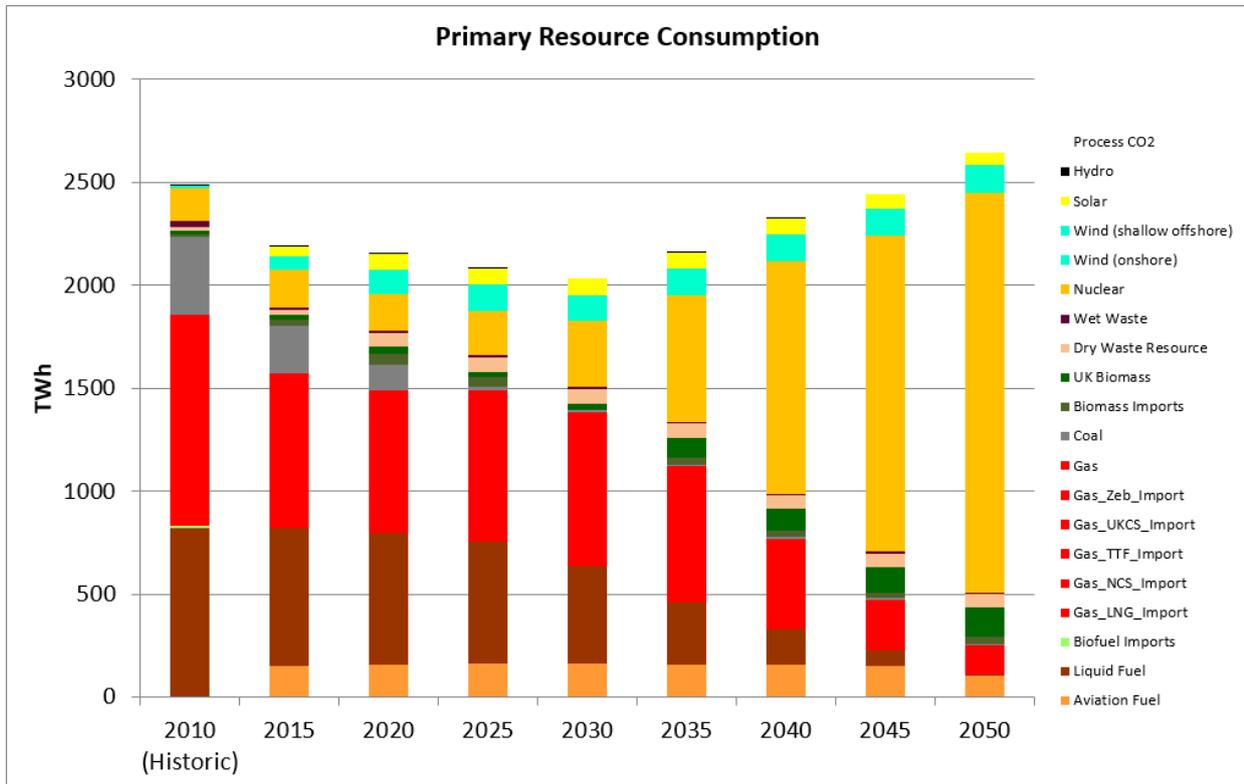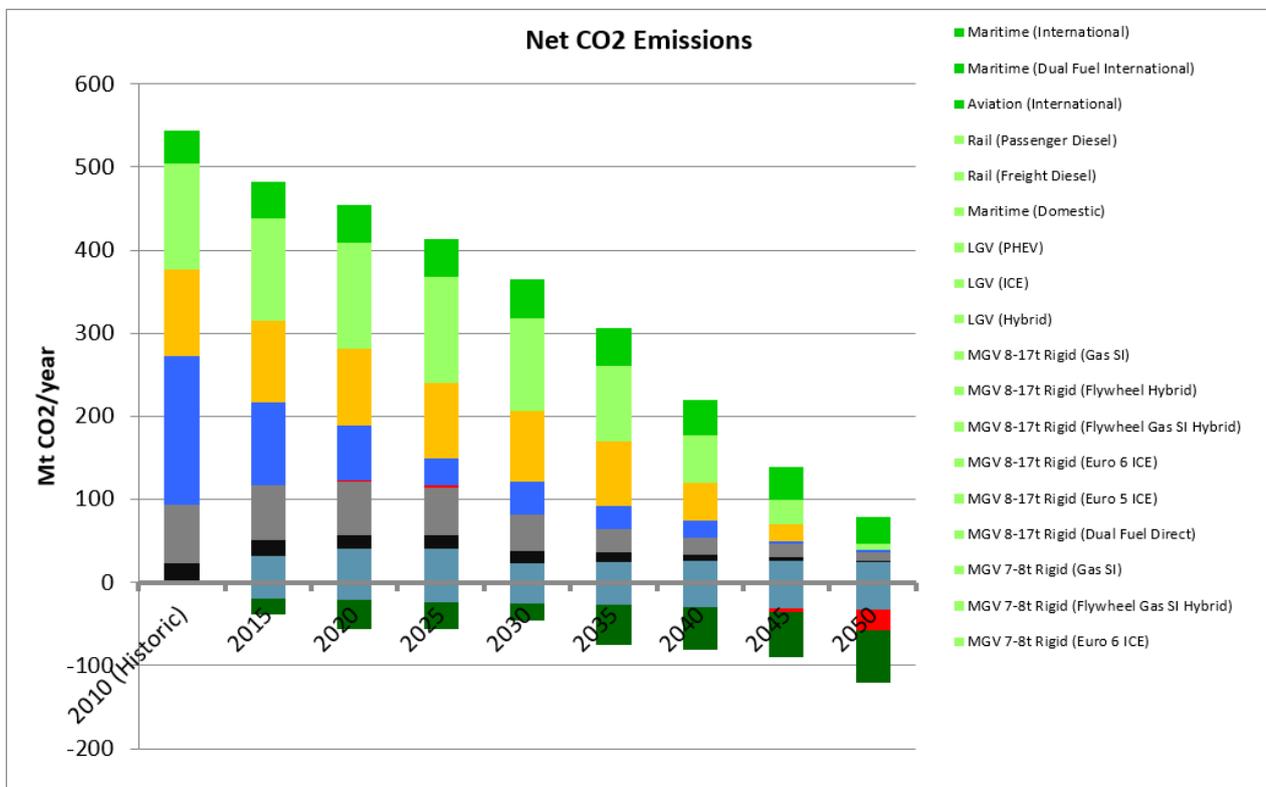

Figure A3-51 – Run 320 Primary Resource Consumption
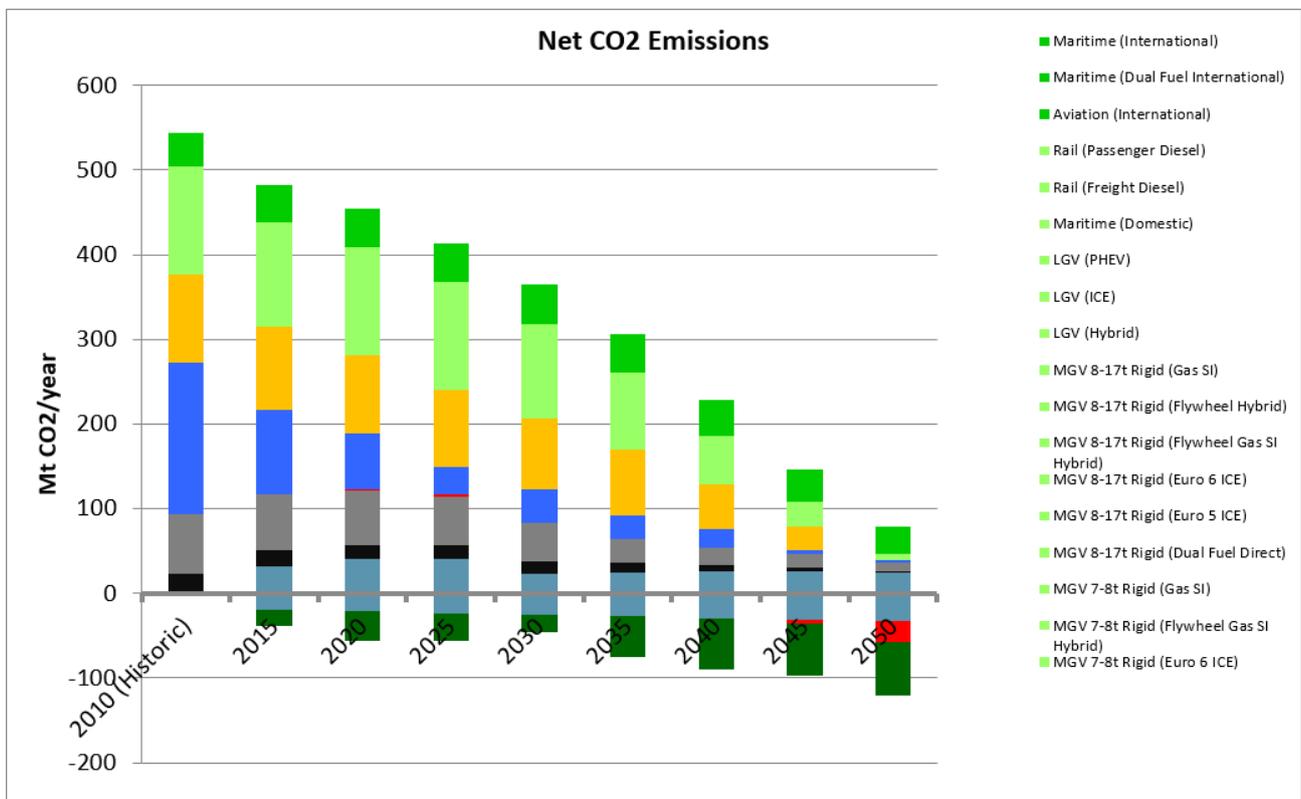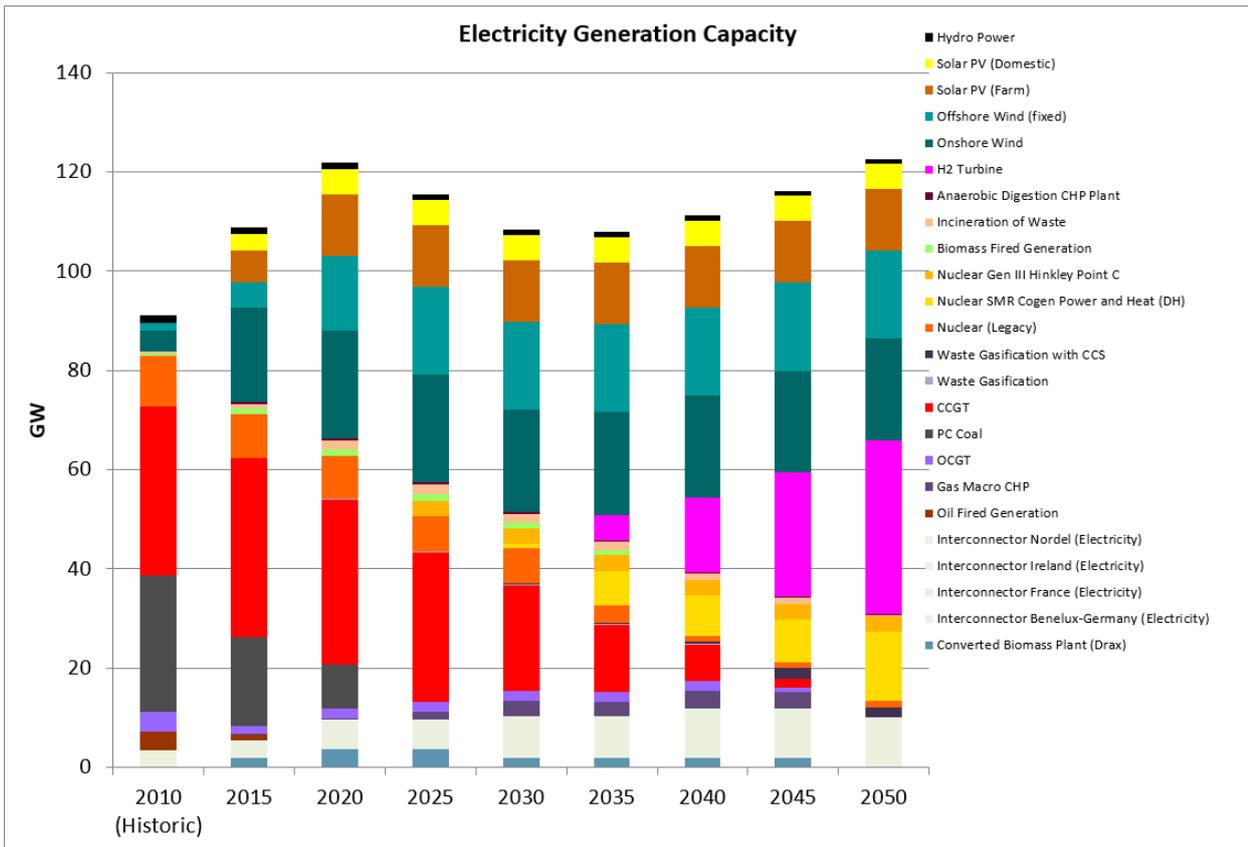

Figure A3-52 – Run 320 Net CO$_2$ Emissions
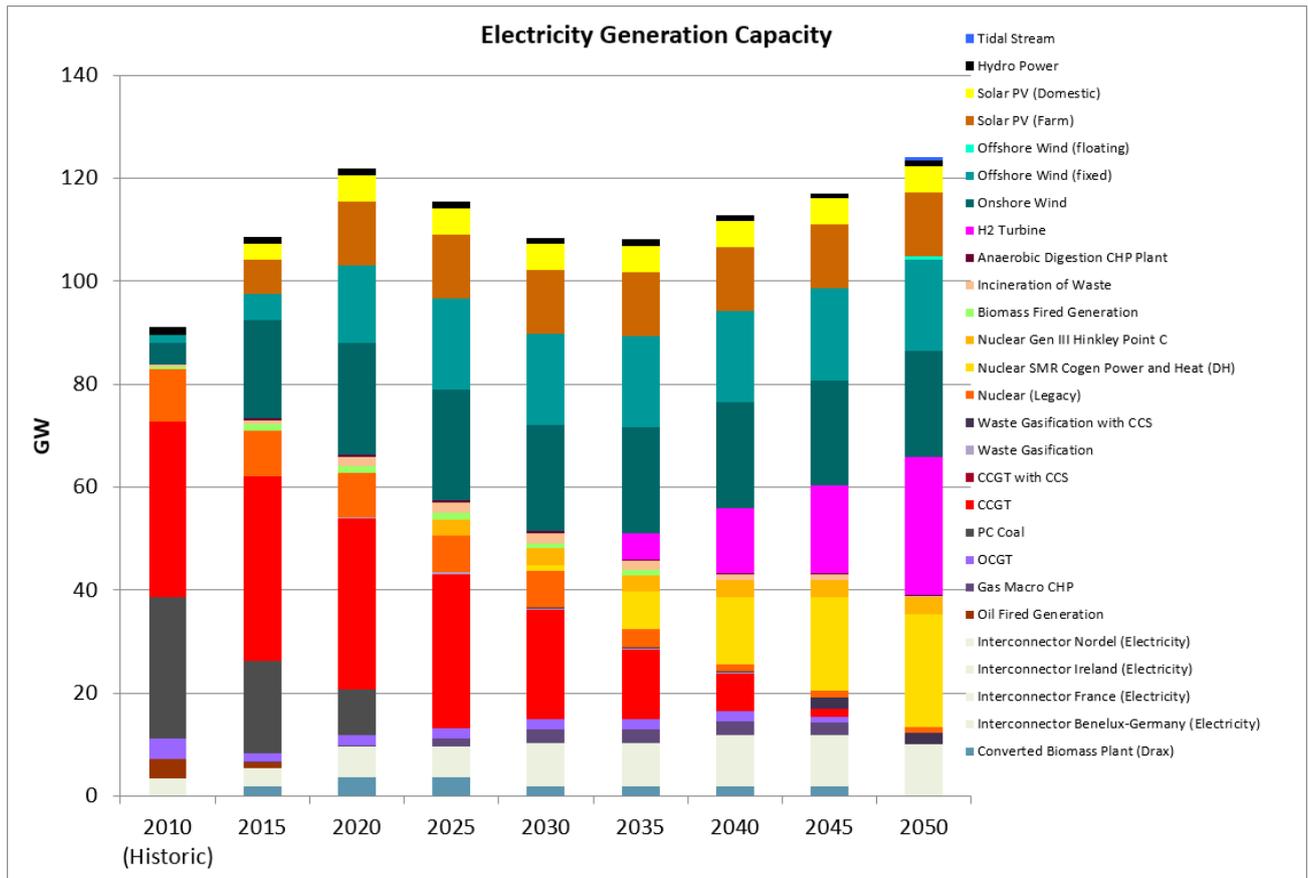
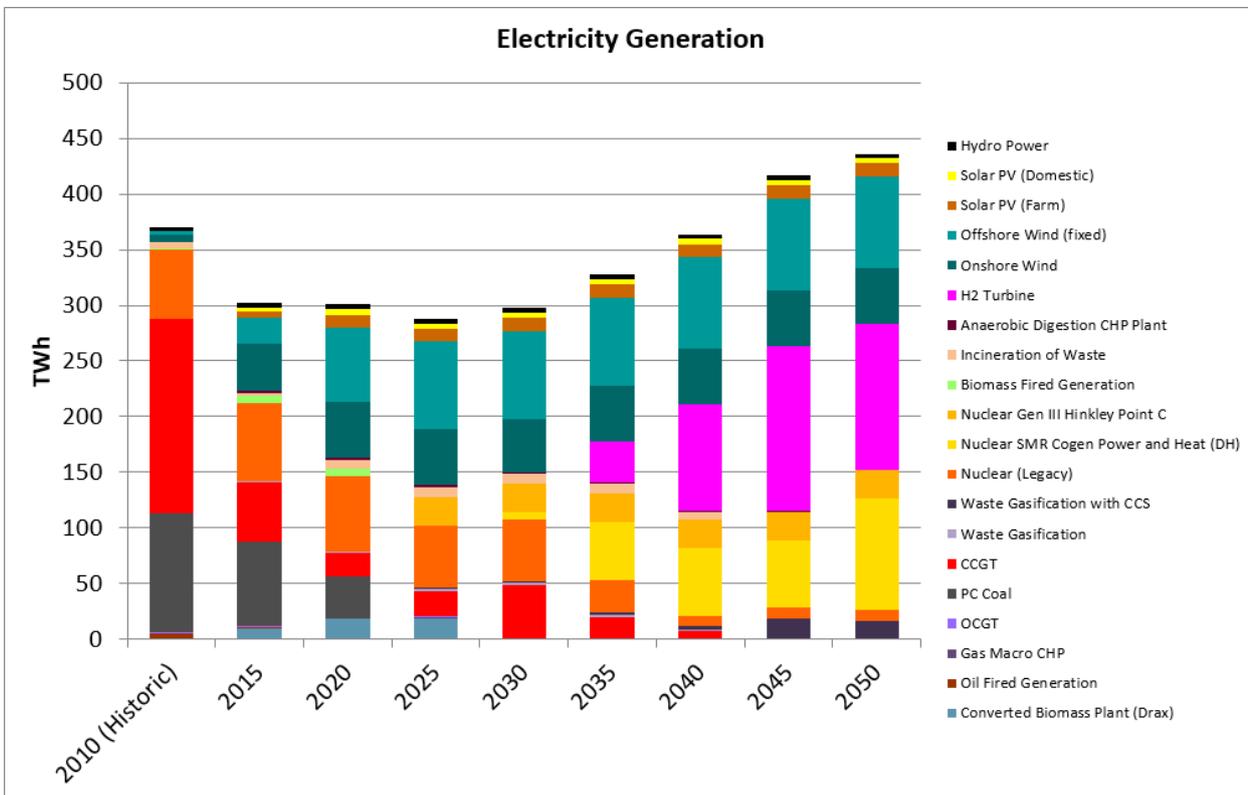Figure A3-53 – Run 320 Electricity Generation Capacity
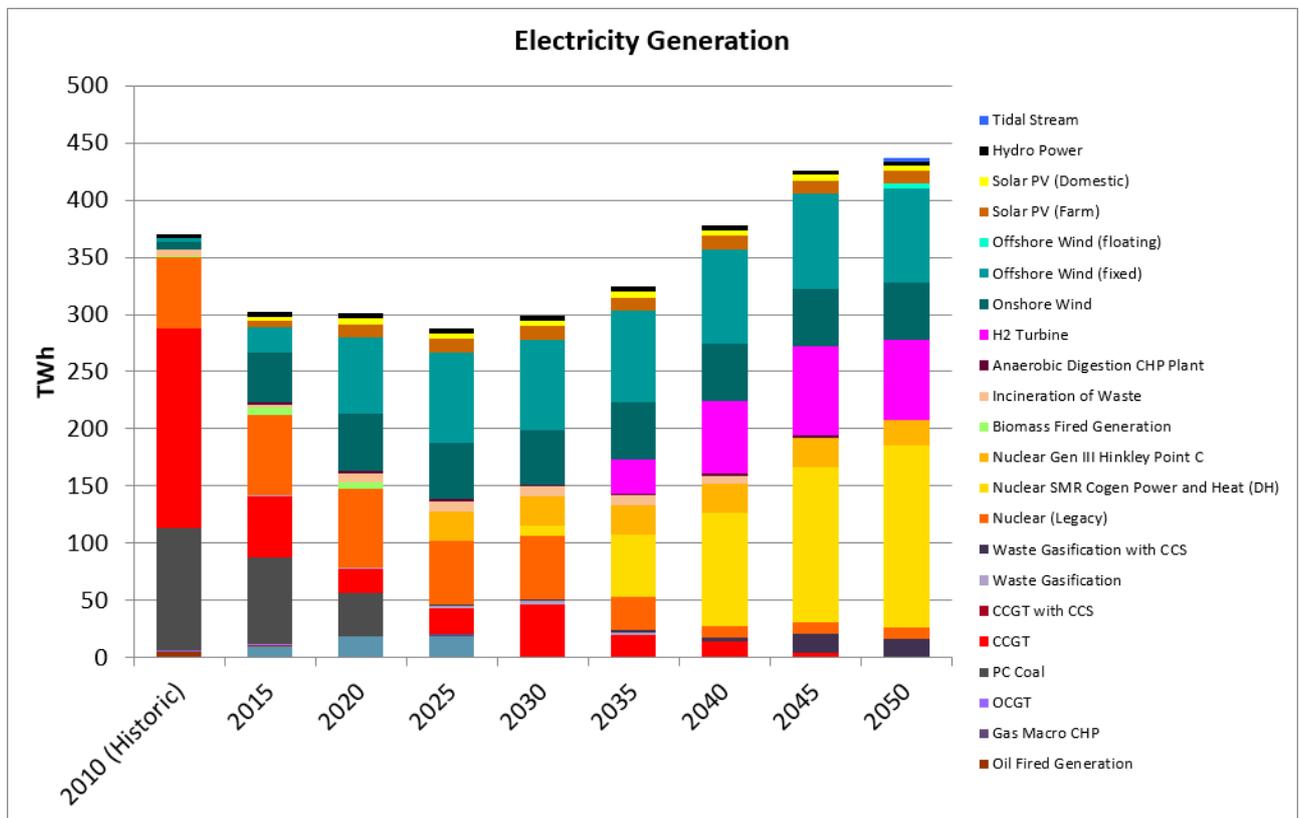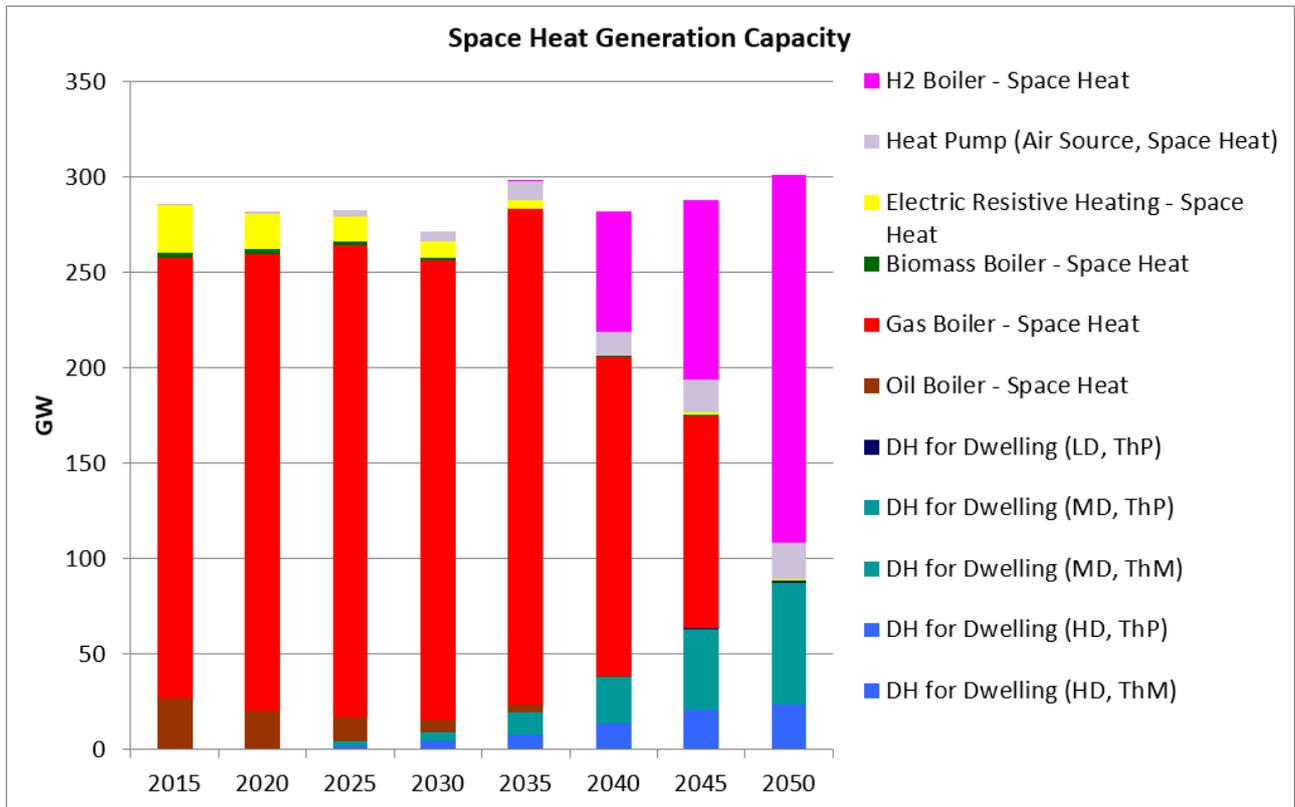

Figure A3-54 – Run 320 Electricity Generation
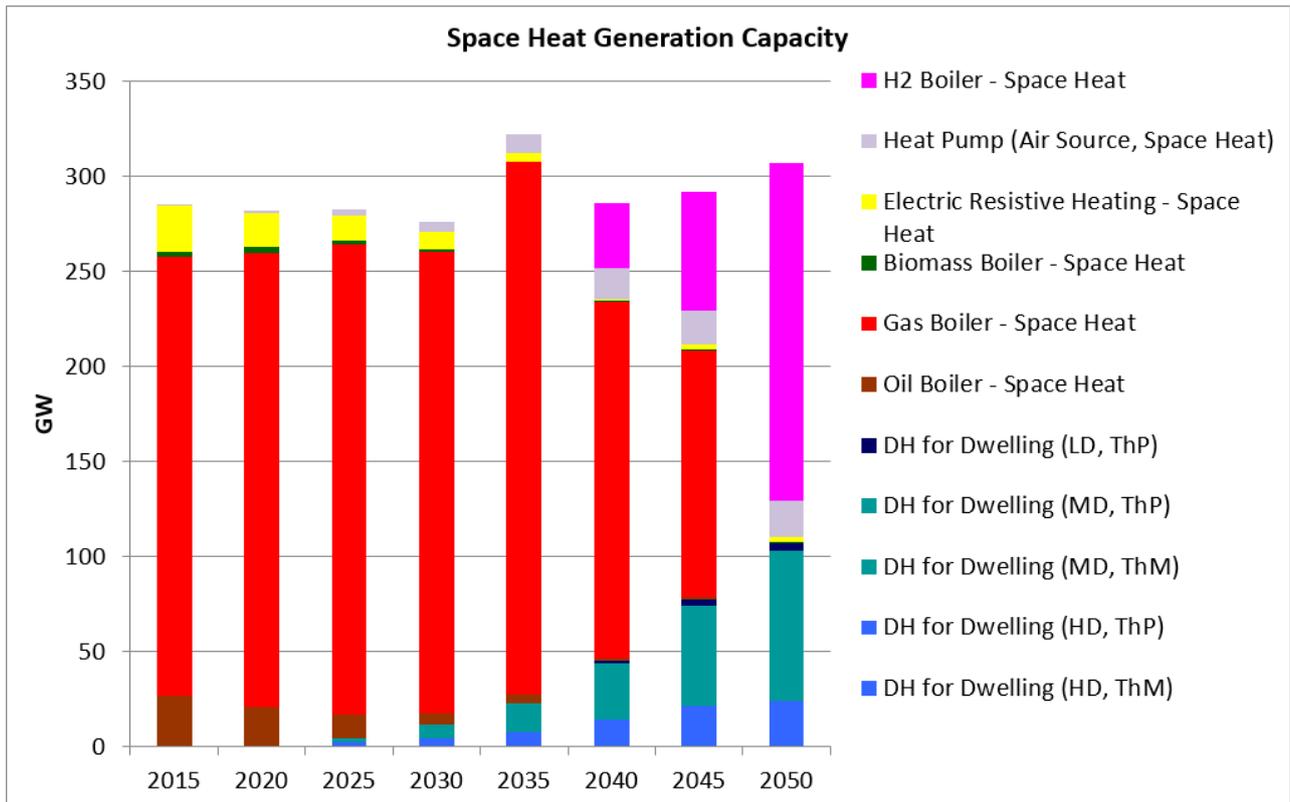
Figure A3-55 – Run 320 Space Heat Generation Capacity
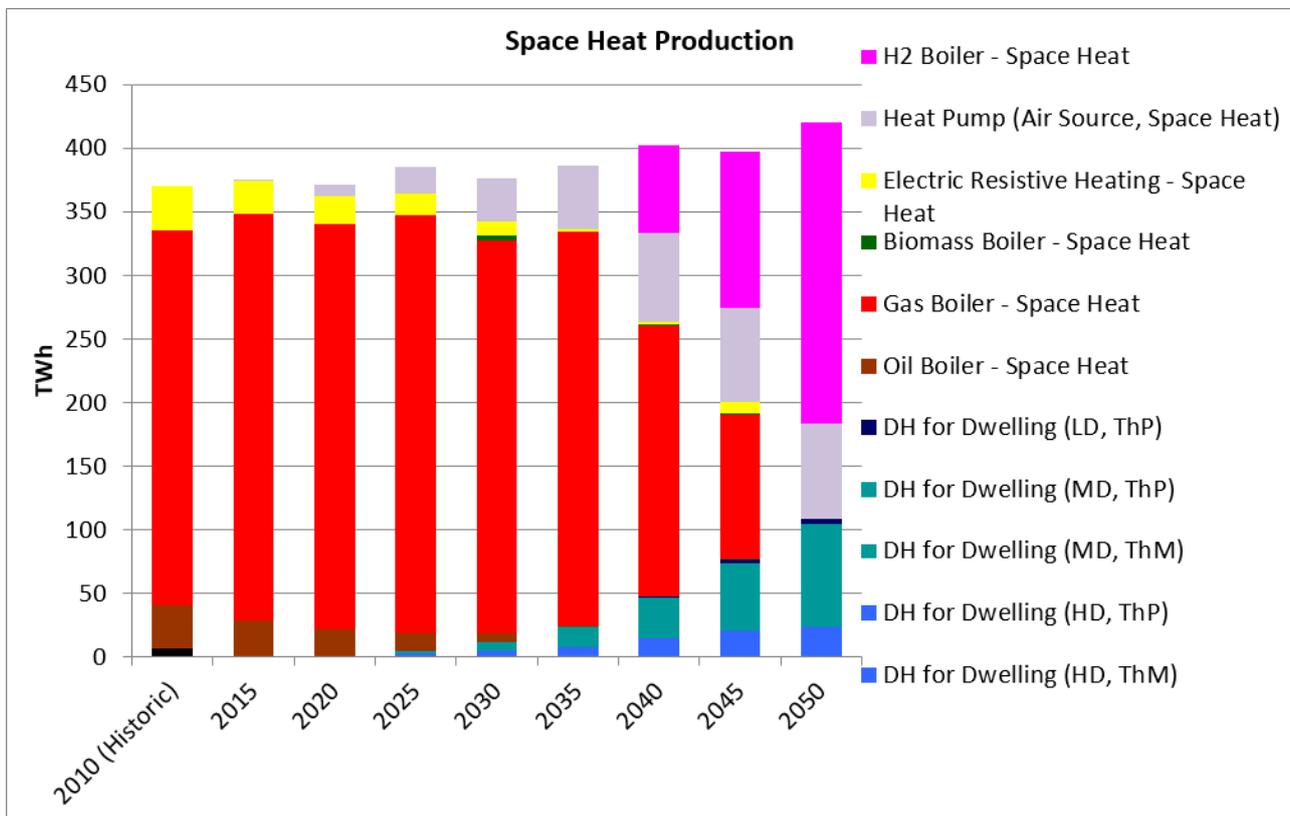
Figure A3-56 – Run 320 Space Heat Production
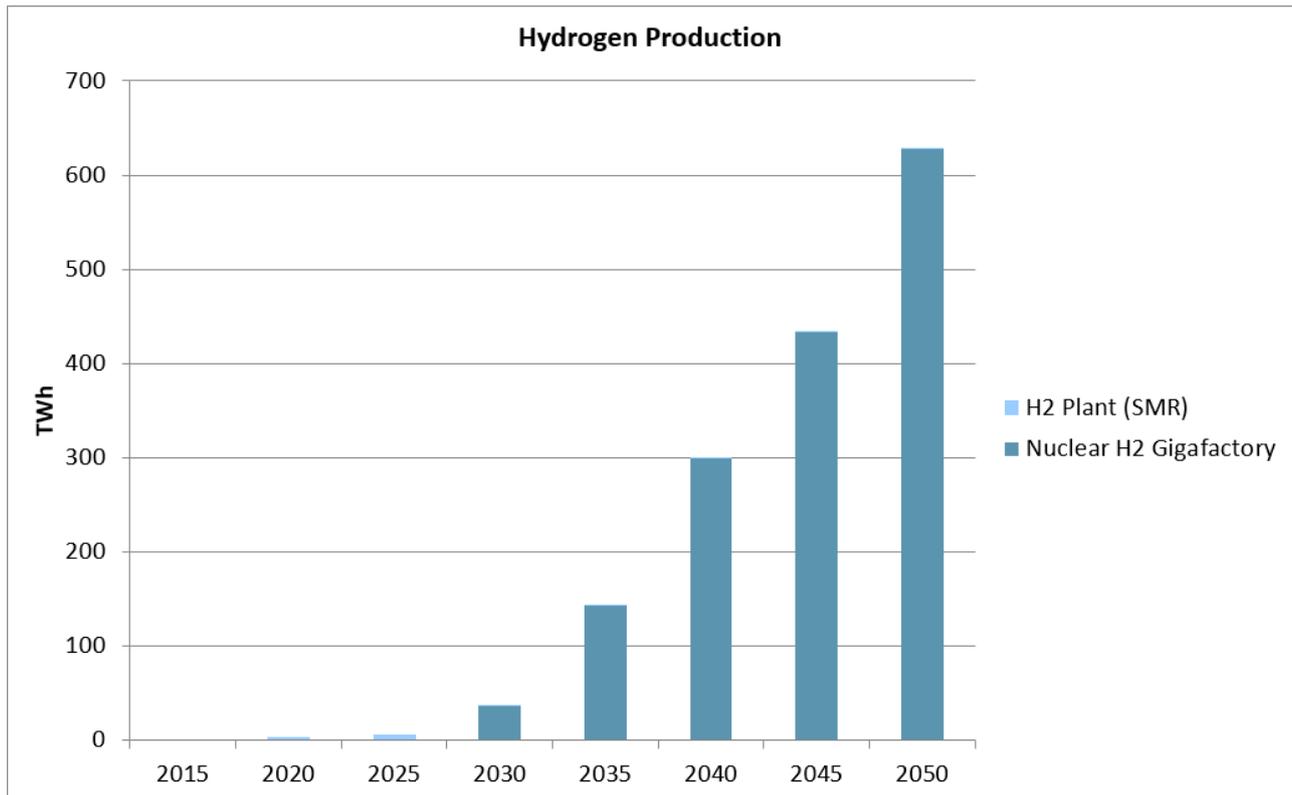
Figure A3-57 – Run 320 Hydrogen Production
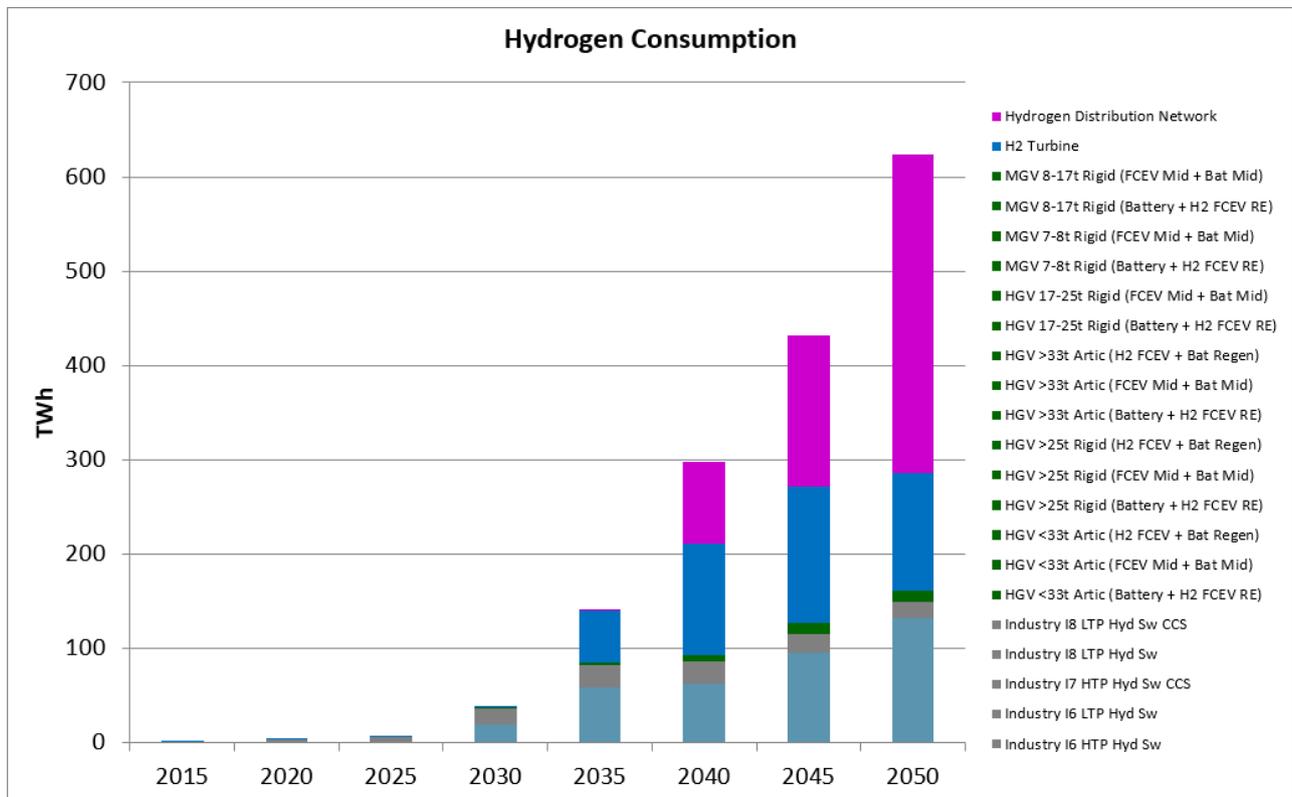
Figure A3-58 – Run 320 Hydrogen consumption
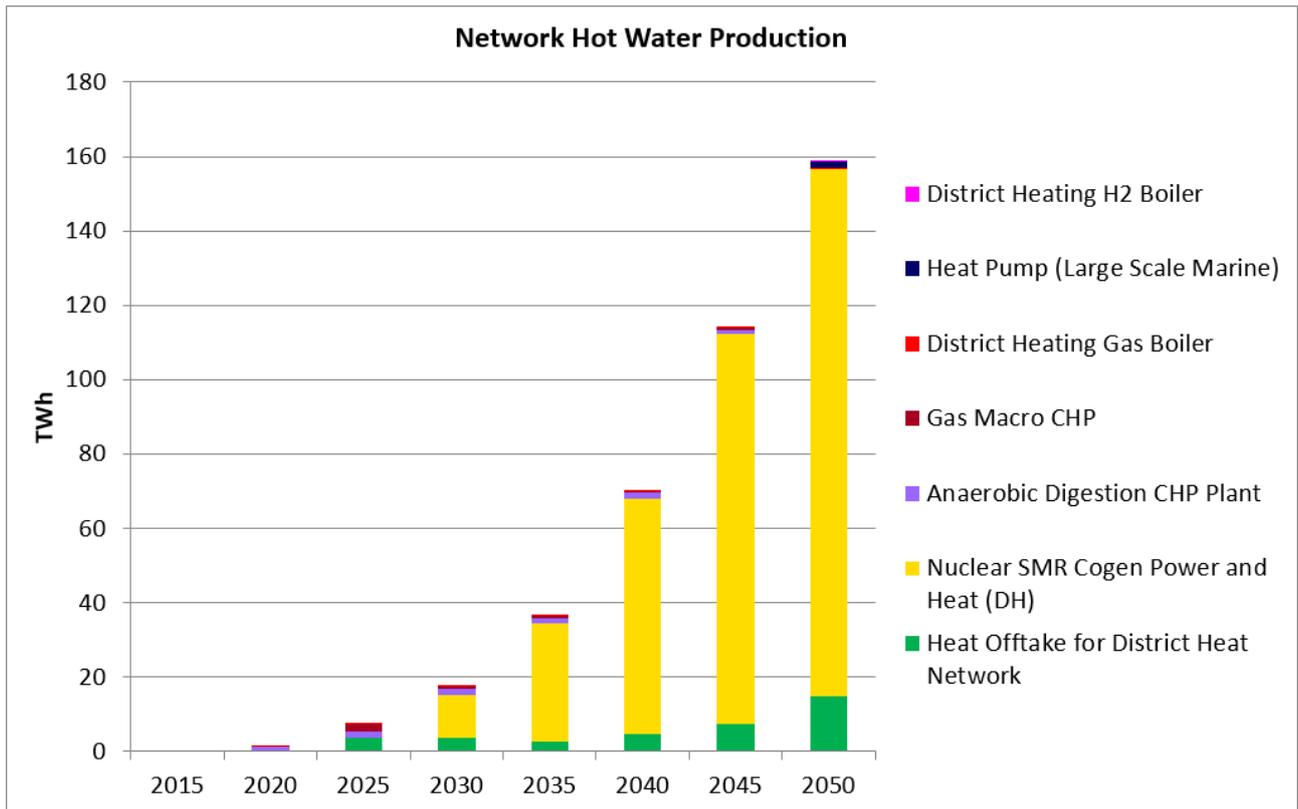
Figure A3-59 – Run 320 Network Hot Water Production
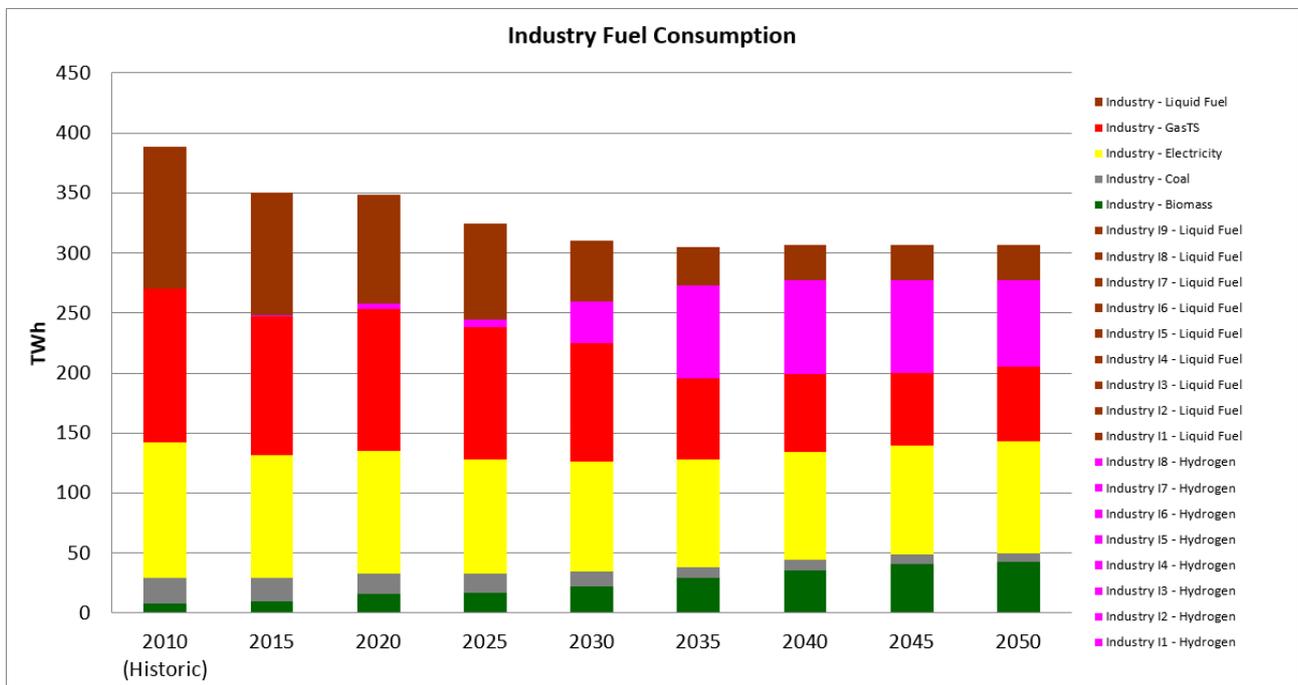
Figure A3-60 – Run 320 Industry Fuel Consumption

Run 321 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 2 x LC values
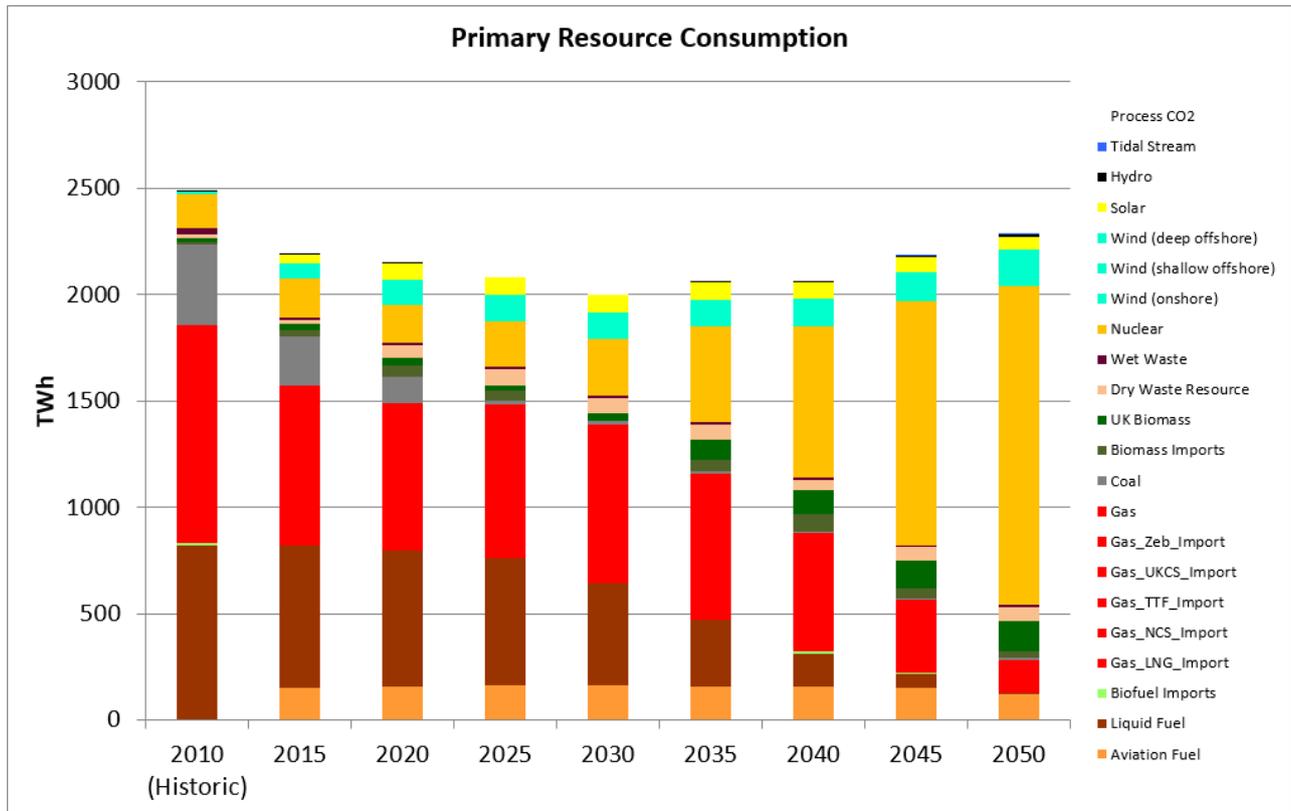
Figure A3-61 – Run 321 Primary Resource Consumption
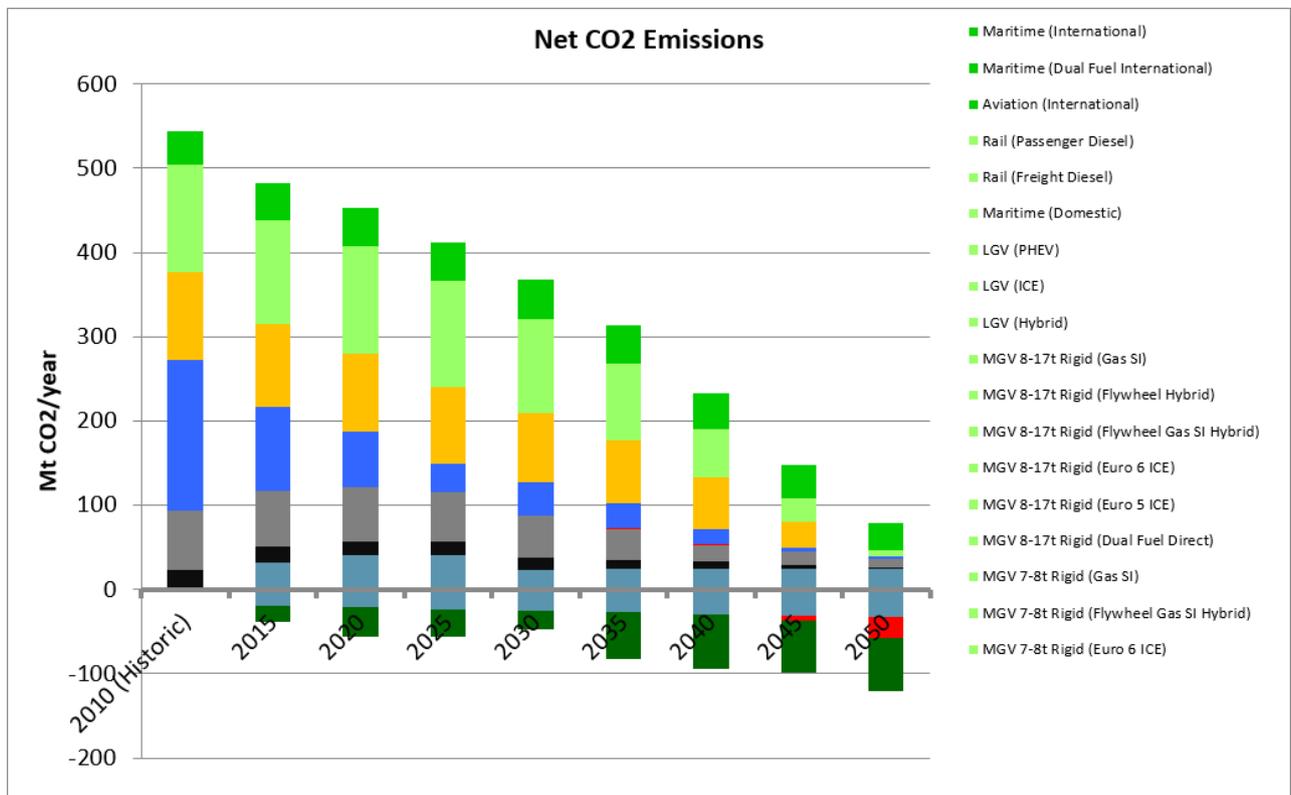
Figure A3-62 – Run 321 Net CO$_2$ Emissions
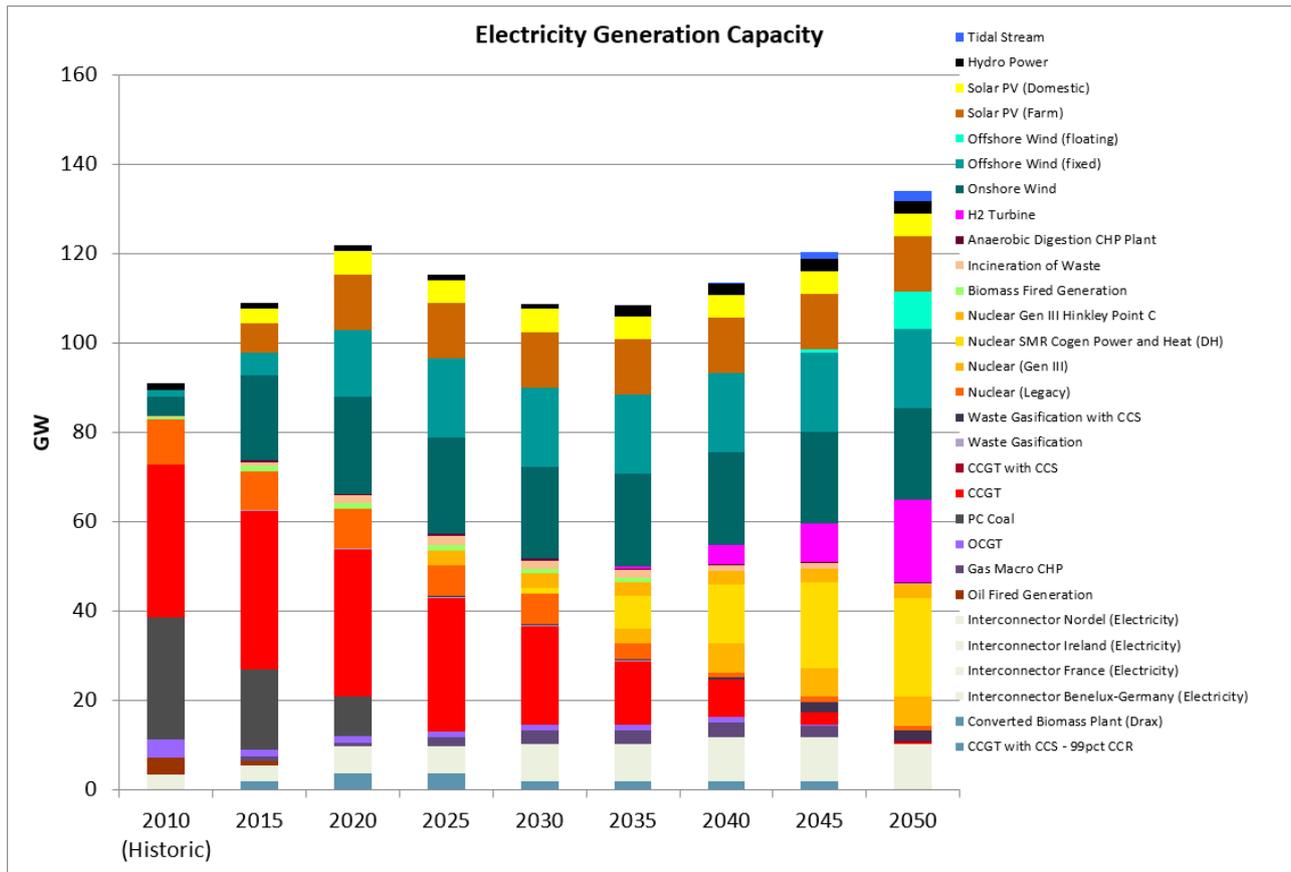
Figure A3-63 – Run 321 Electricity Generation Capacity
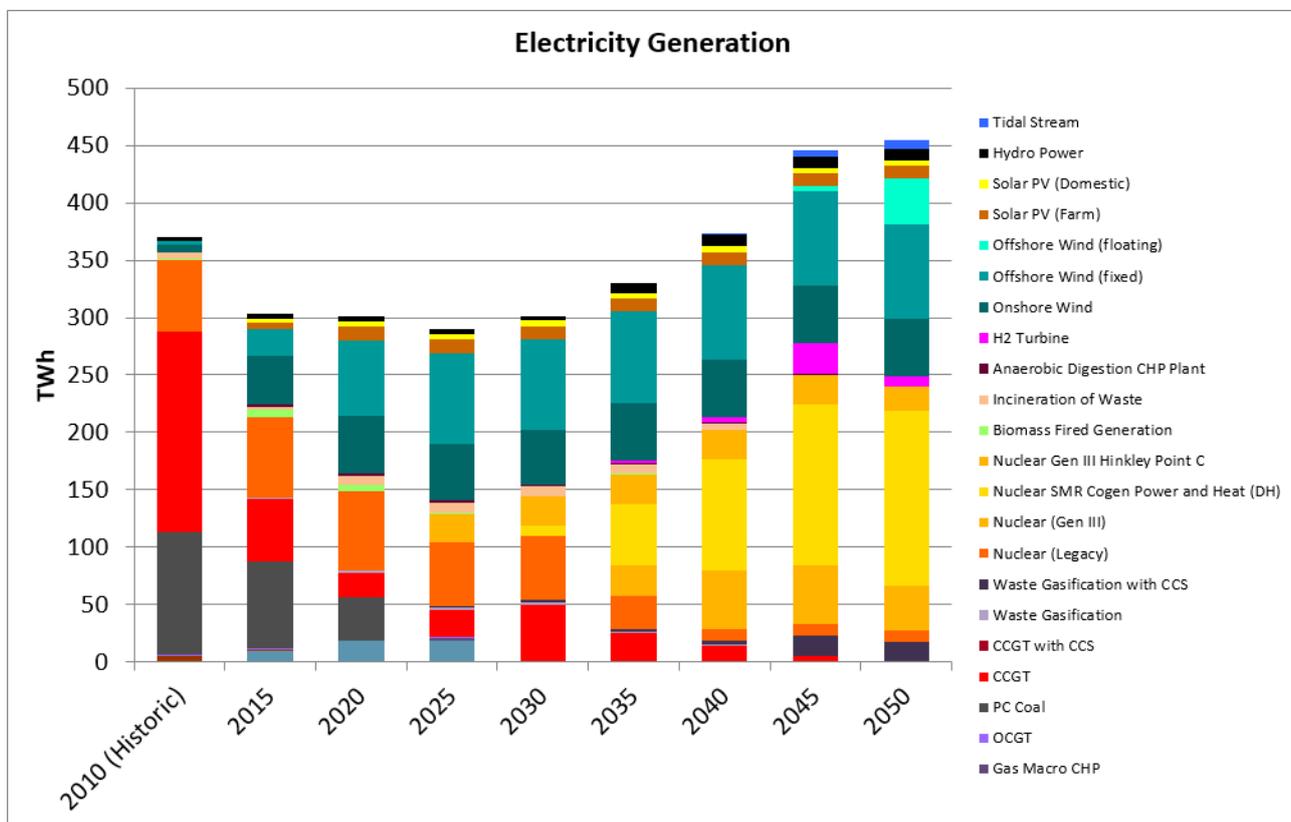
Figure A3-64 – Run 321 Electricity Generation
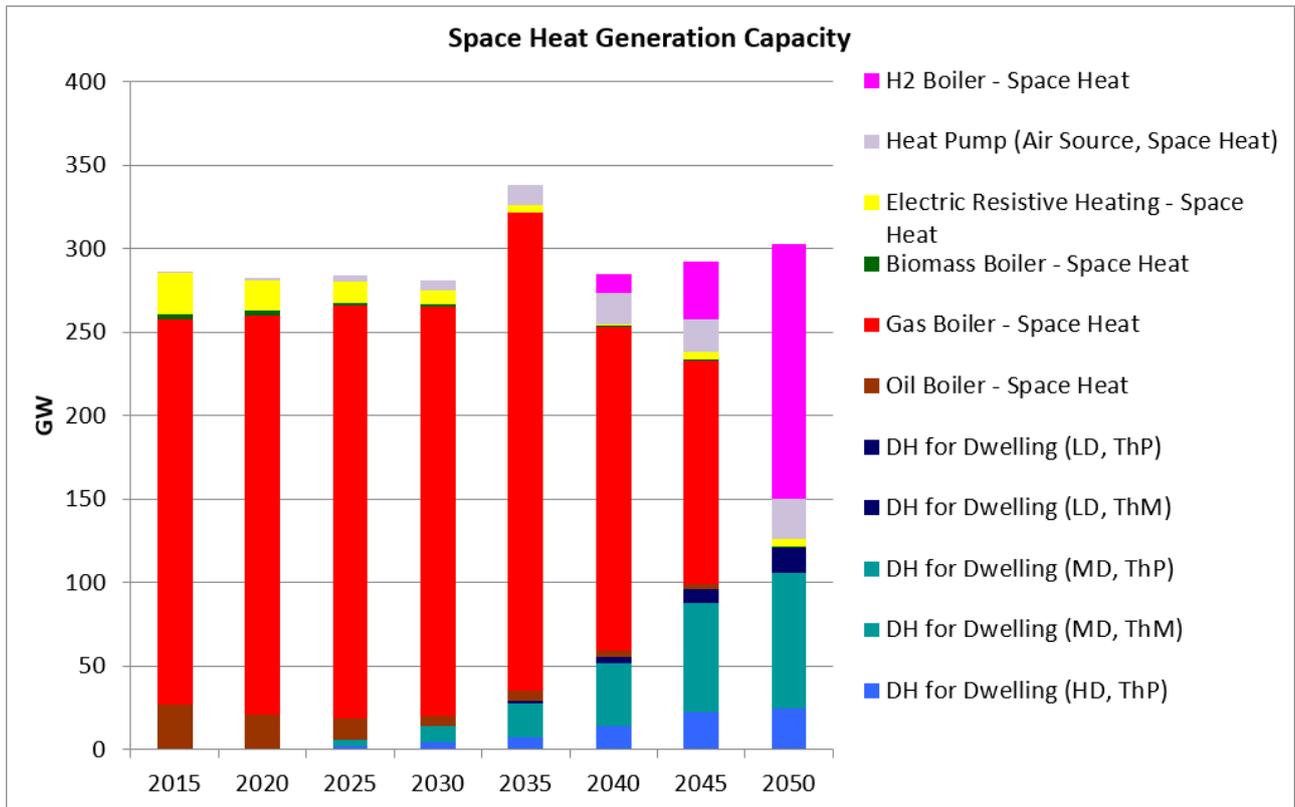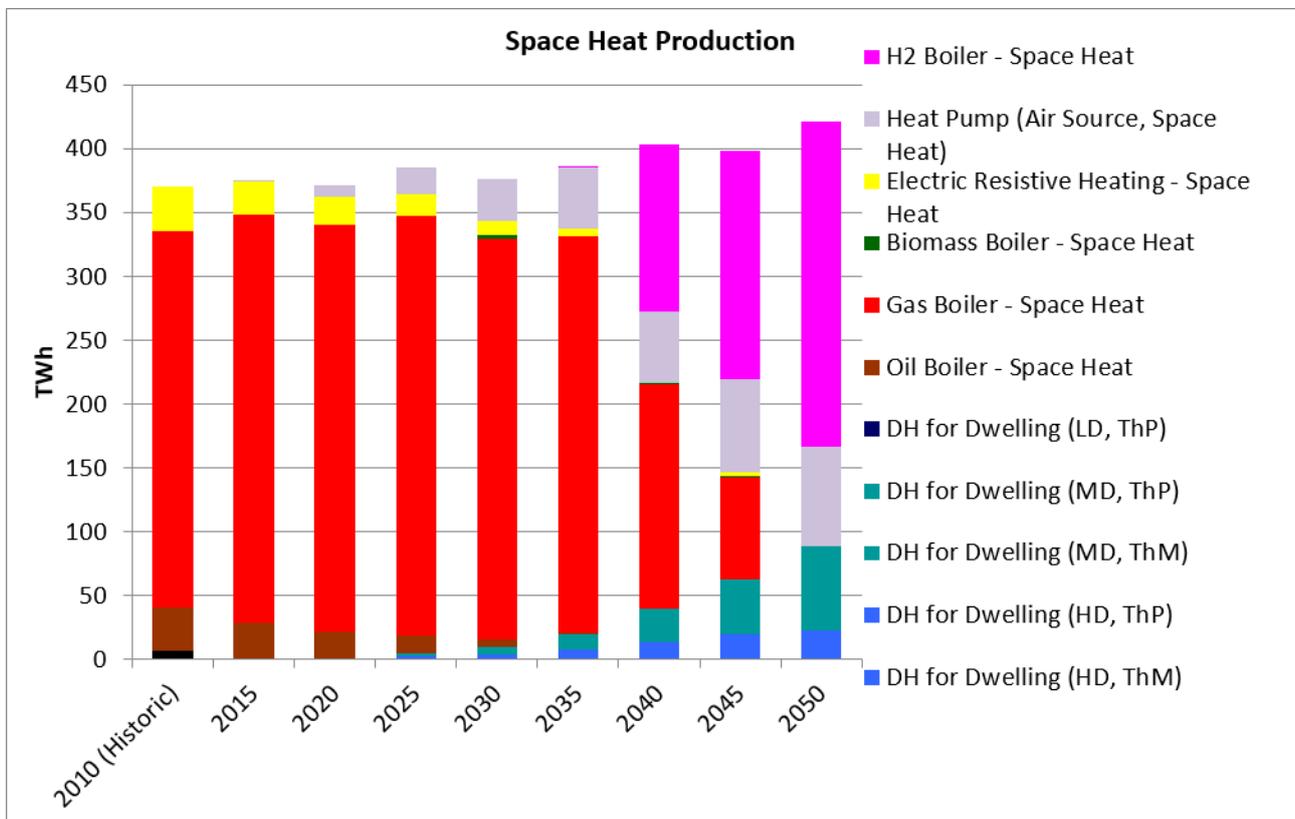
Figure A3-65 – Run 321 Space Heat Generation Capacity
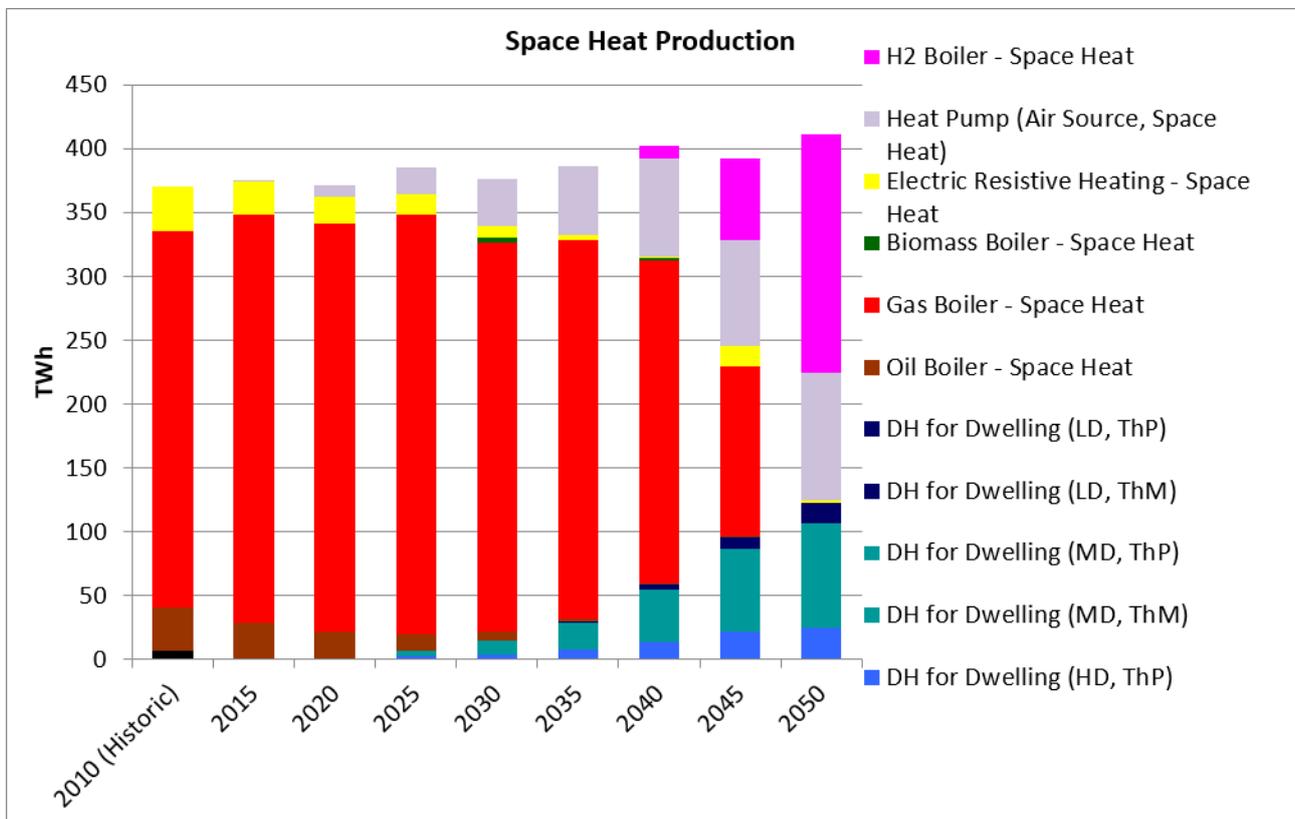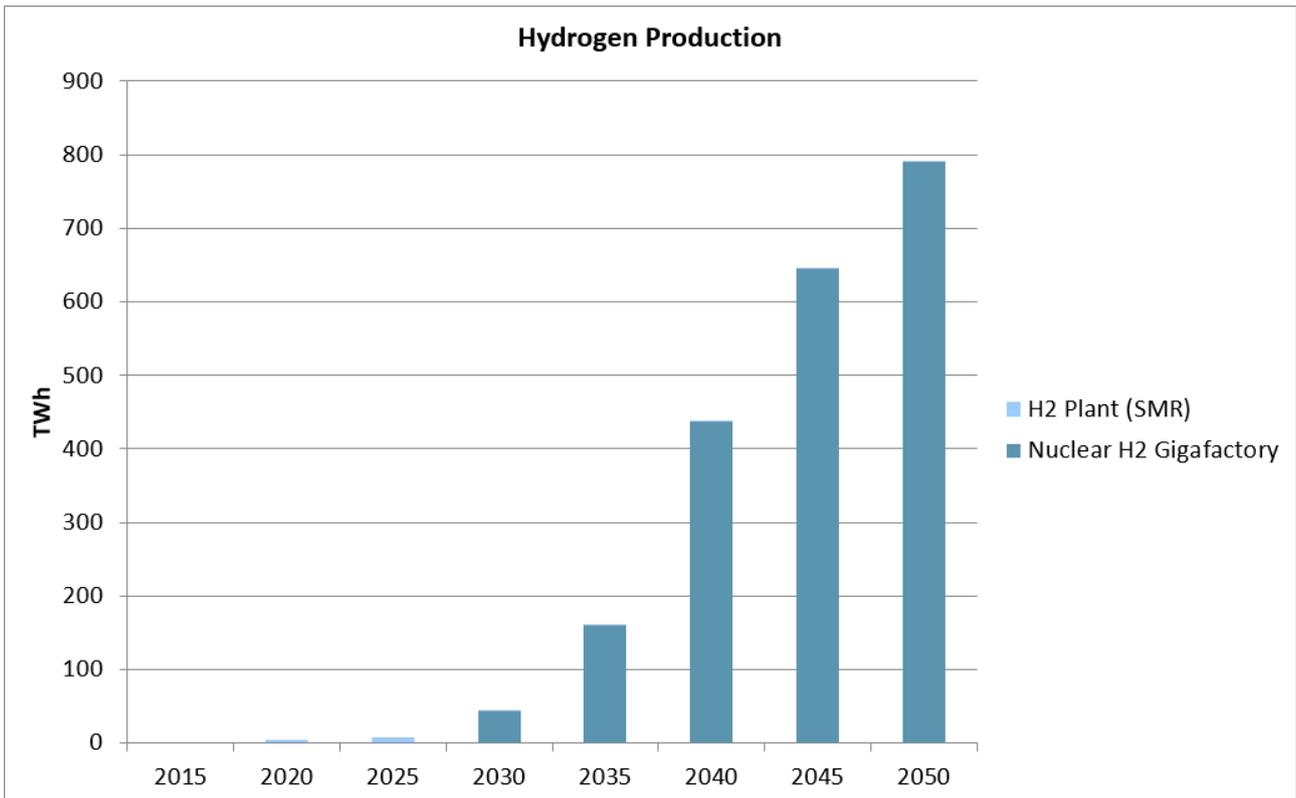

Figure A3-66 – Run 321 Space Heat Production
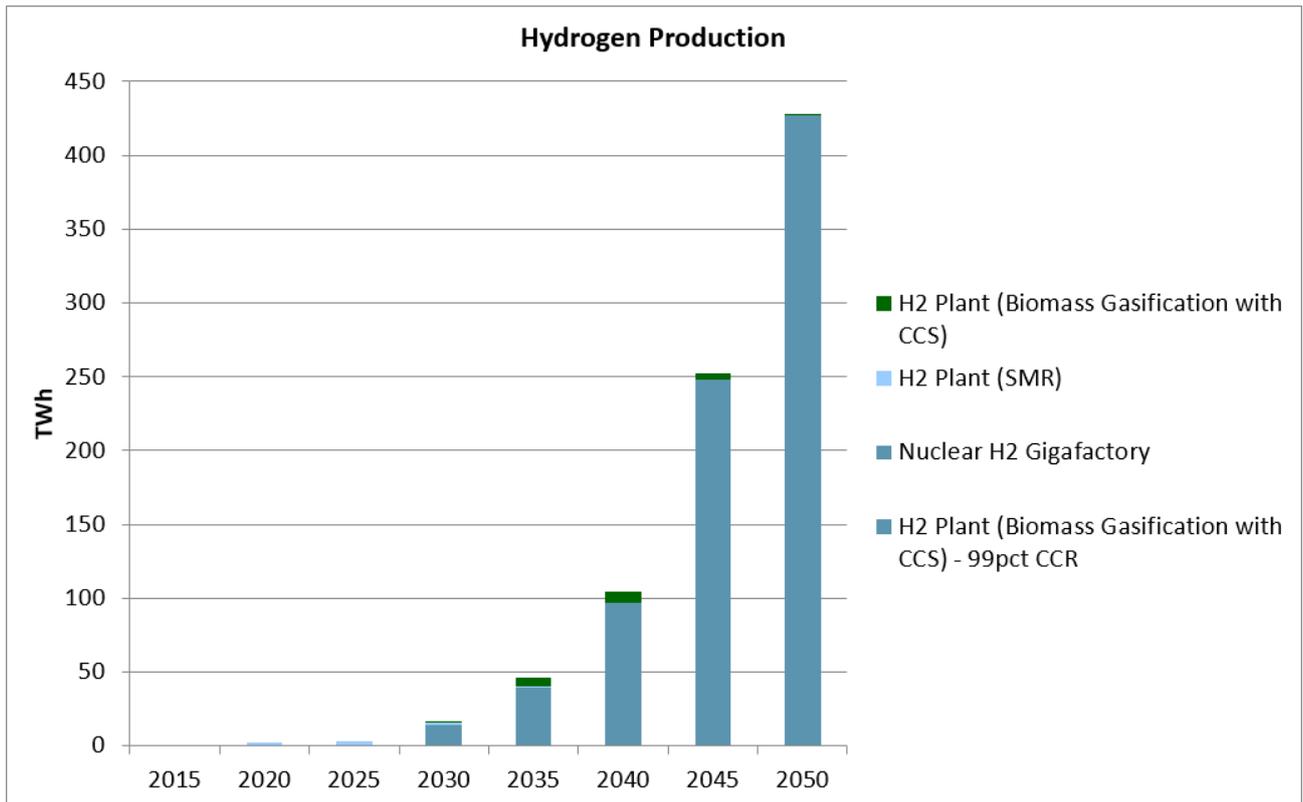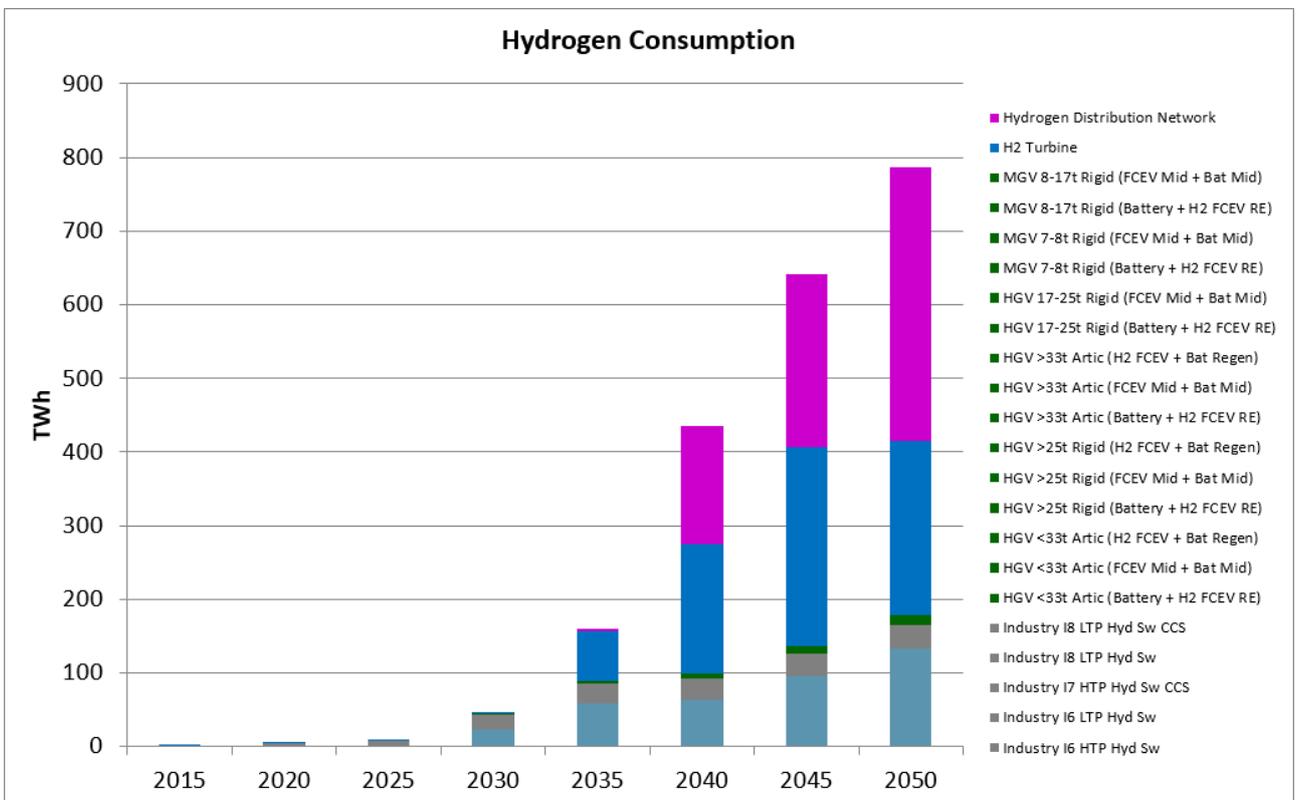
Figure A3-67 – Run 321 Hydrogen Production
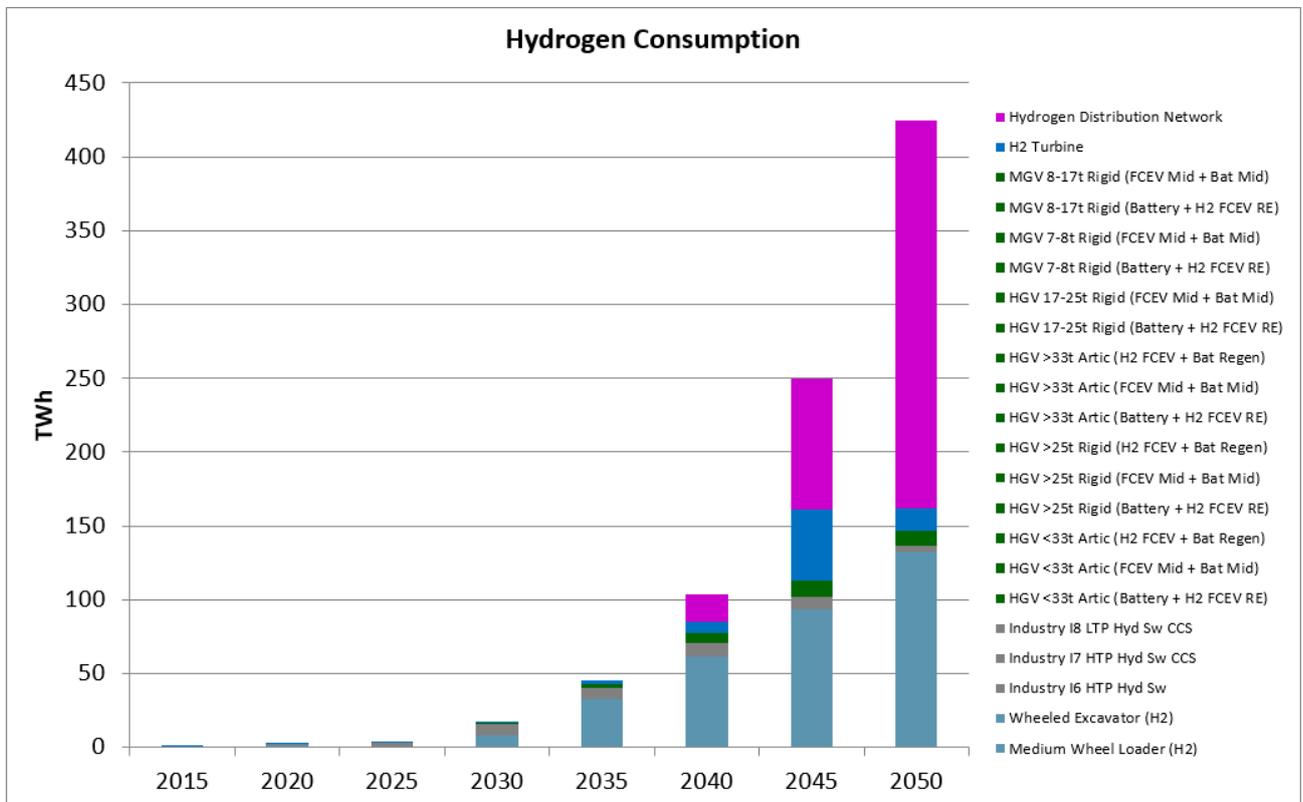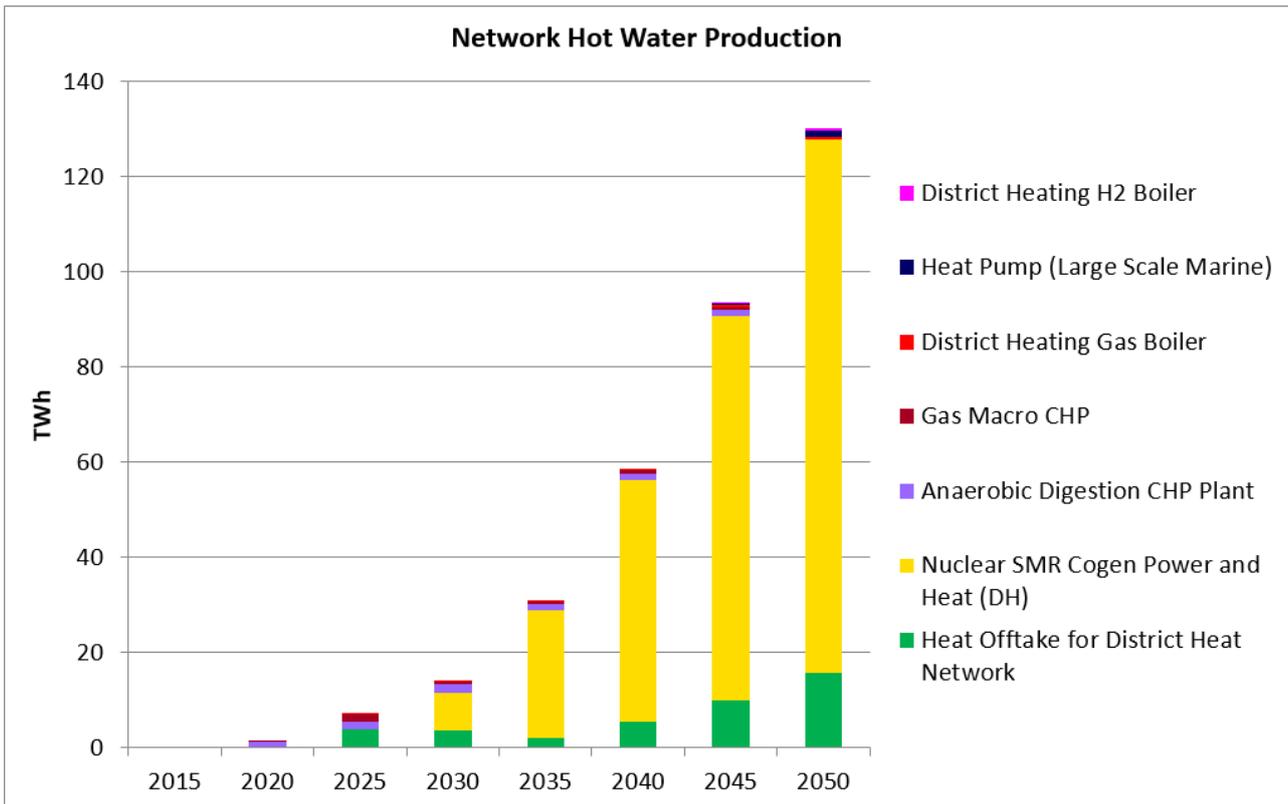

Figure A3-68 – Run 321 Hydrogen consumption
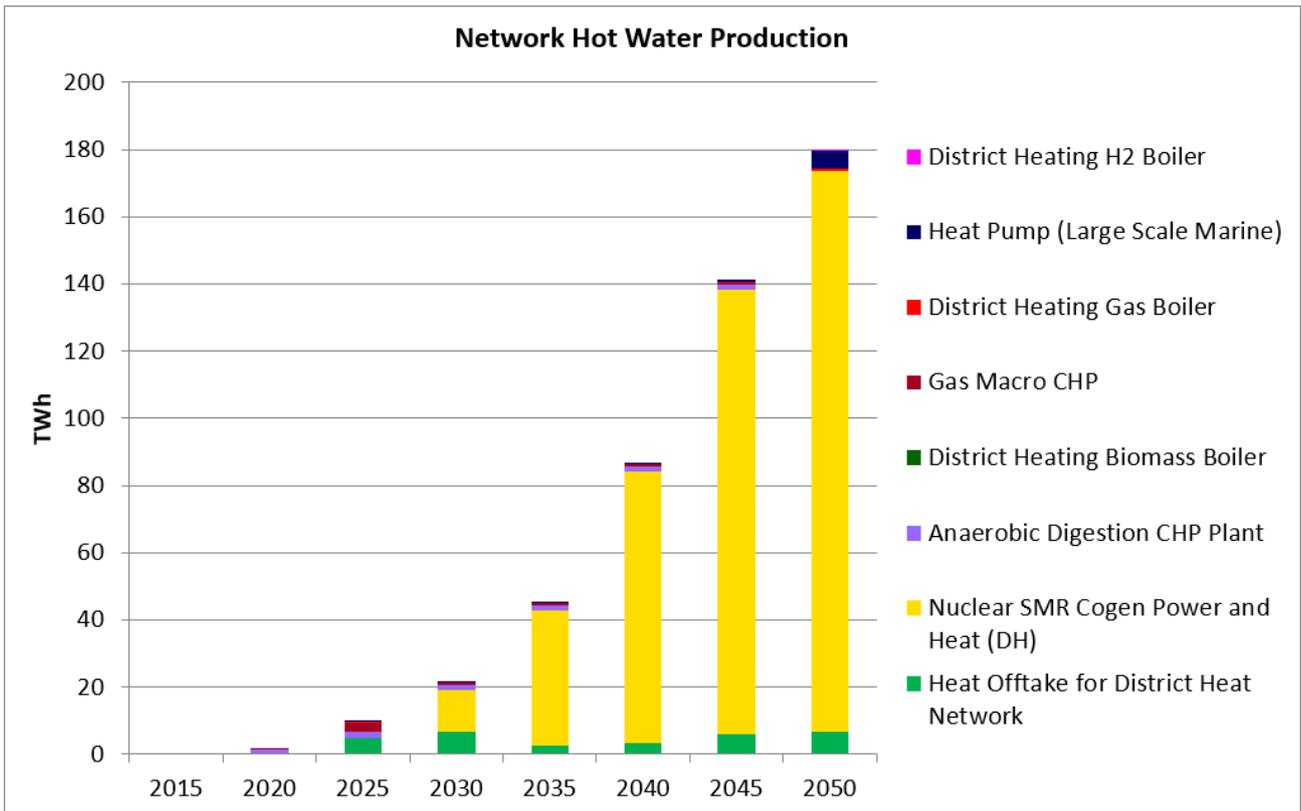
Figure A3-69 – Run 321 Network Hot Water Production
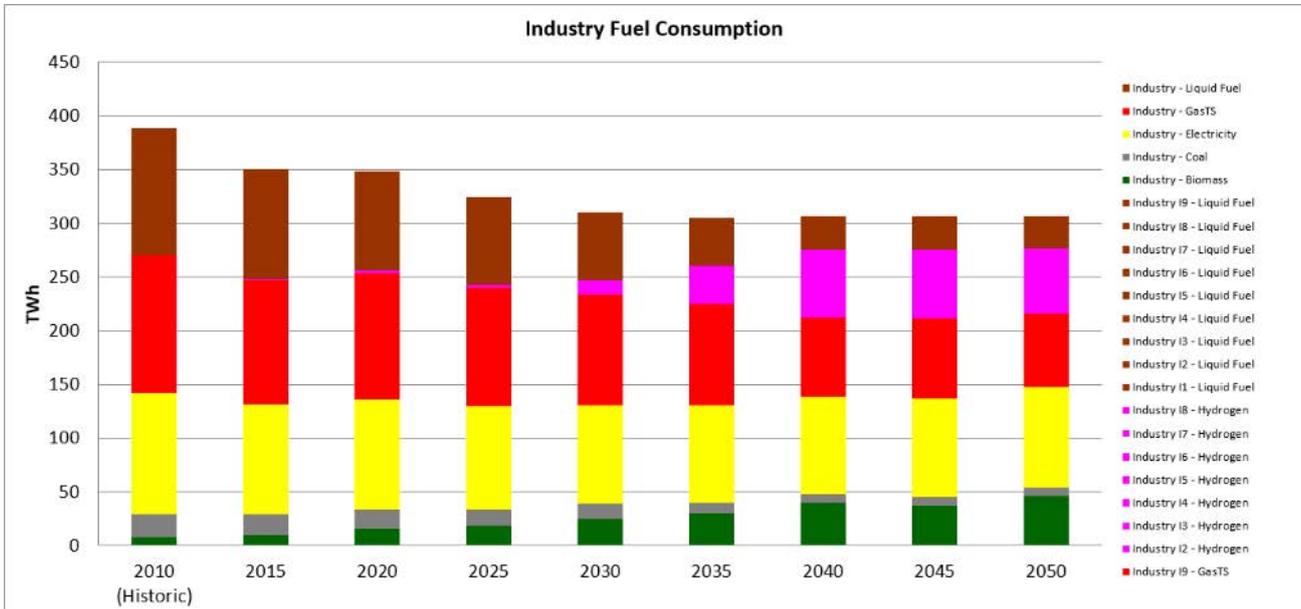
Figure A3-70 – Run 321 Industry Fuel Consumption

Run 322 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 3 x LC values

Figure A3-71 – Run 322 Primary Resource Consumption

Figure A3-72 – Run 322 Net CO$_2$ Emissions

Figure A3-73 – Run 322 Electricity Generation Capacity

Figure A3-74 – Run 322 Electricity Generation

Figure A3-75 – Run 322 Space Heat Generation Capacity

Figure A3-76 – Run 322 Space Heat Production
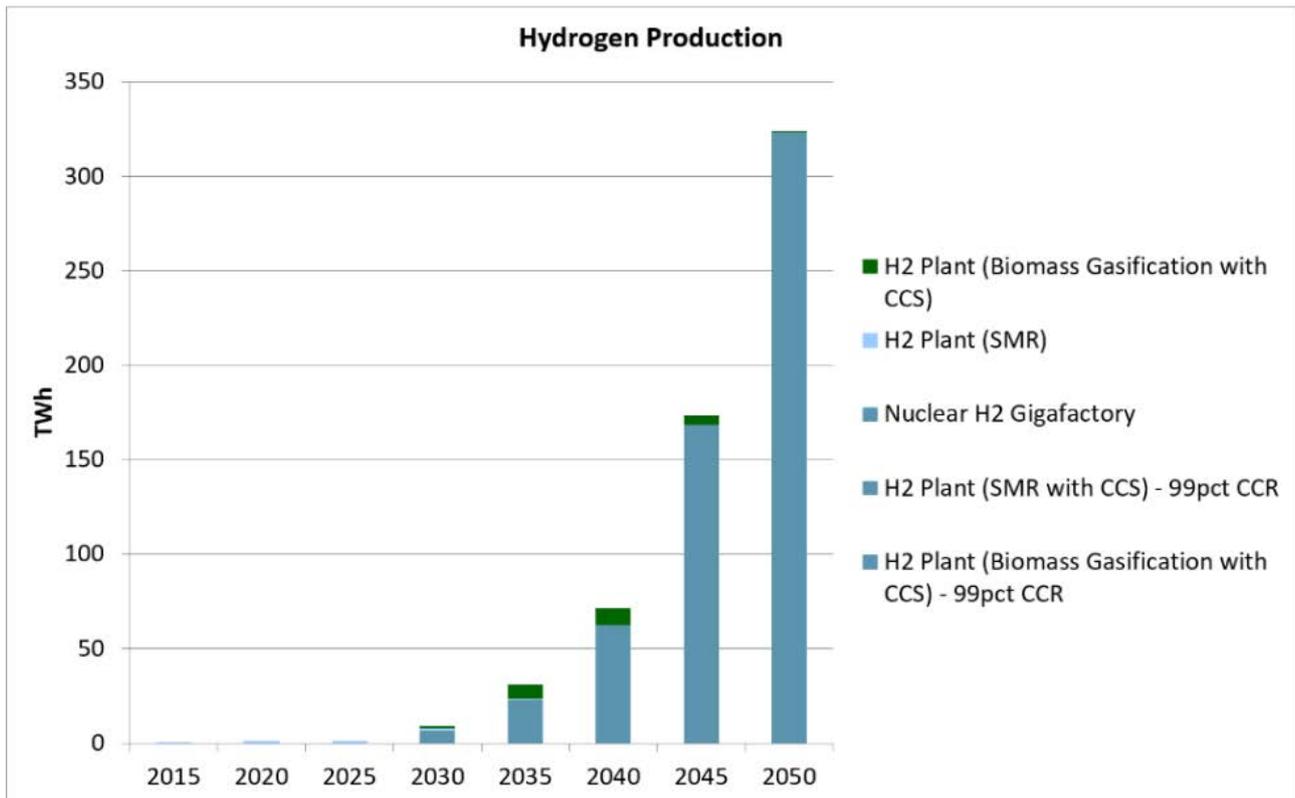
Figure A3-77 – Run 322 Hydrogen Production
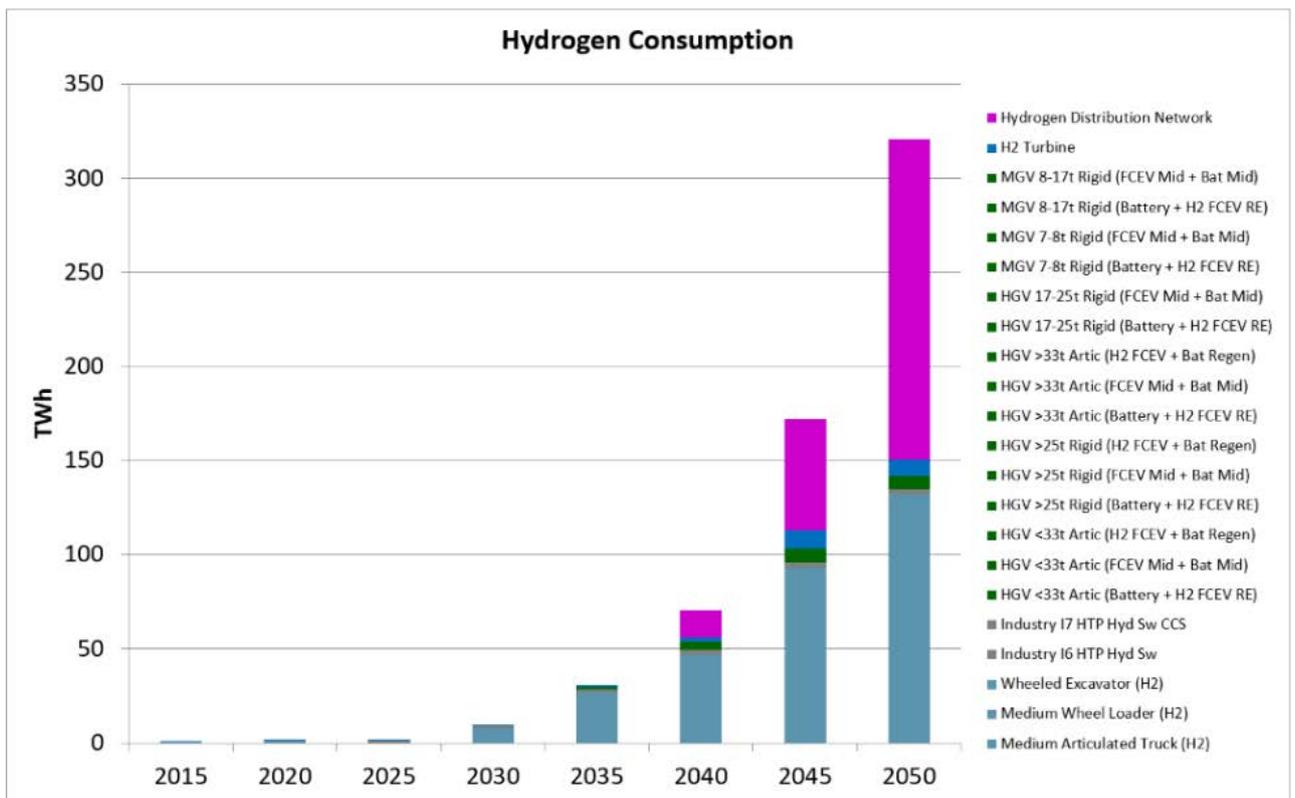
Figure A3-78 – Run 322 Hydrogen consumption
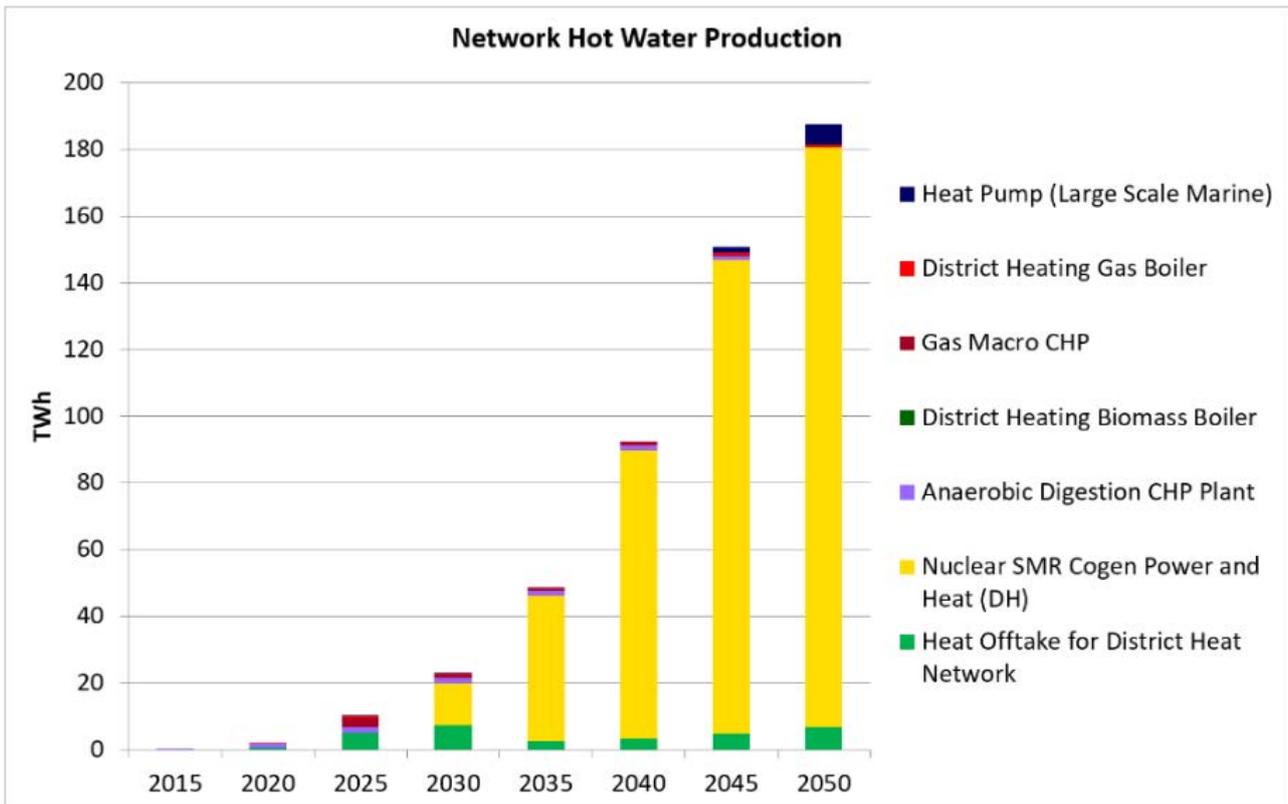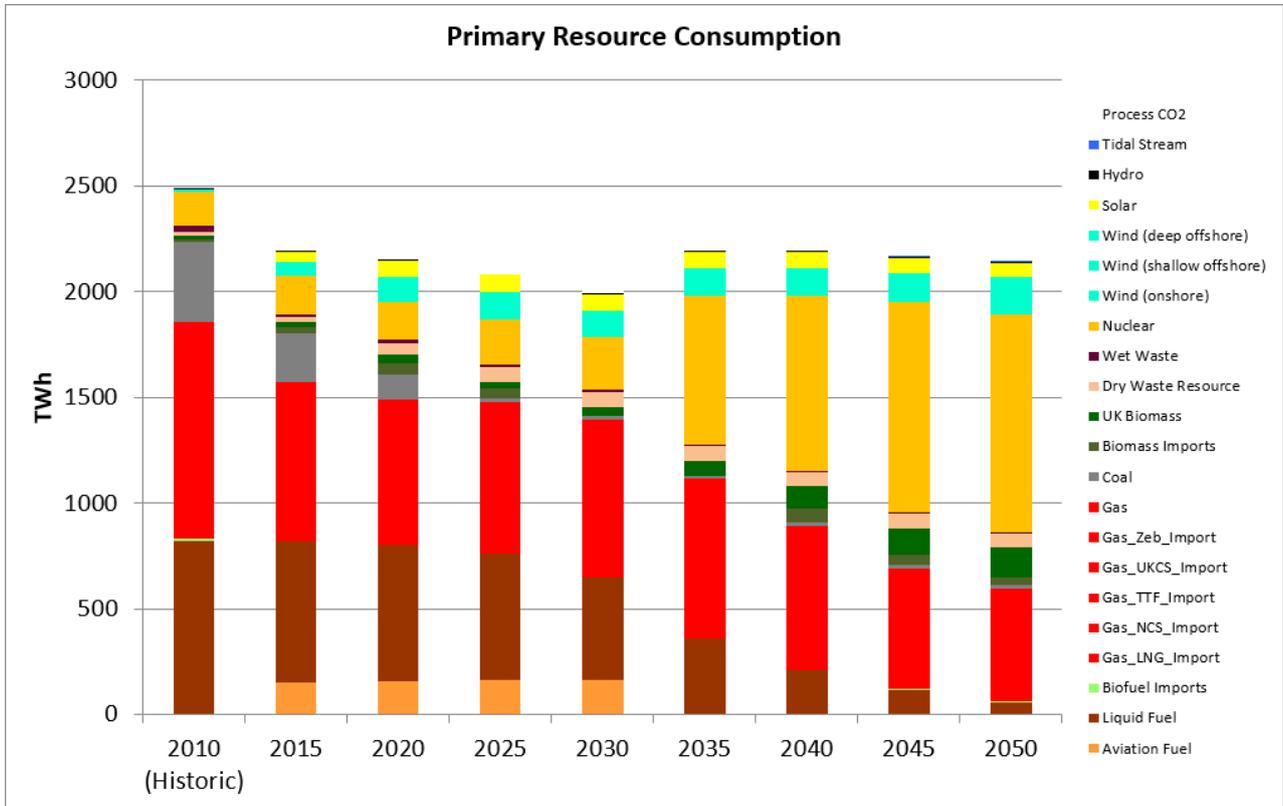
Figure A3-79 – Run 322 Network Hot Water Production
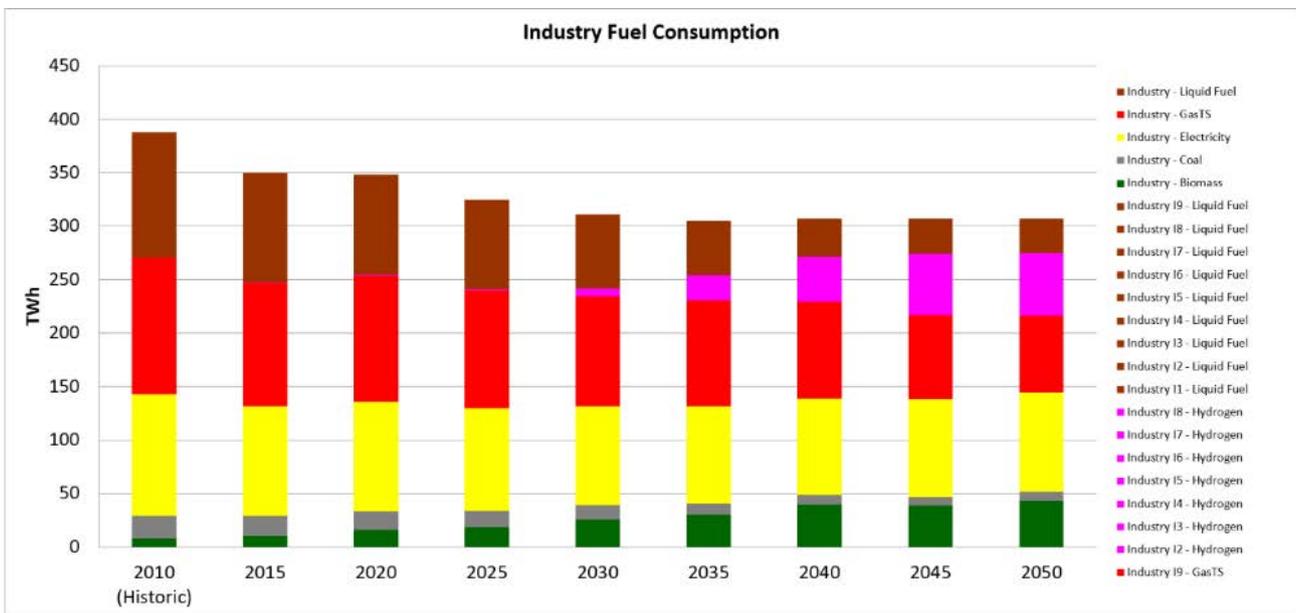
Figure A3-80 – Run 322 Industry Fuel Consumption

Run 323 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 4 x LC values

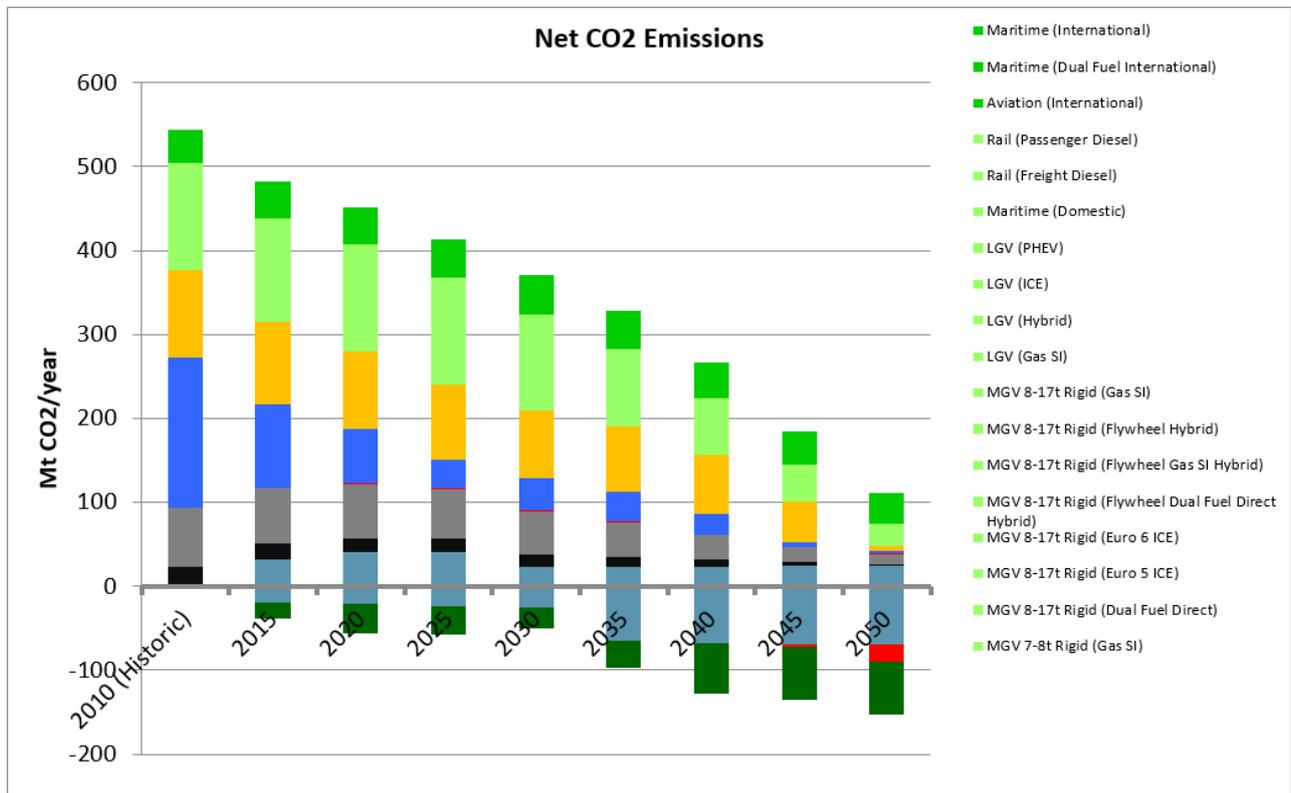Figure A3-81 – Run 323 Primary Resource Consumption
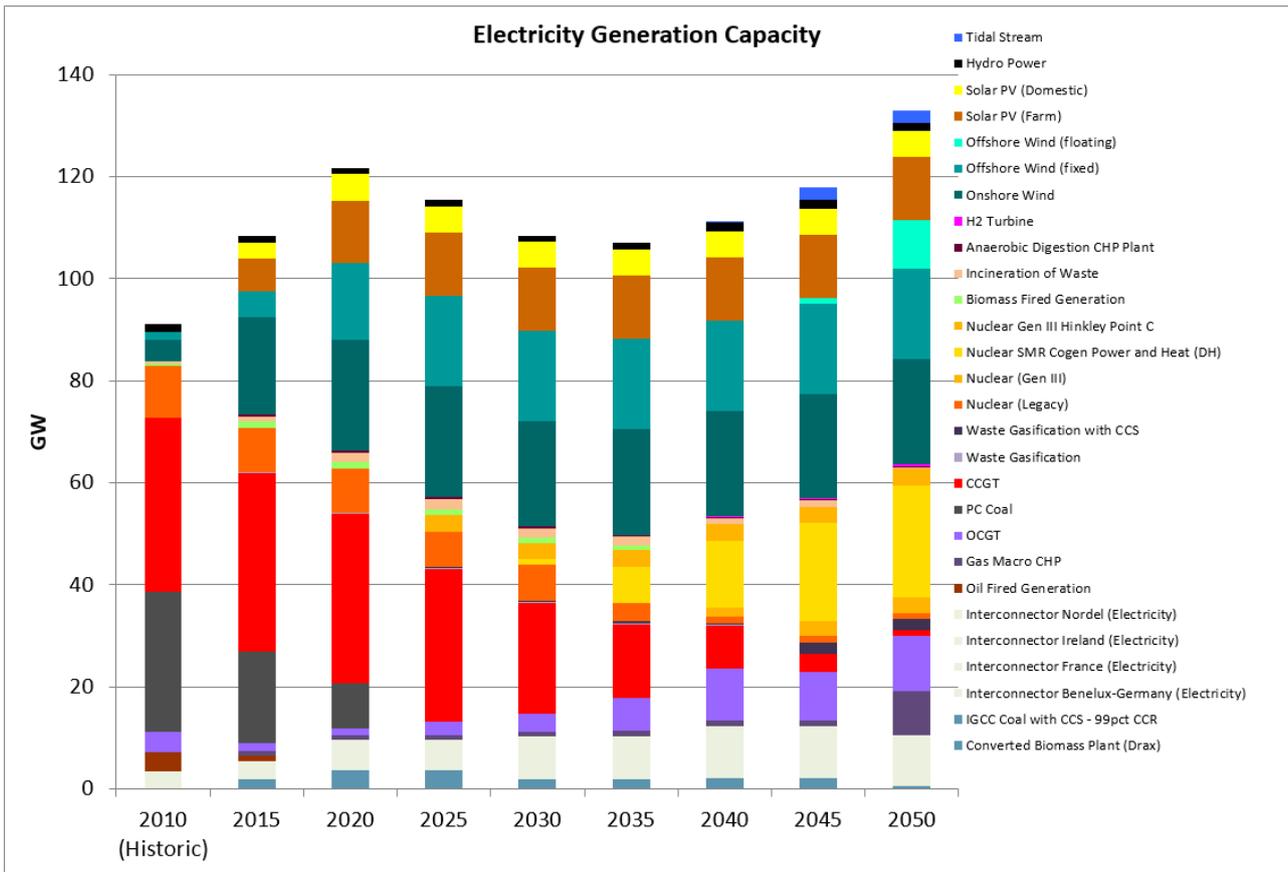

Figure A3-82 – Run 323 Net CO$_2$ Emissions

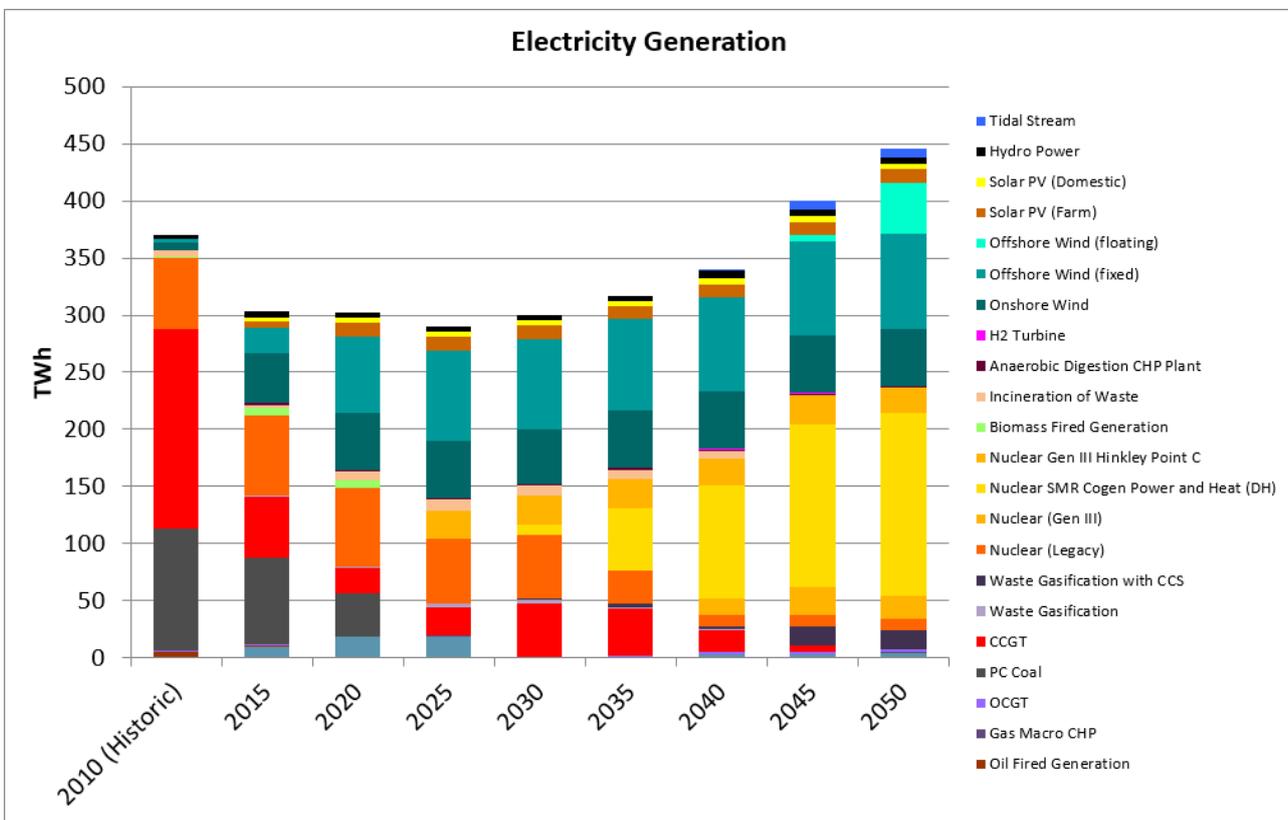Figure A3-83 – Run 323 Electricity Generation Capacity
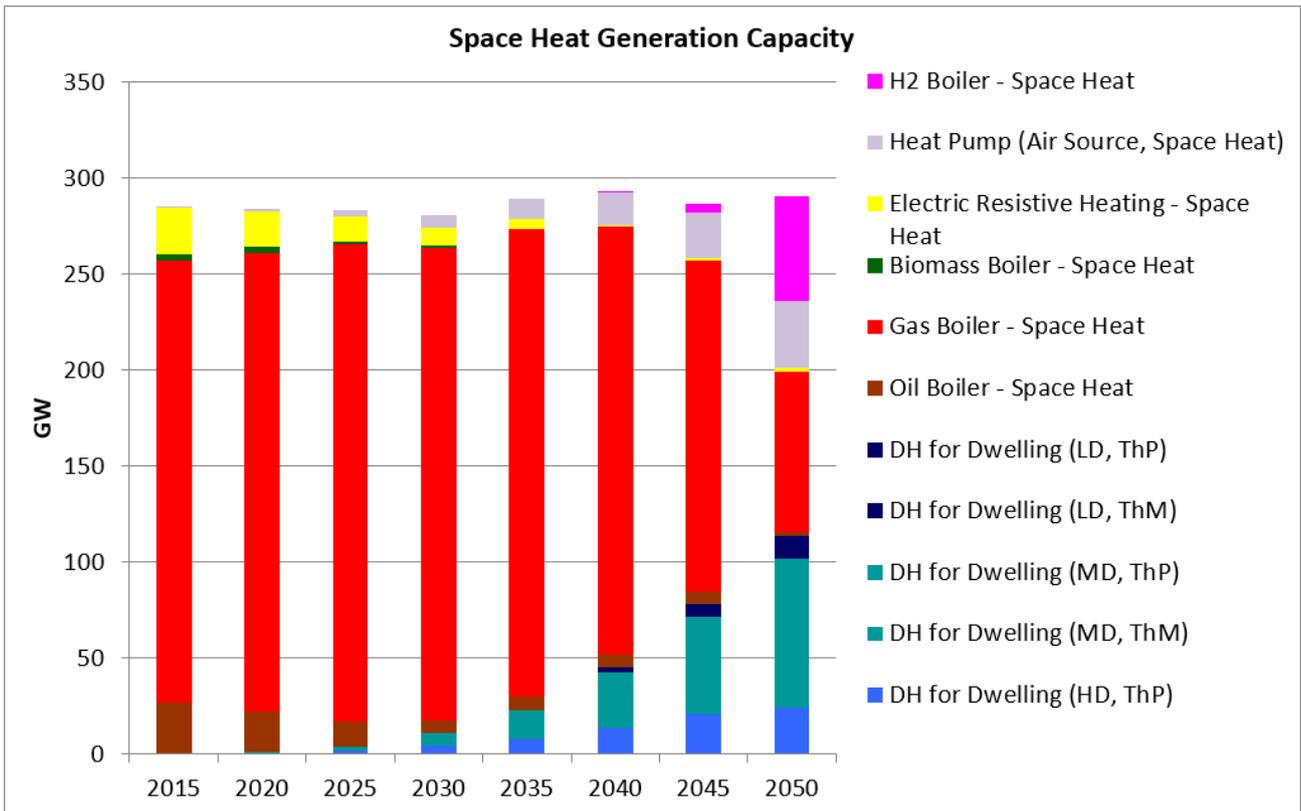

Figure A3-84 – Run 323 Electricity Generation

Figure A3-85 – Run 323 Space Heat Generation Capacity

Figure A3-86 – Run 323 Space Heat Production

Figure A3-87 – Run 323 Hydrogen Production

Figure A3-88 – Run 323 Hydrogen consumption

Figure A3-89 – Run 323 Network Hot Water Production

Figure A3-90 – Run 323 Industry Fuel Consumption

Run 324 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 5 x LC values

Figure A3-91 – Run 324 Primary Resource Consumption

Figure A3-92 – Run 324 Net CO$_2$ Emissions

Figure A3-93 – Run 324 Electricity Generation Capacity

Figure A3-94 – Run 324 Electricity Generation
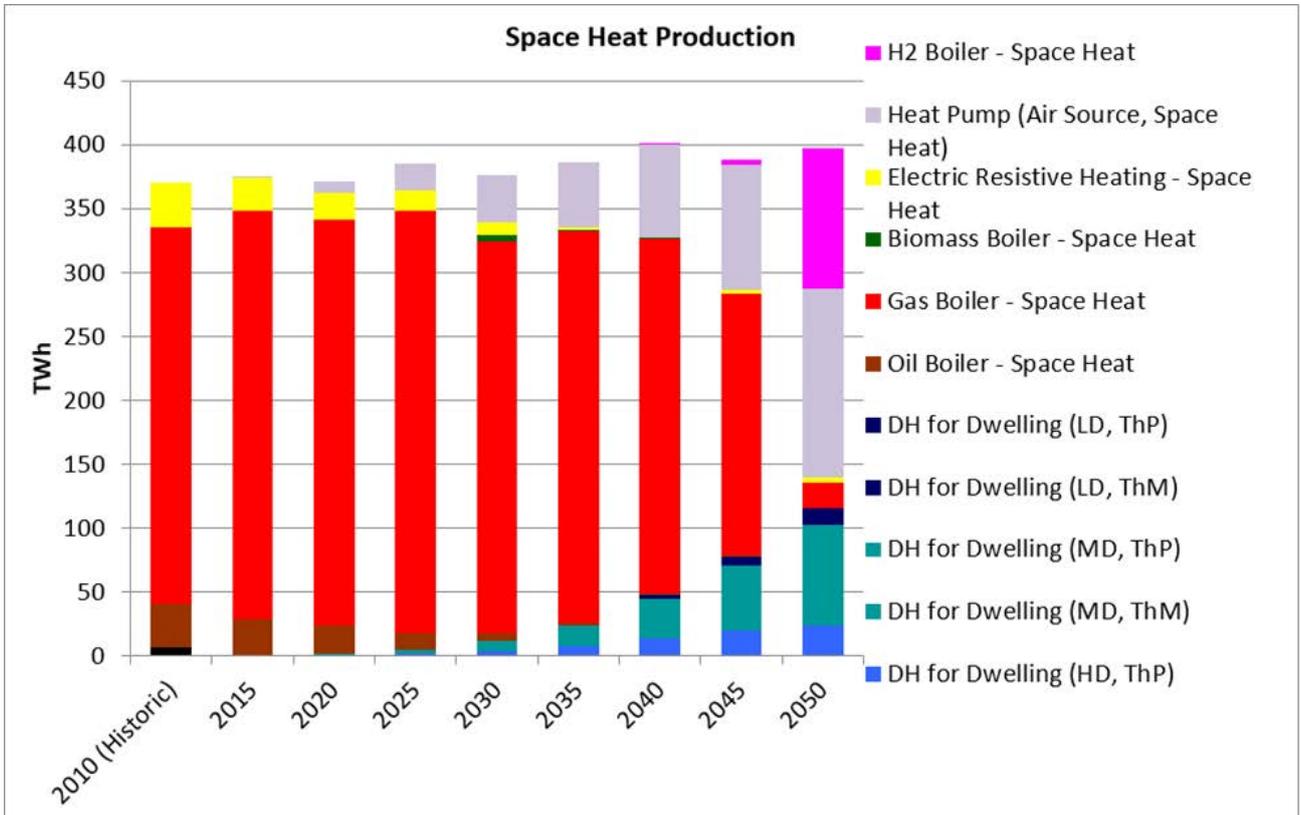
Figure A3-95 – Run 324 Space Heat Generation Capacity
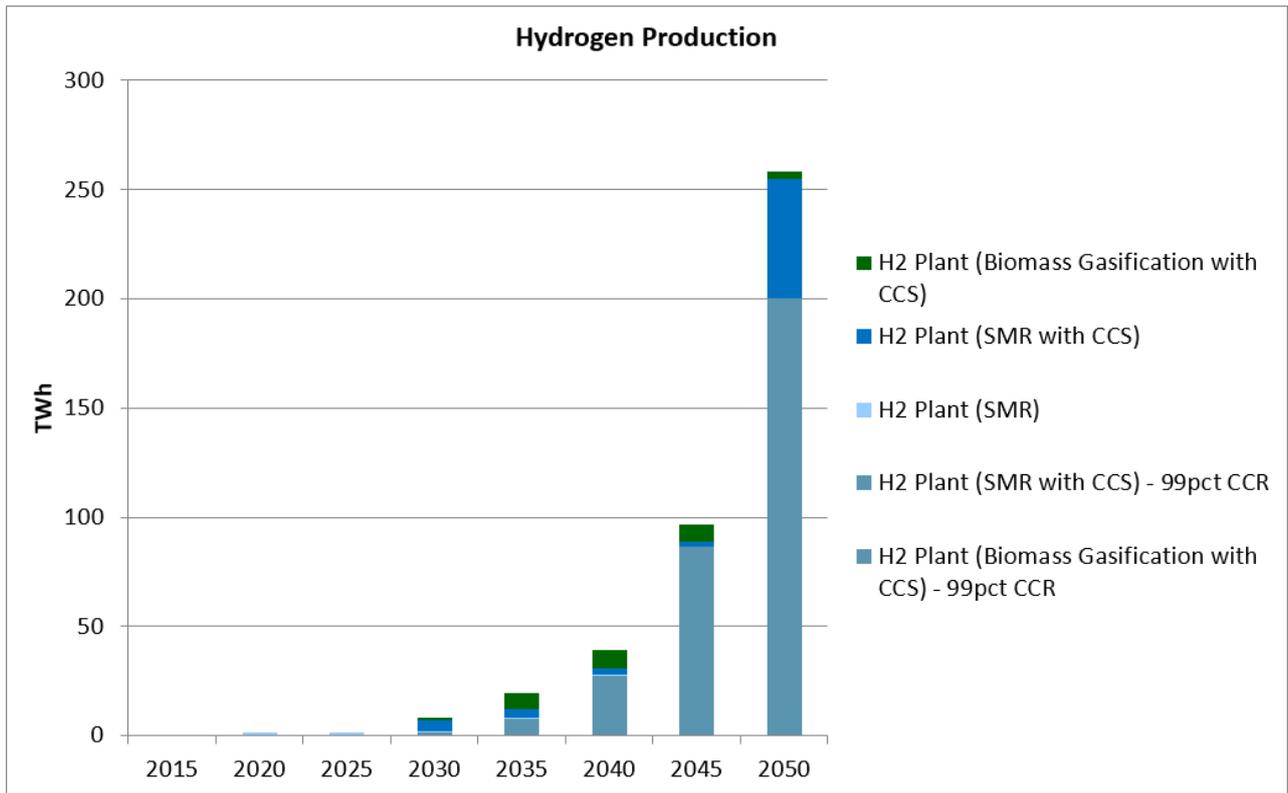

Figure A3-96 – Run 324 Space Heat Production
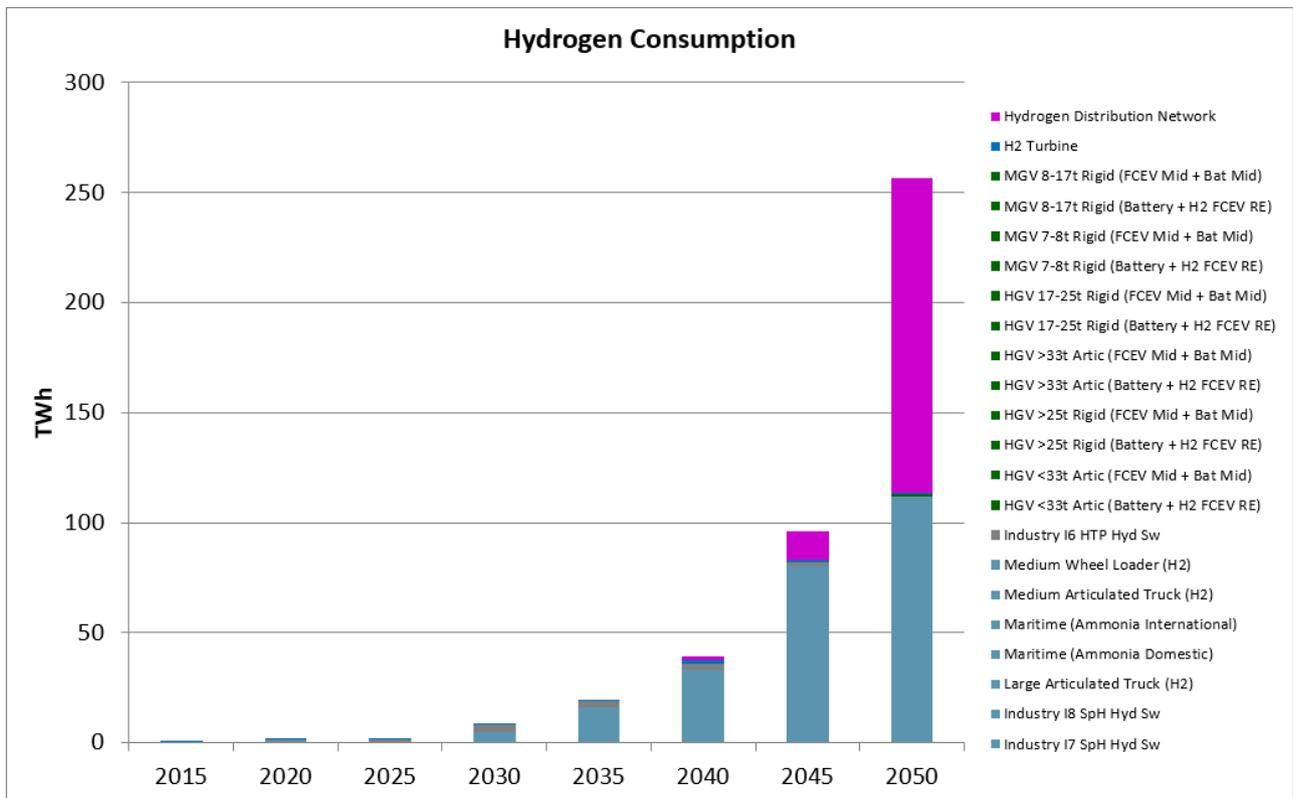
Figure A3-97 – Run 324 Hydrogen Production
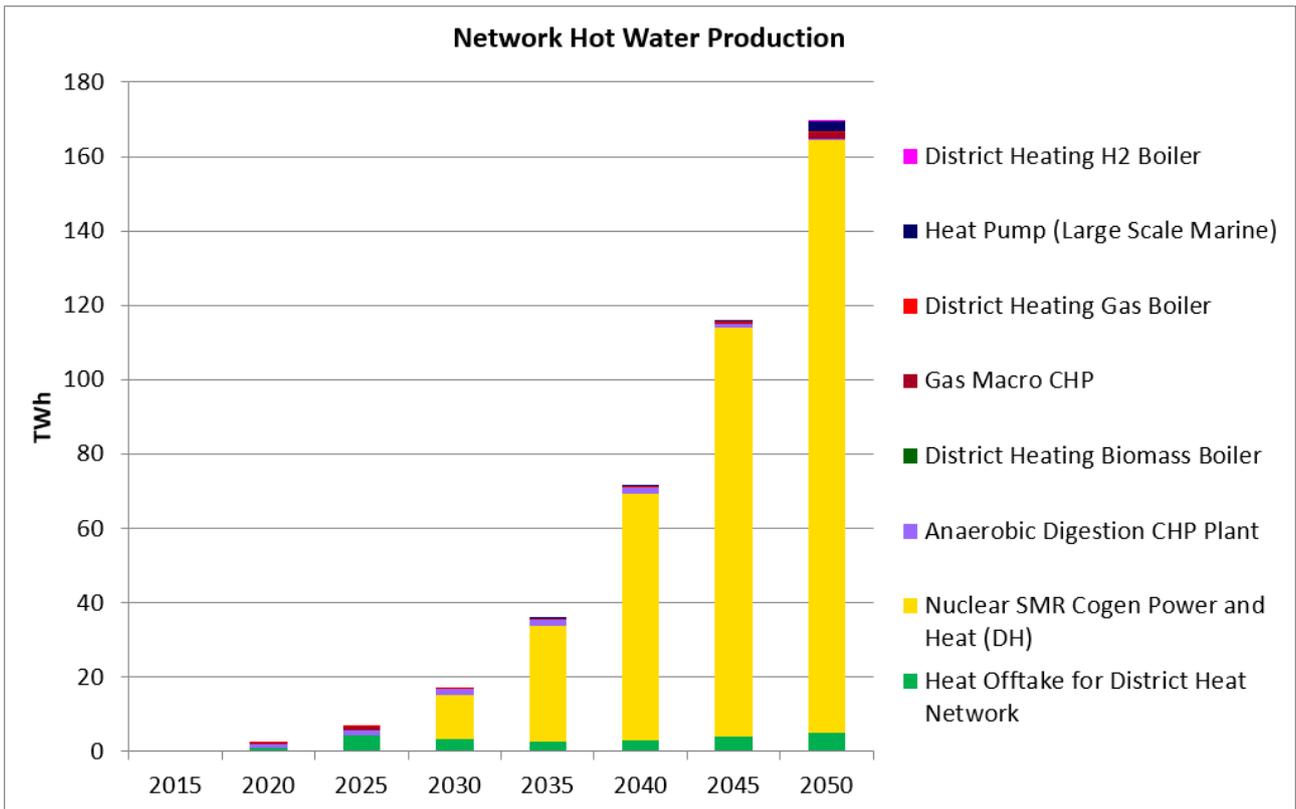

Figure A3-98 – Run 324 Hydrogen consumption

Figure A3-99 – Run 324 Network Hot Water Production

Figure A3-100 – Run 324 Industry Fuel Consumption

Run 325 TECH100 – Gen III+, LWSMR cogen, gigafactory and no synthetic fuel plant; base case data except gigafactory capex at 0.66 x LC values

Figure A3-101 – Run 325 Primary Resource Consumption

Figure A3-102 – Run 325 Net CO₂ Emissions

Figure A3-103 – Run 325 Electricity Generation Capacity

Figure A3-104 – Run 325 Electricity Generation

Figure A3-105 – Run 325 Space Heat Generation Capacity

Figure A3-106 – Run 325 Space Heat Production

Figure A3-107 – Run 325 Hydrogen Production

Figure A3-108 – Run 325 Hydrogen consumption
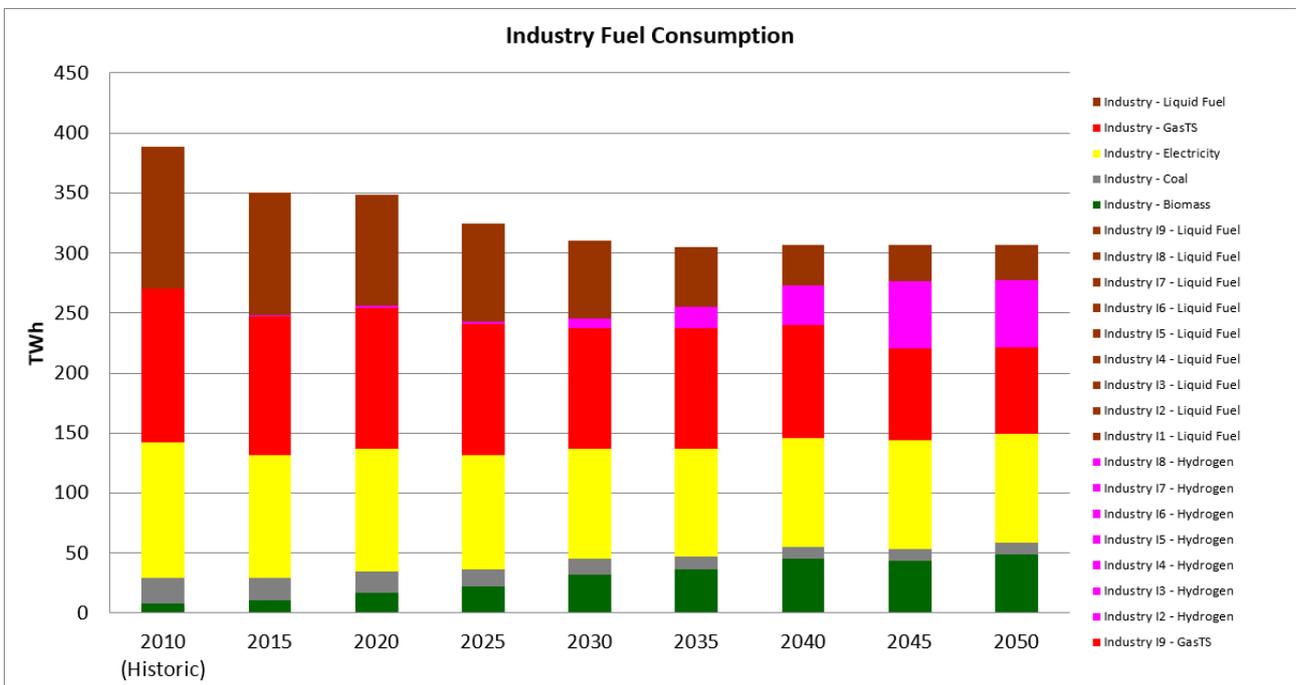
Figure A3-109 – Run 325 Network Hot Water Production
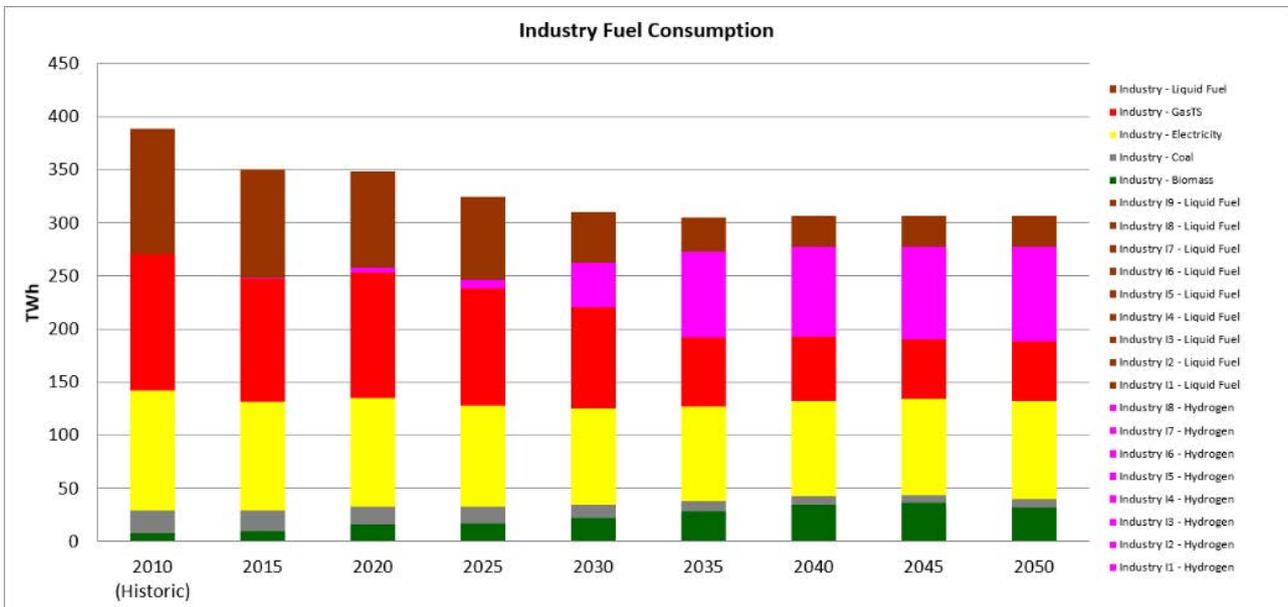
Figure A3-110 – Run 325 Industry Fuel

Run 350 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 1 x LC values
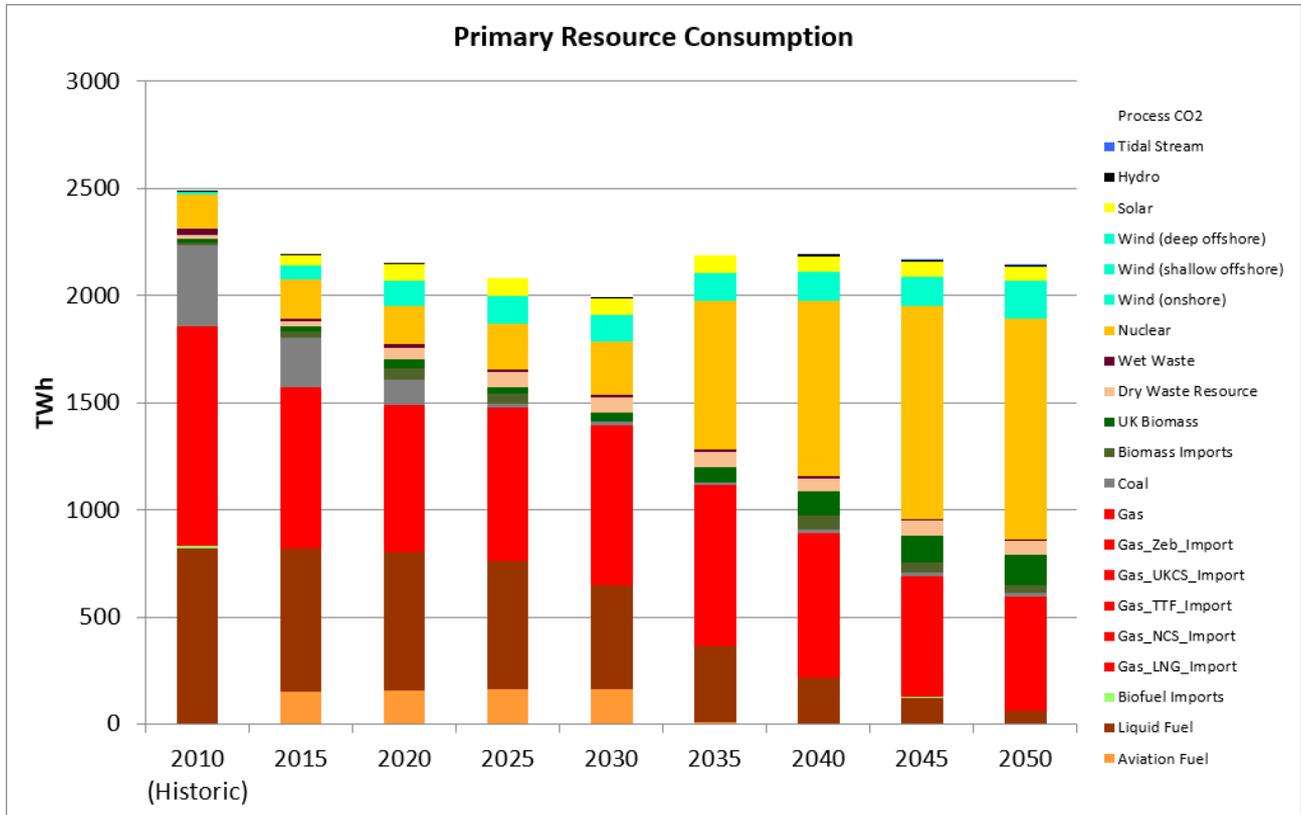
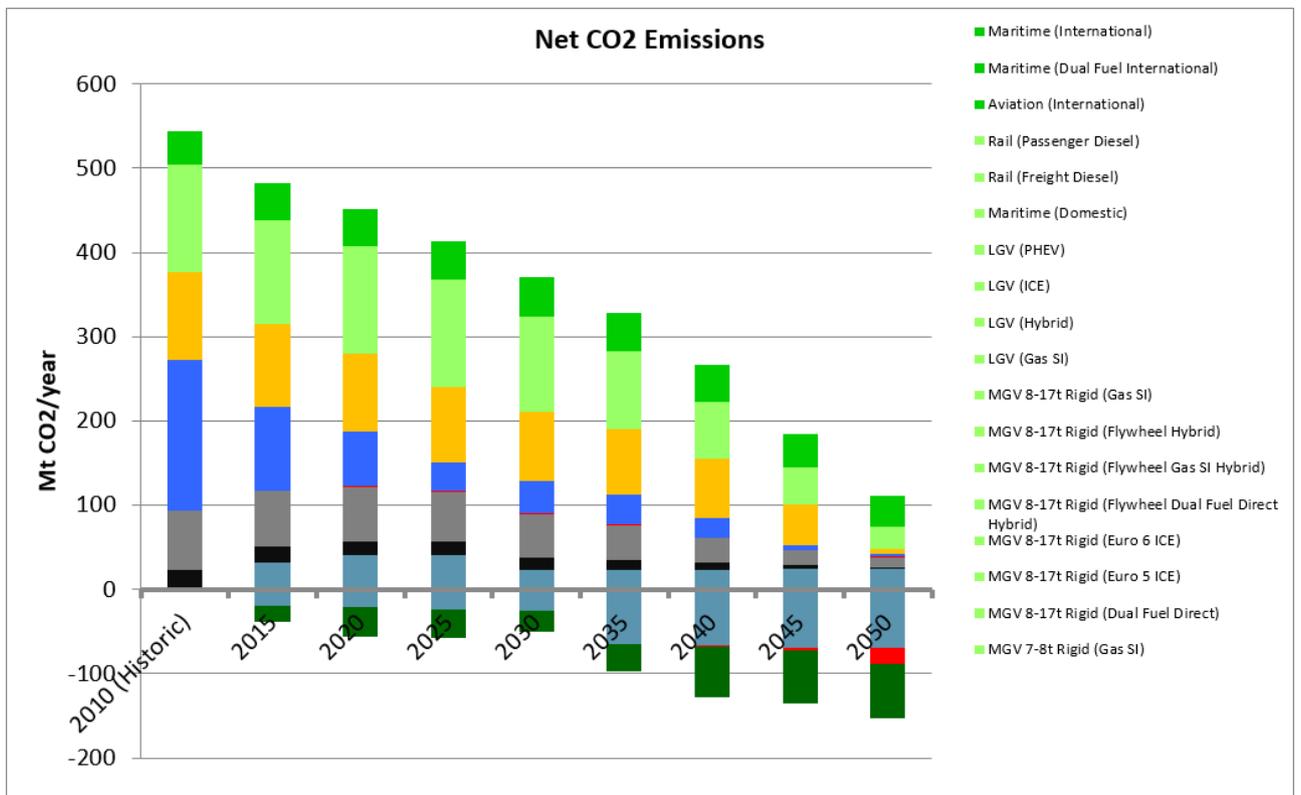

Figure A3-111 – Run 350 Primary Resource Consumption

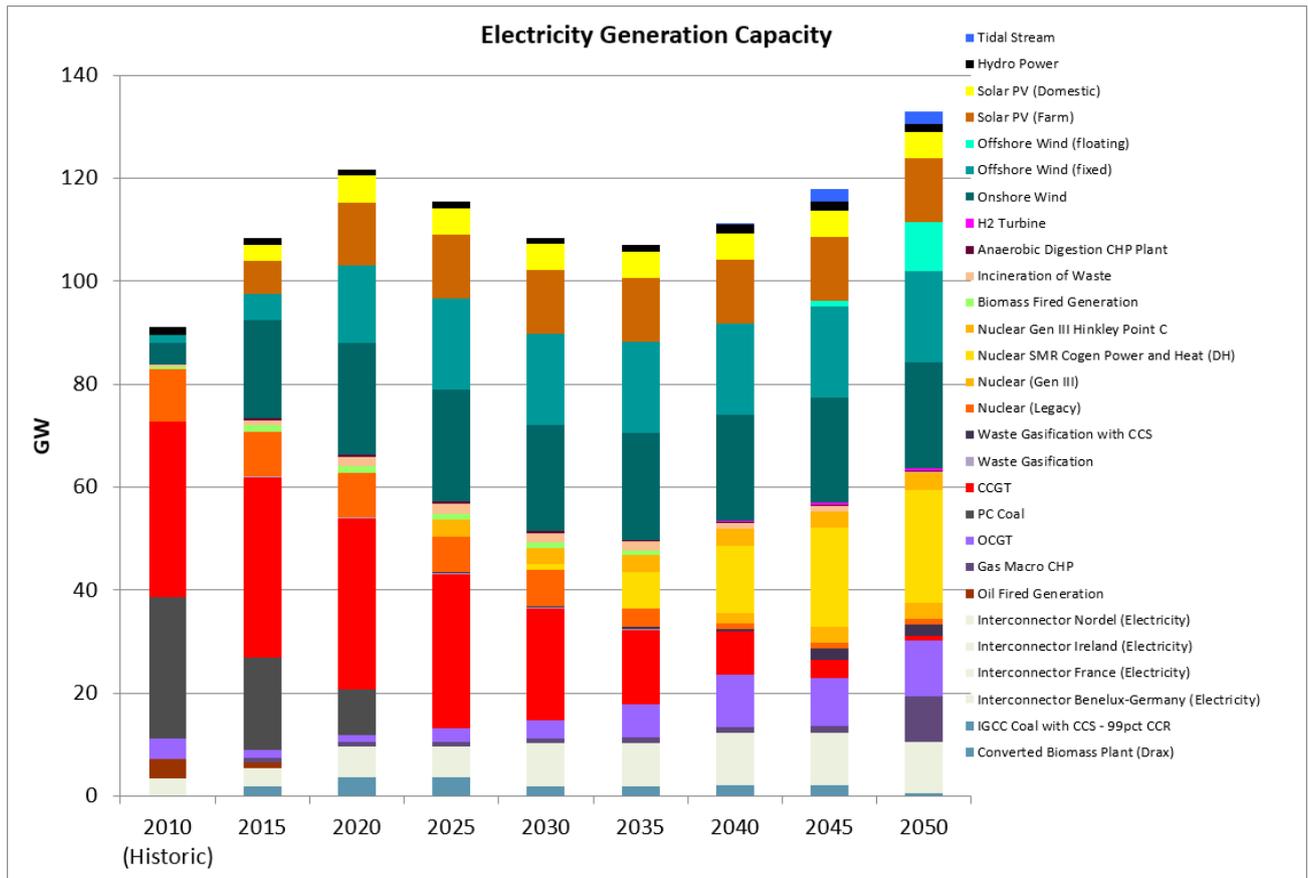Figure A3-112 – Run 350 Net CO$_2$ Emissions

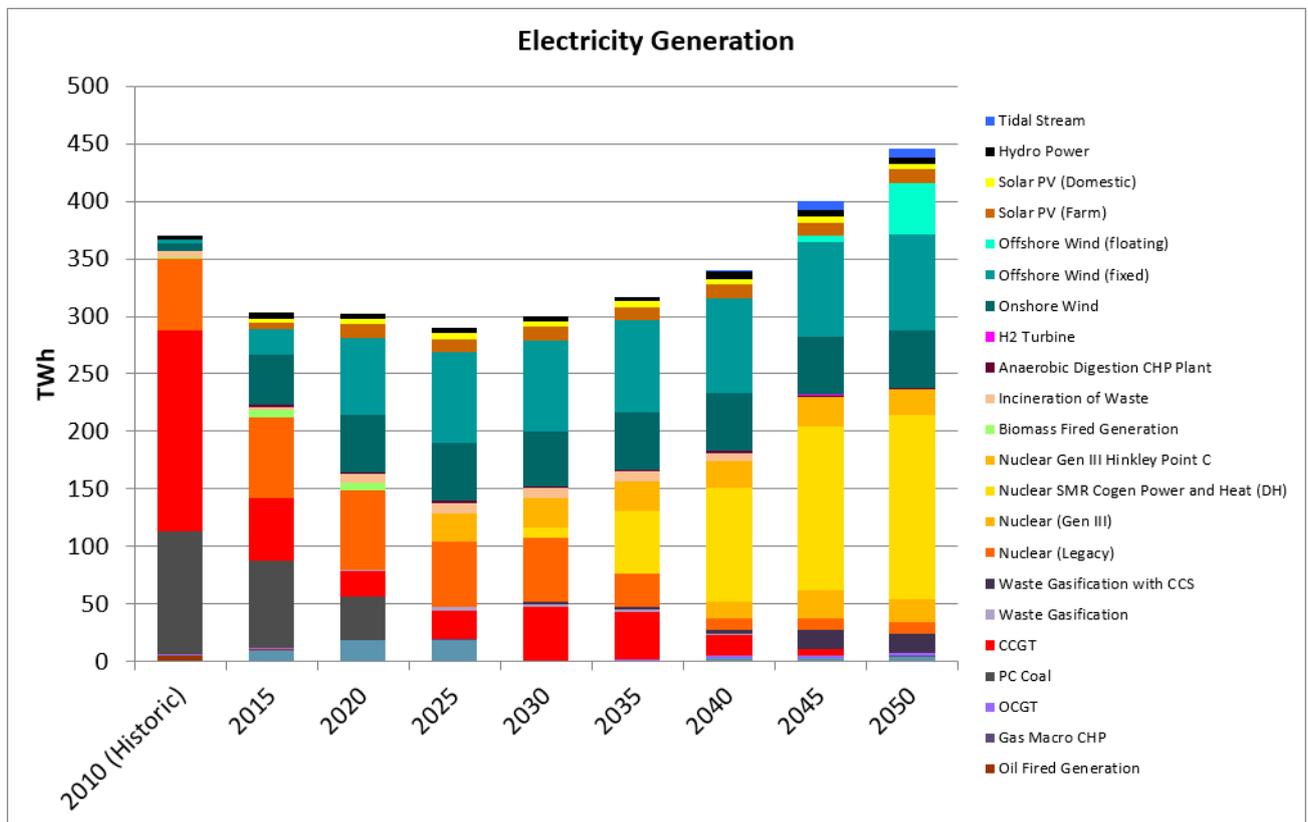Figure A3-113 – Run 350 Electricity Generation Capacity
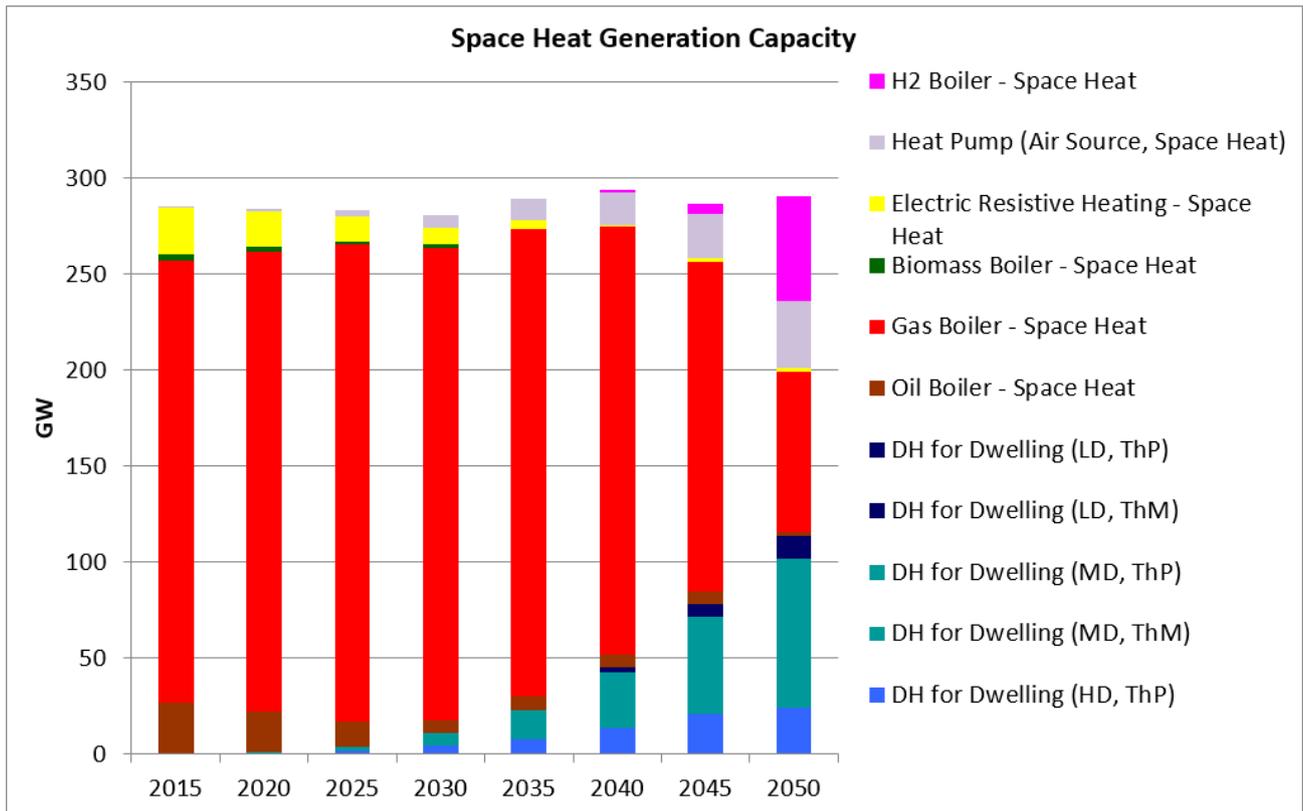

Figure A3-114 – Run 350 Electricity Generation

Figure A3-115 – Run 350 Space Heat Generation Capacity

Figure A3-116 – Run 350 Space Heat Production

Figure A3-117 – Run 350 Hydrogen Production

Figure A3-118 – Run 350 Hydrogen consumption

Figure A3-119 – Run 350 Network Hot Water Production

Figure A3-120 – Run 350 Industry Fuel Consumption

Run 351 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 2 x LC values

Figure A3-121 – Run 351 Primary Resource Consumption

Figure A3-122 – Run 351 Net CO$_2$ Emissions

Figure A3-123 – Run 351 Electricity Generation Capacity

Figure A3-124 – Run 351 Electricity Generation

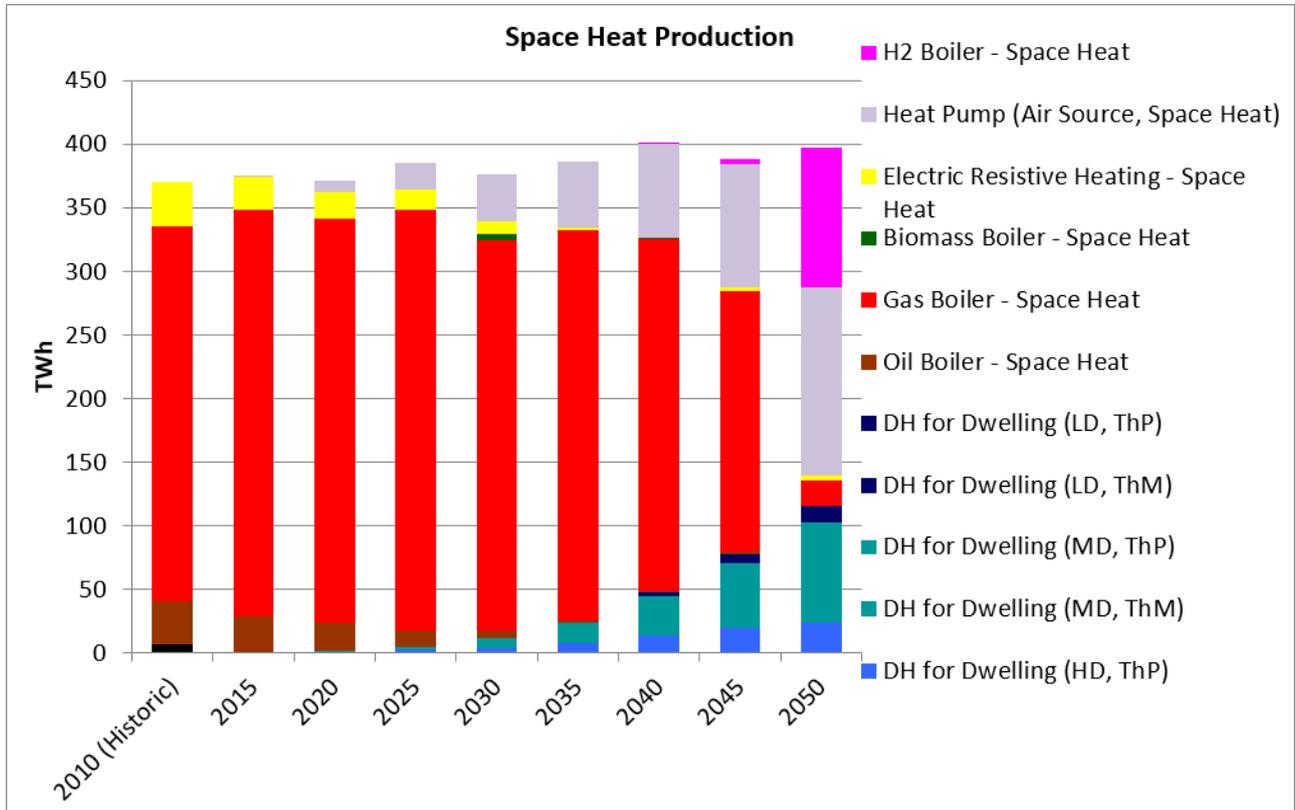Figure A3-125 – Run 351 Space Heat Generation Capacity

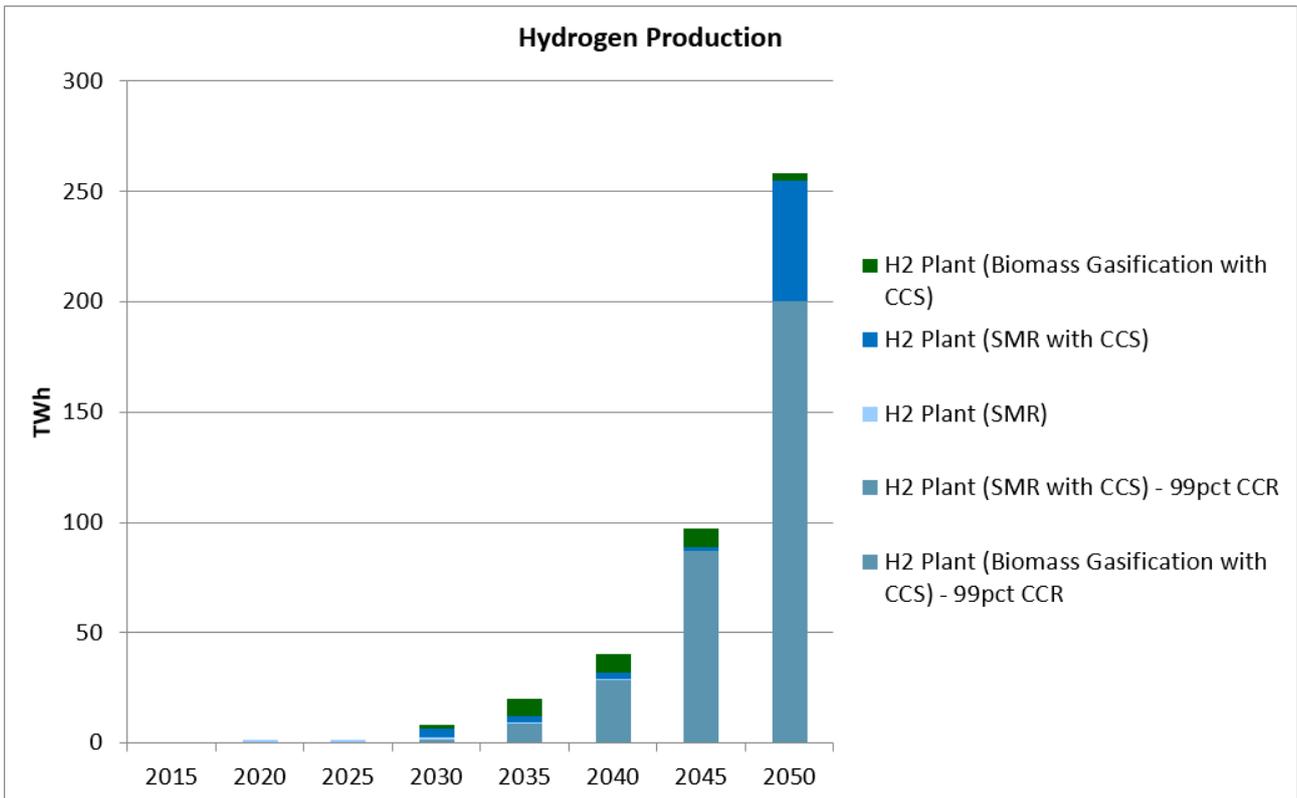Figure A3-126 – Run 351 Space Heat Production
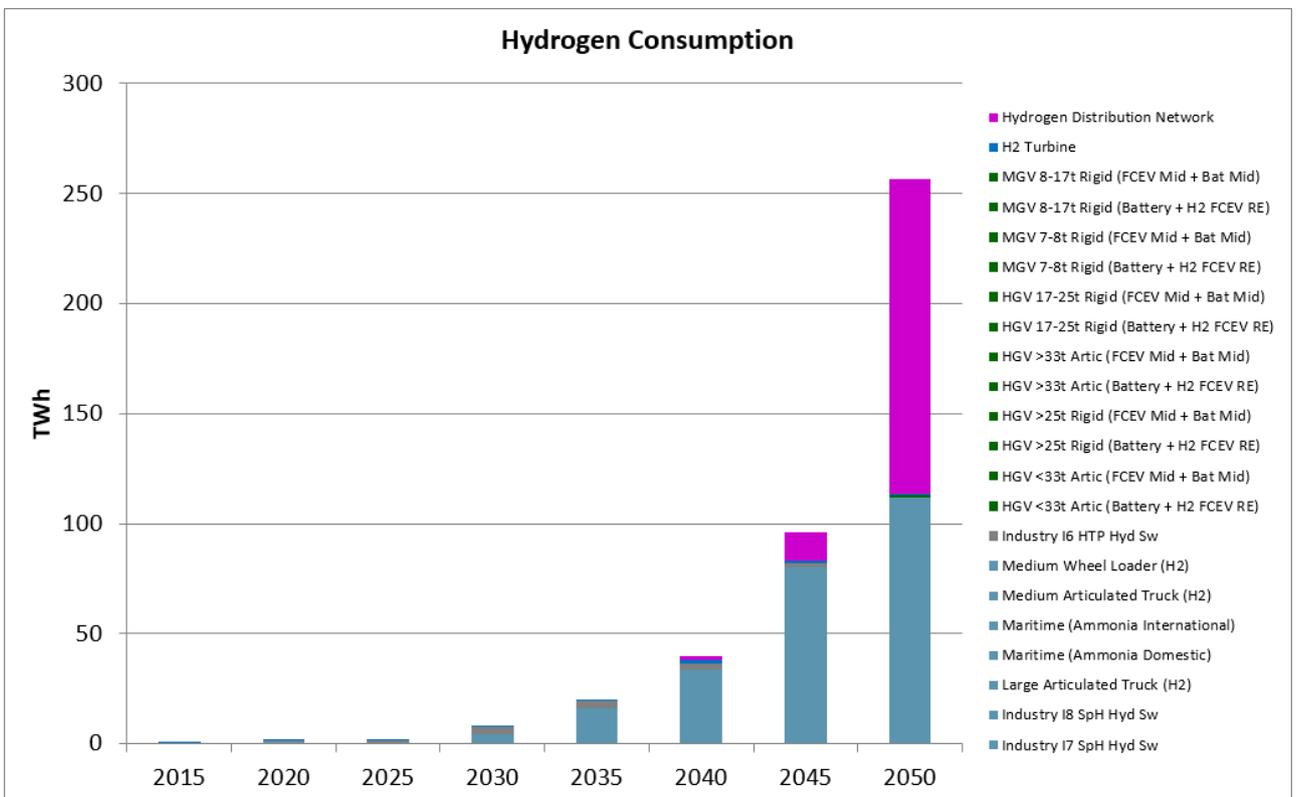
Figure A3-127 – Run 351 Hydrogen Production

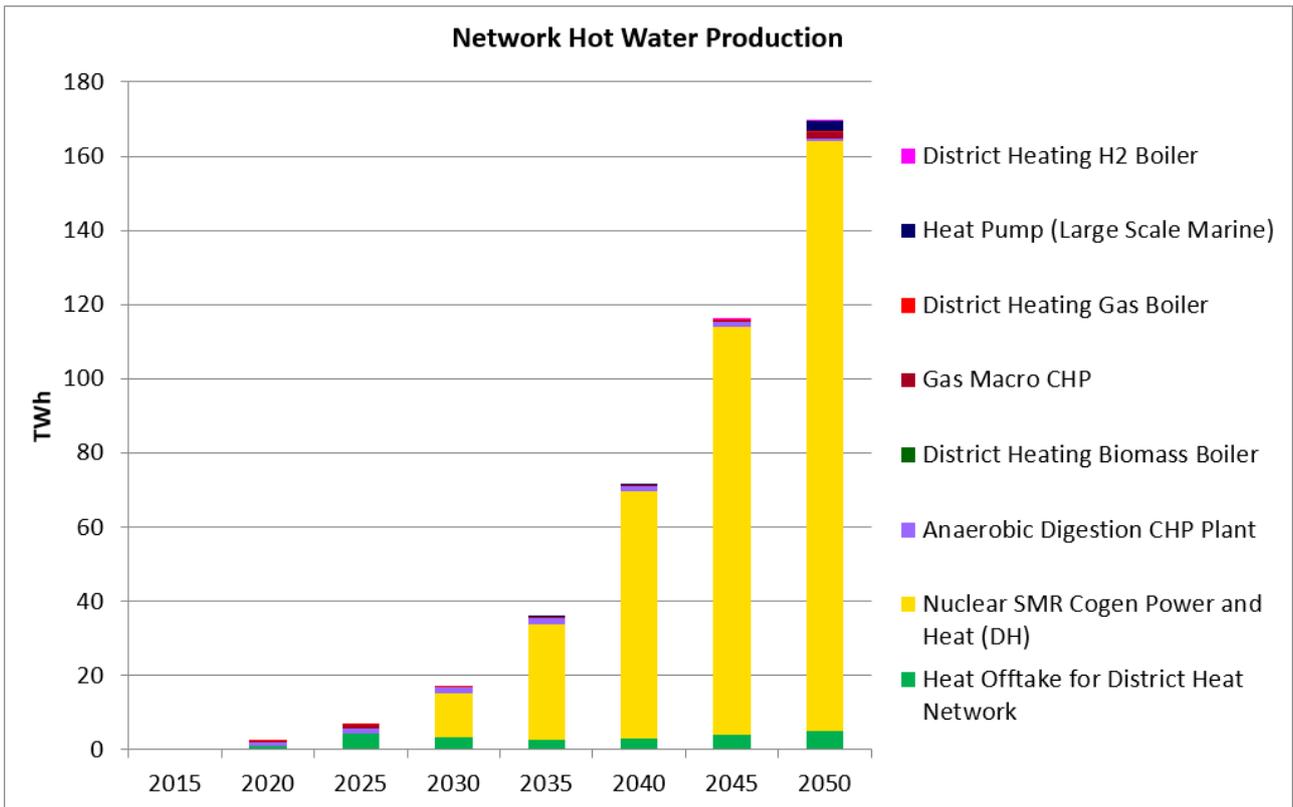Figure A3-128 – Run 351 Hydrogen consumption

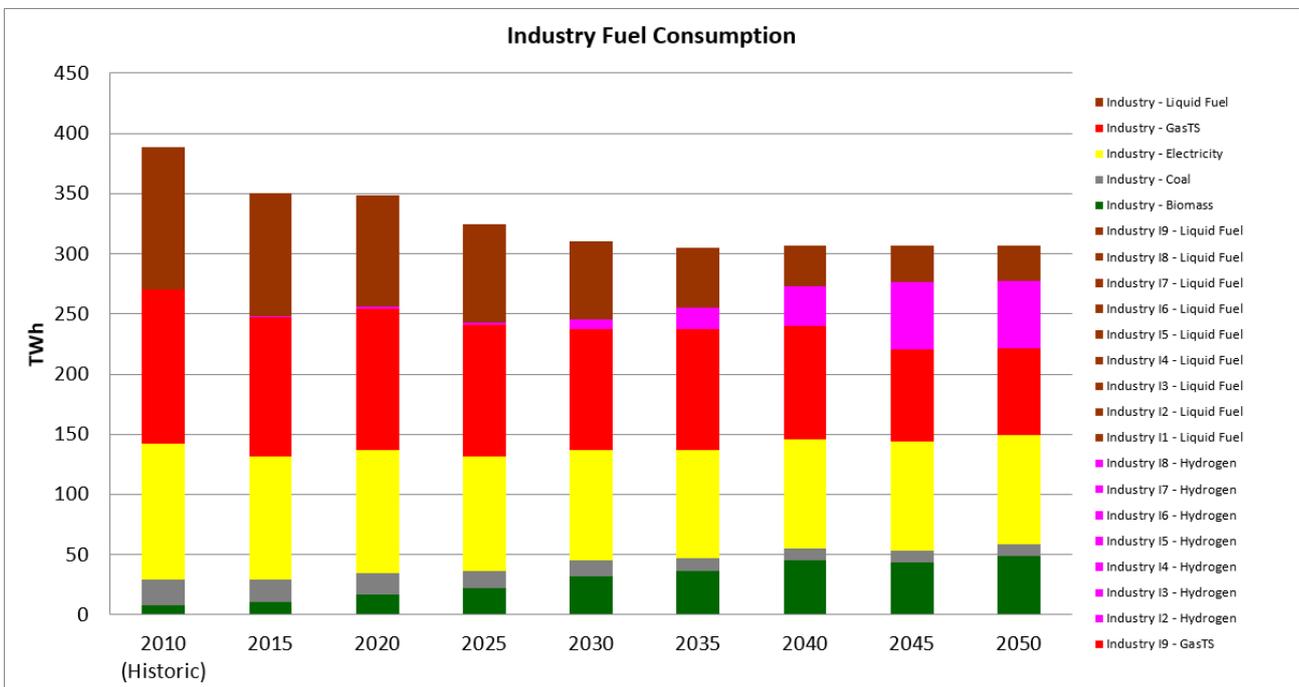Figure A3-129 – Run 351 Network Hot Water Production

Figure A3-130 – Run 351 Industry Fuel Consumption

Run 352 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 4 x LC values
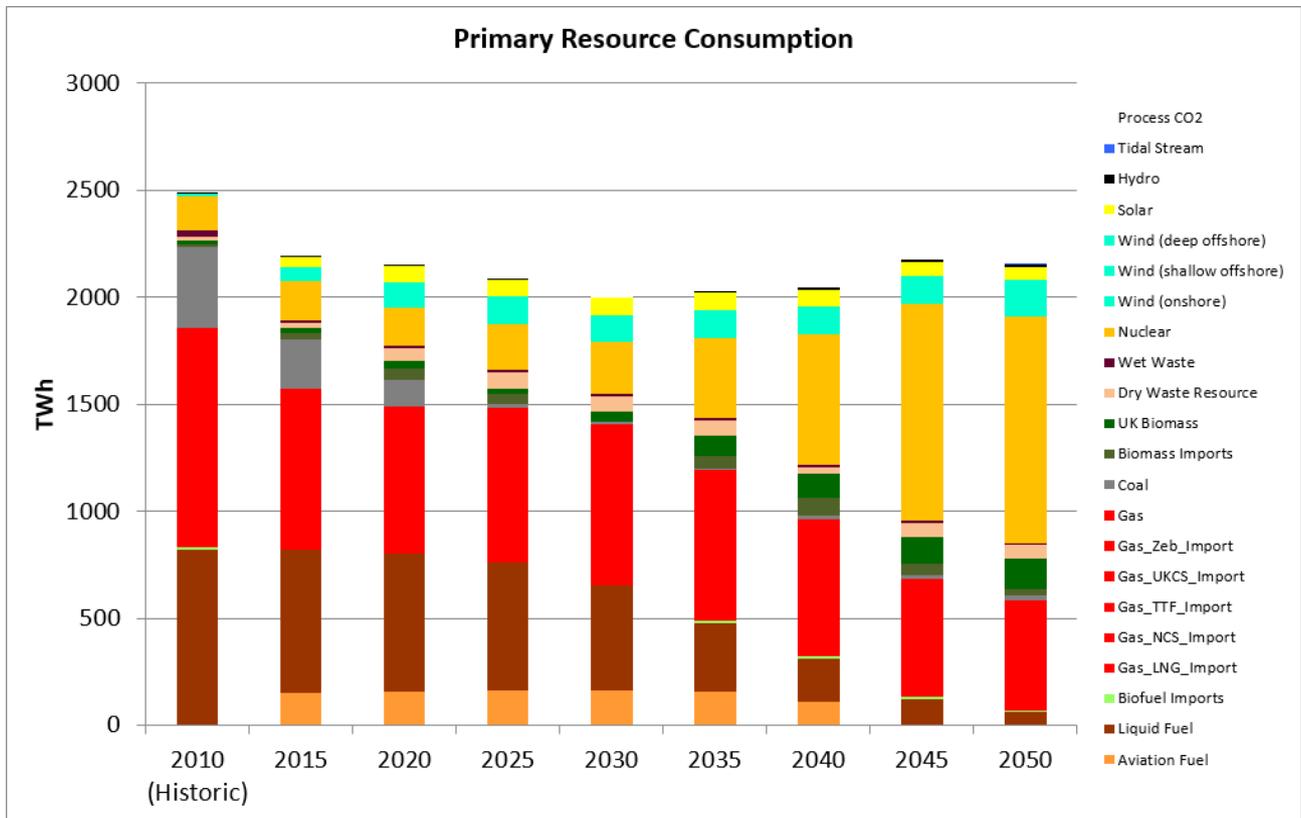

Figure A3-131 – Run 352 Primary Resource Consumption

Figure A3-132 – Run 352 Net CO$_2$ Emissions

Figure A3-133 – Run 352 Electricity Generation Capacity

Figure A3-134 – Run 352 Electricity Generation

Figure A3-135 – Run 352 Space Heat Generation Capacity

Figure A3-136 – Run 352 Space Heat Production

Figure A3-137 – Run 352 Hydrogen Production

Figure A3-138 – Run 352 Hydrogen consumption

Figure A3-139 – Run 352 Network Hot Water Production

Figure A3-140 – Run 352 Industry Fuel Consumption

Run 353 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 10 x LC values

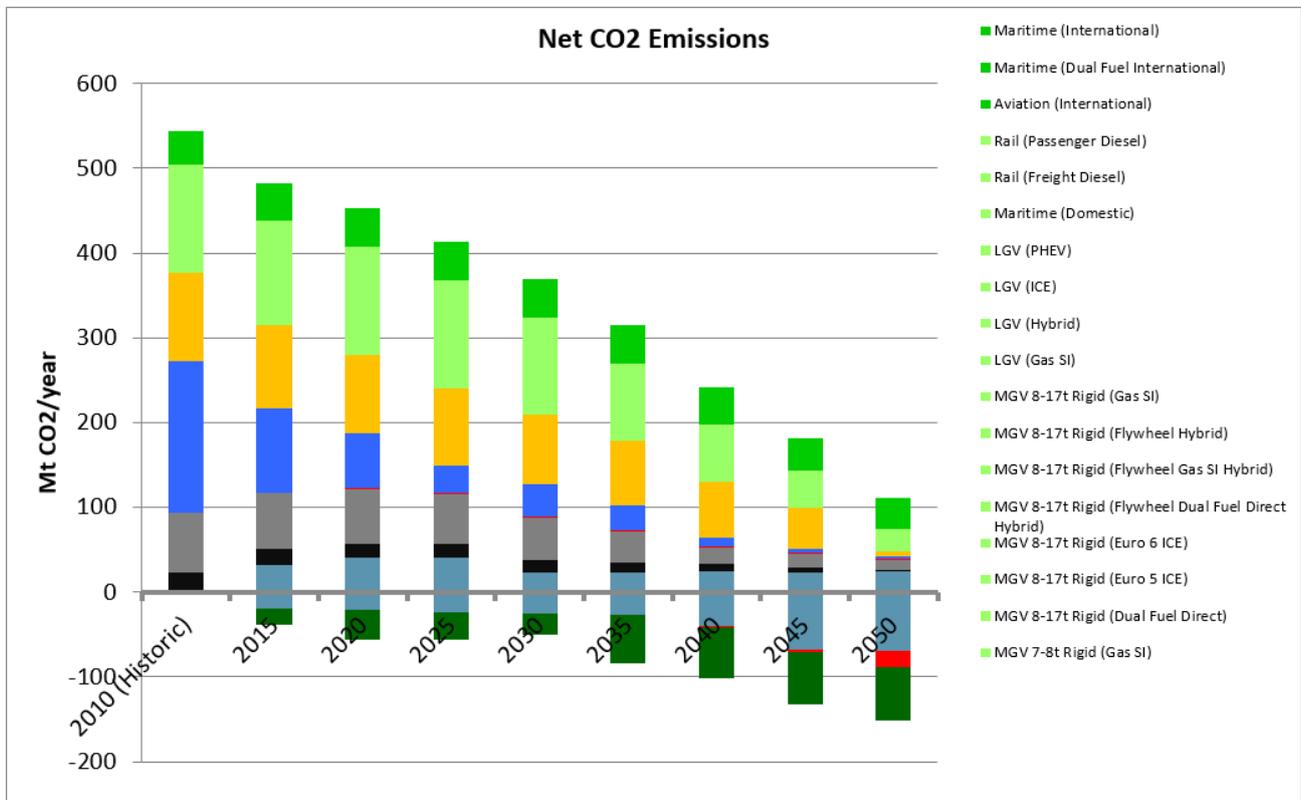Figure A3-141 – Run 353 Primary Resource Consumption

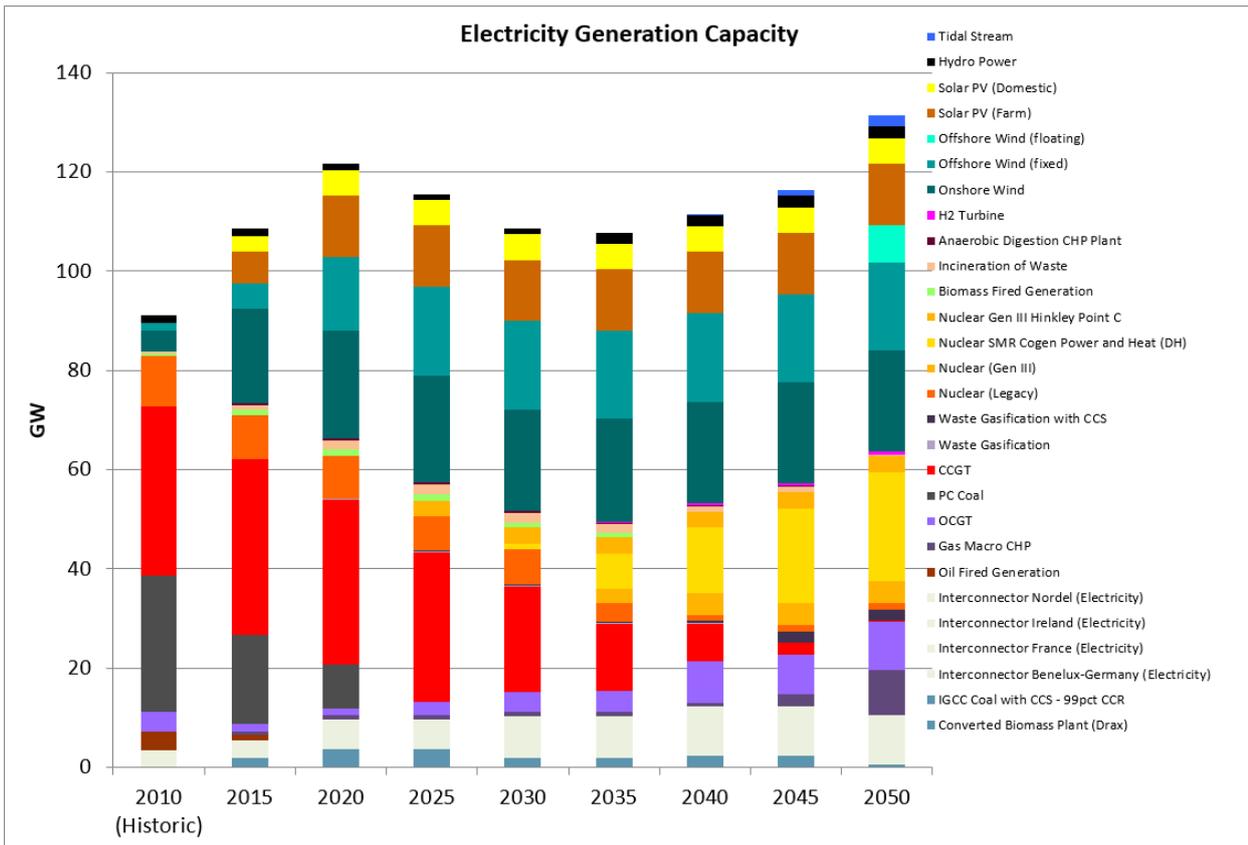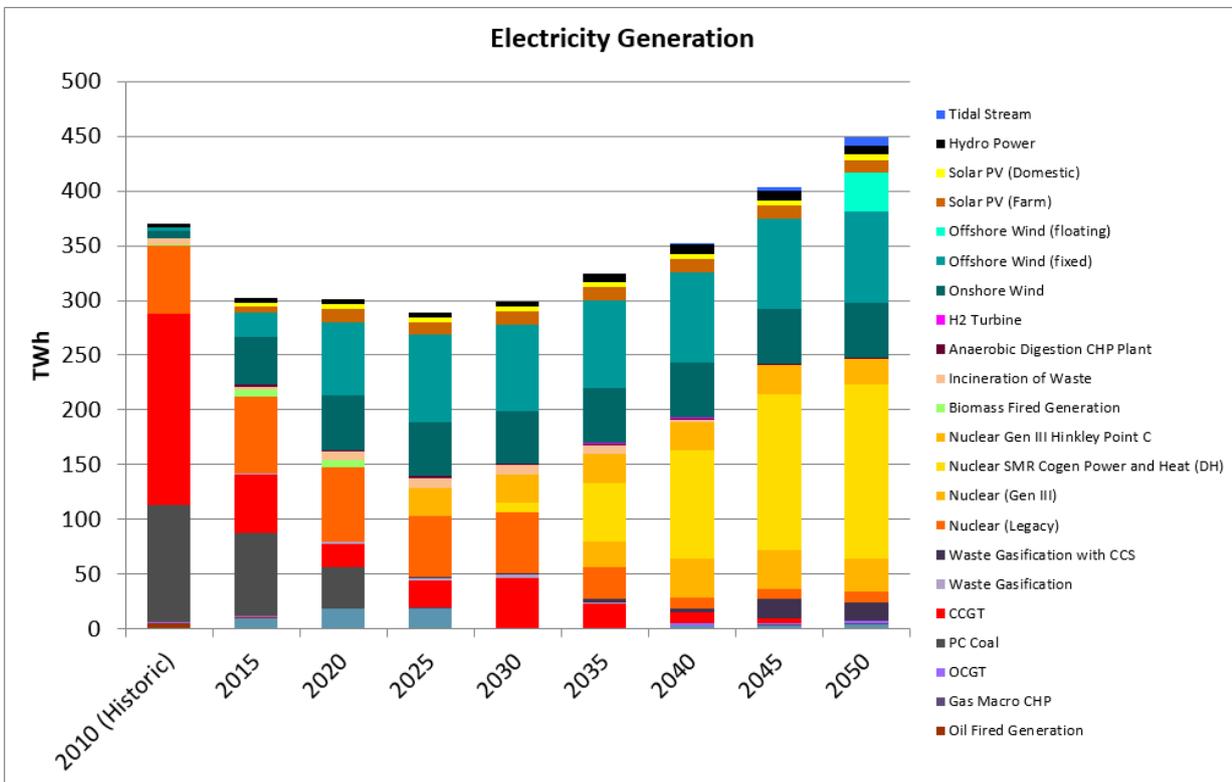Figure A3-142 – Run 353 Net CO$_2$ Emissions

Figure A3-143 – Run 353 Electricity Generation Capacity

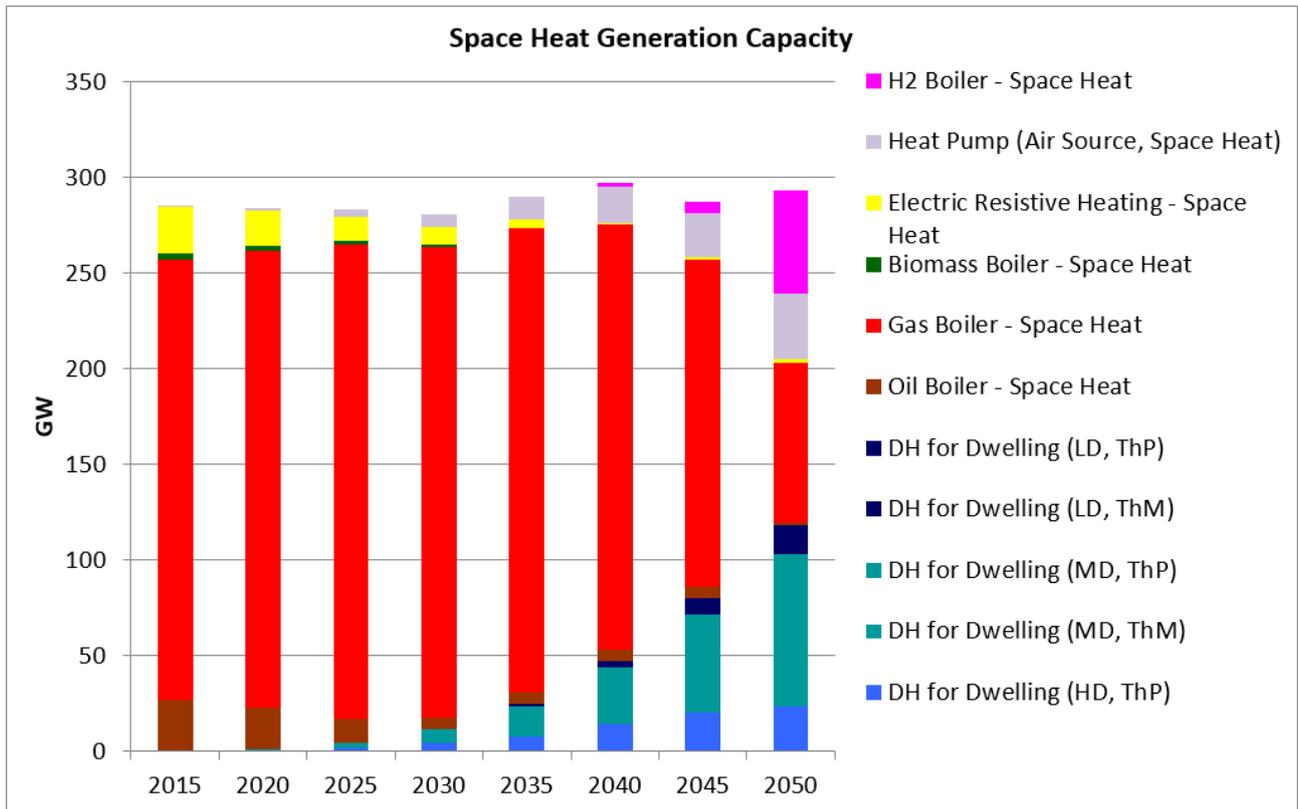Figure A3-144 – Run 353 Electricity Generation

Figure A3-145 – Run 353 Space Heat Generation Capacity

Figure A3-146 – Run 353 Space Heat Production

Figure A3-147 – Run 353 Hydrogen Production

Figure A3-148 – Run 353 Hydrogen consumption
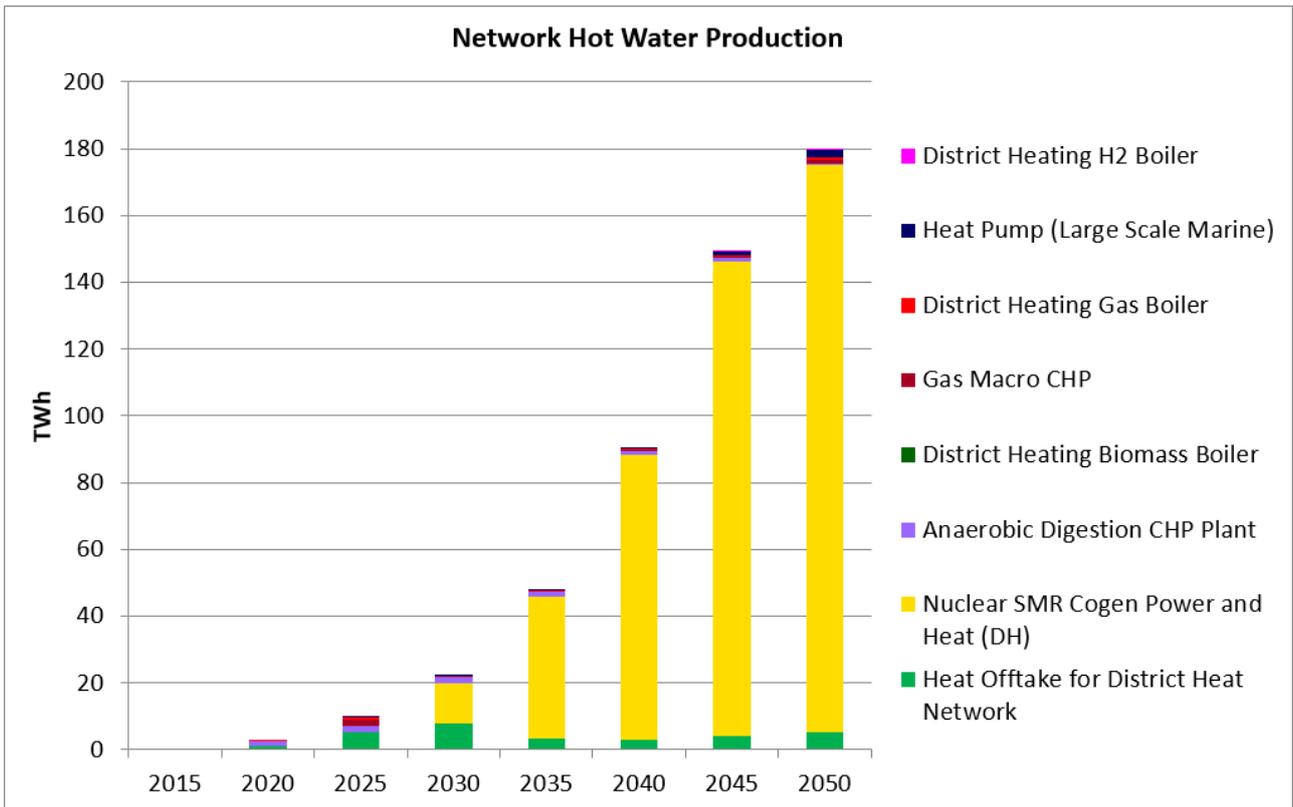
Figure A3-149 – Run 353 Network Hot Water Production
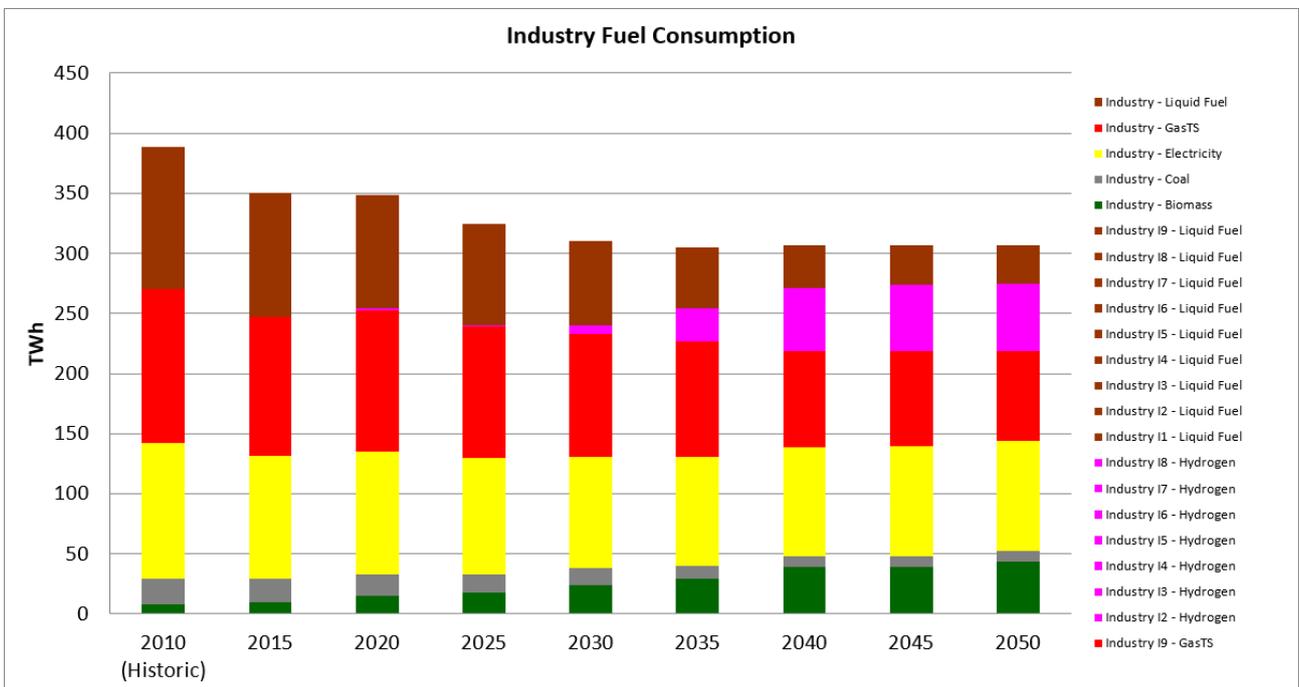
Figure A3-150 – Run 353 Industry Fuel Consumption

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Run 354 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 30 x LC values
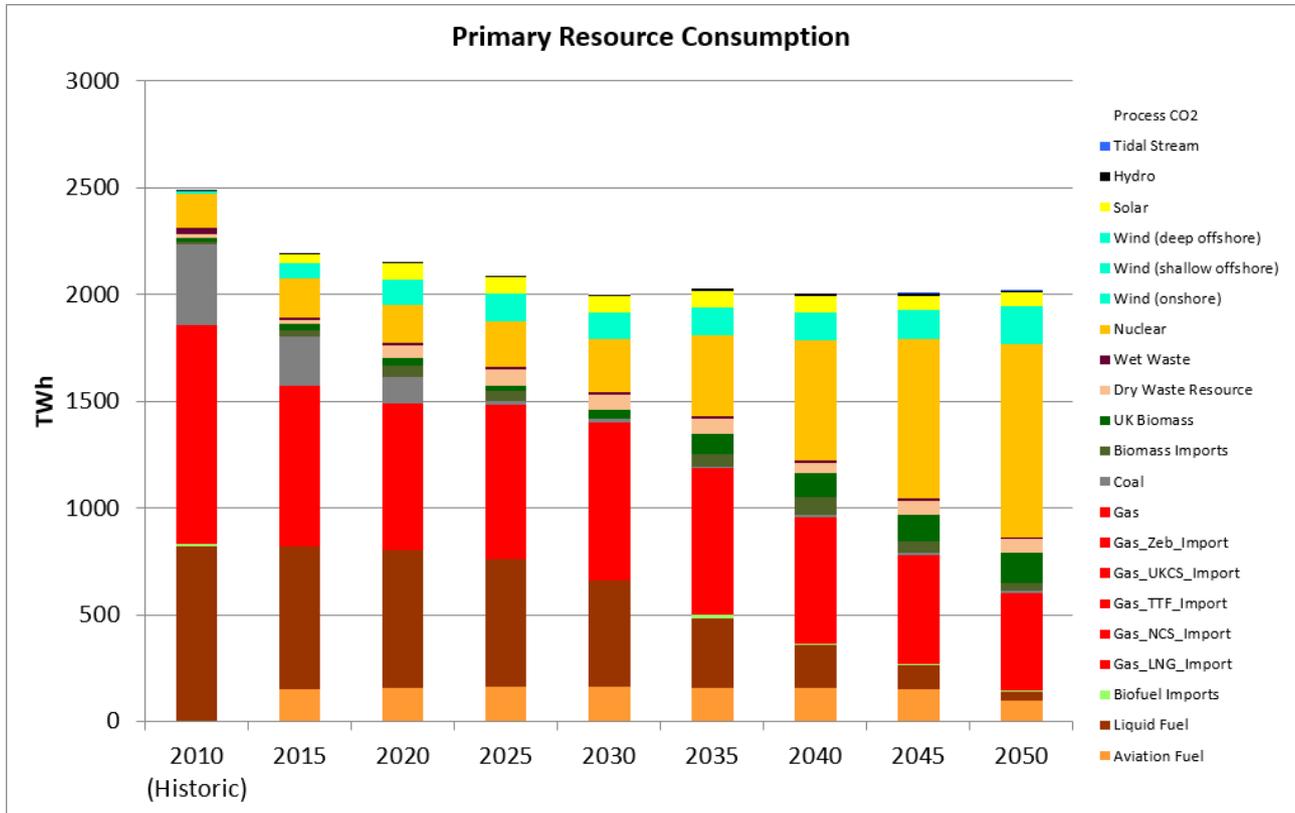
Figure A3-151 – Run 354 Primary Resource Consumption
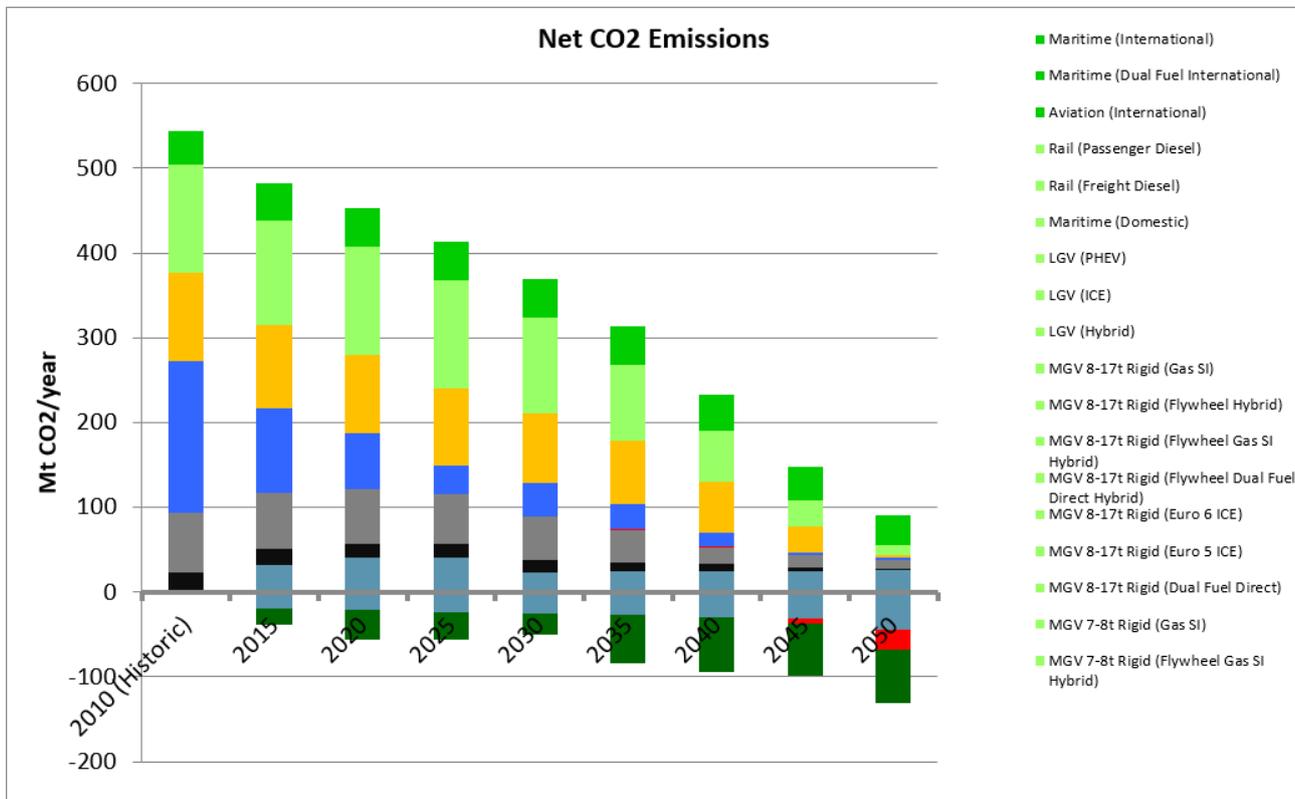
Figure A3-152 – Run 354 Net CO$_2$ Emissions
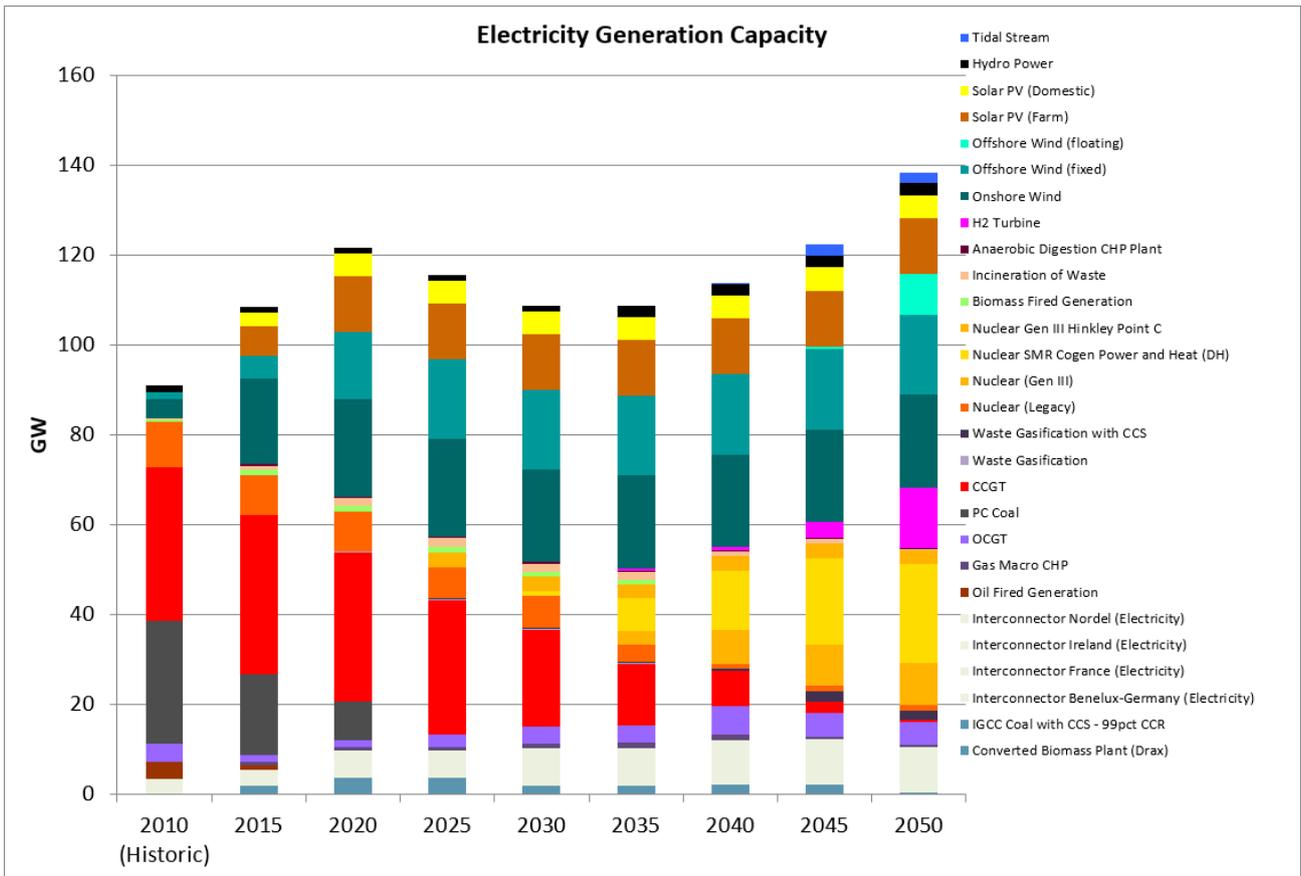
Figure A3-153 – Run 354 Electricity Generation Capacity
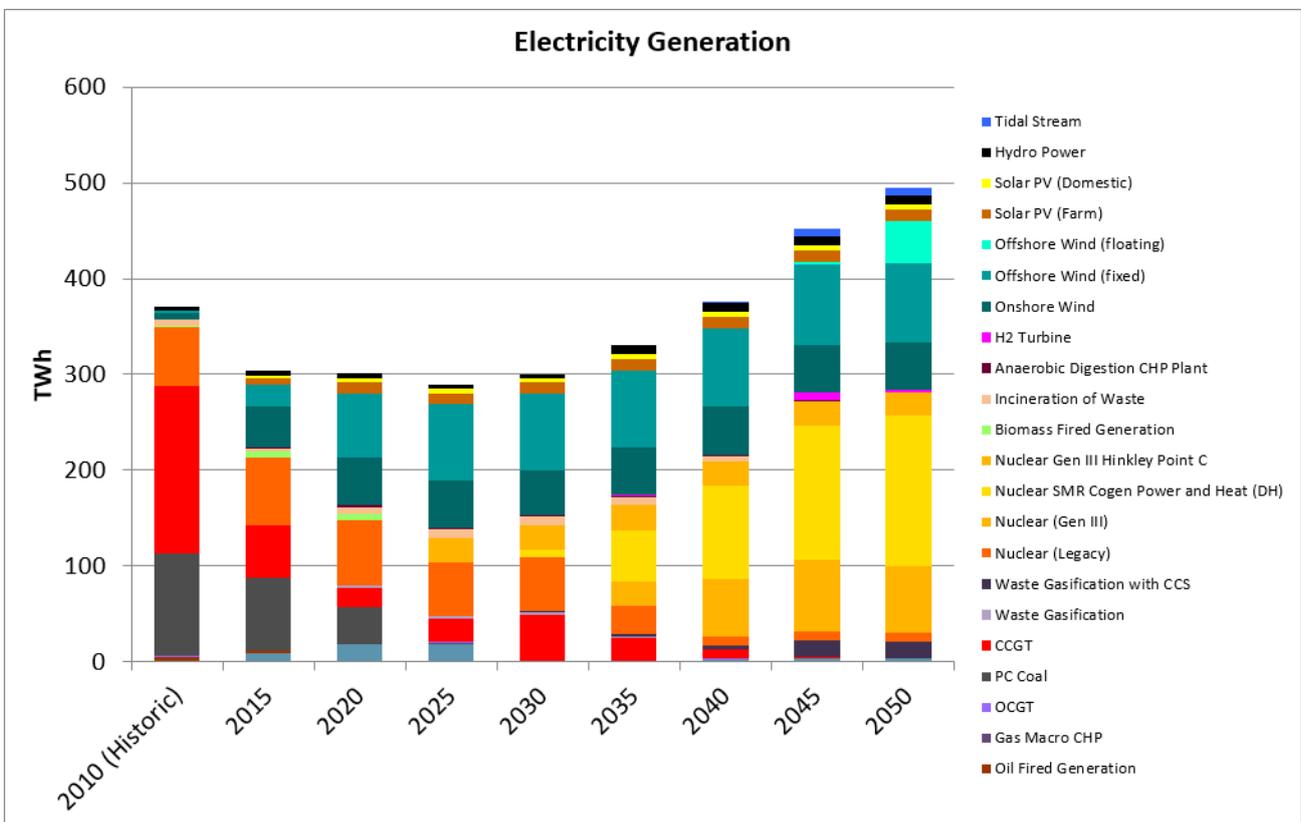
Figure A3-154 – Run 354 Electricity Generation
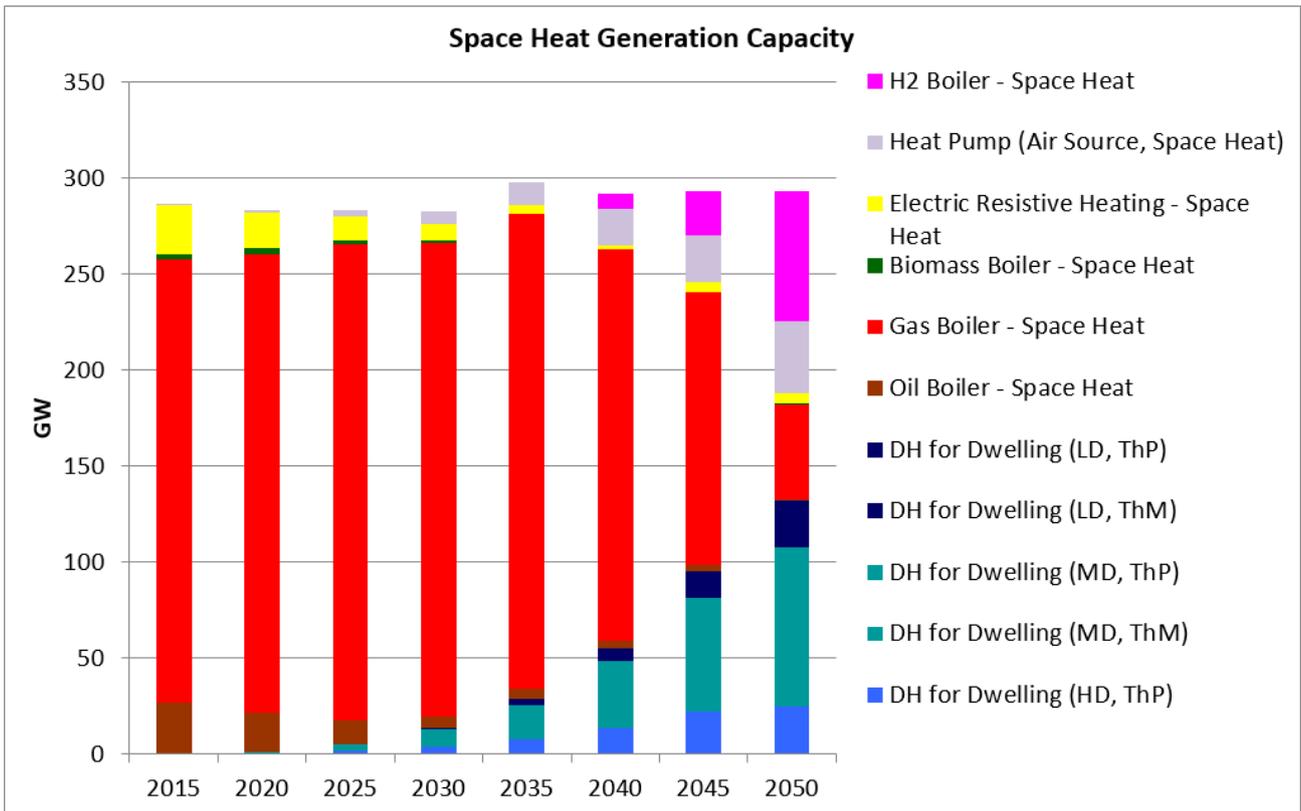
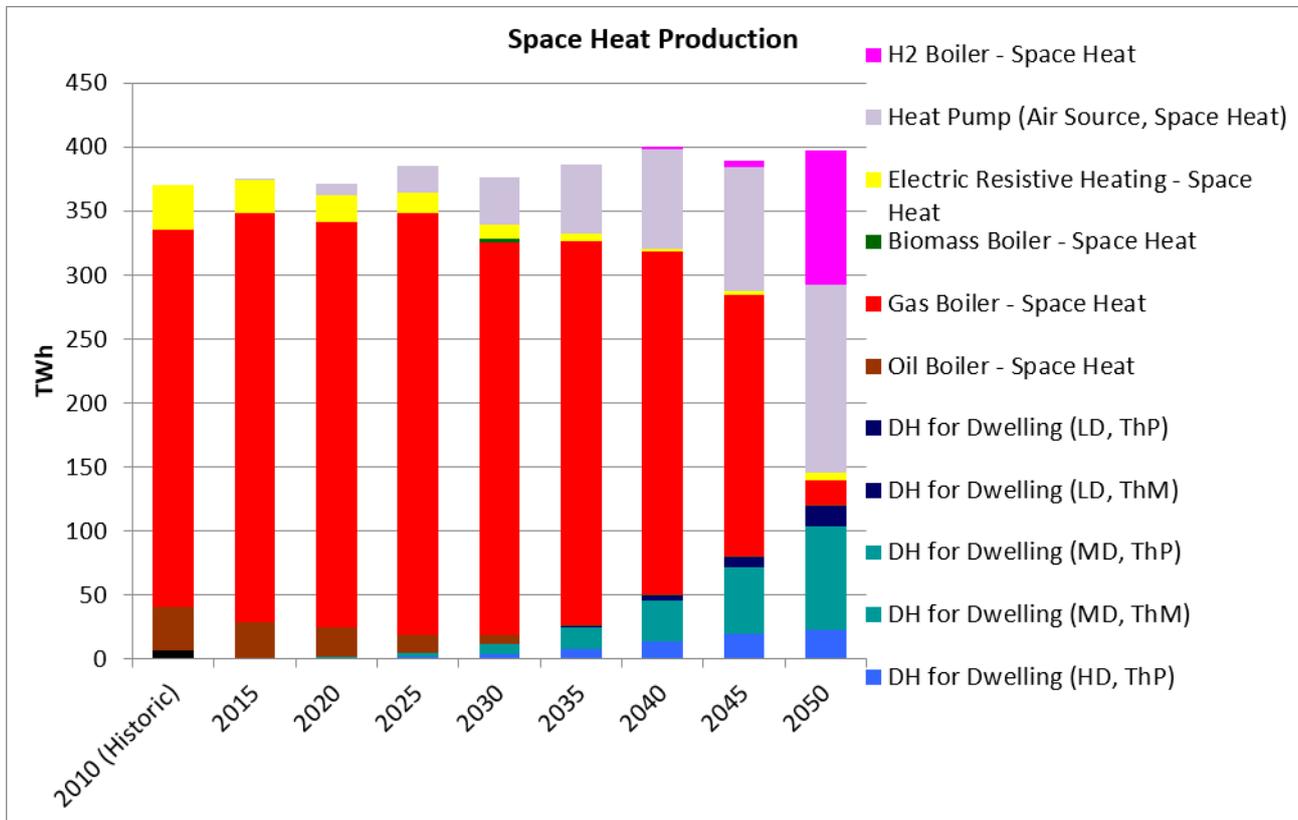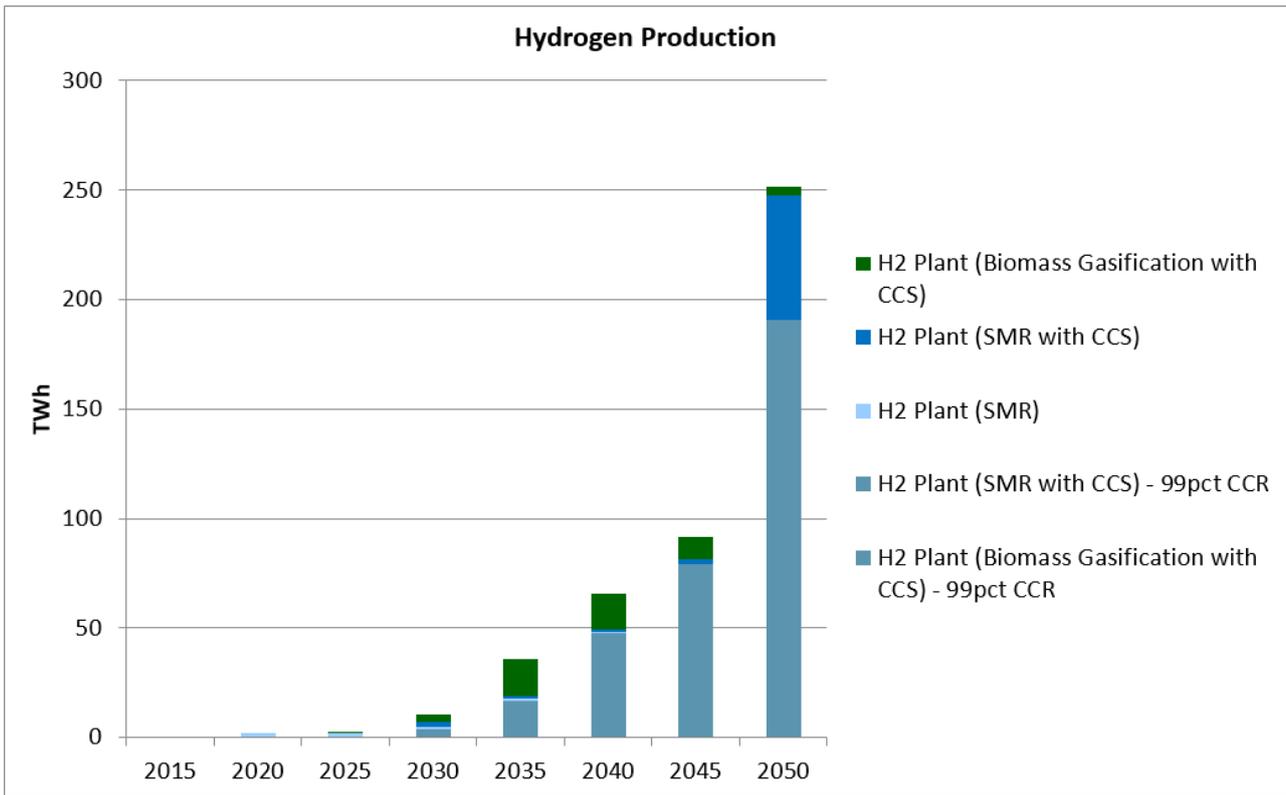Figure A3-155 – Run 354 Space Heat Generation Capacity
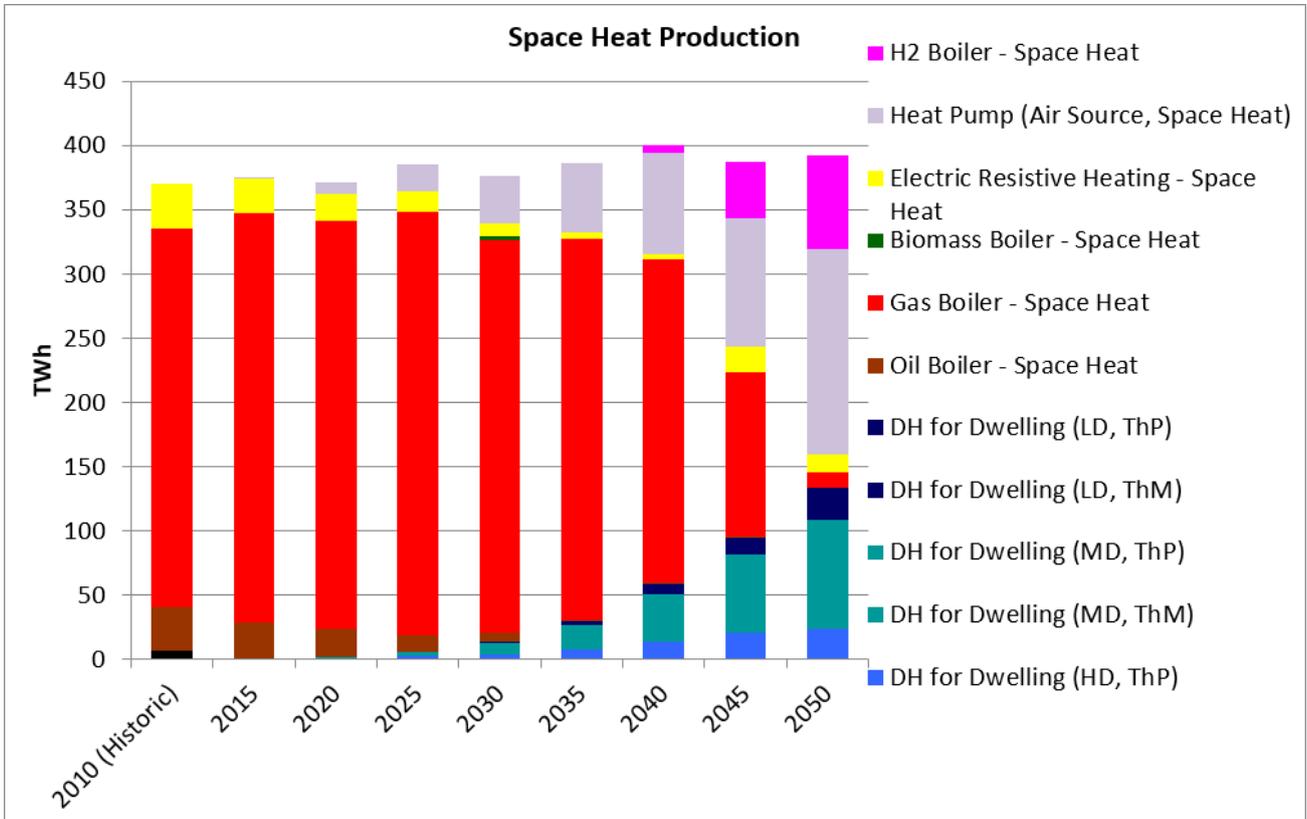
Figure A3-156 – Run 354 Space Heat Production
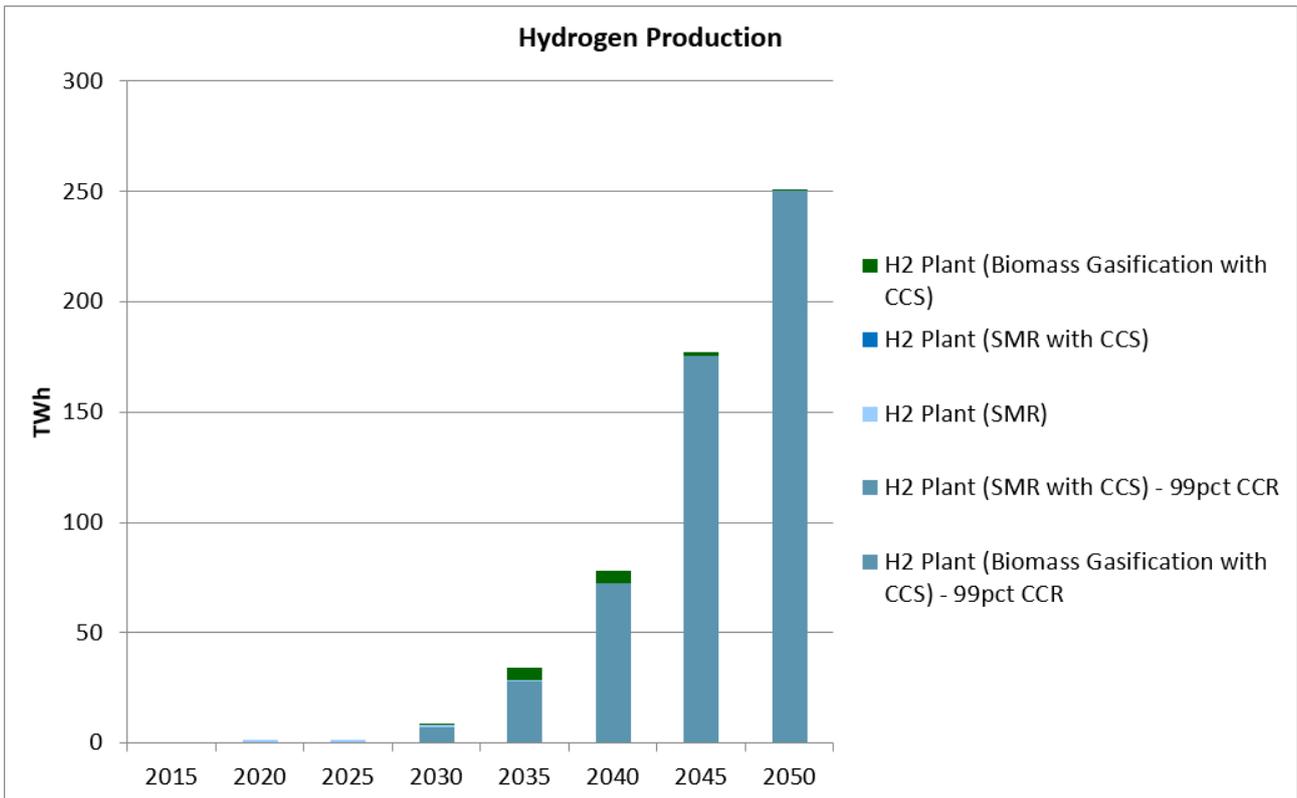
Figure A3-157 – Run 354 Hydrogen Production
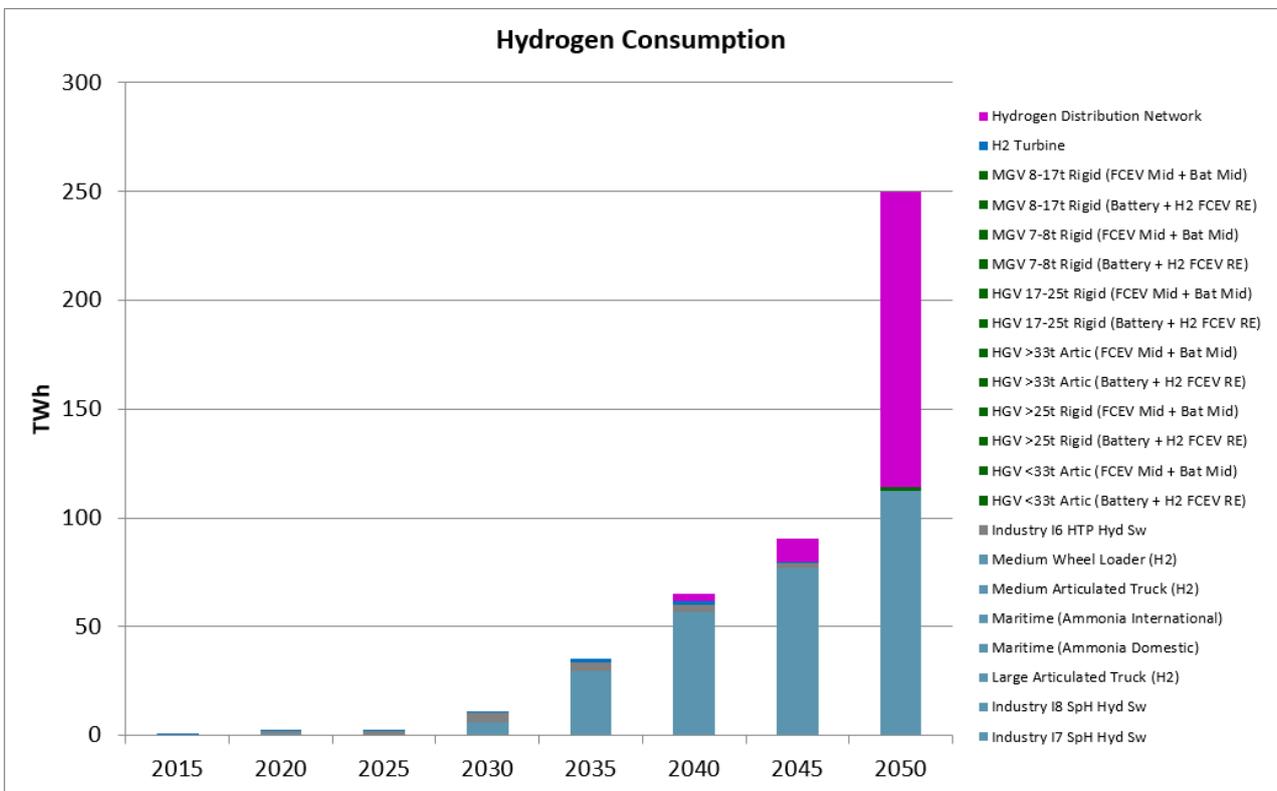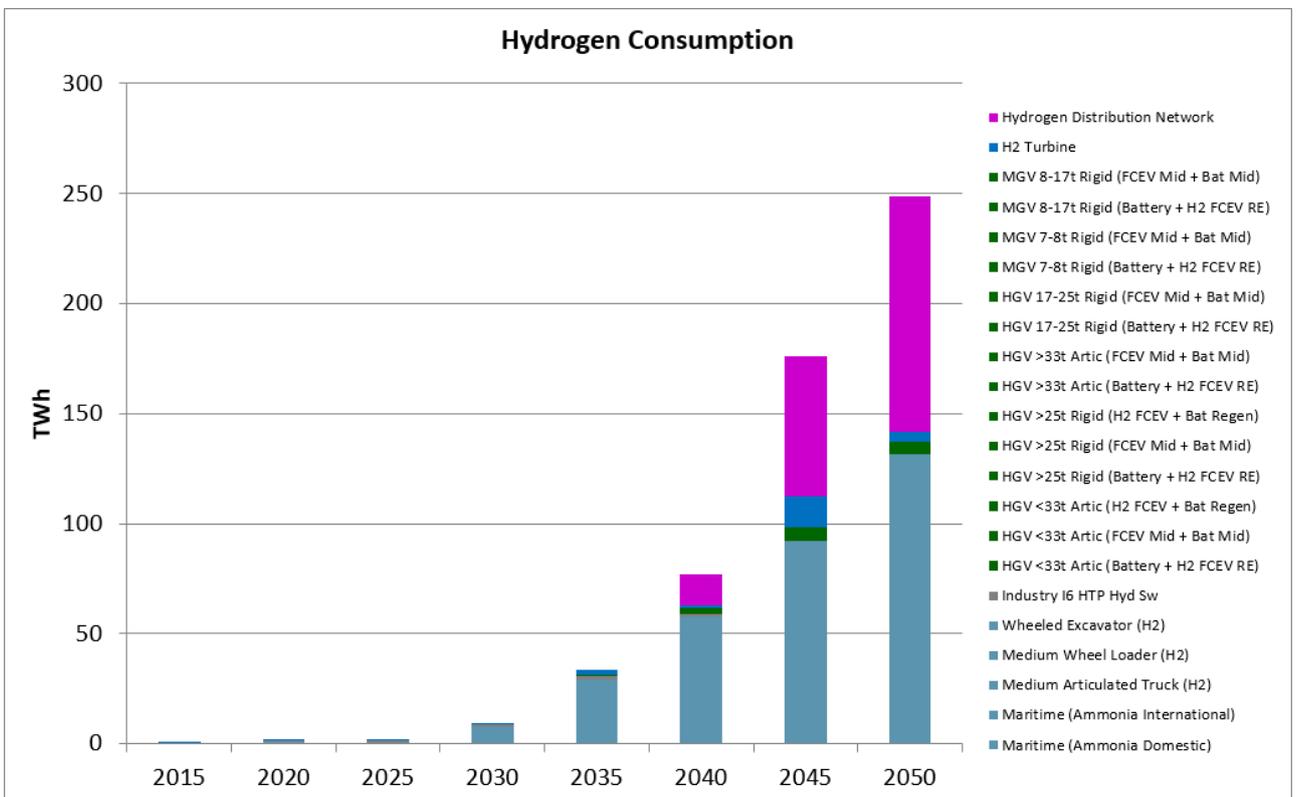

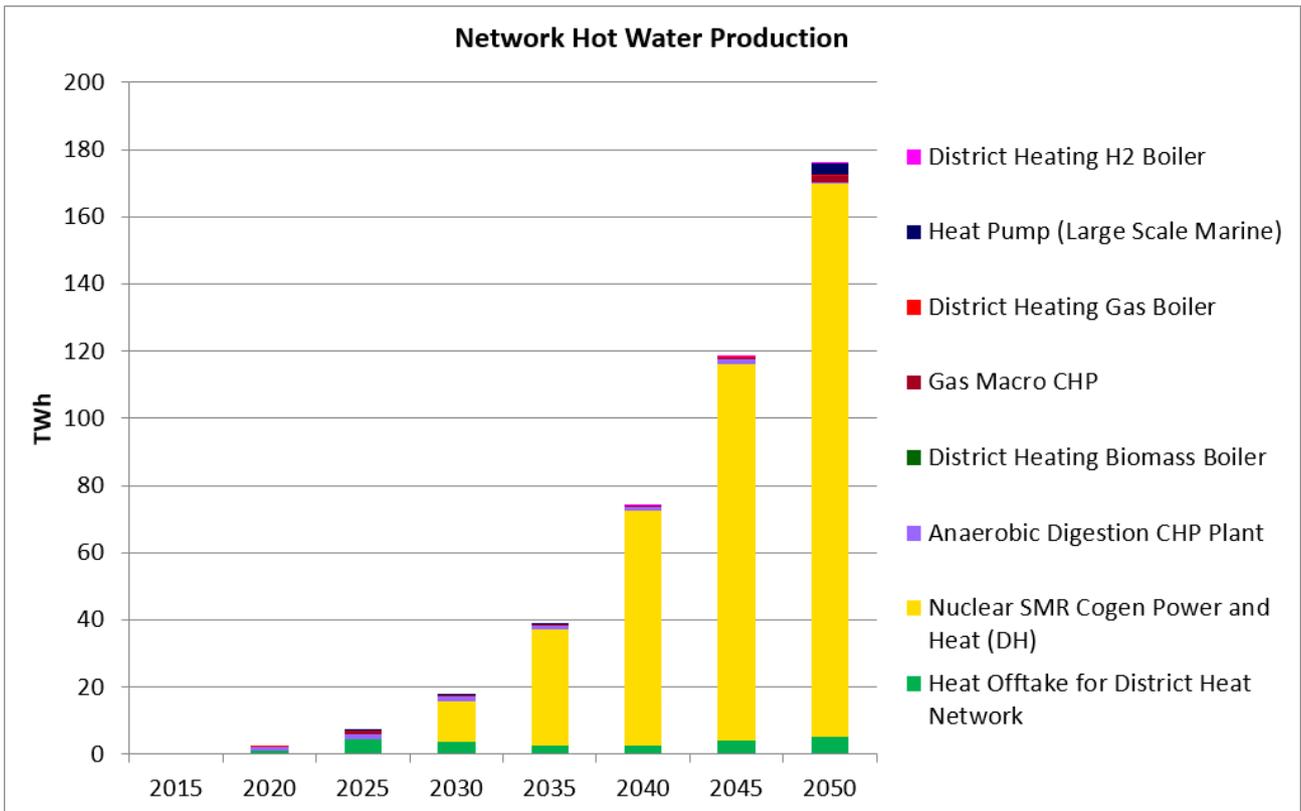Figure A3-158 – Run 354 Hydrogen consumption
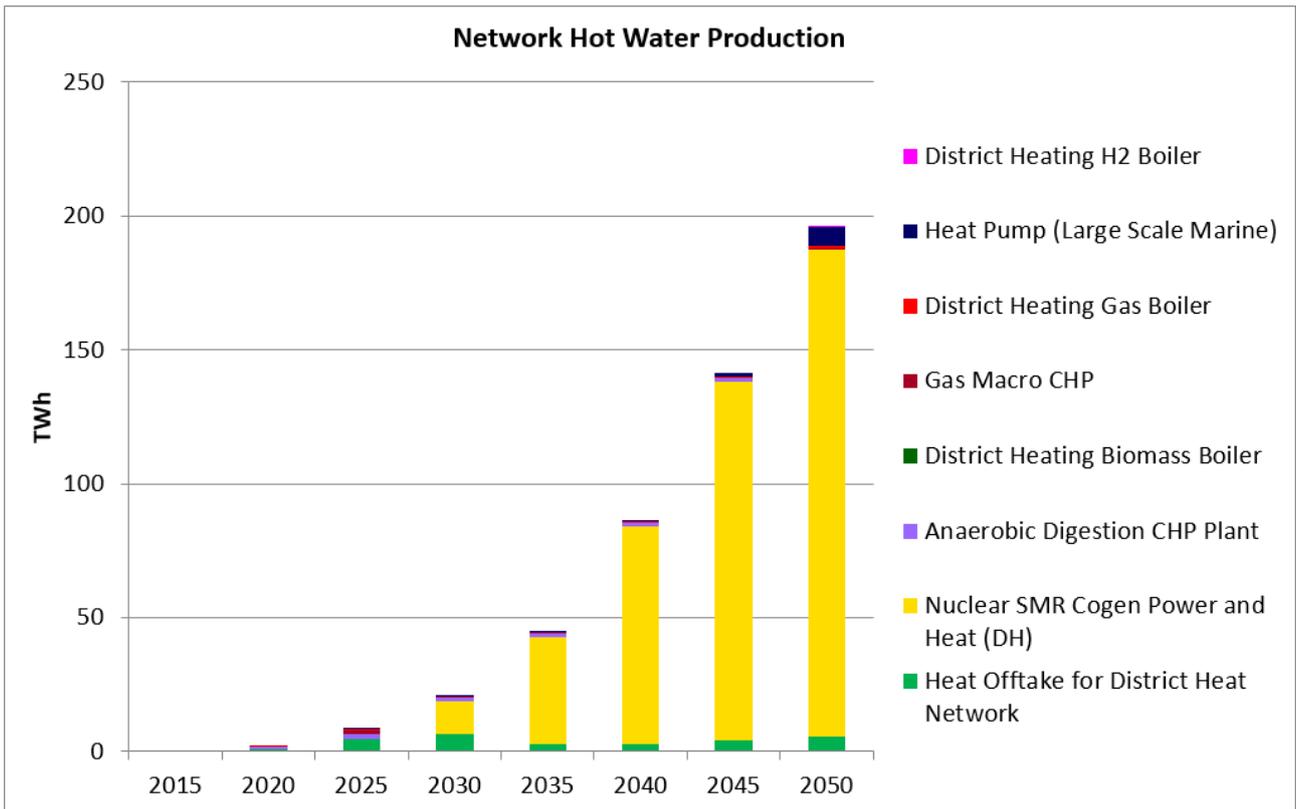
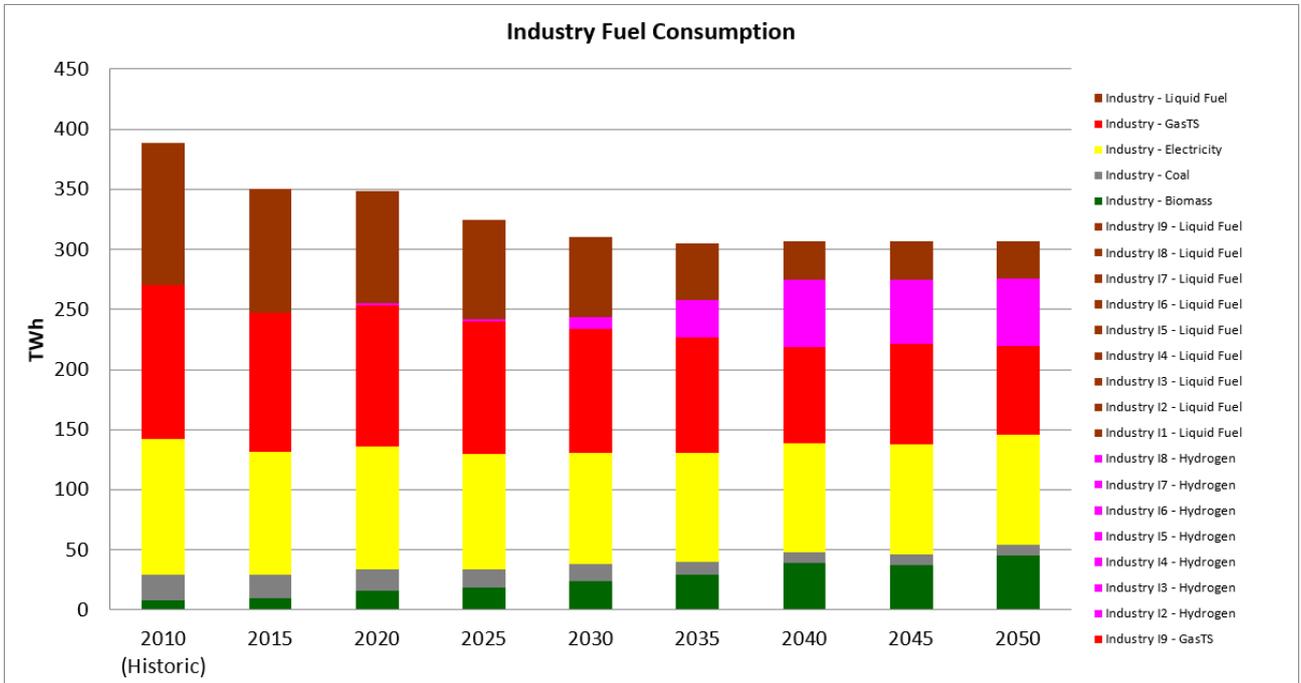Figure A3-159 – Run 354 Network Hot Water Production
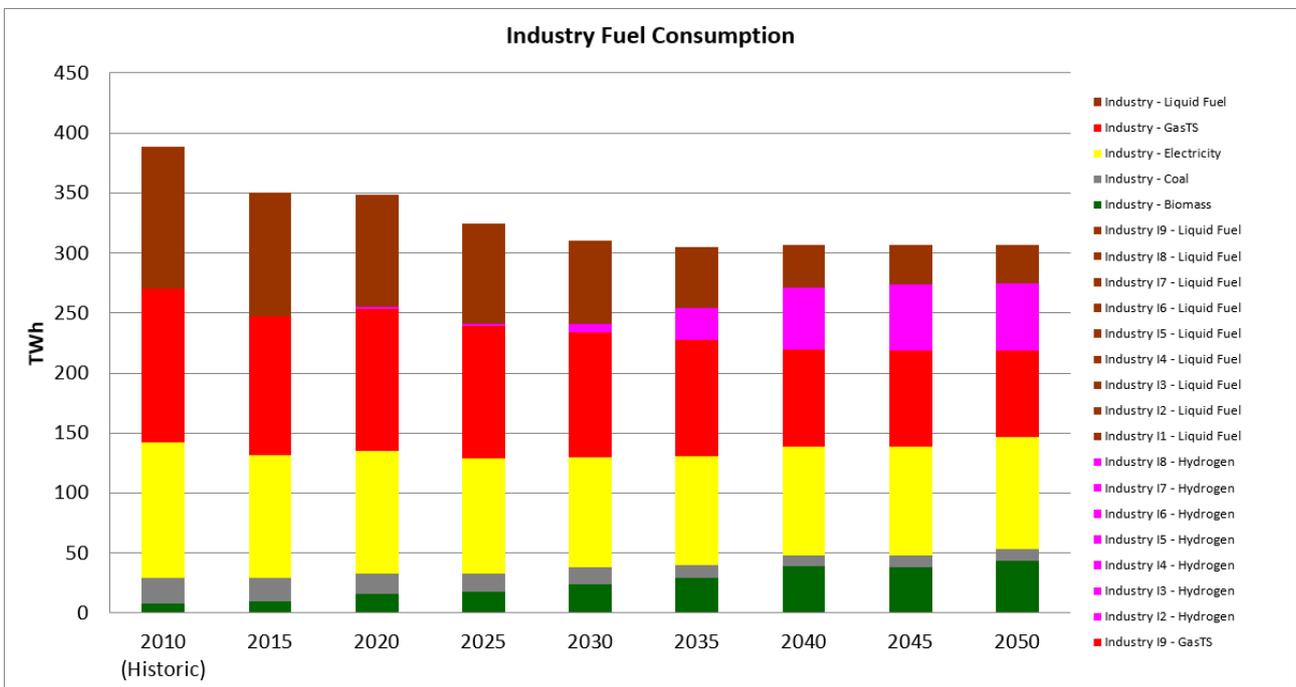
Figure A3-160 – Run 354 Industry Fuel Consumption

Run 355 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 40 x LC values
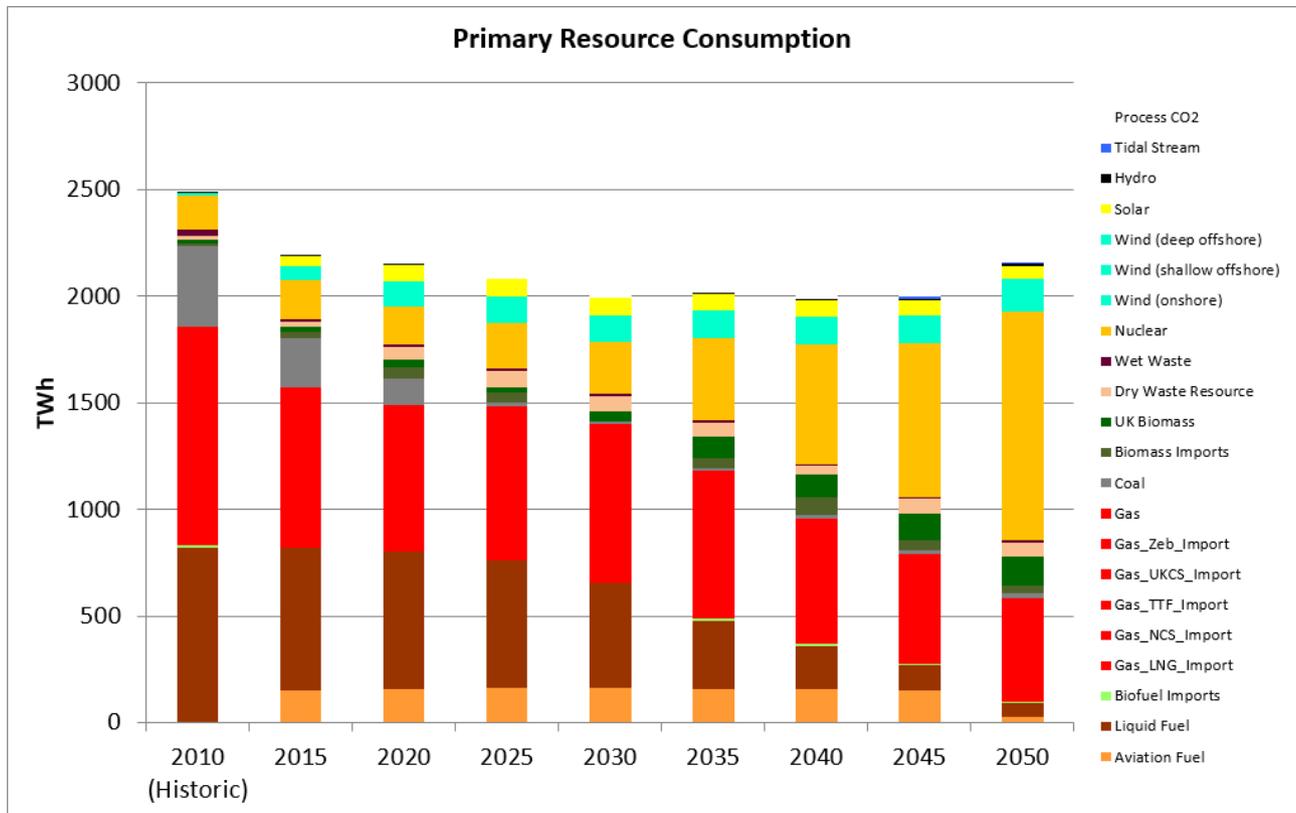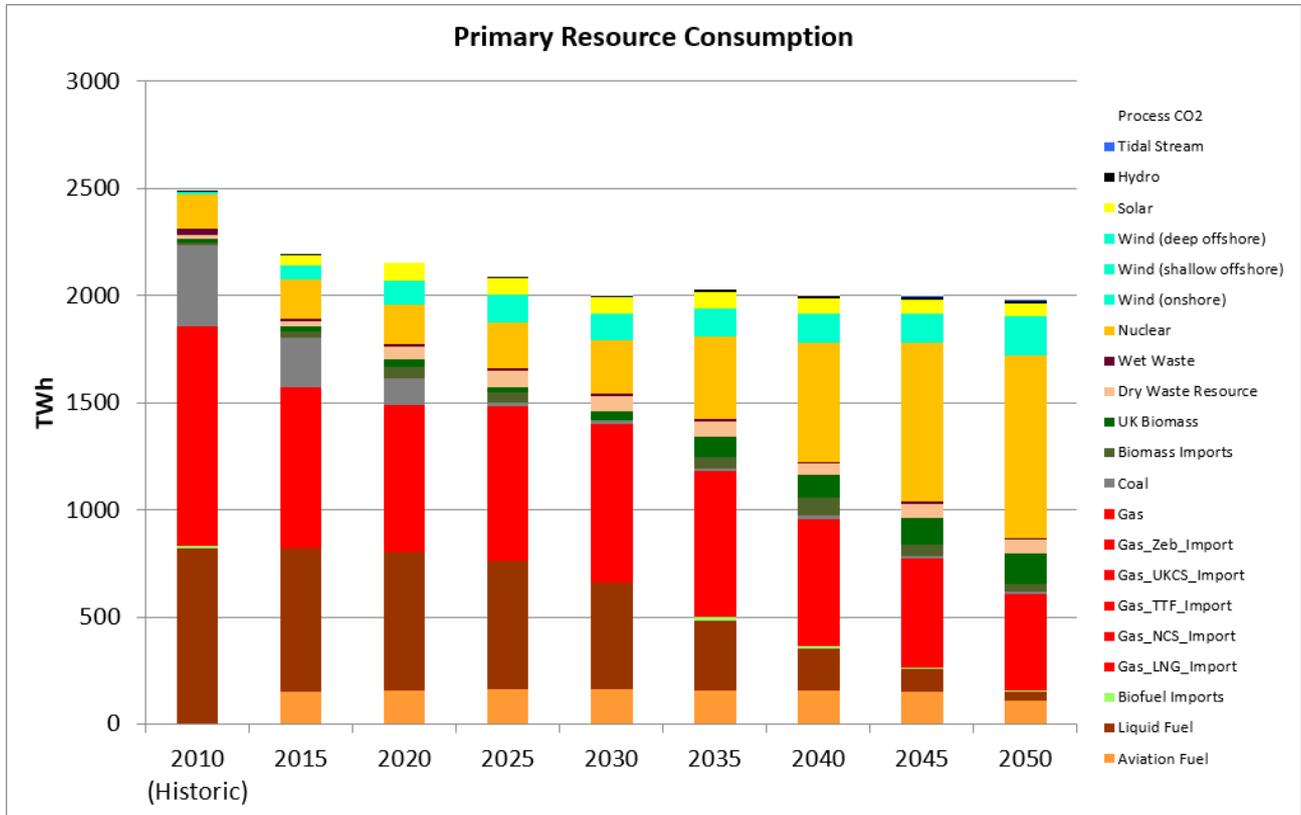

Figure A3-161 – Run 355 Primary Resource Consumption
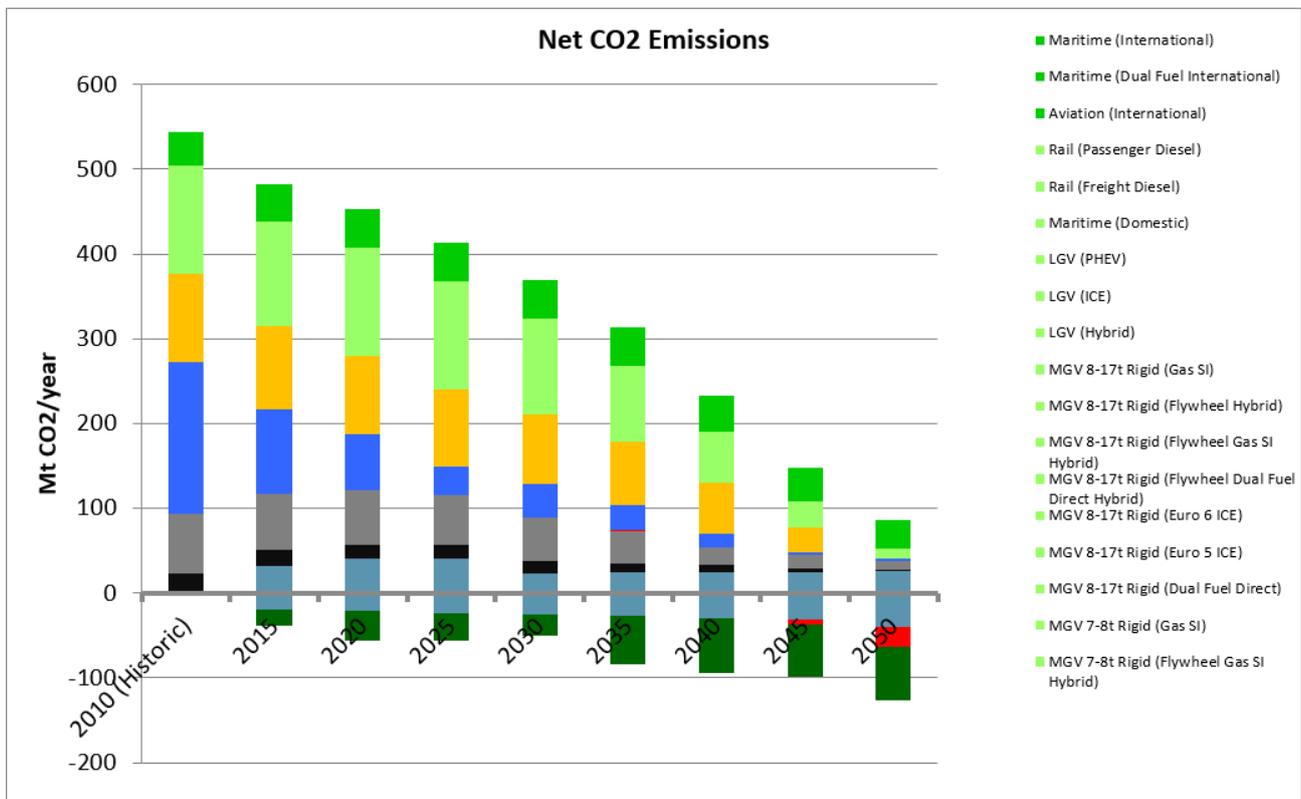
Figure A3-162 – Run 355 Net CO$_2$ Emissions
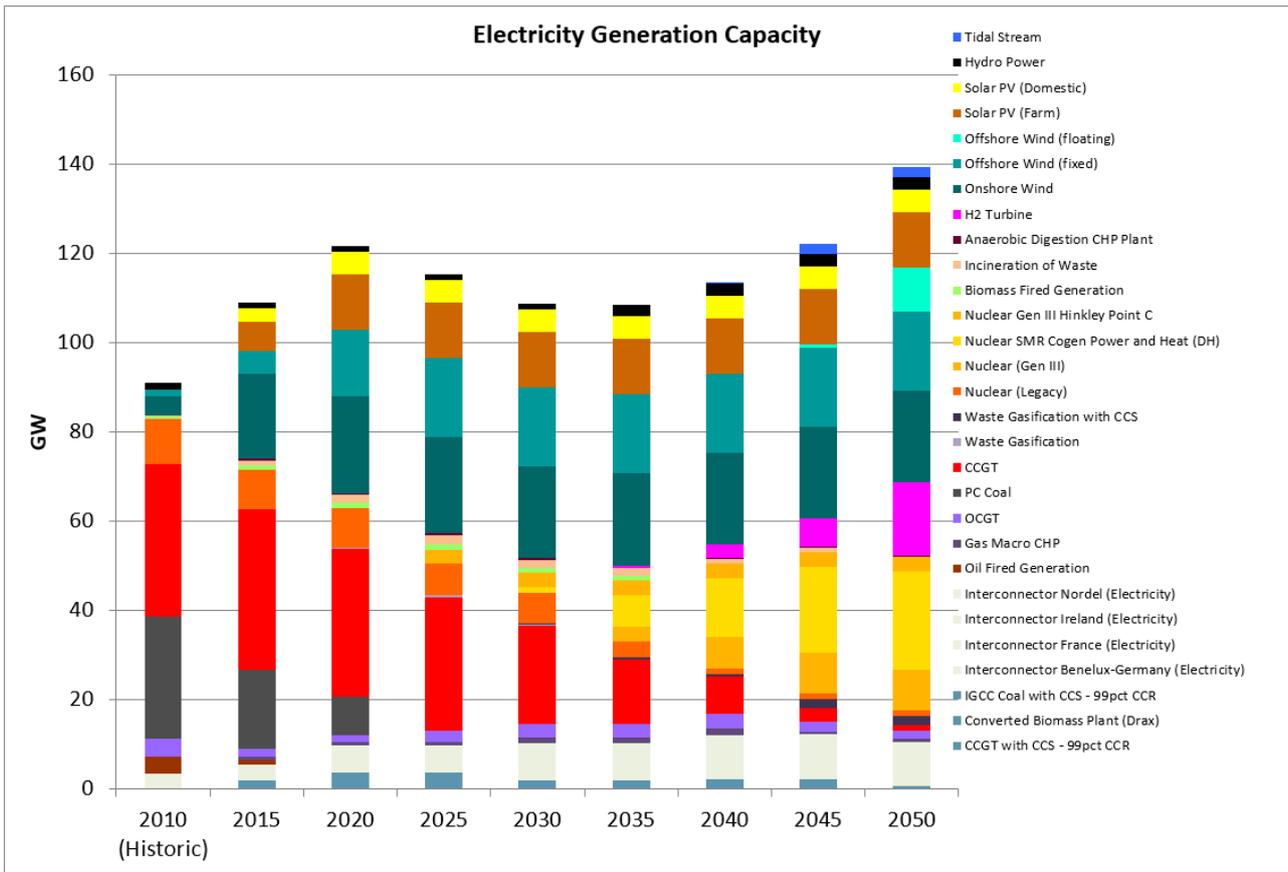
Figure A3-163 – Run 355 Electricity Generation Capacity
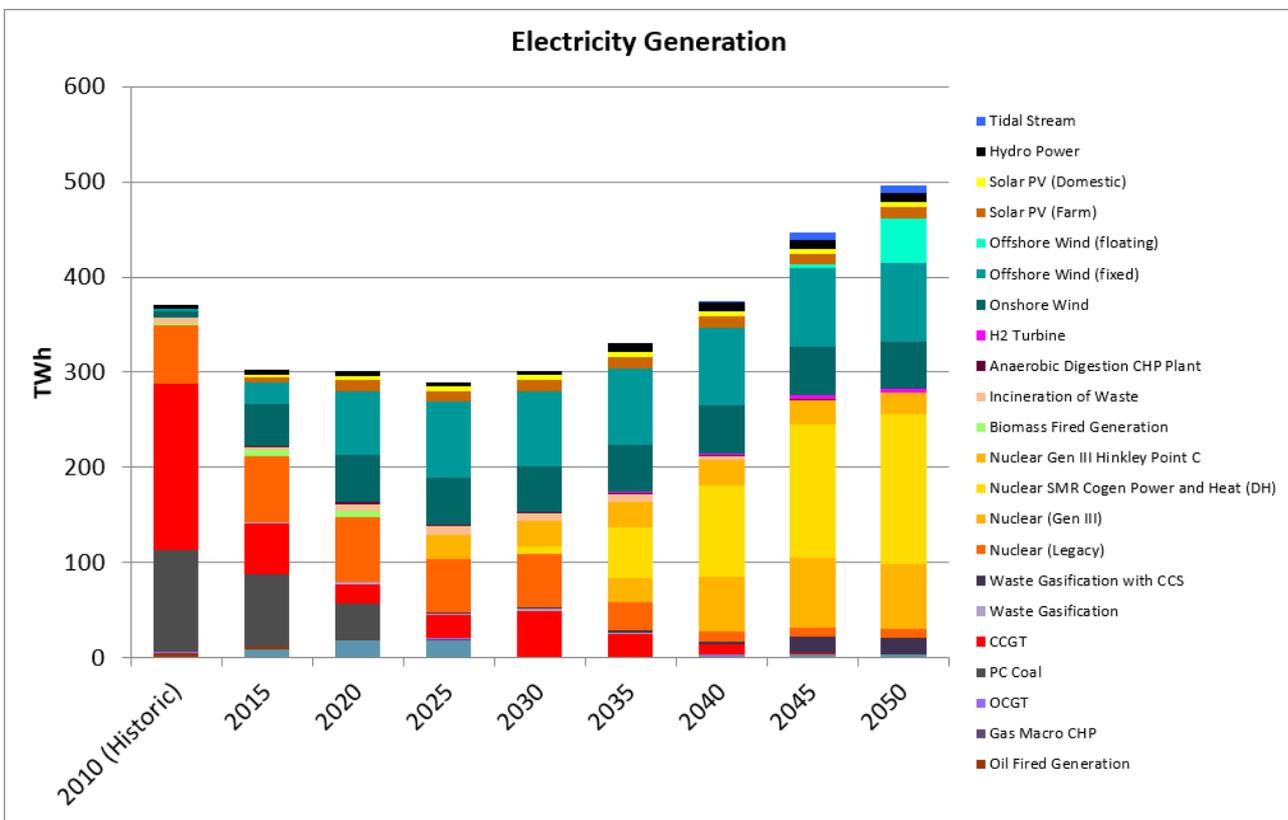
Figure A3-164 – Run 355 Electricity Generation
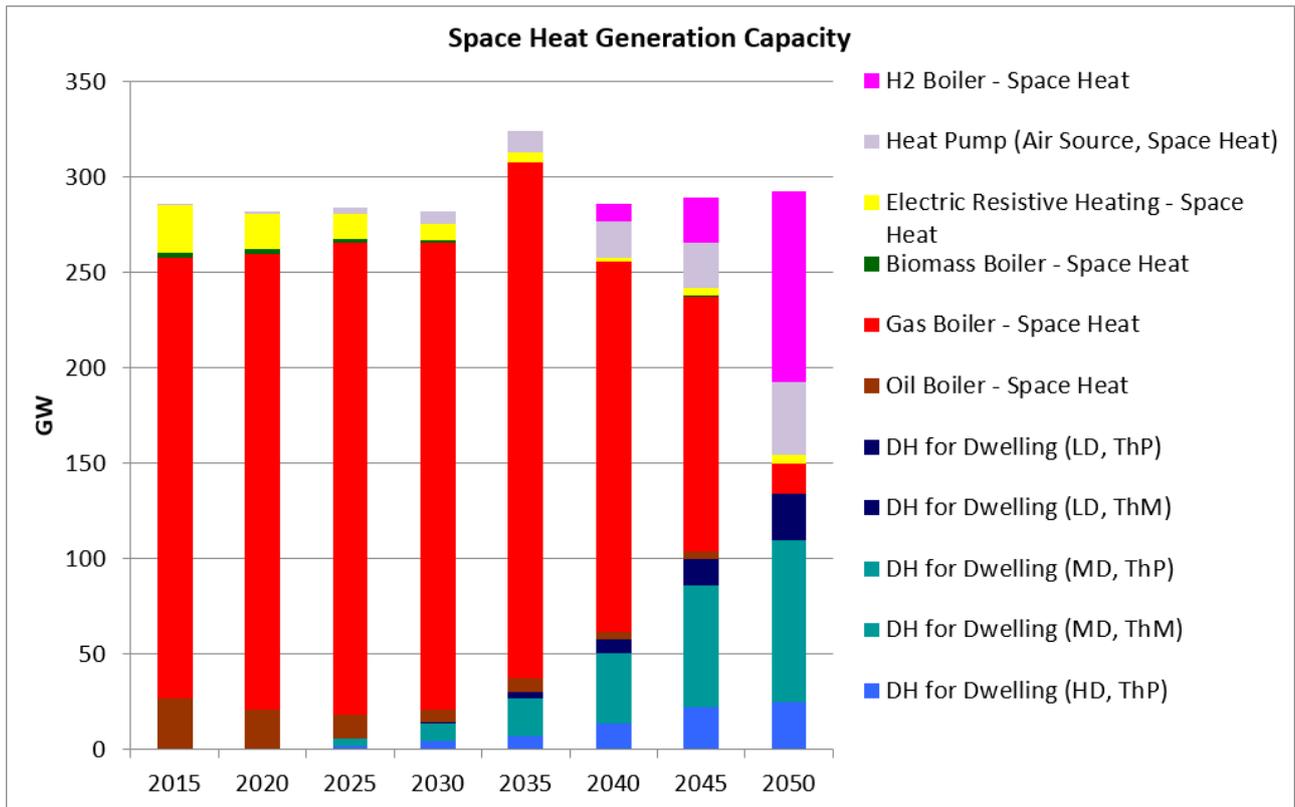
Figure A3-165 – Run 355 Space Heat Generation Capacity
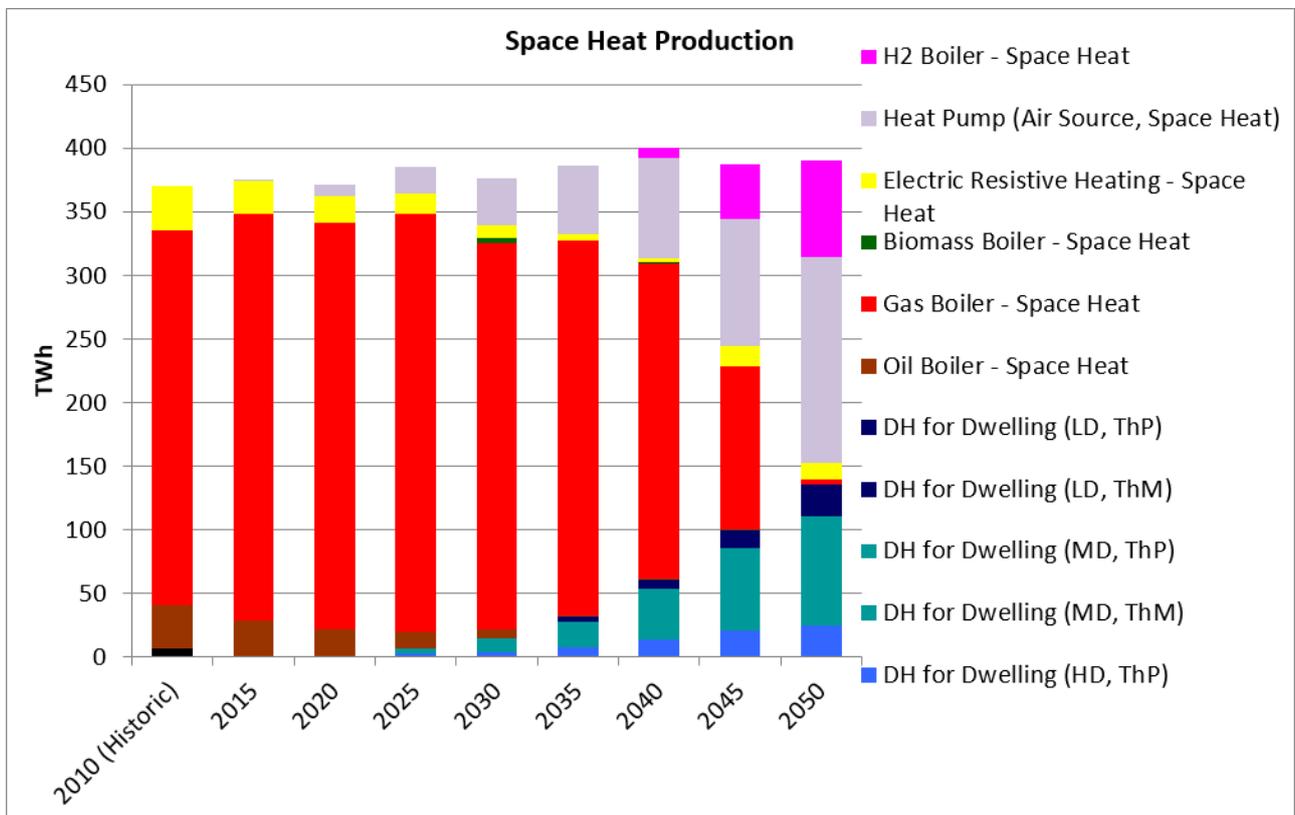
Figure A3-166 – Run 355 Space Heat Production
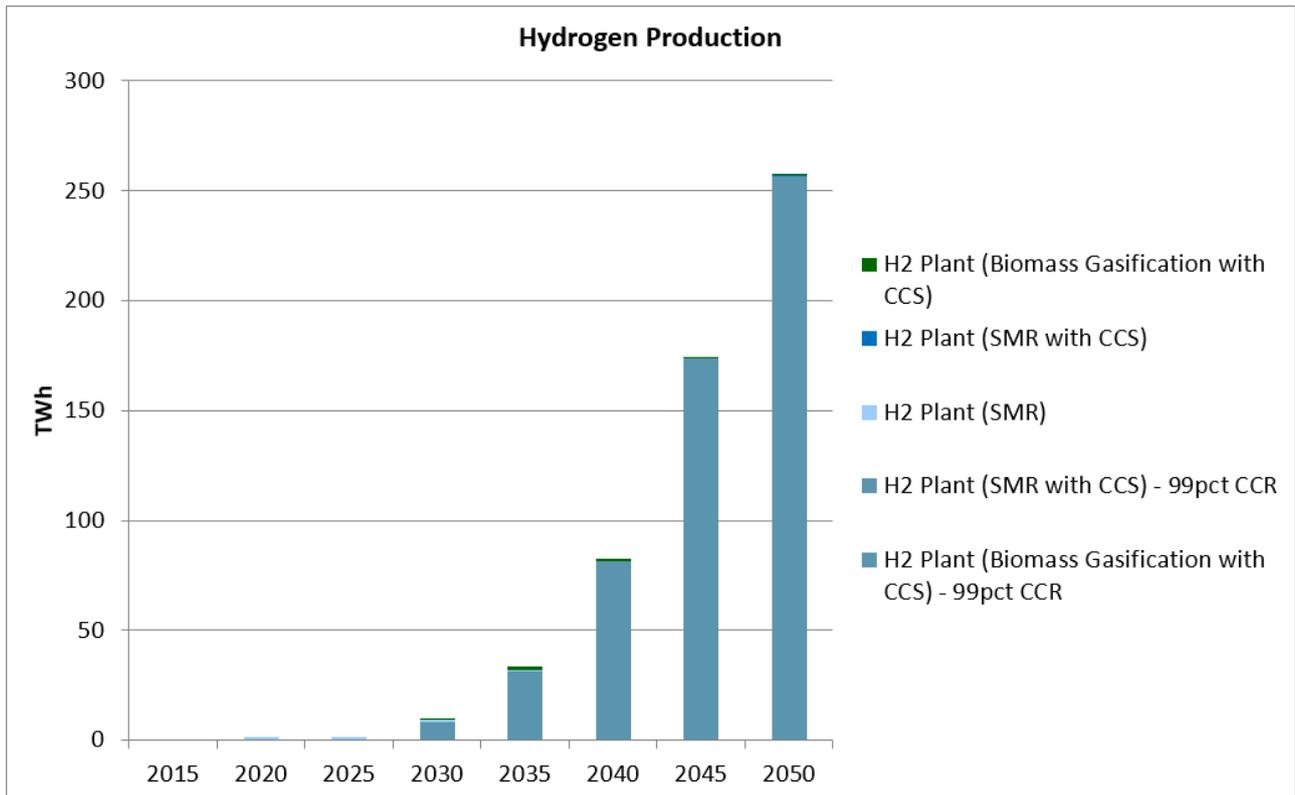
Figure A3-167 – Run 355 Hydrogen Production
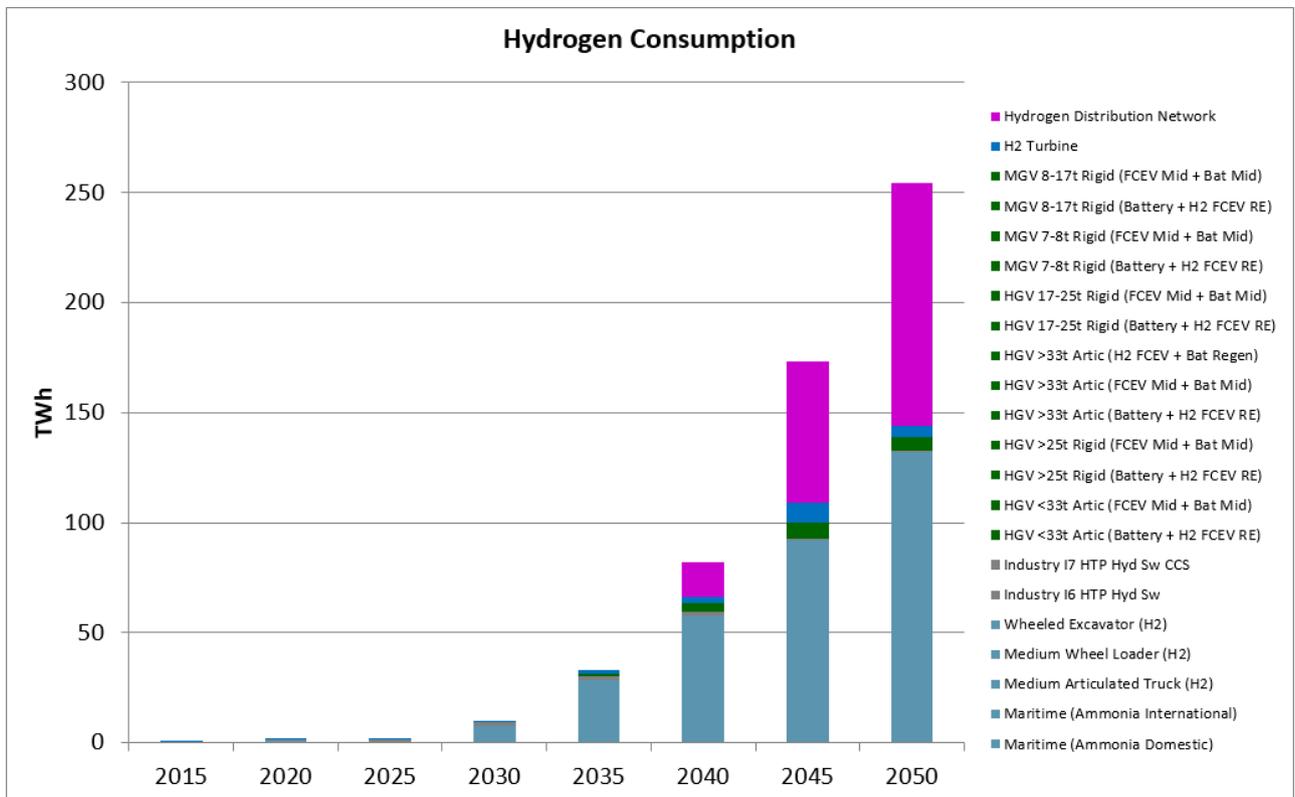
Figure A3-168 – Run 355 Hydrogen consumption
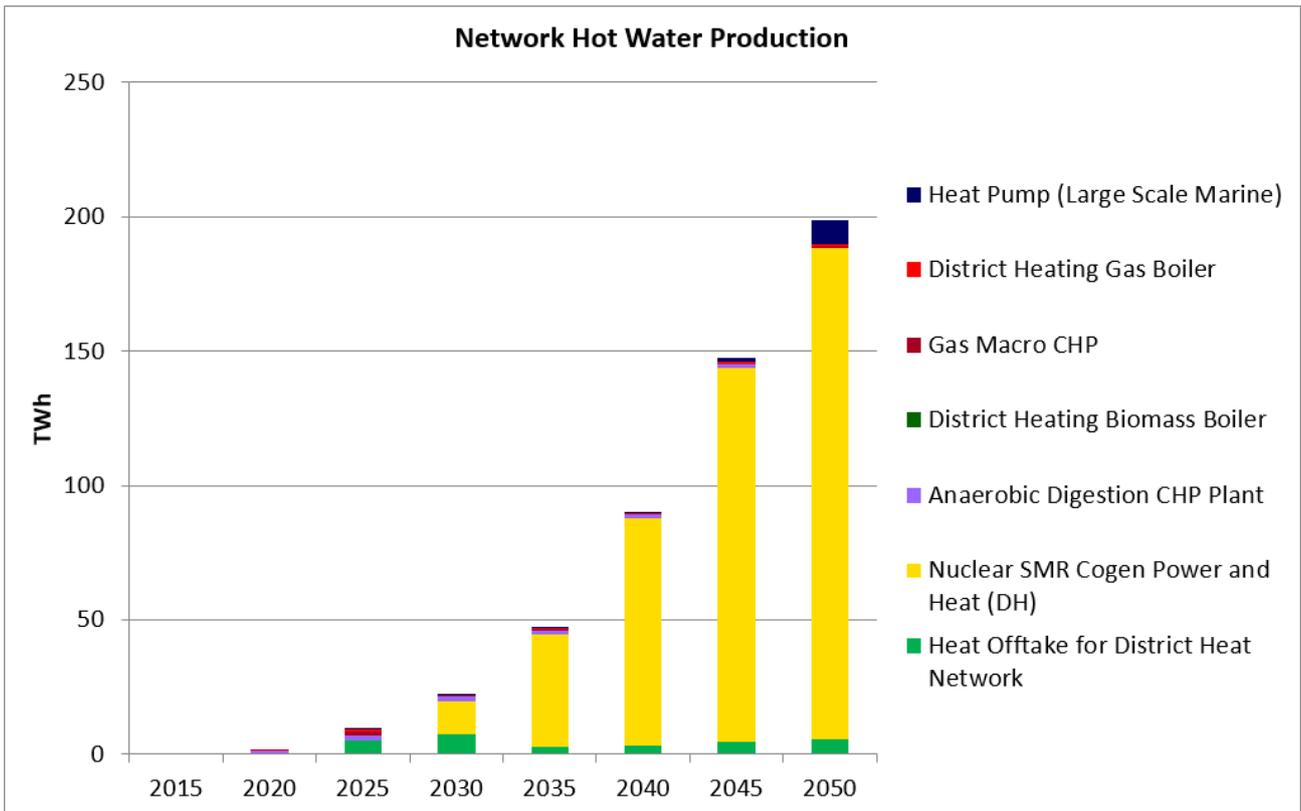
Figure A3-169 – Run 355 Network Hot Water Production
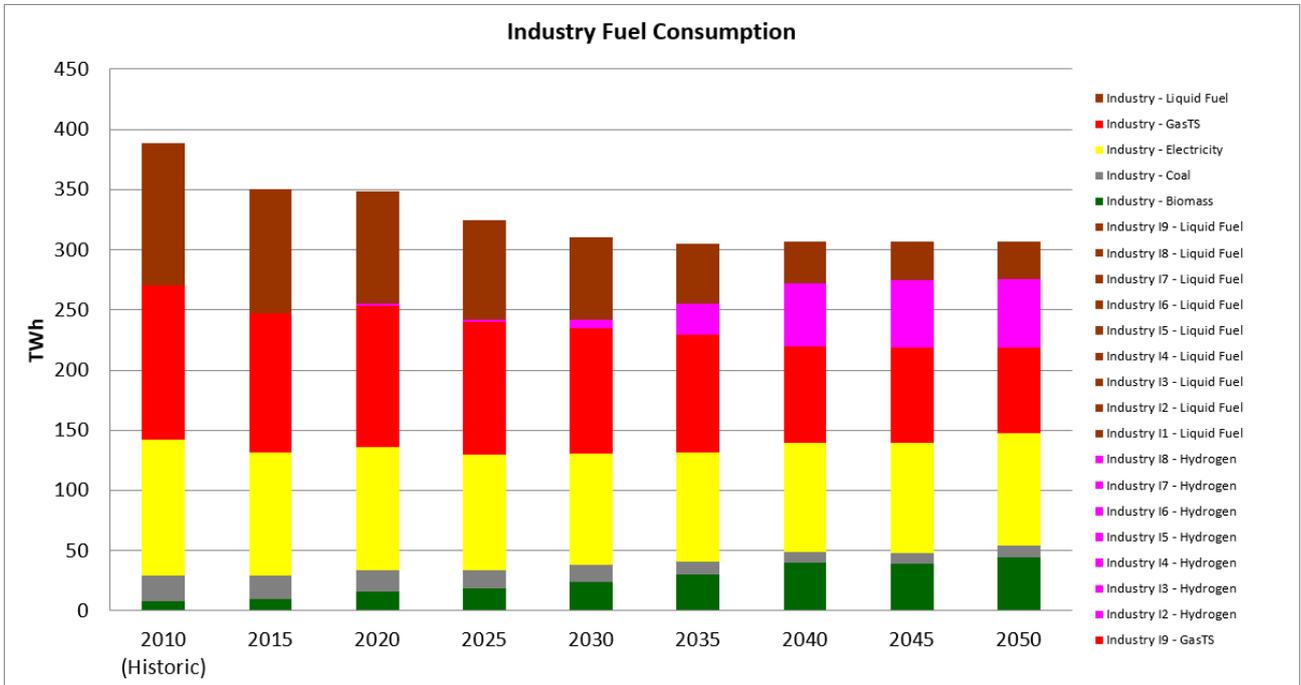
Figure A3-170 – Run 355 Industry Fuel Consumption

Run 356 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 50 x LC values
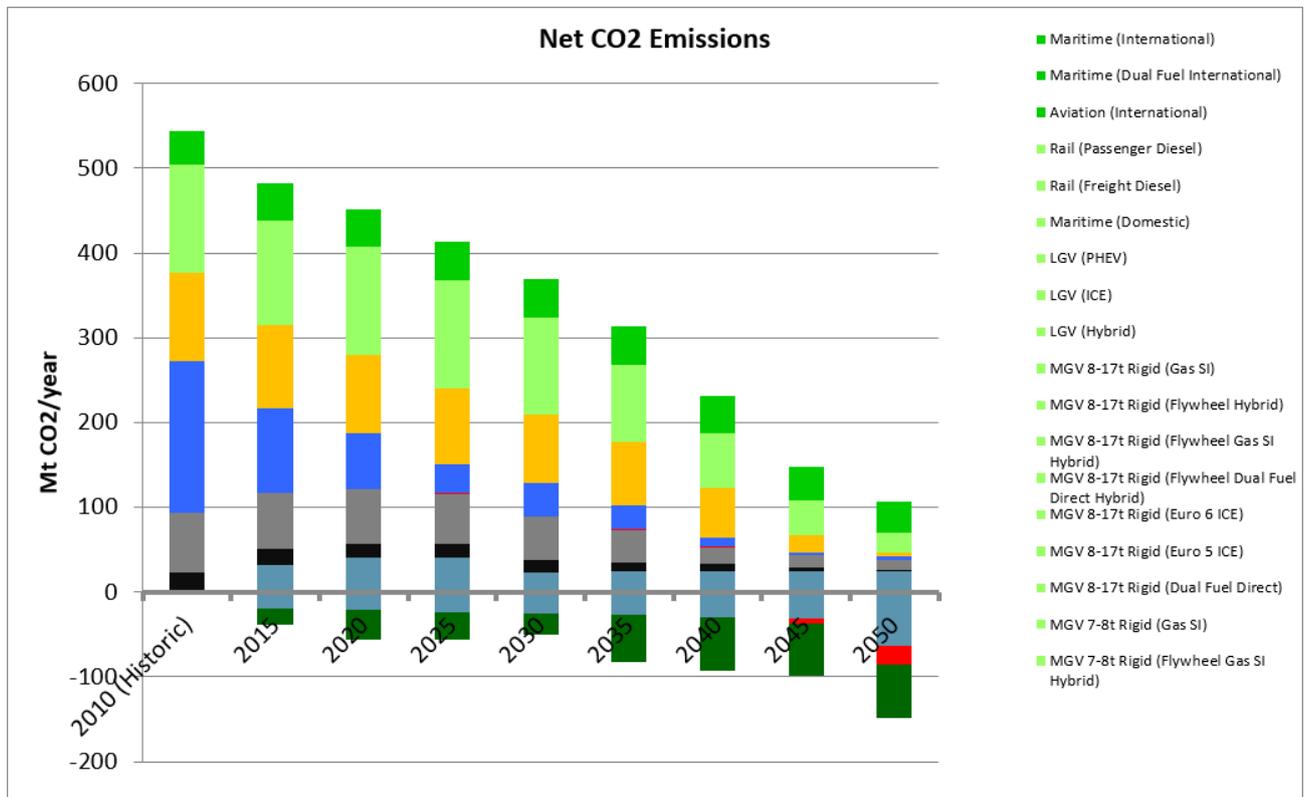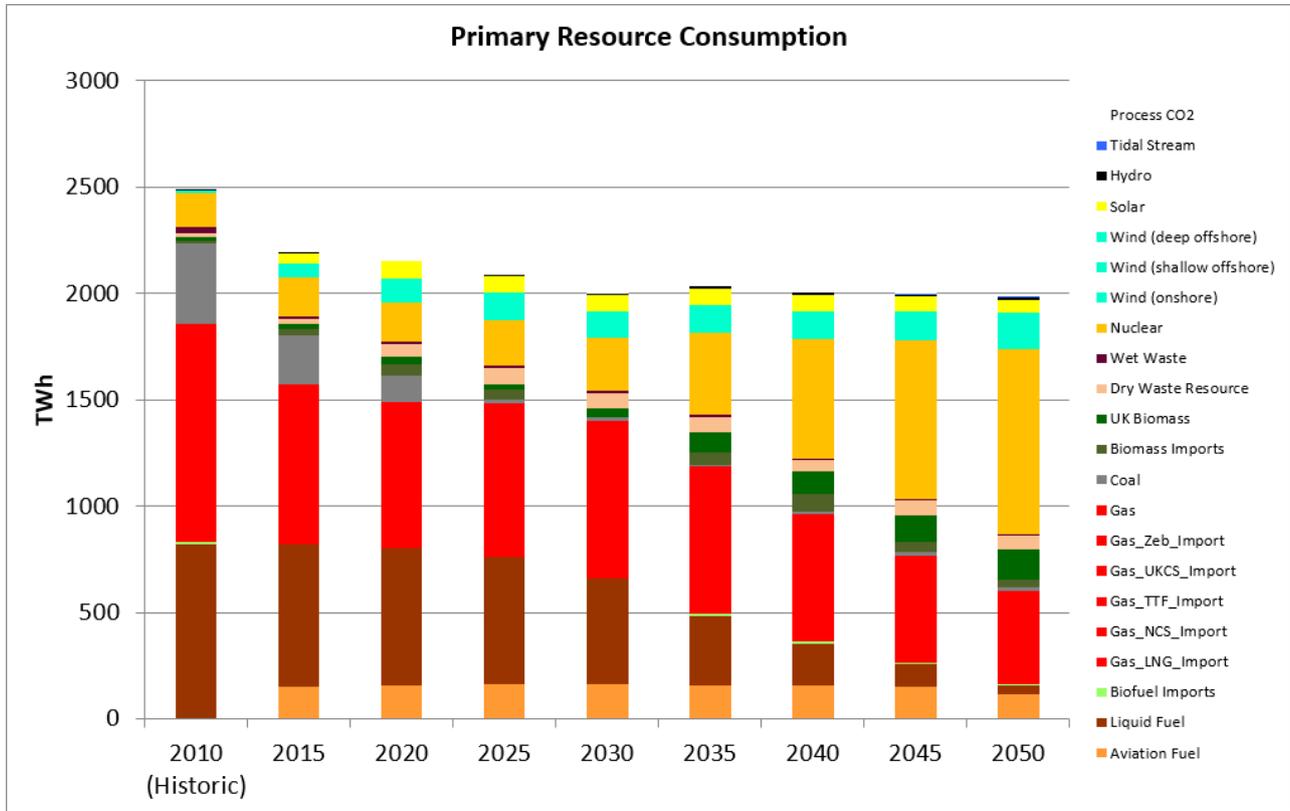

Figure A3-171 – Run 356 Primary Resource Consumption
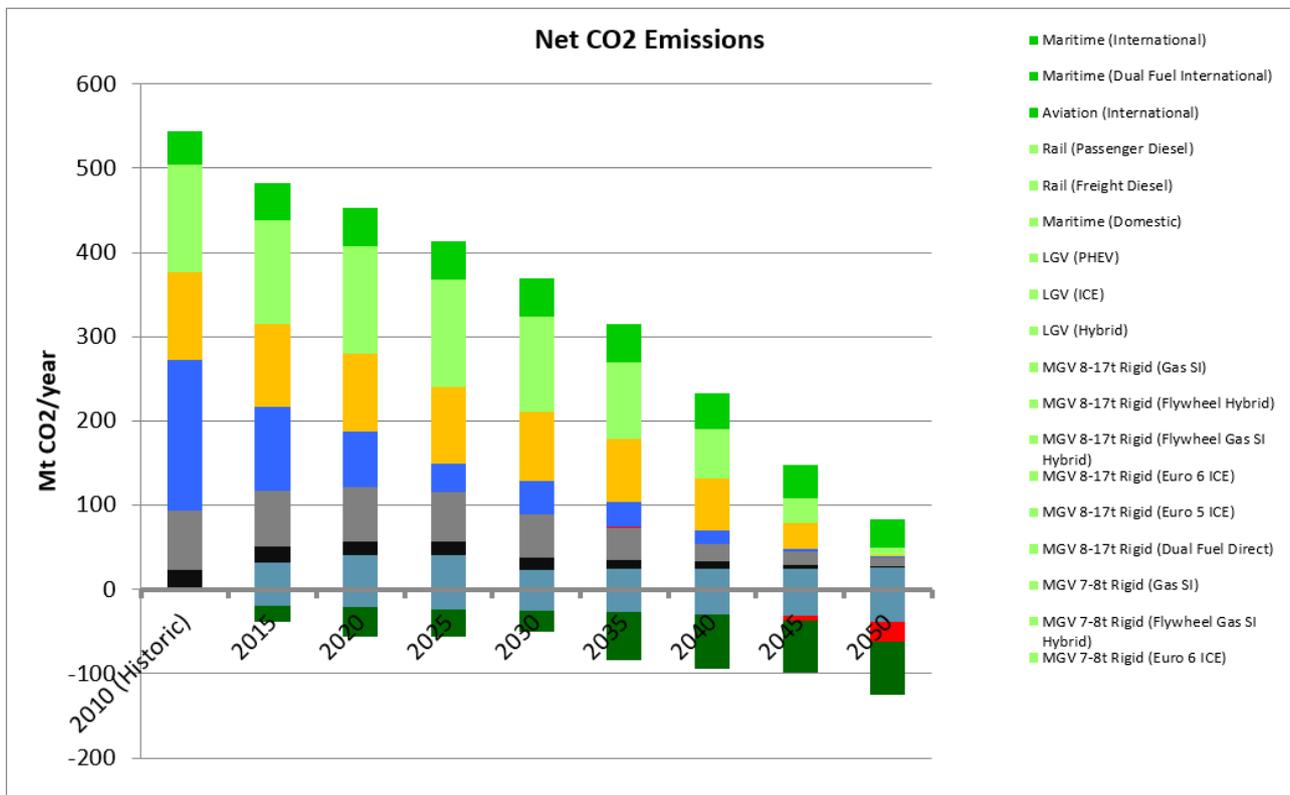
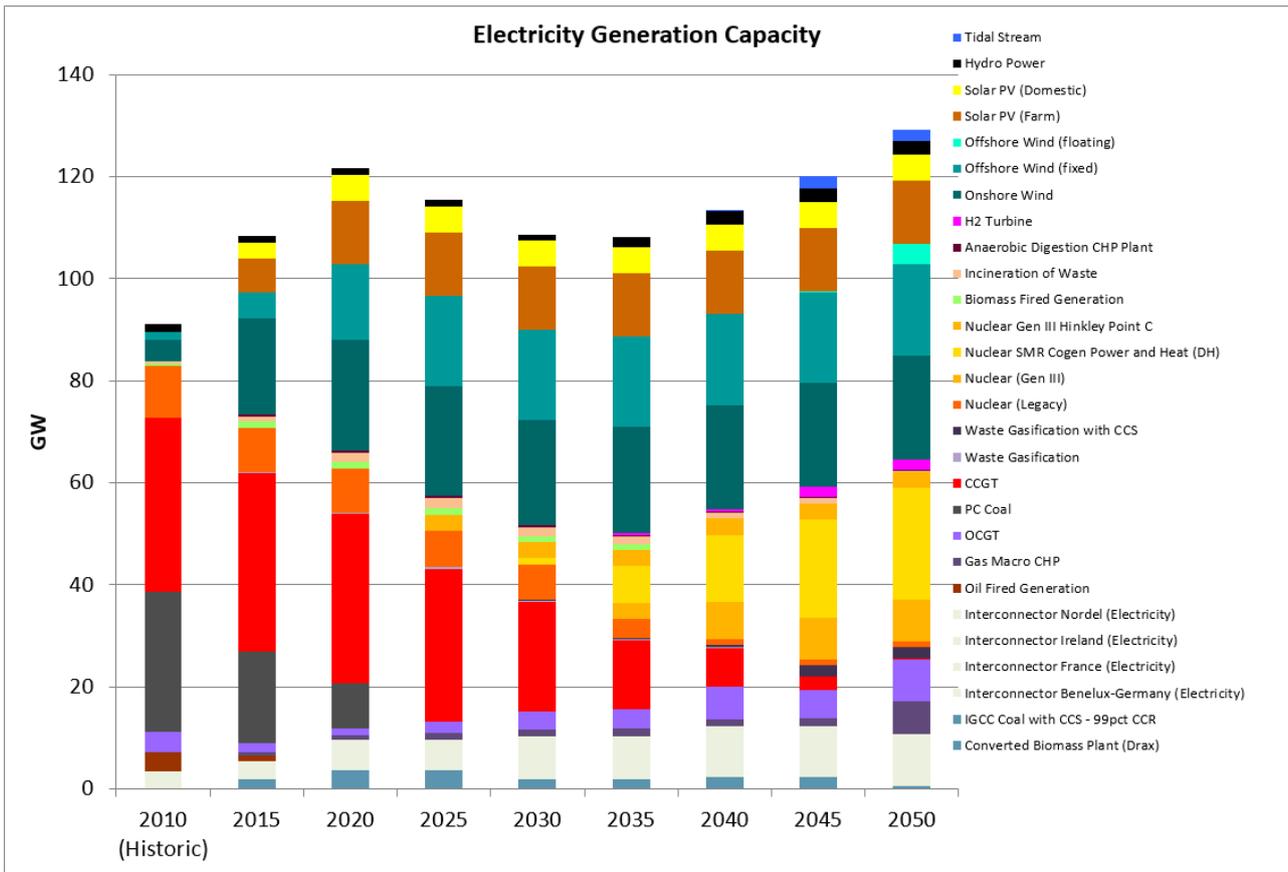Figure A3-172 – Run 356 Net CO$_2$ Emissions
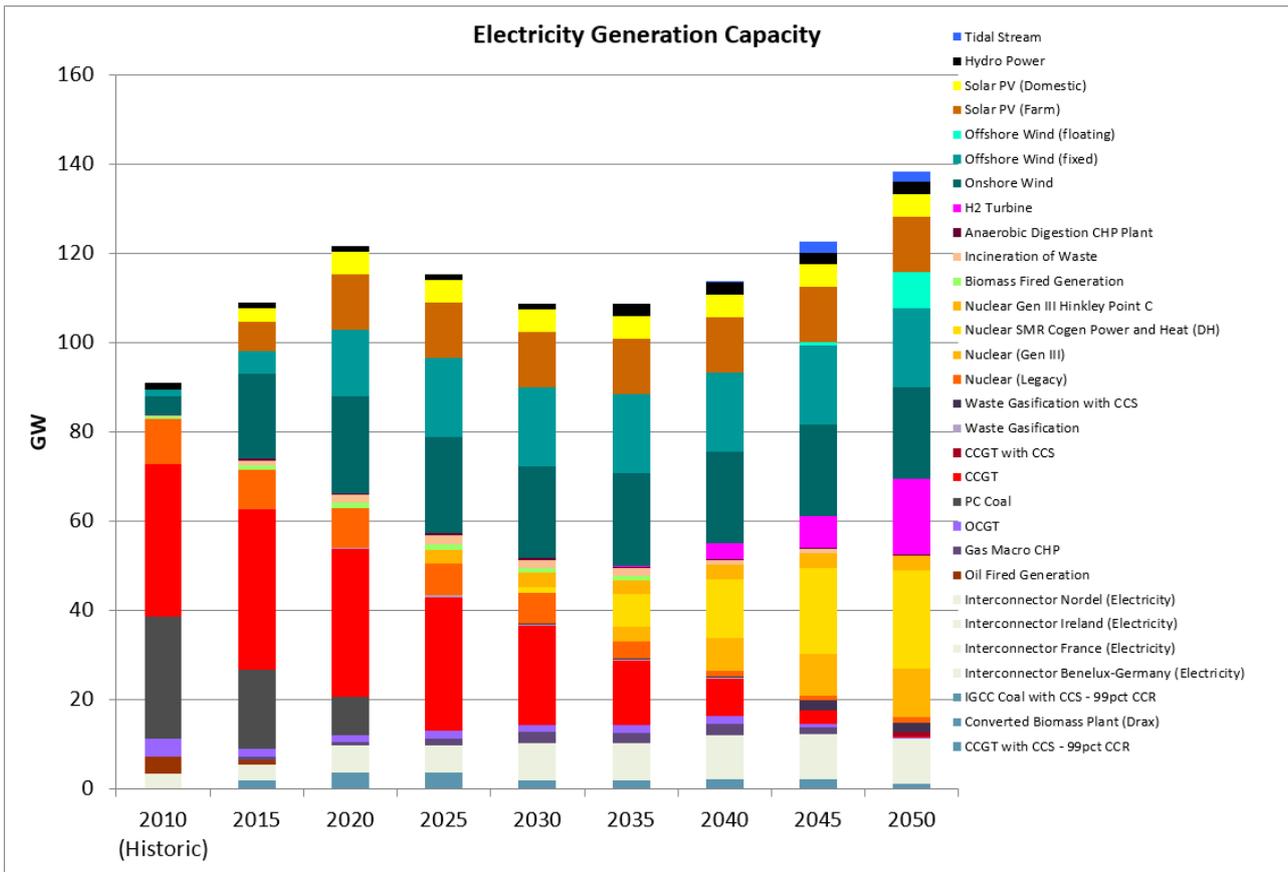
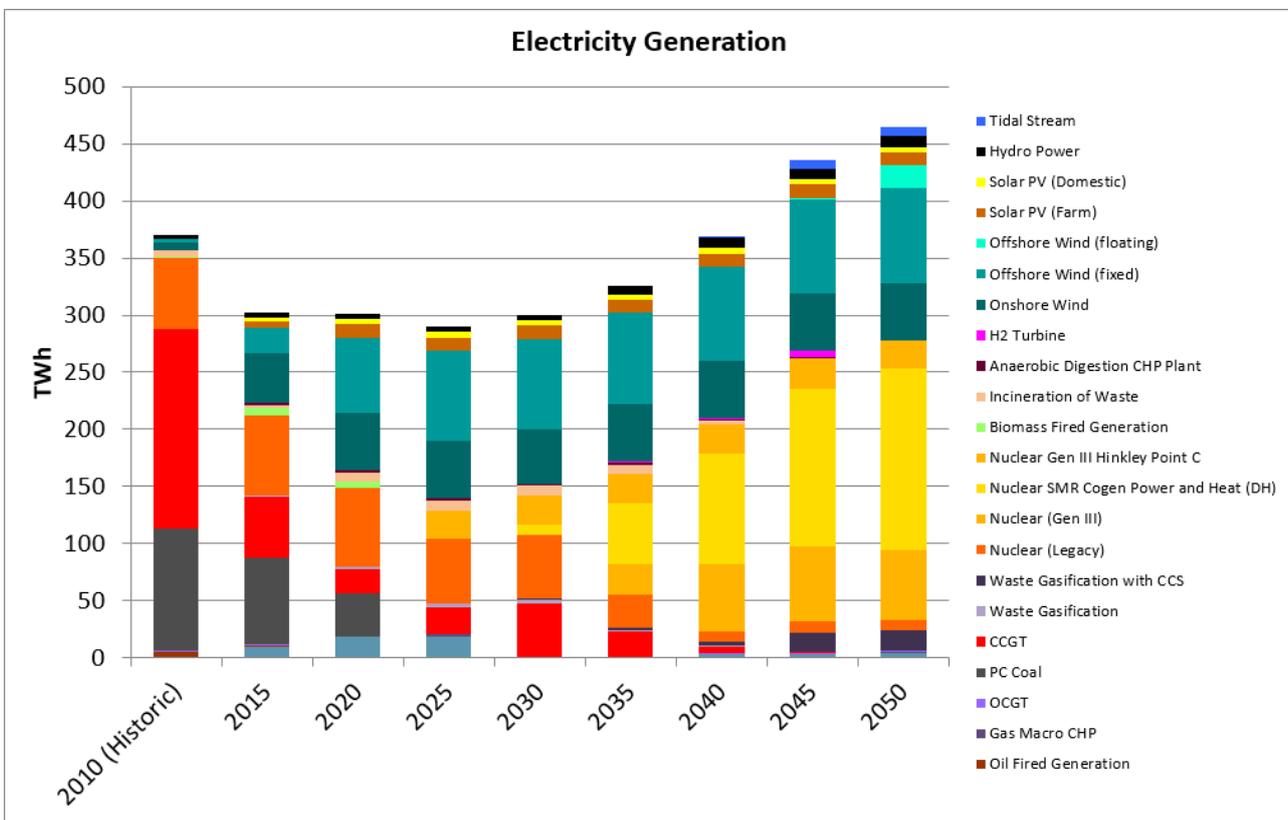Figure A3-173 – Run 356 Electricity Generation Capacity
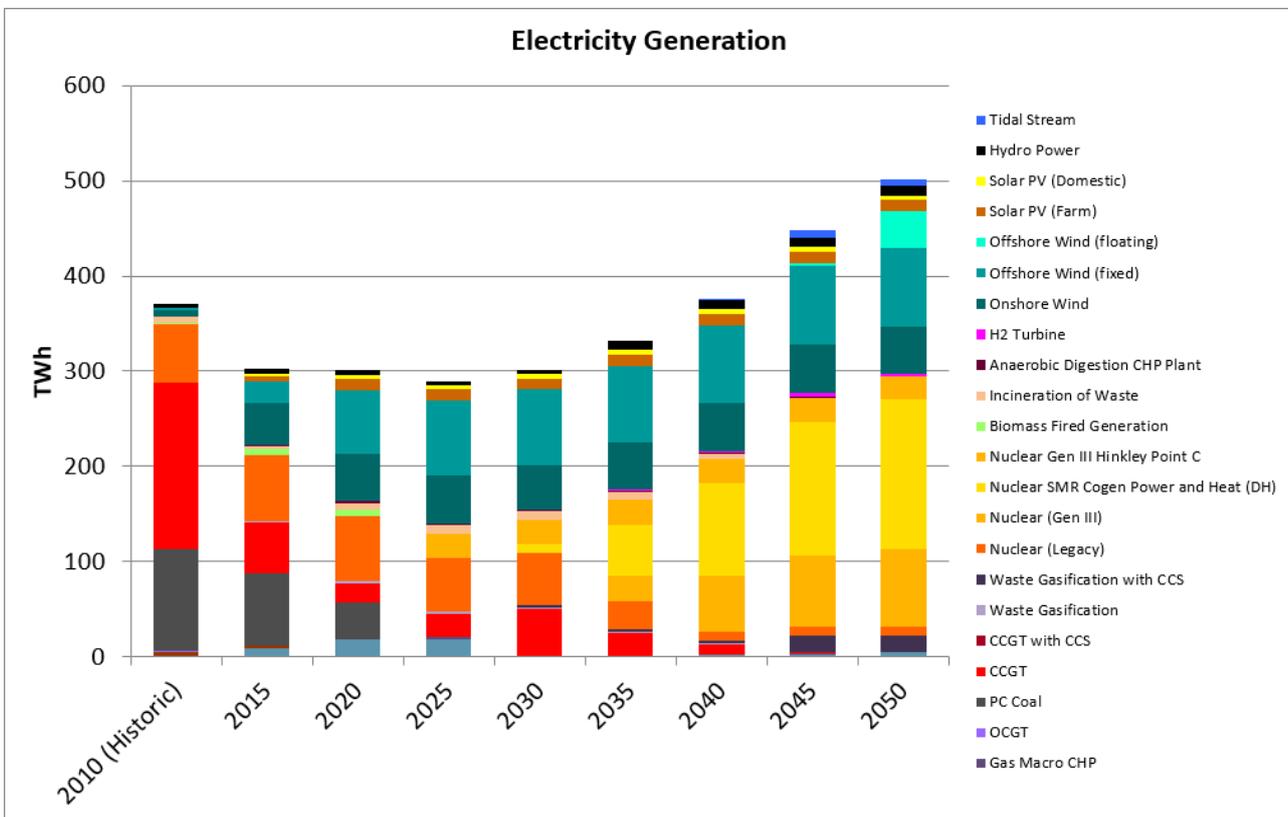
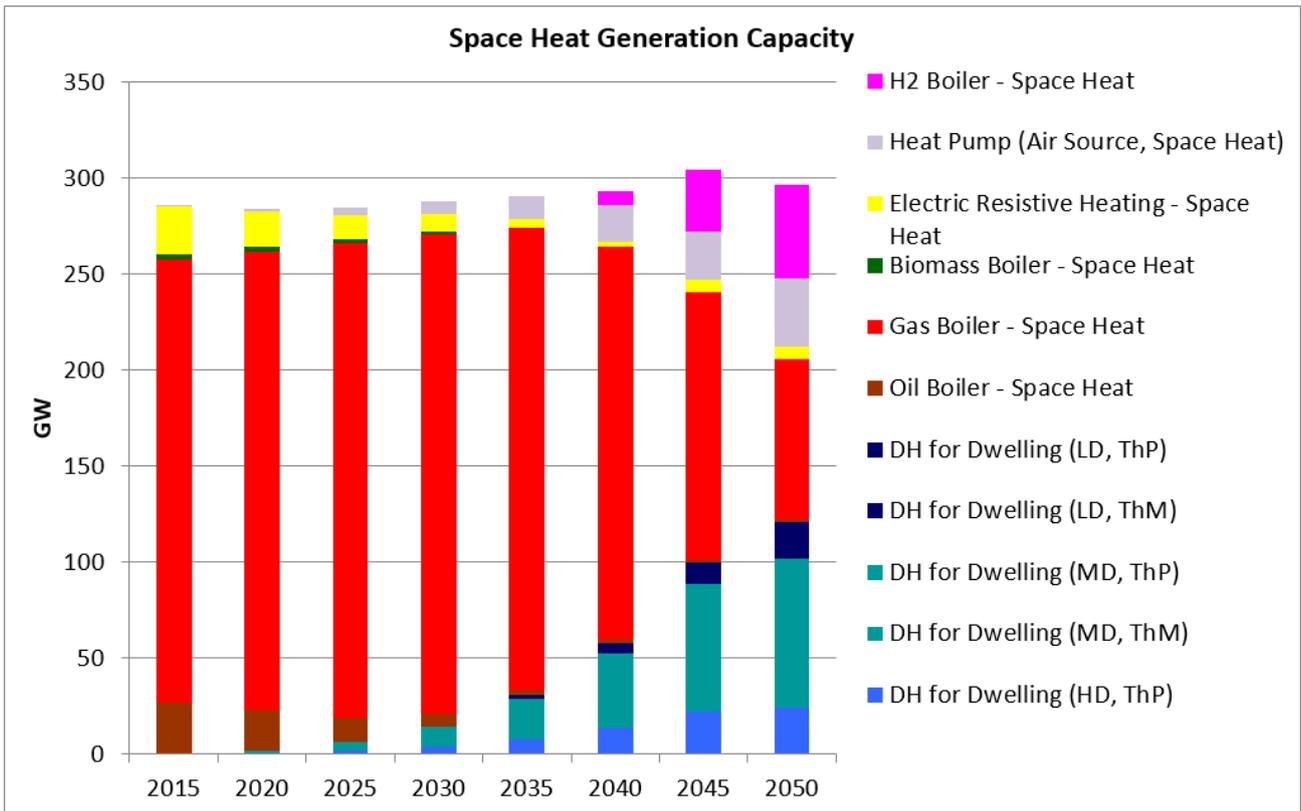Figure A3-174 – Run 356 Electricity Generation
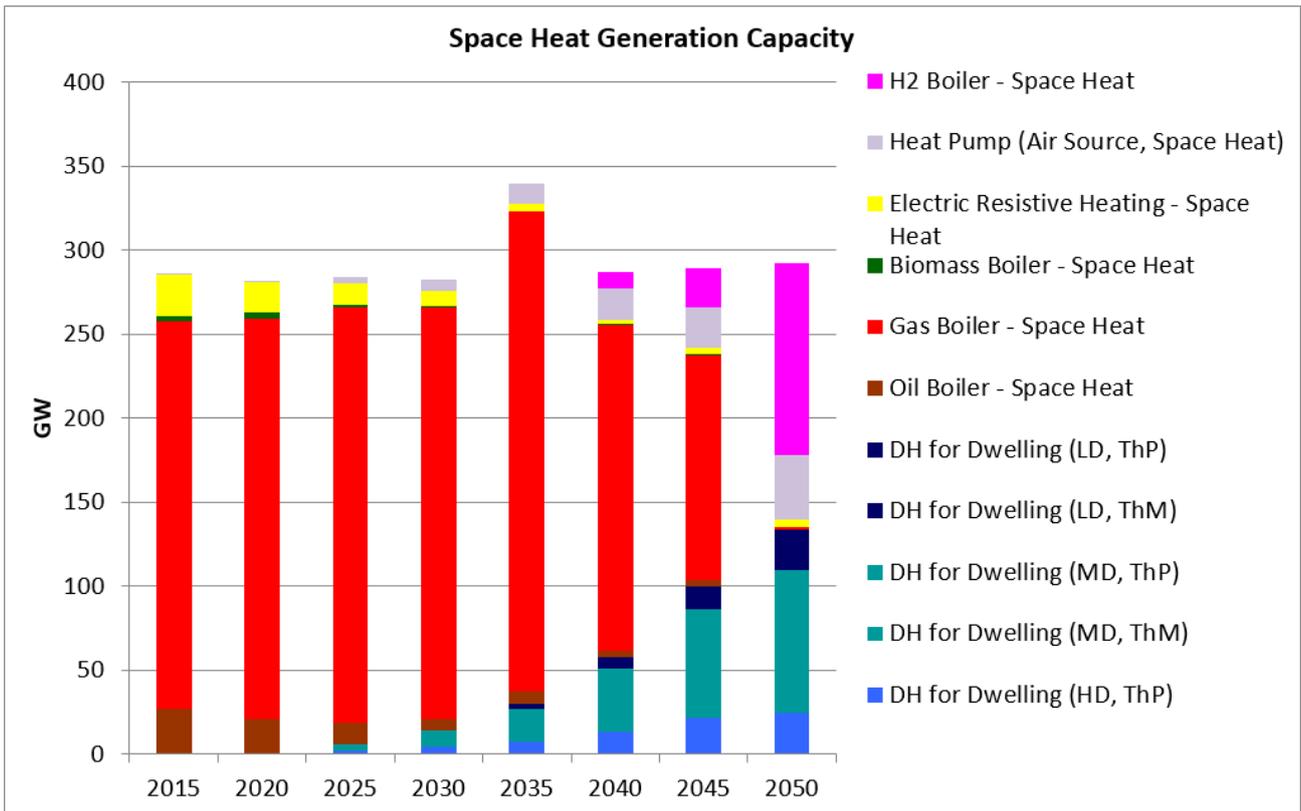
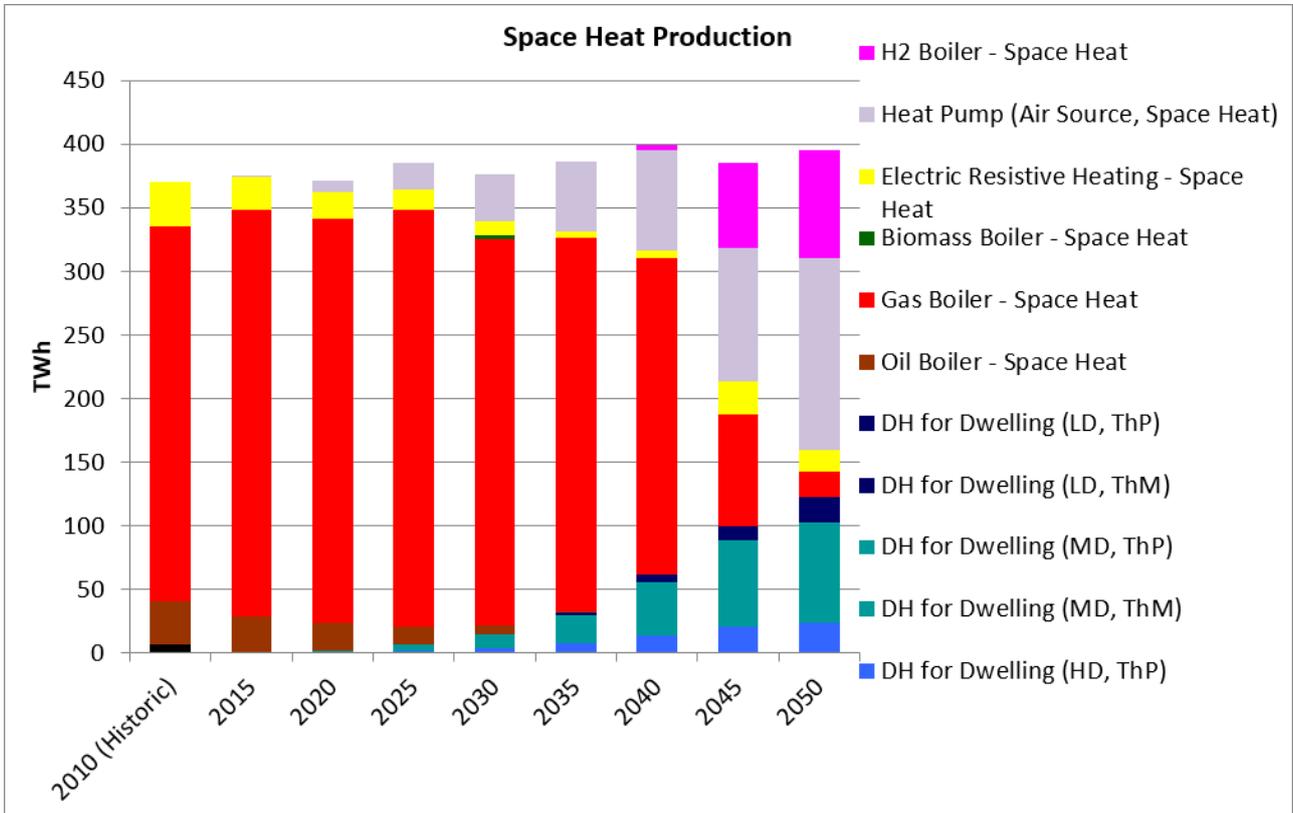Figure A3-175 – Run 356 Space Heat Generation Capacity
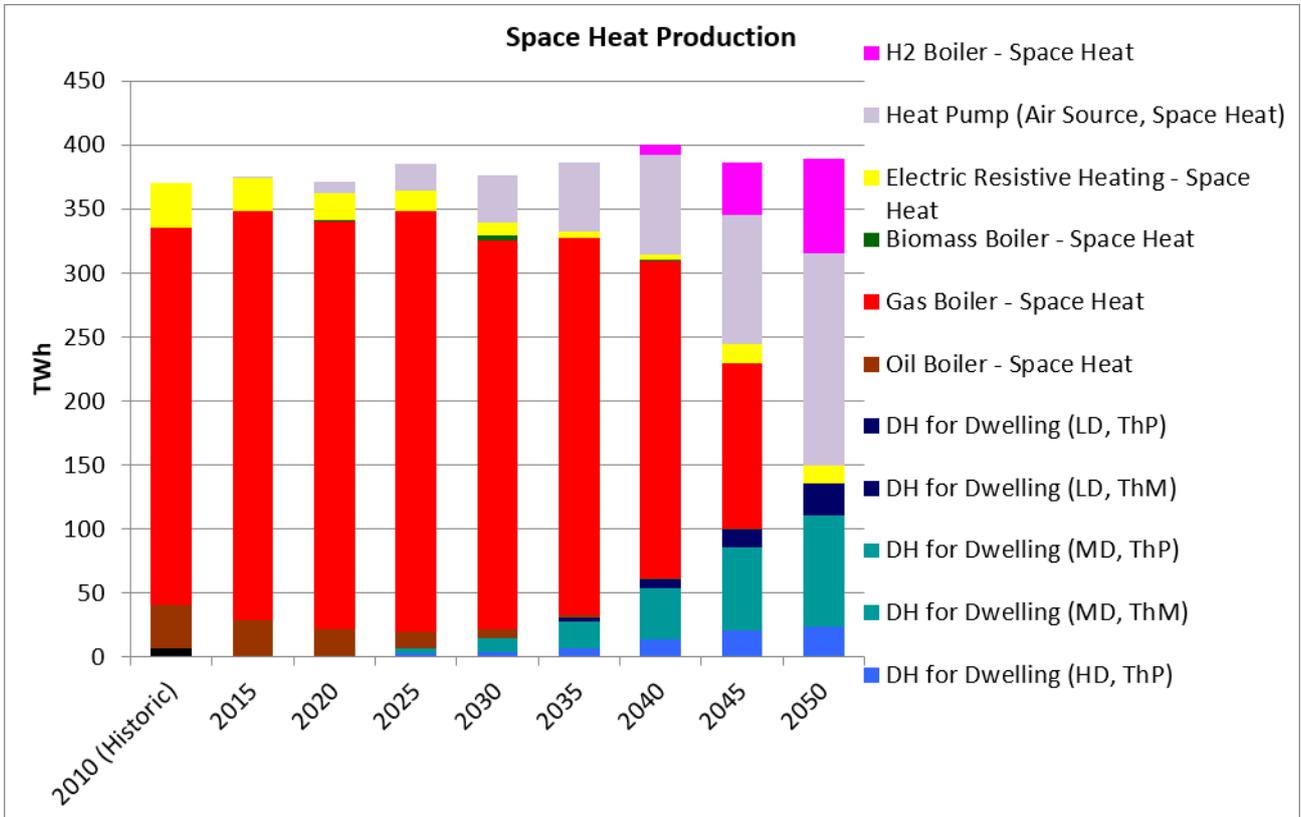
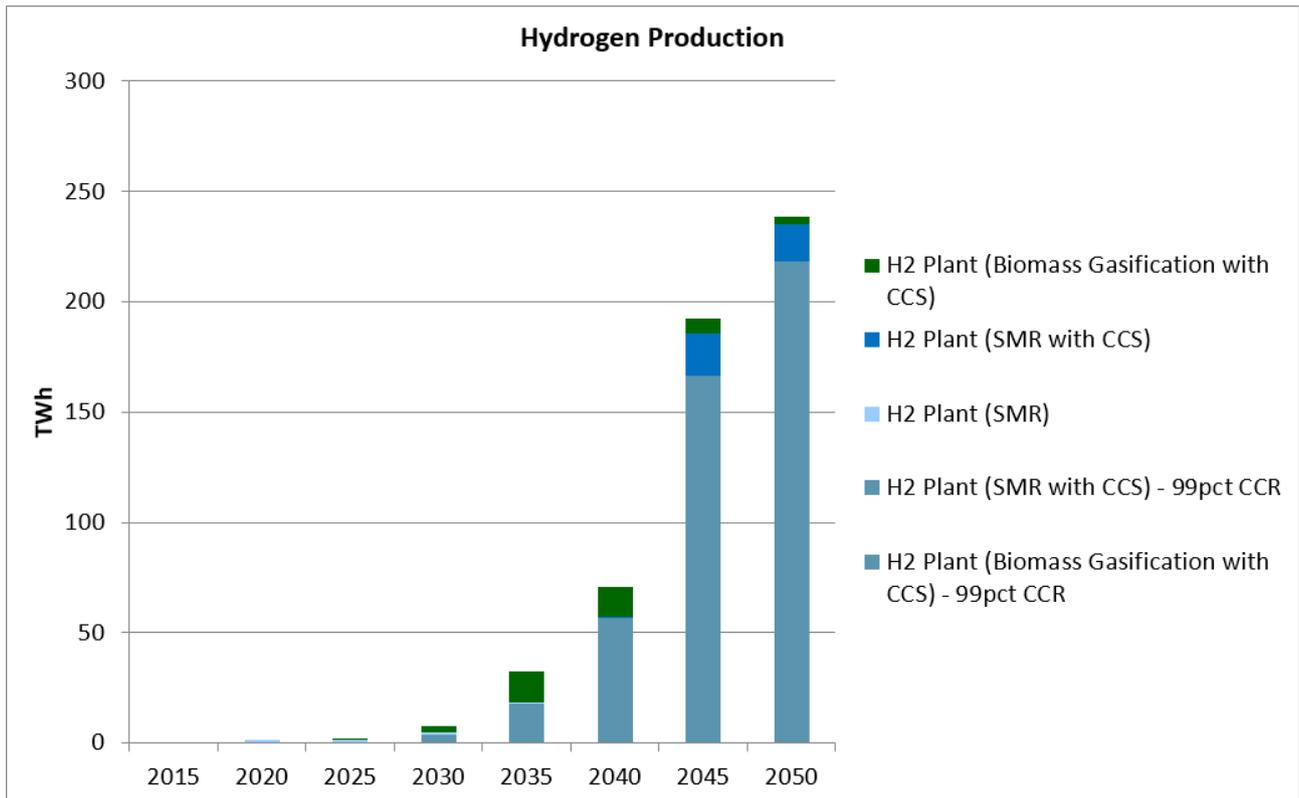Figure A3-176 – Run 356 Space Heat Production
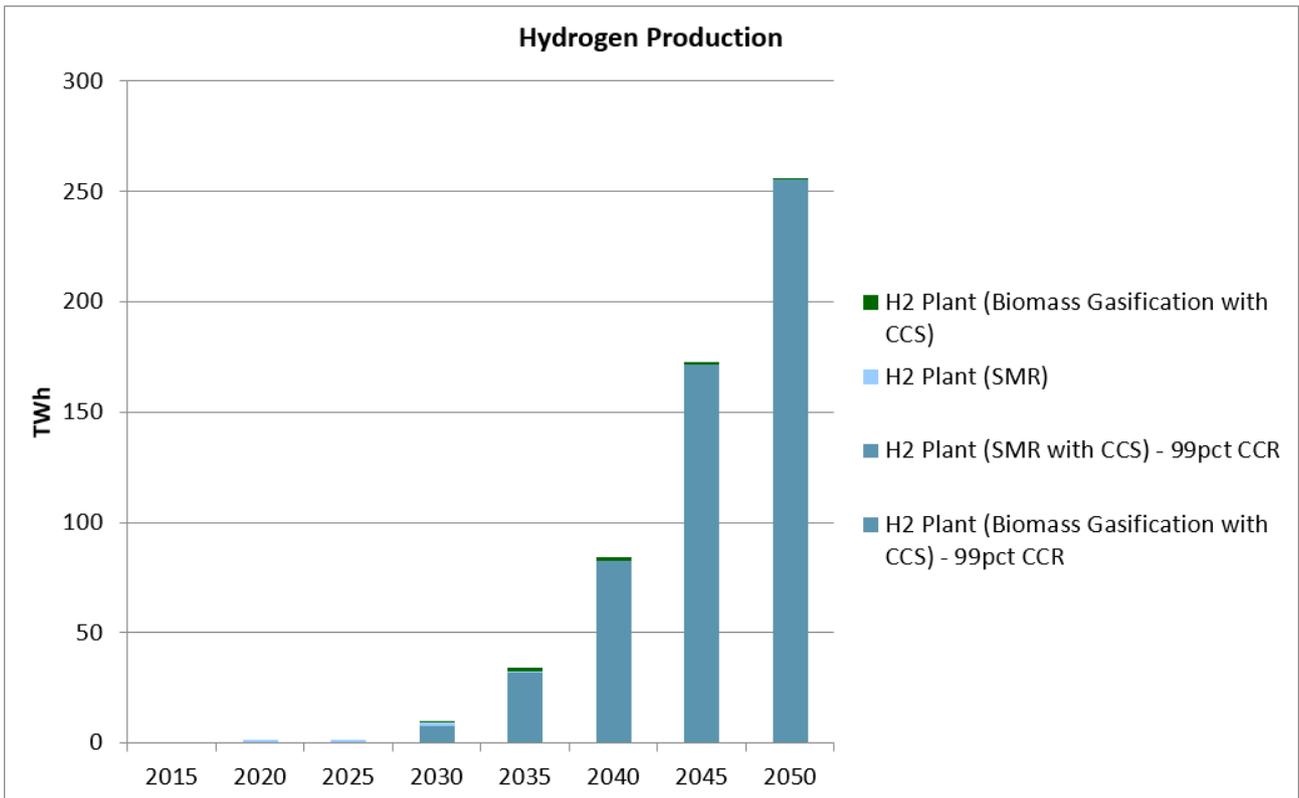
Figure A3-177 – Run 356 Hydrogen Production
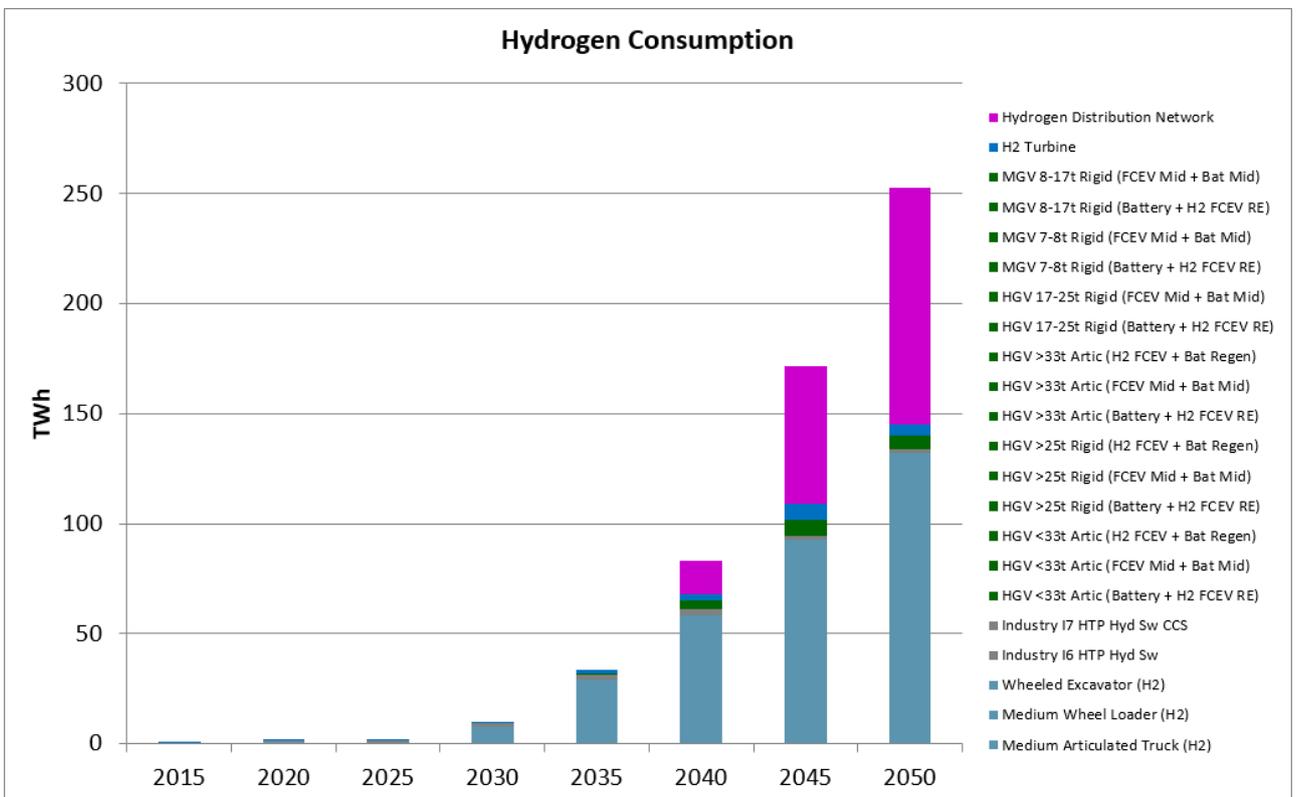
Figure A3-178 – Run 356 Hydrogen consumption
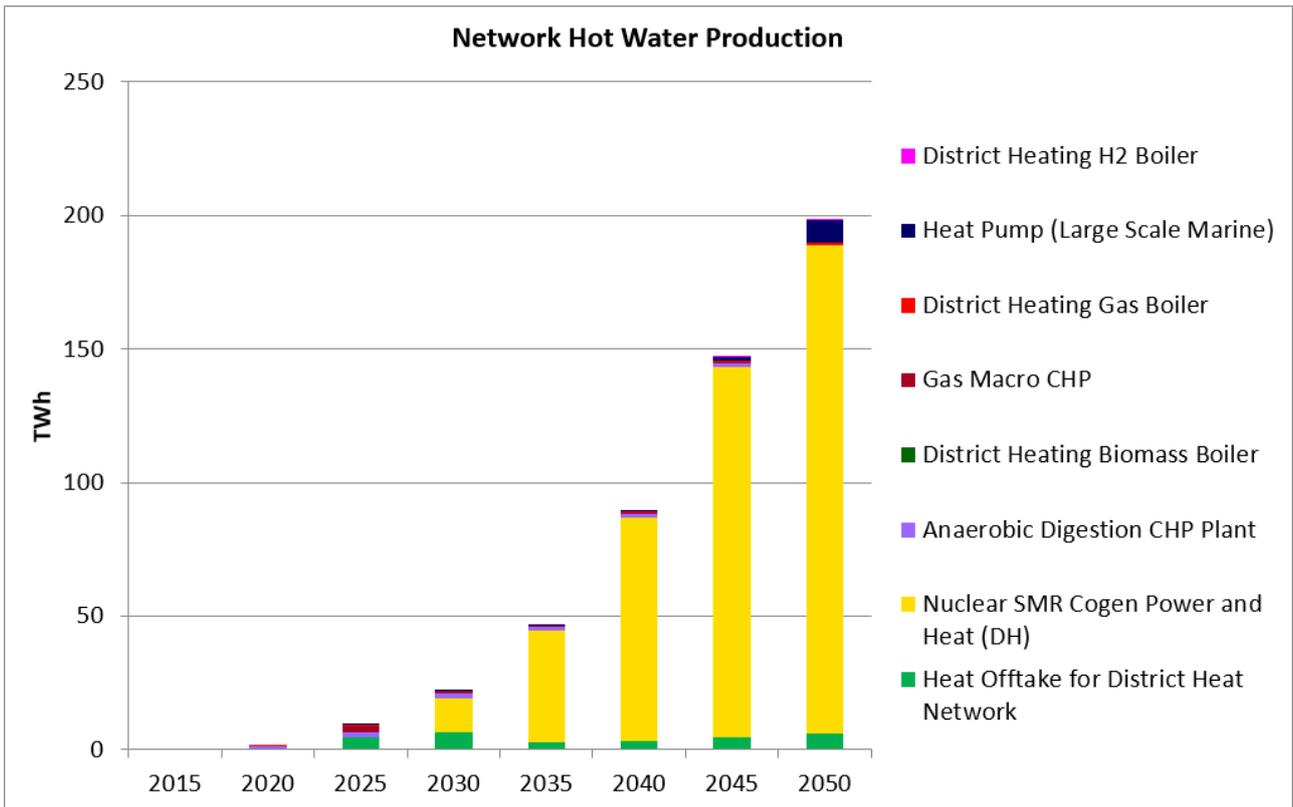
Figure A3-179 – Run 356 Network Hot Water Production
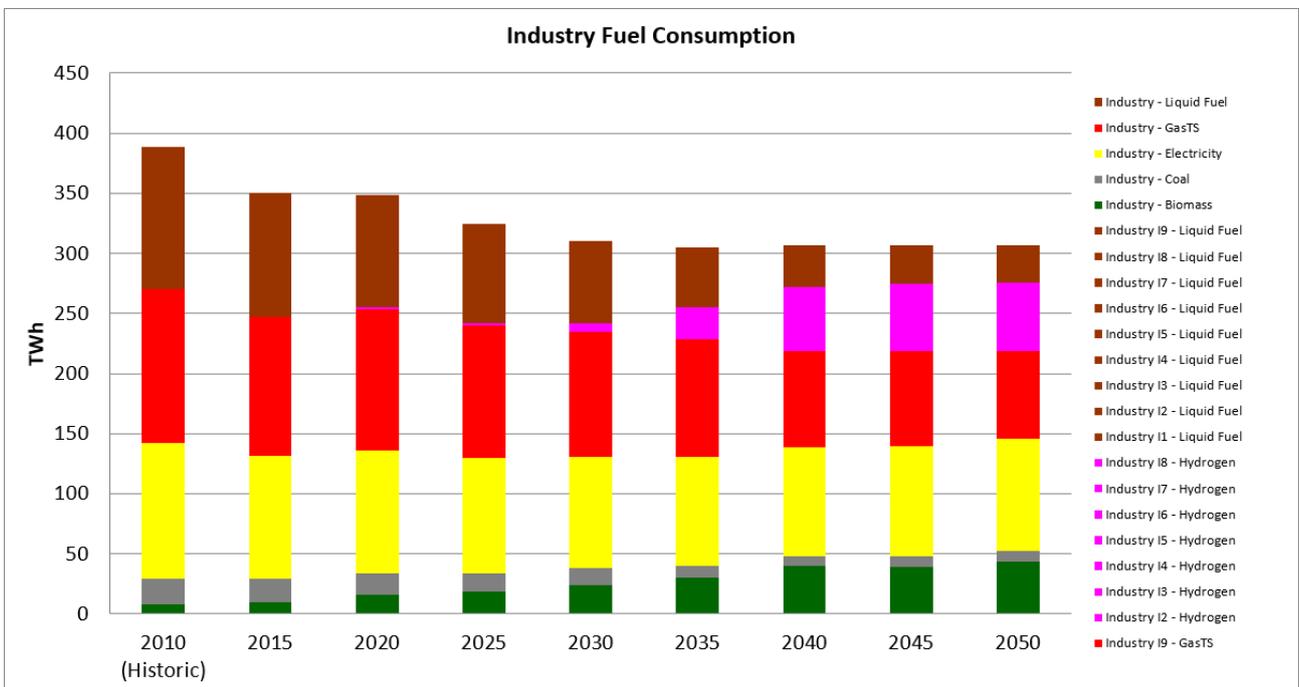
Figure A3-180 – Run 356 Industry Fuel Consumption

Run 357 TECH100 – Gen III+, LWSMR cogen, liquid synthetic fuel plant and no gigafactory; base case data except liquid synthetic fuel plant capex at 60 x LC values
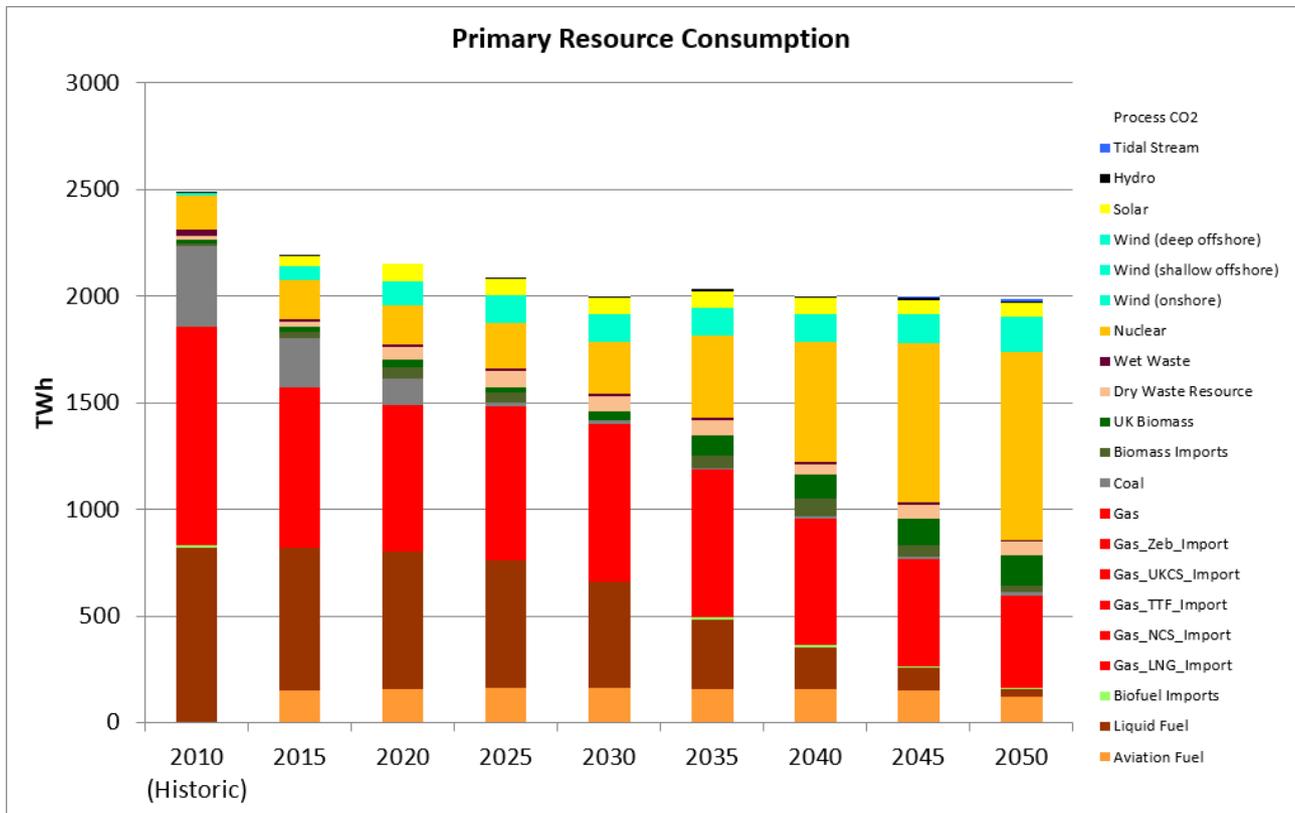
Figure A3-181 – Run 357 Primary Resource Consumption
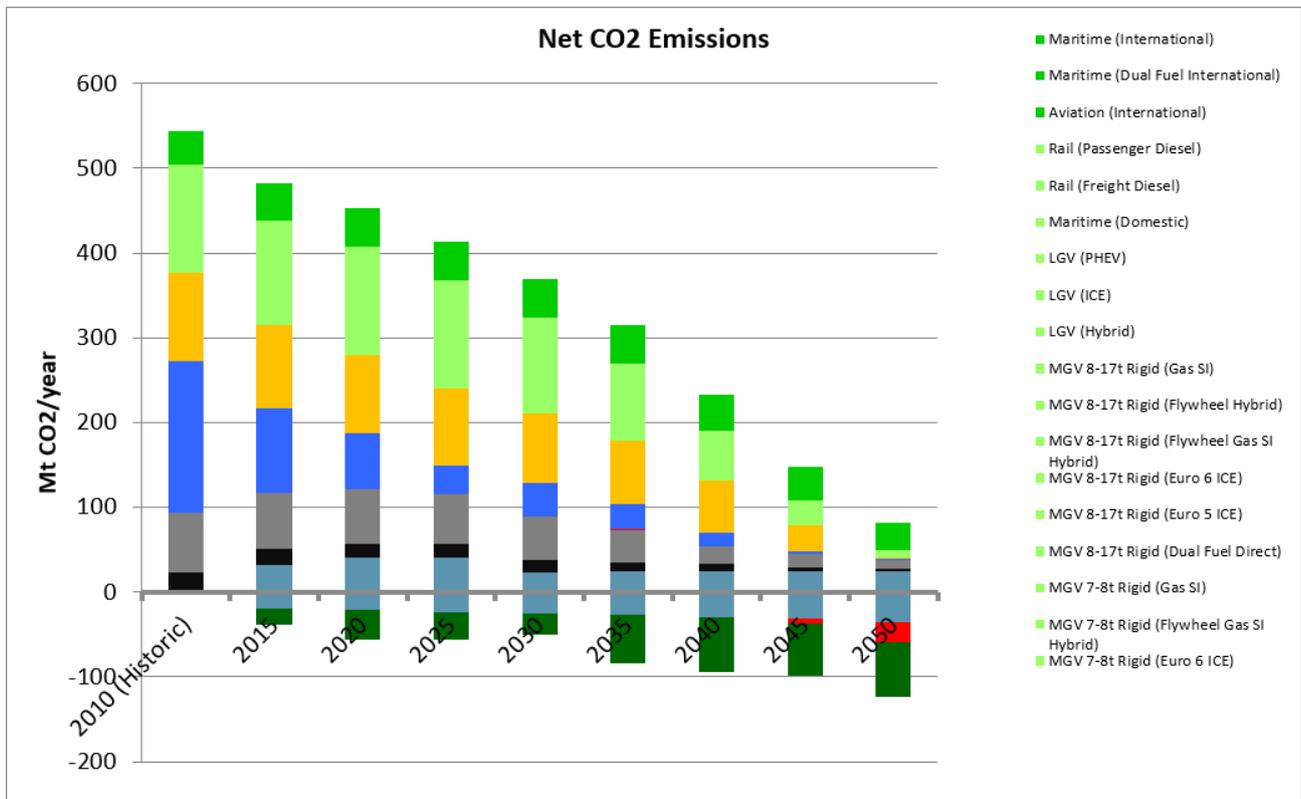
Figure A3-182 – Run 357 Net CO_2 Emissions
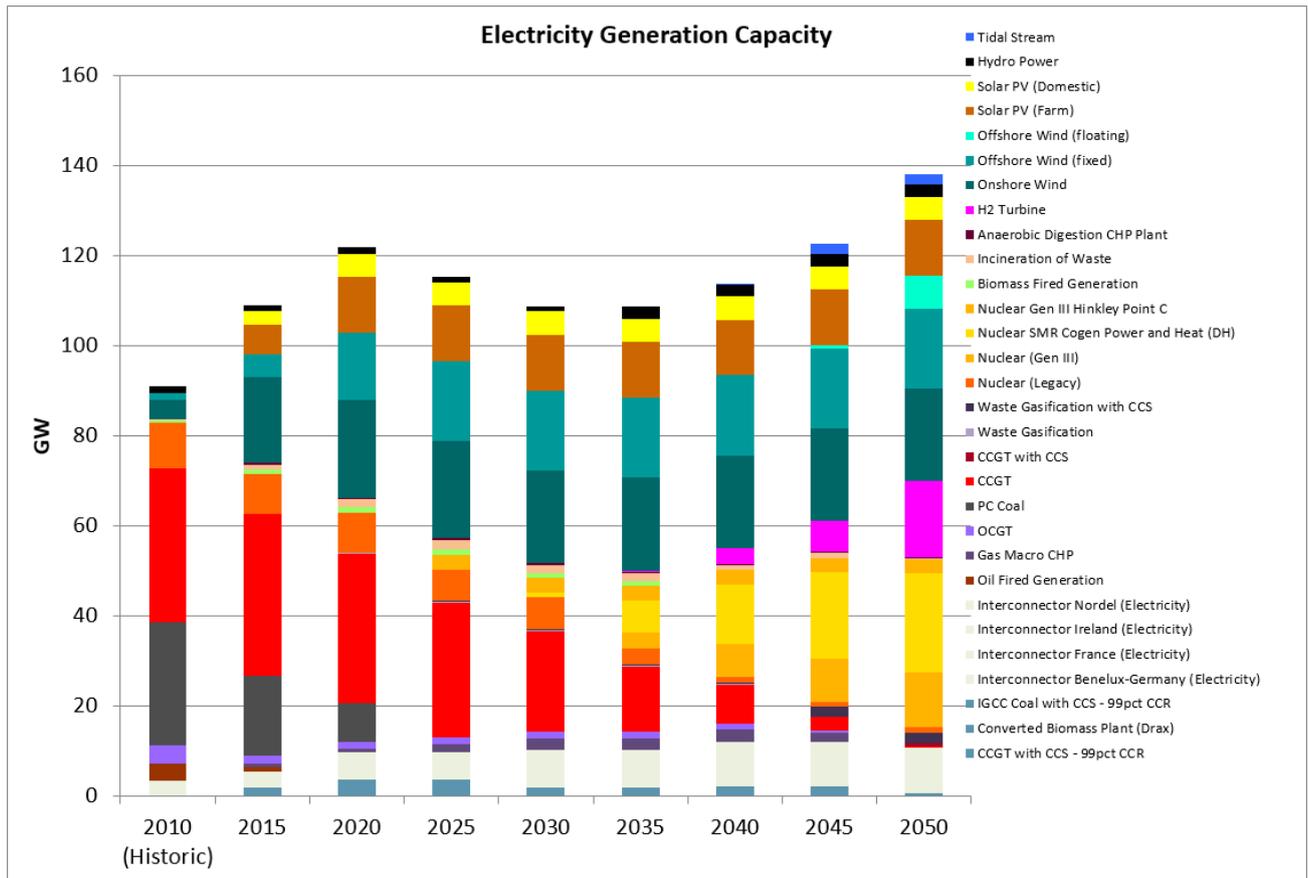
Figure A3-183 – Run 357 Electricity Generation Capacity
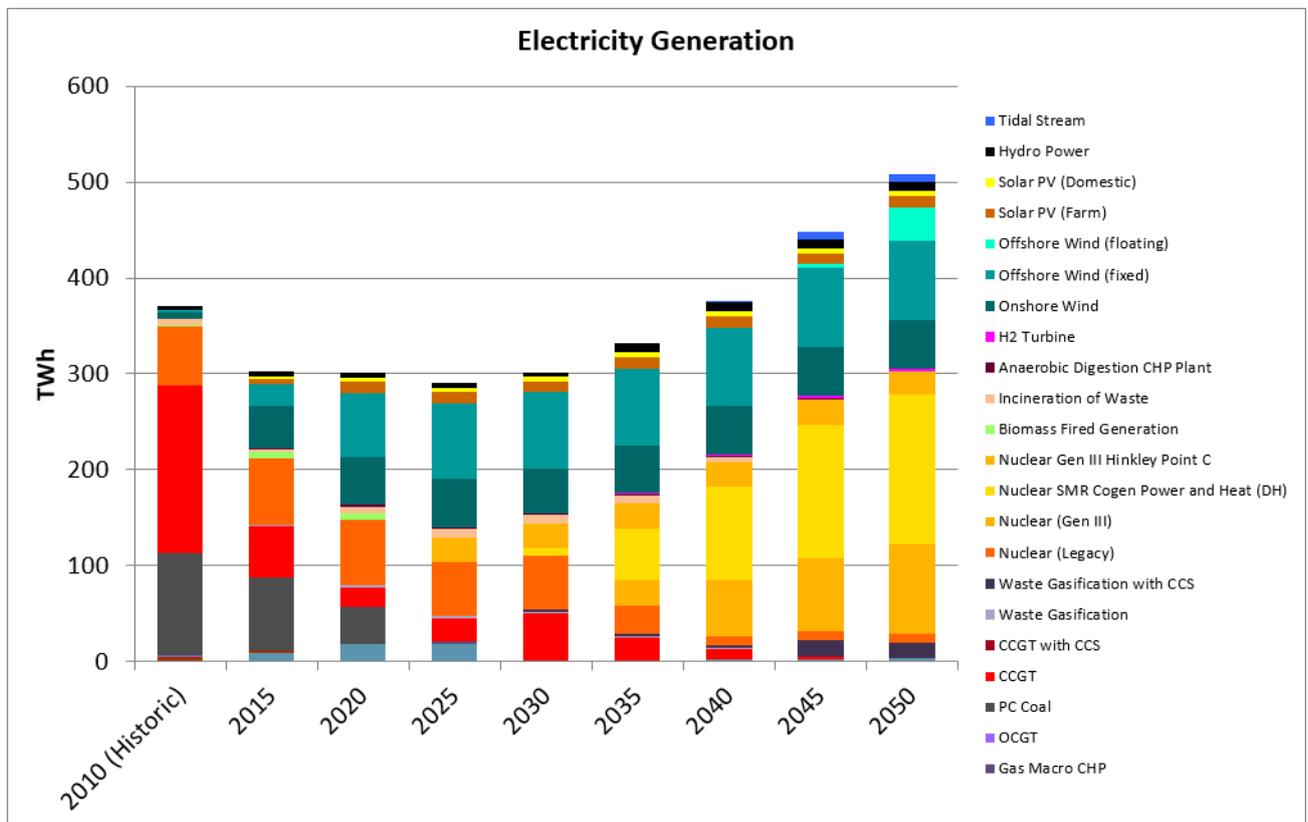
Figure A3-184 – Run 357 Electricity Generation
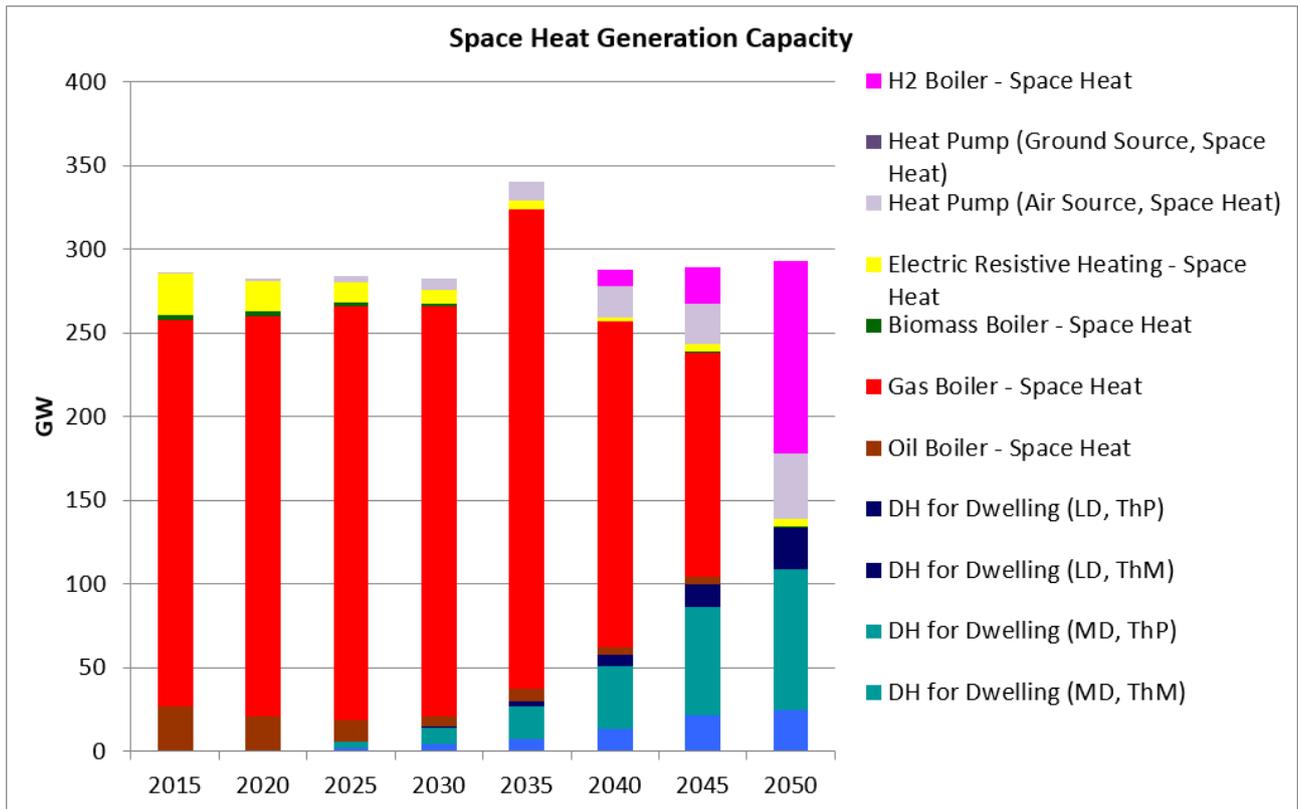
Figure A3-185 – Run 357 Space Heat Generation Capacity
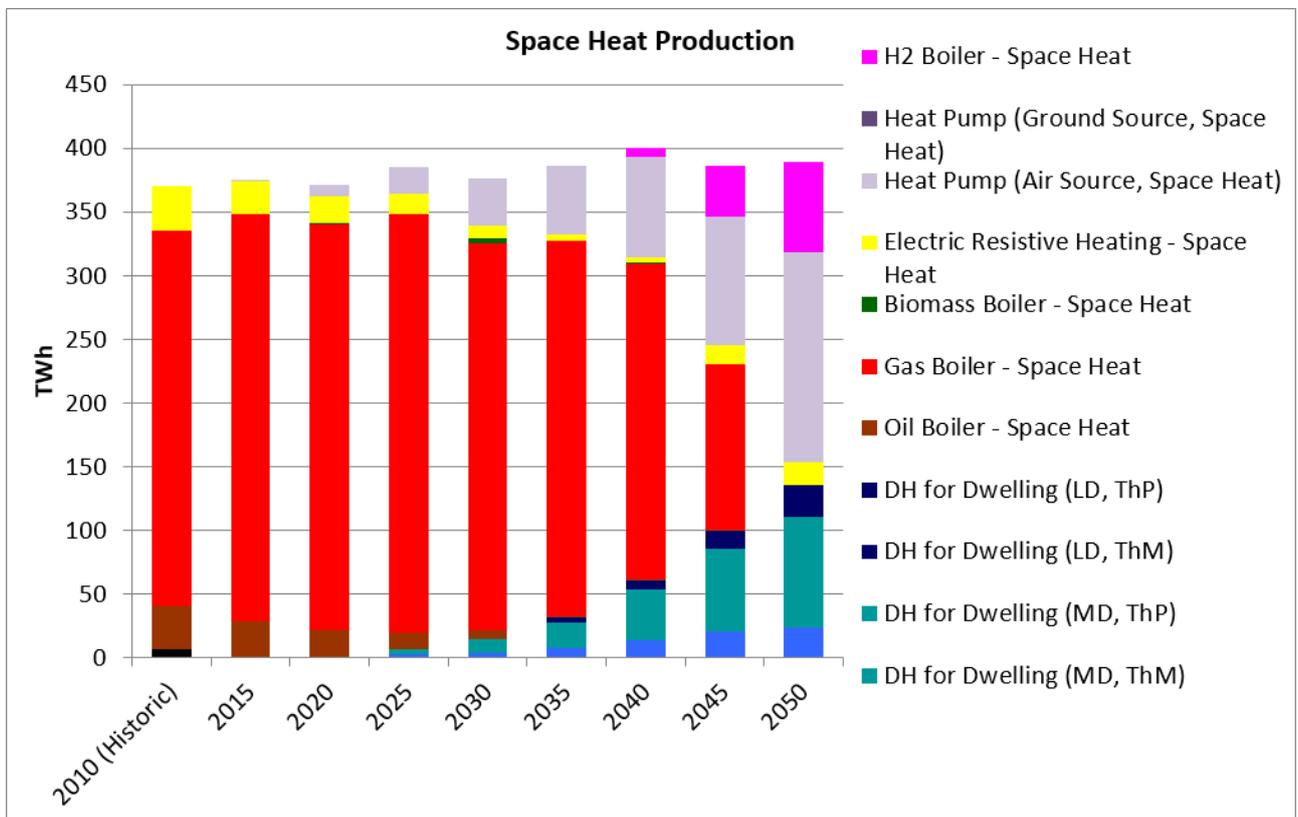
Figure A3-186 – Run 357 Space Heat Production
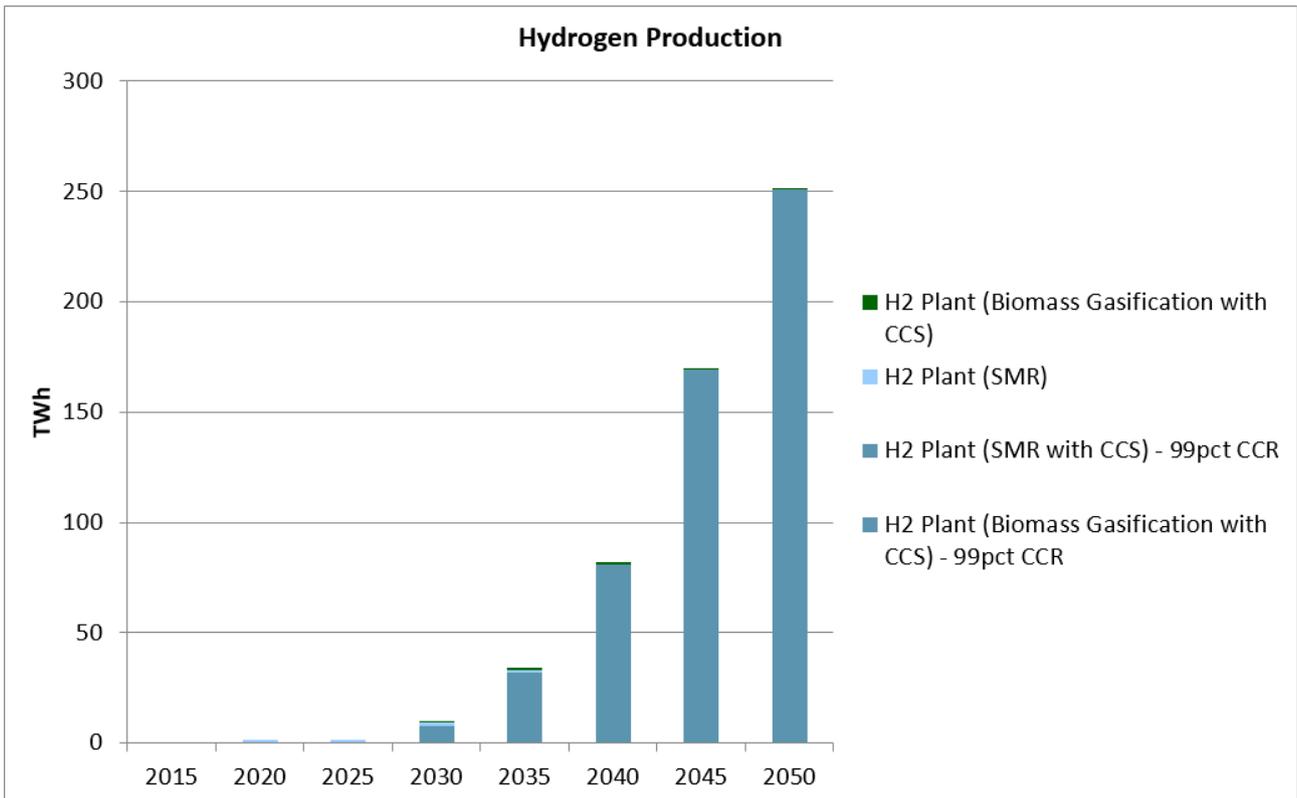
Figure A3-187 – Run 357 Hydrogen Production
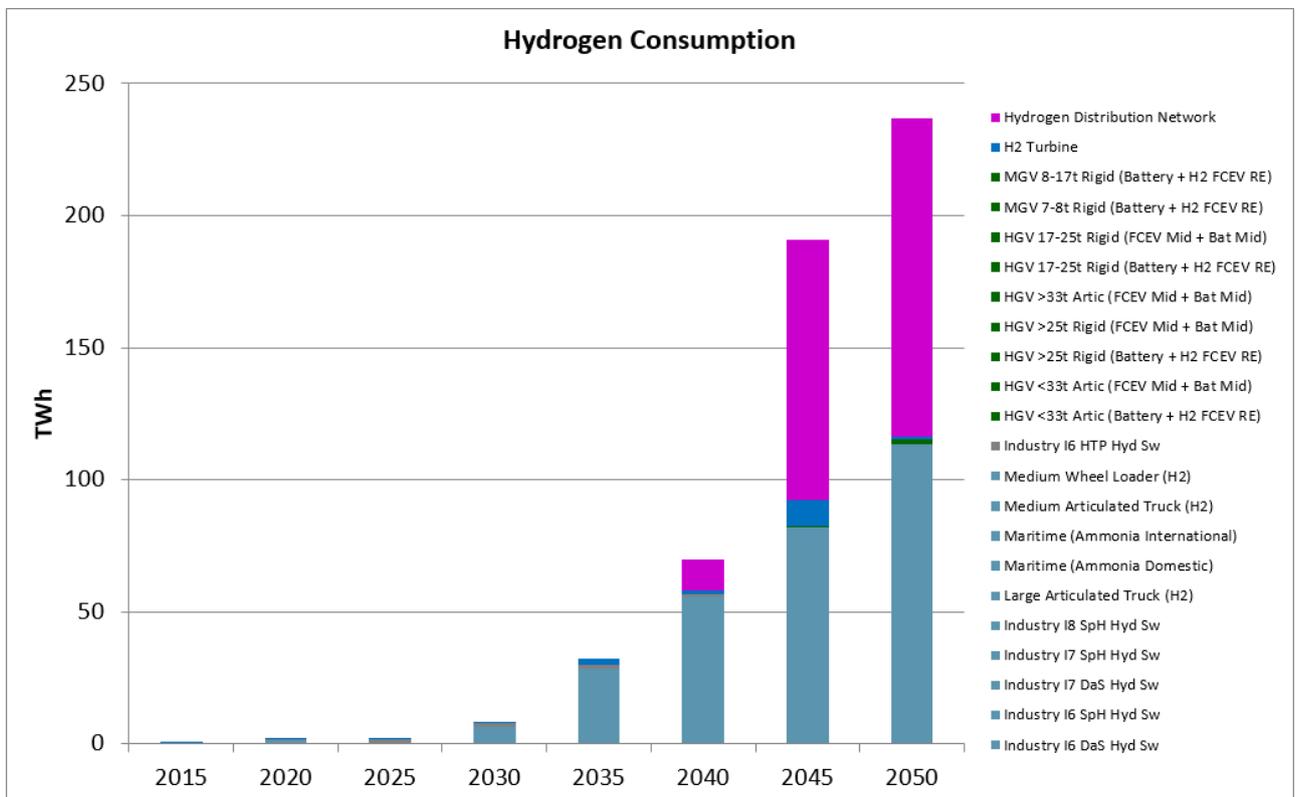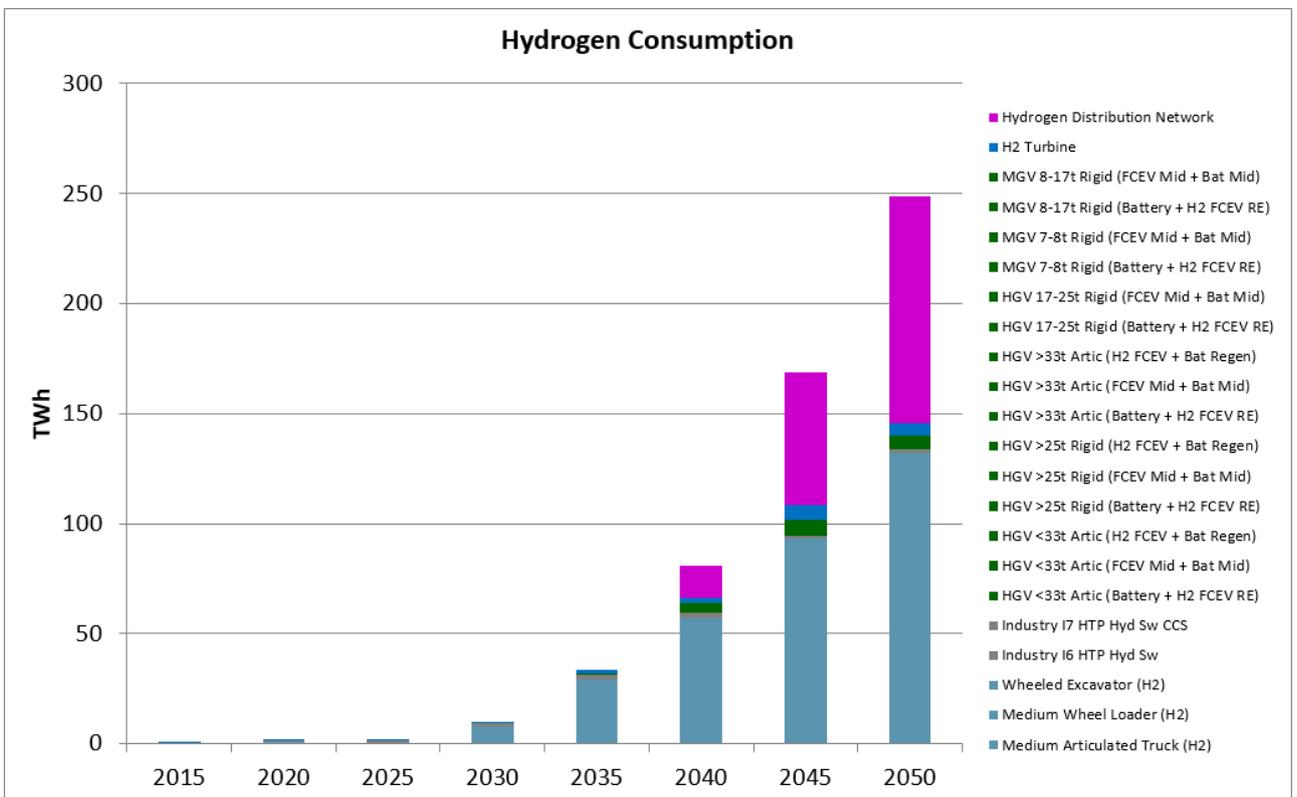

Figure A3-188 – Run 357 Hydrogen consumption
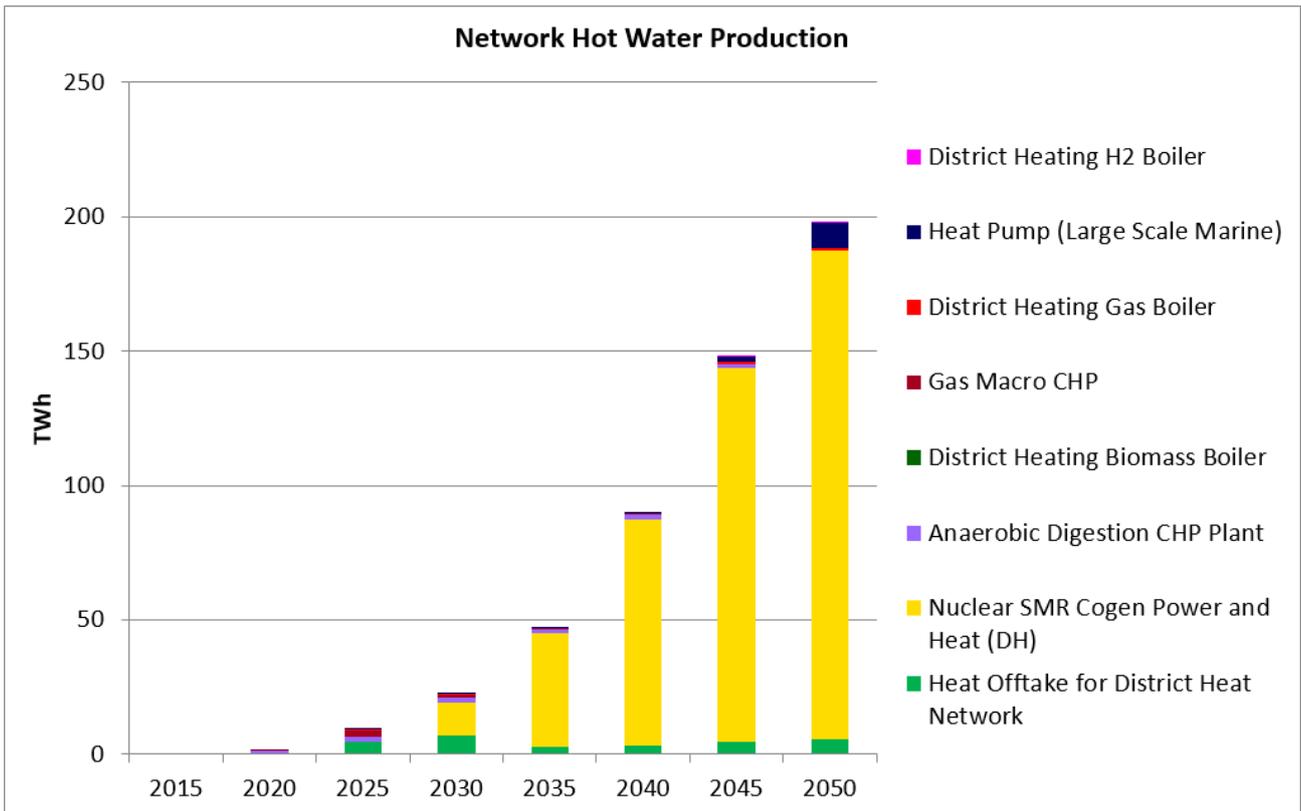
Figure A3-189 – Run 357 Network Hot Water Production
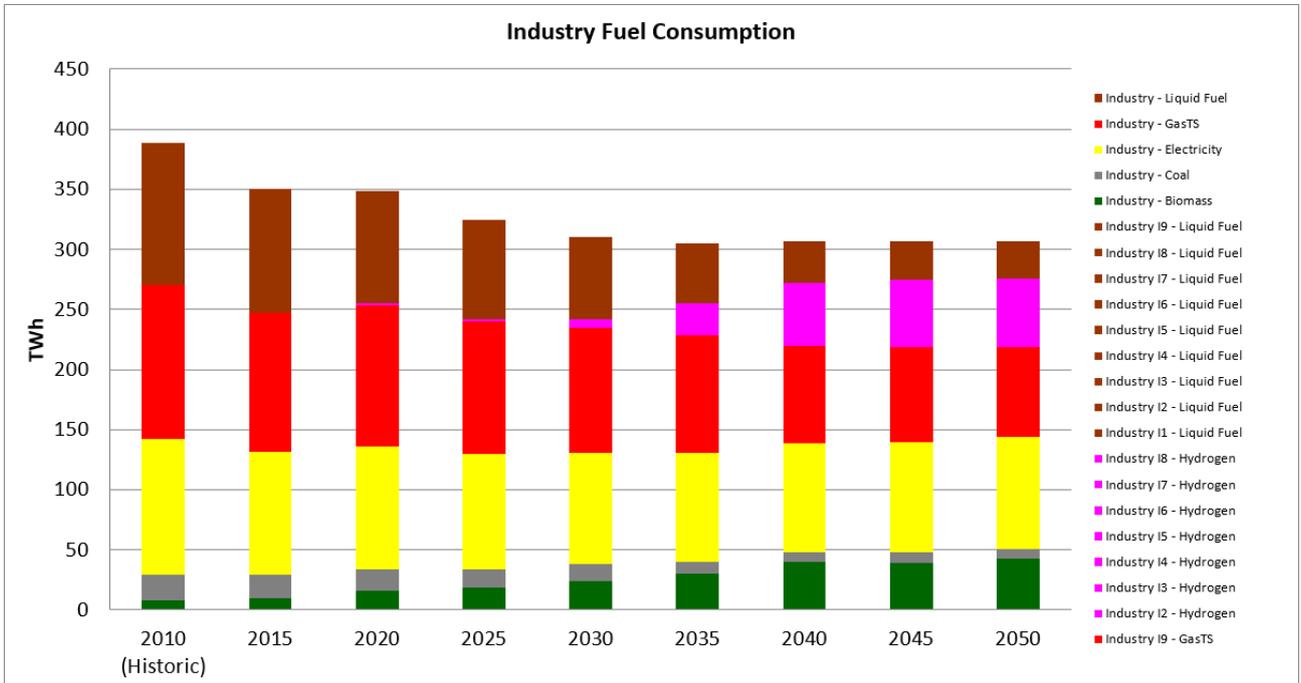
Figure A3-190 – Run 357 Industry Fuel Consumption

Monte Carlo Run TECH100 – Nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR deployed as cogen for flexible power and heat for district heating energisation; gigafactory for high volume hydrogen production and liquid synthetic fuel plant for "drop-in" Jet A replacement
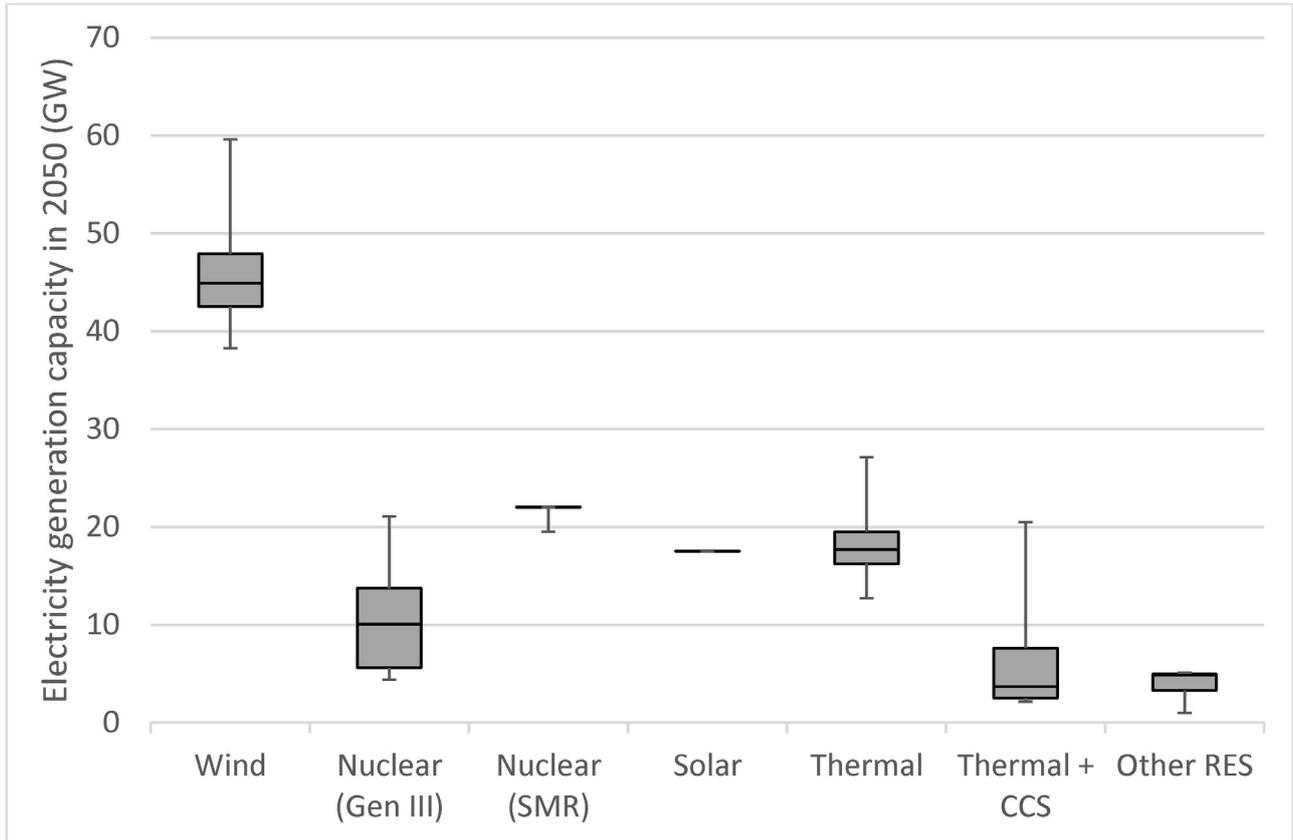
Figure A3-191- 2050 Electrical Generation Capacity by Technology – Probabilistic (Monte Carlo) analysis Based on Deterministic Run 310 TECH with Hydrogen Gigafactory and Liquid Synthetic Fuel Plant
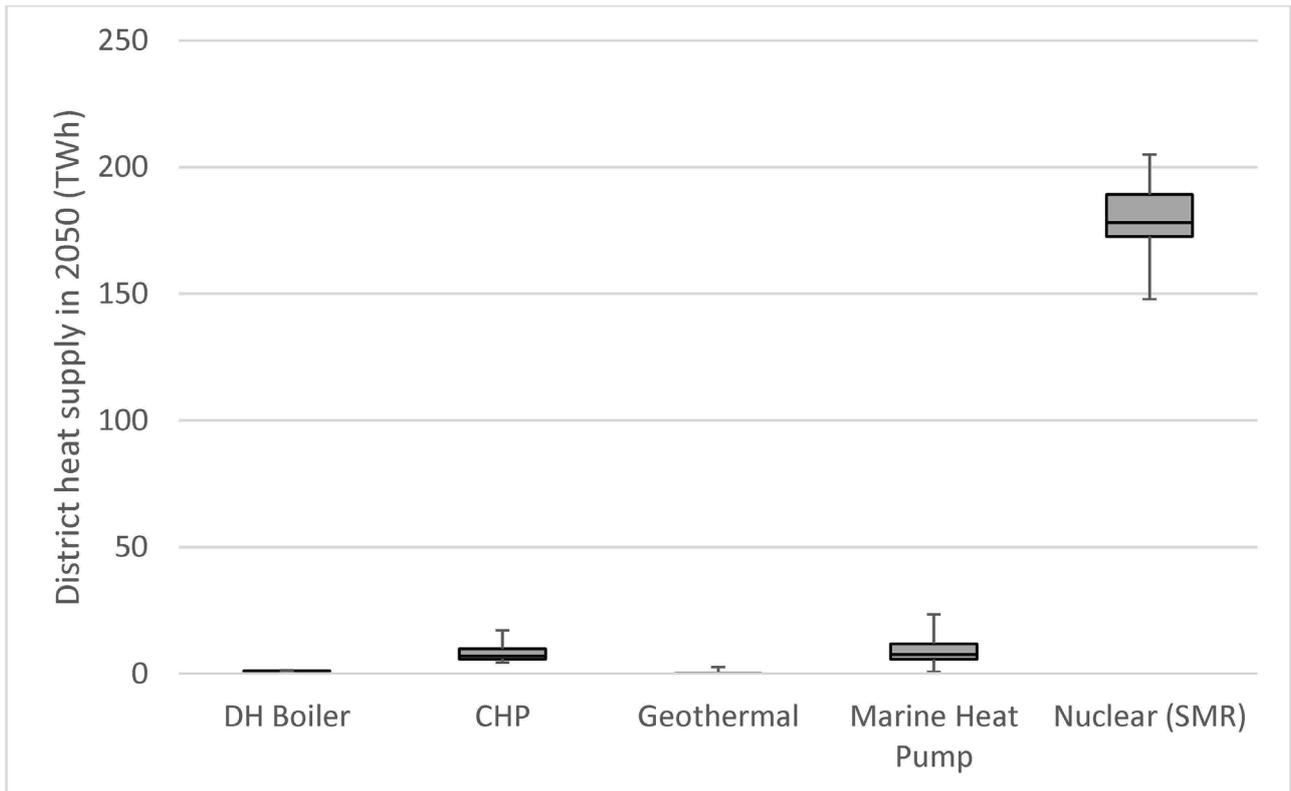
Figure A3-192 – 2050 District Heat Supply by Technology – Probabilistic (Monte Carlo) Analysis Based on Deterministic Run 310 TECH with Hydrogen Gigafactory and Liquid Synthetic Fuel Plant

Monte Carlo Run TECH100 – Nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR deployed as cogen for flexible power and heat for district heating energisation; gigafactory for high volume hydrogen production; no deployment of liquid synthetic fuel plant
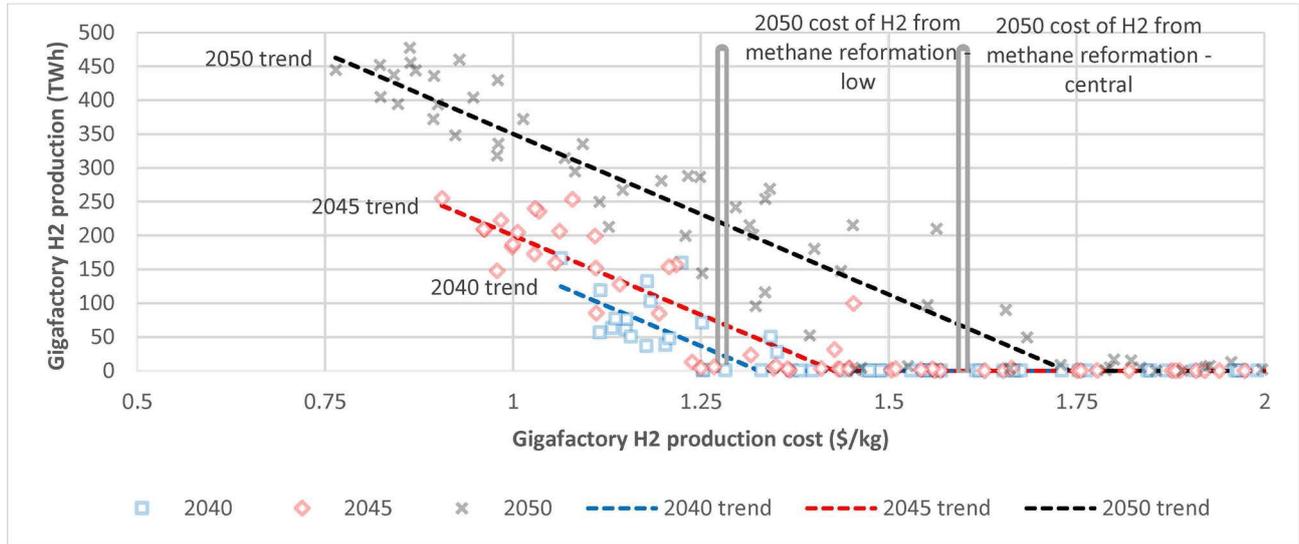
Figure A3-193 – SR No.3 Probabilistic (Monte Carlo) run showing hydrogen production from the gigafactory as a function of production cost ($2017) – Decarbonisation scenario TECH100

Monte Carlo Run TECH100 – Nuclear new build technologies enabled for deployment alongside nuclear legacy; large Gen III+ plants for flexible power; light-water nuclear SMR deployed as cogen for flexible power and heat for district heating energisation; liquid synthetic fuel plant for Jet A with no net emissions; no deployment of hydrogen gigafactory
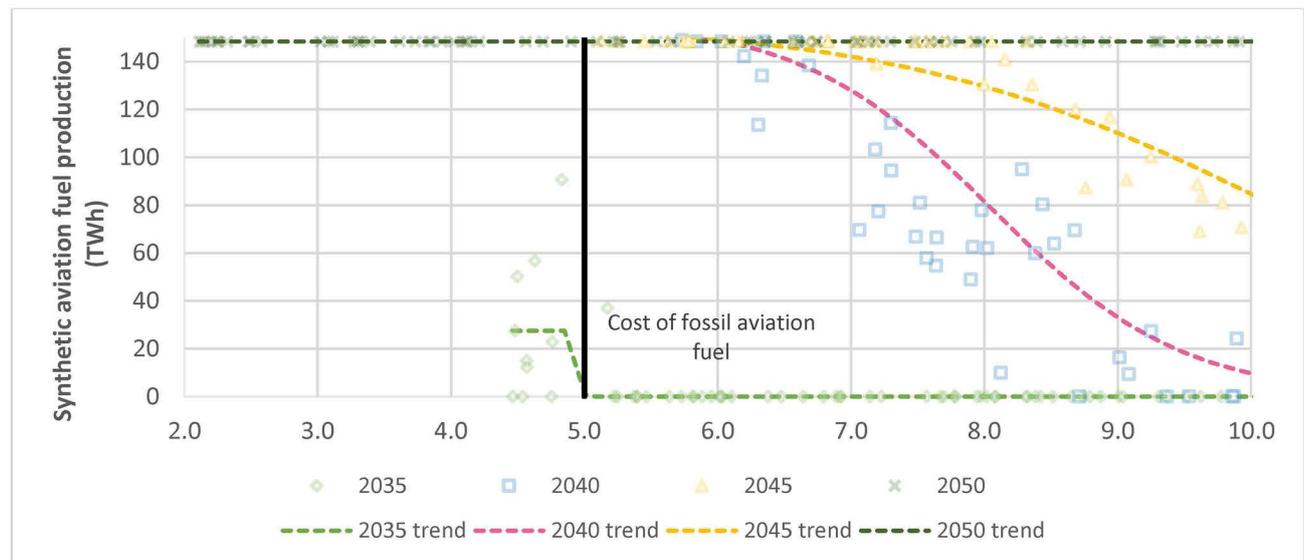
Figure A3-194 – SR No.3 Probabilistic (Monte Carlo) Run Showing Liquid Synthetic Fuel Production as a Function of Production Cost (£2010 p/kWh of aviation fuel) – Decarbonisation Scenario

Annex 4 – Nuclear deployment scenarios in greater definition for fuel cycle modelling

Table A4-1 – "Constrained Nuclear Deployment Scenario" Defined by Run 5

Note: these tables do not include AGRs or SZB	2025	2030	2035	2040	2045	2050
Large Gen III+						
Installed Capacity Hinkley Point C	3	3	3	3	3	3
Installed capacity (GWe)	0	1	6	10	10	10
Thermal efficiency	38%	38%	38%	38%	38%	38%
Installed capacity (GWth)	8.42	10.13	24.10	34.74	34.74	34.74
Annual Load Factor	0%	92%	92%	92%	92%	92%
Annual Energy Supply TWh(electrical)	0	5	48	81	81	81
Annual Energy Supply HPC TWh (electrical)	25	26	26	26	26	26
Annual Reactor Core Energy Generated TWh(th)	66.2	81.7	194.3	279.9	280.0	279.9
LWSMR						
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Gen IV (HTGR)	0	0	0	0	0	0
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Hydrogen GigaFactory						
(HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Liquid Synthetic Fuel Plant						
(HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0

Table A4-2 – "Base Case Nuclear Deployment Scenario" Defined by Run 26a

Note: these tables do not include AGRs or SZB	2025	2030	2035	2040	2045	2050
Large Gen III+						
Installed Capacity Hinkley Point C	3	3	3	3	3	3
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	38%	38%	38%	38%	38%	38%
Installed capacity (GWth)	8.42	8.42	8.42	8.42	8.42	8.42
Annual Load Factor	1%	92%	92%	92%	92%	92%
Annual Energy Supply TWh(electrical)	0	0	0	0	0	0
Annual Energy Supply HPC TWh (electrical)	25	26	26	26	26	26
Annual Reactor Core Energy Generated TWh(th)	66.2	67.9	67.9	67.9	67.9	67.9
LWSMR						
Installed capacity (GWe)	0	1	7	11	14	19
Thermal efficiency	34%	34%	34%	34%	34%	34%
Installed capacity (GWth)	0.0	3.5	21.2	33.3	42.0	55.2
Annual Load Factor	0.0%	92.0%	92.0%	92.0%	92.0%	92.0%
TWh Hot water Supply	0	13	45	89	140	167
TWh Electricity	0	8	53	81	100	133
Total TWh ouput	0	21	98	171	240	299
TWh in Cogen mode	0	18.18	65	129	203	241
TWh in elec only mode	0	2.68	33	42	37	58
Annual Reactor Core Energy Generated TWh(th)	0	28	171	269	339	445
Gen IV (HTGR)						
Installed capacity (GWe)	0	0	2	9	17	22
Thermal efficiency	46%	46%	46%	46%	46%	46%
Installed capacity (GWth)	0.00	0.00	3.26	19.57	35.87	47.83
Annual Load Factor	0%	0%	90%	90%	90%	90%
TWh Electricity	0	0	12	69	129	129
TWh Hydrogen	0	0	0	2	0	33
Annual Reactor Core Energy Generated TWh(th)	0.0	0.0	25.7	154.3	282.9	378.5
Hydrogen GigaFactory (HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Liquid Synthetic Fuel Plant (HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0

Table A4-3 – "Higher Optimism Nuclear Deployment Scenario" Defined by Run 228

Note: these tables do not include AGRs or SZB	2025	2030	2035	2040	2045	2050
Large Gen III+						
Installed Capacity Hinkley Point C	3	3	3	3	3	3
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	38%	38%	38%	38%	38%	38%
Installed capacity (GWth)	8.42	8.42	8.42	8.42	8.42	8.42
Annual Load Factor	0%	92%	92%	92%	92%	92%
Annual Energy Supply TWh(electrical)	0	0	0	0	0	0
Annual Energy Supply HPC TWh (electrical)	25	26	26	26	26	26
Annual Reactor Core Energy Generated TWh(th)	66.2	67.9	67.9	67.9	67.9	67.9
LWSMR						
Installed capacity (GWe)	0	0	2	5	9	13
Thermal efficiency	34%	34%	34%	34%	34%	34%
Installed capacity (GWth)	0.0	1.2	6.1	15.7	26.1	39.5
Annual Load Factor	0.0%	92.0%	92.0%	92.0%	92.0%	92.0%
TWh Hot water Supply	0	5	22	55	94	131
TWh Electricity	0	3	14	37	61	94
Total TWh ouput	0	8	37	92	155	225
TWh in Cogen mode	0	6.96	32	80	136	189
TWh in elec only mode	0	0.75	4	12	19	36
Annual Reactor Core Energy Generated TWh(th)	0	10	49	127	210	318
Gen IV (HTGR)						
Installed capacity (GWe)	0	2	12	23	32	49
Thermal efficiency	46%	46%	46%	46%	46%	46%
Installed capacity (GWth)	0.00	4.23	25.77	49.46	68.94	106.41
Annual Load Factor	0%	0%	90%	90%	90%	90%
TWh Electricity	0	13	89	175	241	269
TWh Hydrogen	0	2	3	3	7	87
Annual Reactor Core Energy Generated TWh(th)	0.0	33.4	203.3	390.1	543.9	842.8
Hydrogen GigaFactory (HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Liquid Synthetic Fuel Plant (HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Installed capacity (GWth)	0	0	0	0	0	0
Annual Load Factor	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0

Table A4-4 – "Greater Nuclear Ambition Deployment Scenario" Defined by Run 310

Note: these tables do not include AGRs or SZB	2025	2030	2035	2040	2045	2050
Large Gen III+						
Installed Capacity Hinkley Point C	3	3	3	3	3	3
Installed capacity (GWe)	0	0	0	0	0	0
Thermal efficiency	38%	38%	38%	38%	38%	38%
Installed capacity (GWth)	8.42	8.42	8.42	8.42	8.42	8.42
Annual Load Factor	0%	92%	92%	92%	92%	92%
Annual Energy Supply TWh(electrical)	0	0	0	0	0	0
Annual Energy Supply HPC TWh (electrical)	25	26	26	26	26	22
Annual Reactor Core Energy Generated TWh(th)	65.1	67.9	67.9	67.9	67.9	58.0
LWSMR						
Installed capacity (GWe)	0	1	6	11	17	19
Thermal efficiency	34%	34%	34%	34%	34%	34%
Installed capacity (GWth)	0.0	2.0	18.0	31.8	49.4	56.4
Annual Load Factor	0.0%	92.0%	92.0%	92.0%	92.0%	92.0%
TWh Hot water Supply	0	7	23	50	81	123
TWh Electricity	0	5	47	82	126	140
Total TWh ouput	0	11	70	131	207	262
TWh in Cogen mode	0	10	34	72	116	177
TWh in elec only mode	0	1.71	36	59	91	85
Annual Reactor Core Energy Generated TWh(th)	0	16	145	256	398	451
Gen IV (HTGR)						
Installed capacity (GWe)	0	0	0	0	0	0
Annual Reactor Core Energy Generated TWh(th)	0	0	0	0	0	0
Hydrogen GigaFactory (HTGR)						
Installed capacity (GWe)	0	4.90	12.79	23.42	36.57	80.83
Thermal efficiency	52%	52%	52%	52%	52%	52%
Installed capacity (GWth)	0.0	9.4	24.6	45.0	70.3	155.4
Annual Load Factor	0	92%	92%	92%	84%	75%
Annual H2 Production TWh H2	0	39	103	188	270	532
Annual Reactor Core Energy Generated TWh(th)	0.0	75.9	198.1	362.3	519.5	1023.3
Liquid Synthetic Fuel Plant (HTGR)						
Installed capacity (GWe)	0.00	0.00	19.33	19.33	19.33	19.33
Thermal efficiency	40%	40%	40%	40%	40%	40%
Installed capacity (GWth)	0	0	48.33	48.33	48.33	48.33
Annual Load Factor	0	0	92%	92%	90%	88%
Annual Synthetic Fuel Production (TWh)	0	0	156	156	153	148
Annual Reactor Core Energy Generated TWh(th)	0	0	390	390	382	371

Annex 5 – Recommended further scope to substantiate model inputs, assumptions and to explore potential technology benefits

1. Government policy to support clean energy

HM Government is committed to achieving clean growth, while ensuring an affordable energy supply for businesses and consumers. Clean growth is at the heart of the UK's Industrial Strategy, which in turn is designed to increase productivity, create good jobs, boost earning power for people right across the country, grow UK exports, and help protect the climate and environment.

Through the Clean Growth Strategy, Government will identify and support opportunities for sustainable clean growth, including nuclear innovation to supply products for domestic and export markets. As discussed below, innovative nuclear processes to produce hydrogen and carbon-neutral synthetic fuels provide promising new opportunities for achieving the Net Zero target by 2050. This strategy also aligns with the social, economic and environmental aims outlined in the UK's Industrial Strategy and the Nuclear Sector Deal.

2. Input for Supplementary Report No.3

As part of the energy system modelling project delivered by Energy Systems Catapult for the National Nuclear Laboratory and LucidCatalyst, Supplementary Report No.3 documents a scenario for a much higher level of nuclear ambition intended to deliver a step change in the quantity of affordable clean hydrogen into a UK Net Zero economy. This involves the inclusion of a new technology type into ESME with an associated change in ESME functionality.

In the following sections, LucidCatalyst provides a description of this technology type represented within ESME, along with a description of the necessary supporting evidence that would subsequently need to be delivered through a separate project to underpin the credibility of this technology type. This description was provided as Deliverable No.1 within the project and is incorporated here as Annex 4 to Supplementary Report No.3.

3. Evidence procurement process for nuclear hydrogen and synfuels pathways

This Annex describes the evidence required to demonstrate that nuclear-enabled hydrogen, ammonia, and carbon-neutral synfuels can technically and economically contribute to UK clean growth goals. It specifies the outcomes of a project that will provide evidence of the step change reduction in advanced nuclear technology costs for hydrogen and synfuel production, and the roadmaps for achieving these cost reductions. Achieving these cost targets may open up additional decarbonisation pathways for the energy system. These would be complementary to those currently being pursued, significantly increasing the affordability and feasibility of achieving the UK Net Zero Goal.

The proposed innovative nuclear technology would use heat from advanced reactors to produce cost-competitive hydrogen as an intermediate input for synthetic fuel production. These fuels may be functionally identical to existing products, so called 'drop-in' fuels, which can be used without any modification to the end use applications, or they may require acceptable modifications to the end use technology and or business practices. The technology modelled will include carbon-based fuels, whose carbon is extracted, either directly or indirectly, from the environment, and ammonia, a variant of this in which the hydrogen is combined with nitrogen for long-distance transport of hydrogen and/ or direct use of the ammonia in chemical and energy (fuel) applications. The final and simplest variant is a large-scale hydrogen production facility that makes hydrogen to supply a large portion of the energy consumed e.g. via the (converted) gas grid.

The proposed synthetic fuels technology in ESME shall take inputs of electricity, heat, and hydrogen from advanced, low-cost nuclear and inputs of nitrogen or carbon dioxide from one or more sources. Its output shall be gaseous and liquid fuels substitutes for use in applications that currently use traditional hydrocarbons such as natural gas, diesel, gasoline, and aviation fuels. The project will provide evidence for how these synthetic fuels can be produced at a scale suitable for meeting large percentages of UK domestic fuel consumption, as well as enabling exports. The integrated synthetic fuel facilities using nuclear hydrogen production would provide fuels for a range of applications such as transport (aviation, rail or long-distance heavy haulage) as well as for the power grid and industrial heat.

In addition to large quantities of heat, electricity, and hydrogen, the manufacture of carbon-based fuels also requires a supply of green or clean carbon dioxide such that the resulting fuel has no net carbon footprint associated with its subsequent combustion and conversion back to gaseous carbon dioxide in air. The main potential sources are biomass, seawater and air. Several technologies already exist for extracting carbon from each of these sources. It is expected that these technology options would decrease in cost and expand in scale over the coming years, reaching maturity in time for low-cost large-scale carbon extraction in combination with the innovative nuclear technology envisioned for the modelling.

By developing world-class advanced nuclear technology, the UK will lower CO_2 emissions not only in its domestic energy system but also outside the UK through exports of nuclear hydrogen and carbon-neutral synfuels. In this way, HM Government will support the UK nuclear industry, in line with the Government's commitments in the Clean Growth Strategy and Industrial Strategy, including the Nuclear Sector Deal, without necessarily exporting the nuclear technology itself, which would require a long lead-time and potential constraints regarding sensitive technical know-how.

The following sections describe the evidence base that would be procured to sunstantiate the

technical and economic feasibility of the nuclear-to-fuels decarbonisation pathways ("Nuclear Hydrogen and Synfuels Pathways") for the UK. Specifically, this evidence would enable inclusion of the Nuclear Hydrogen and Synfuels Pathways in the ESME whole energy system modelling framework. Each step in the evidence procurement methodology described below could constitute a deliverable with the specified purpose and scope.

3.1. Outcome #1: Market matrix and report on applications economics

The major first piece of evidence for the technical and economic feasibility of the Nuclear Hydrogen and Synfuels Pathways is a matrix of market applications for these energy products mapped to the end use applications for fuels in the UK (the "Market Matrix"). This Market Matrix will include cost thresholds that specify the price levels at which nuclear hydrogen and synfuels become competitive with conventional fossil fuels in each of the major end use applications. Evidence of the key constraints and enablers for synfuels to enter each major market will be included in the Market Matrix.

Deliverable 1.1 Market Matrix and Market Matrix Report

3.1.1. Key energy non-electricity end uses

The Market Matrix and associated report will identify key end uses for nuclear-enabled hydrogen and carbon-neutral synfuels within the ESME modelling framework. The end uses would likely include such applications as automobiles, aircraft, locomotives, marine vessels, industrial processes, and residential/commercial heating. The suitable level of granularity for assessing these end uses within the modelling framework would be determined based on the level of granularity in the ESME model's energy consumption modules. For example, the Market Matrix may need to divide automobile energy consumption into passenger vehicles, lorries, motorcycles, etc. Similarly, marine vessels may be divided into ferries, small boats, and ocean-going vessels. The scope and detail of fuel end uses for these new energy products would reflect the ESME model's functionality and the particular objectives of this modelling analysis.

3.1.2. Energy requirements and prioritised substitution options

The Market Matrix and associated report will provide the energy requirements for the fuels end uses for Nuclear Hydrogen and Synfuels Pathways. These will match the modelling period, accounting for potential future improvements in energy efficiency. Energy consumption by application starts from current energy efficiency and total consumption for the various end uses, e.g. automobiles, aircraft, locomotives, marine vessels, industrial processes, and residential/commercial heating, as already specified in the modelling framework. The final version of the Market Matrix and associated report will result from a review and refinement of these energy requirements that is responsive to the latest expectations and government policies as identified in a defined set of reference documents when the project is procured. The Market Matrix and associated report will compare the main alternative options for satisfying energy requirements across the various end uses to understand how the Nuclear Hydrogen and Synfuels Pathways fit into the competitive energy supply landscape.

3.1.3. Cost/price thresholds

The Market Matrix and associated report will provide the cost/price thresholds that the products from Nuclear Hydrogen and Synfuels Pathways must achieve to enter markets at large scale for the various end uses. This will include the current costs for production and delivery of conventional hydrogen, conventional fossil fuels, or other competing options for the end uses, and their future projected costs over the modelling period. The analysis will account for government policies, such as restrictions or pricing instruments, that would affect the costs and delivery of hydrogen and fuels in coming decades. The cost/price thresholds resulting from this analysis will set the maximum cost/price

levels for Nuclear Hydrogen and Synfuels Pathways that can cost-effectively decarbonise UK energy consumption patterns over the long term and enable meeting the UK Net Zero Goal.

3.1.4. Timeframes and sequencing

The Market Matrix and associated report will address deployment, sequencing, and timeframe issues to ensure realism in modelling of Nuclear Hydrogen and Synfuels Pathways over the next several decades. This analysis will identify such issues as: necessary precursors before hydrogen end use applications deployment, such as hydrogen vehicle up-take; and synfuel deployment, such as modification of engines to use ammonia in shipping, and any other issues that would affect 'drop-in' fuels. These precursor steps and preconditions will be translated into a set of timelines driven by associated assumptions for the key applications identified in the matrix.

3.1.5. Associated existing or required infrastructure

This analysis of the existing or required infrastructure for nuclear-enabled hydrogen and carbon-neutral synfuels production and distribution will highlight where additional constraints exist and where existing infrastructure may be used or upgraded, and where new infrastructure is required. For example, the infrastructure would encompass on-site facilities for energy production and networks for transporting hydrogen and synfuels to depots and end users.

3.1.6. Barriers or rate-limiting factors

This analysis will examine the barriers or rate-limiting factors for hydrogen and synfuels, such as challenges with deployment of hydrogen vehicles and other specialised infrastructure, or challenges with environmental carbon extraction in the case of synfuel production.

3.1.7. Inventory turnover

To model the penetration trajectory for hydrogen and synfuels into UK energy markets, it is necessary to assess the rate of replacement of consumption technologies, such as vehicle engines and building heating systems. Even when these technologies can consume hydrogen and synfuels, other forms of energy, such as electrification, could compete with the new energy pathways in this analysis and affect their long-term deployment. The Market Matrix and associated report will examine inventory turnover as a measure of infrastructure requirements for hydrogen and synfuels.

3.1.8. Opportunities to increase speed and depth of market conversion

Opportunities to increase the speed and depth of market conversion will be identified. The report and modelling guidance will determine how the modelling framework should account for these opportunities.

3.2. Outcome #2: Cost curve for nuclear hydrogen and synfuels pathways

The second major piece of evidence will be a cost curve for the Nuclear Hydrogen and Synfuels Pathways. This cost curve will be supported by a cost and performance model, with modules to estimate improvements in input costs, capital and operating costs, process intensification strategies, system performance improvements. All of these will be explicitly modelled with key assumptions that can be varied to produce a range of scenarios for inclusion in ESME model runs. The cost curve model will also enable parametric analysis of the factors that enable the largest cost reductions. The Cost Curve for Nuclear Hydrogen and Synfuels Pathways will also identify the likely timeframes for cost and performance improvements and therefore enable a forward cost curve by year of the ESME model.

Deliverable 1.2 Nuclear Hydrogen and Synfuels Pathways Cost Reduction Curve Model and Cost Reduction Curve Report.

3.2.1. System cost reduction module

The cost reduction model will identify the principal capital cost drivers and capital cost components of the Nuclear Hydrogen and Synfuels Pathways production processes. As there may be several feasible pathways to produce the hydrogen and synfuels, as well as anticipated future developments, the system cost reduction model will enable evaluation of these alternatives and provide meaningful guidance to policy and investment. The model will also consider operating costs, including input costs such as the cost of procuring carbon dioxide. The report accompanying the model will include schematic designs of each production process and alternative processes will be noted. Strategies to reduce costs below current levels would also be identified.

3.2.2. Process intensification strategies module

As there is substantial scope for process intensification in the Nuclear Hydrogen and Synfuels Pathways production processes, this part of the report would identify the opportunities for 'disruptive innovation' in the cost reduction curve. The aim of this assessment is to incorporate concepts to increase the throughput of hydrogen and synfuels per unit of input, including nuclear heat for hydrogen production and environmental carbon for synfuel production. Boosting the efficiency of these industrial processes would lower the cost of hydrogen and synfuels per unit of product.

3.2.3. Performance improvement module

Performance improvement by key components of the system have the potential to lower costs of production by increasing output per unit of capital or per unit of input. These potential improvements in performance will be located on a timeline driven by assumptions that can be varied to produce a range of scenarios. The improvements from the performance improvement model will feed into the Nuclear Hydrogen and Synfuels Pathways production cost curve.

3.3. Outcome #3: Nuclear hydrogen and synfuels pathways production infrastructure deployment model

This step would consider the factors that affect the deployment speed and scale of Nuclear Hydrogen and Synfuels Pathways production infrastructure, which includes the nuclear facilities, hydrogen apparatus, carbon extraction system, and hydrocarbon combination facilities, as well as the transportation and logistics infrastructure for delivering hydrogen and synfuels to end users. Key factors affecting speed and scale are listed below. These factors will be combined into a Production Infrastructure Deployment Model that takes the identified constraints, infrastructure needs, and enabling policies as input variables and produces deployment scenarios. This model will assess the critical needs for the speed and scale of buildout for the ESME modelling and whether any of these factors present any constraints or barriers to the deployment of the Nuclear Hydrogen and Synfuels Pathways. These scenarios will be built on the evidence described below.

Deliverable 1.3 Nuclear Hydrogen and Synfuels Pathways Production Infrastructure Deployment Model and Deployment Model Report.

3.3.1. Manufacturing

In coming decades as the UK makes progress toward the net-zero goal, facilities would need to be constructed for hydrogen production via nuclear heat and synfuel production via extraction of environmental carbon. This factor relates to the capacity to manufacture and construct the necessary equipment, modules, and facilities for the infrastructure buildout.

3.3.2. Siting

The speed and scale of buildout may be constrained by the available land to site synfuels facilities and transportation networks. This subtask would involve assessing the factors that would affect the availability of sites for projects over the modelling period.

3.3.3. Delivery/construction

This factor relates to the actual delivery/construction of the facilities and associated transportation networks for the hydrogen and synfuels. The assessment would examine likely lead-times necessary to design and build them, accounting for contraction of schedule and costs over time through learning effects.

3.3.4. Staffing and personnel requirements

This sub-step would assess the necessary construction personnel and operational staffing at the combined facilities. This should produce estimates of employment and identify possible constraints due to labour scarcity.

3.3.5. Markets

This factor uses the Market Matrix analysis on the various end uses for hydrogen and synfuels. This sub-step would assess likely up-take rates and demand elasticity for the hydrogen and synfuels expressing the sensitivity of consumption to price changes and any other factors that might affect market demand.

3.3.6. Capital

This module would use the capital costs from Cost Curve for Nuclear Hydrogen and Synfuels Pathways Model to estimate the timing and amounts of investment that would be needed for different scenarios. This will be done with awareness of the potential sources of capital funding for hydrogen and synfuel investments, with splits between debt and equity.

3.3.7. Materials

The production infrastructure buildout would depend on the available materials, such as availability of concrete for facility construction as well as carbon from the sea, air, for extraction and combination with the nuclear-produced hydrogen.

3.4. Outcome #4: Nuclear hydrogen and synfuels pathways deployment scenarios

The findings from Deliverables 1.1, 1.2, 1.3 will be used to develop a set of six deployment scenarios. These will be defined in relation to key ESME Scenarios supplemented by relevant recent policy and resource assessment documents. At least three of the scenarios should be chosen to demonstrate how the Nuclear Hydrogen and Synfuels Pathways can substantially contribute towards the Clean Growth Strategy goals, including the affordability and feasibility of the Net Zero target. This analysis of the scenarios will make some comparisons with other proposed pathways for decarbonization, including: annual and total investments required (capex as well as system costs and associated infrastructure); volumes of fuel and geographical area required, and other helpful comparisons. The scenario analysis will also review the benefits for the whole energy system perspective such as economic benefits, balance of payment benefits, employment benefits, etc.

Deliverable 1.4 Nuclear Hydrogen and Synfuels Pathways Deployment Scenarios Report

3.5. Outcome #5: Stakeholder engagement

The evidence procurement would also use input from experts and energy users through stakeholder engagement. This step would involve reaching out to stakeholders to validate inputs for the modelling analysis, such as technological performance parameters and expected improvement rates, component costs and reduction opportunities, infrastructure requirements, etc. The stakeholder engagement will also review the intended modelling scenarios and results from the model runs.

Deliverable 1.5 Report on Stakeholder engagement process.

3.6. Outcome #6: Inputs for the modelling framework

This step would develop inputs for the modelling framework by compiling all the necessary data for the two new energy pathways, including: capital costs, operating costs, facility size, lead-time, learning curve parameters for cost reductions over time, and transportation costs. The siting of the new facilities would depend on the number of zones in the modelling framework and analysis of high-demand areas of the UK, accounting for transportation costs from production points to consumption points. The step would also consider whether export of synfuels outside the UK is relevant for the modelling framework and the analysis objectives.

Deliverable 1.6 Inputs for the UK Energy System Modelling Environment (ESME) with user guide and sources/explanations.

3.7. Outcome #7: Modelling the results from Deliverable 1.4 in ESME

Key scenarios from Deliverable 1.4 will be included in runs of the ESME modelling framework. These results will be written into a report describing and quantifying the contributions that these Nuclear Hydrogen and Synfuels Pathways can make towards the UK's clean growth, exports, and an economically and socially viable clean energy transition.

Deliverable 1.7 Summary results into the UK Energy System Modelling Environment (ESME)

Deliverable 1.8 Report on the analysis and conclusions from the modelliIng

Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

Energy Systems Catapult
7th Floor, Cannon House
18 Priory Queensway
Birmingham
B4 6BS

es.catapult.org.uk
info@es.catapult.org.uk
+44 (0)121 203 3700

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LucidCatalyst is a highly specialised international consultancy offering thought leadership, strategy development and techno-economic expertise.

LucidCatalyst
New Kings Beam House
22 Upper Ground
London
SE1 9PD

lucidcatalyst.com
info@lucidcatalyst.com

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