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SCENARIOS FOR A SUSTAINABLE ENERGY SYSTEM IN THE ÅLAND ISLANDS IN 2030

Results of EnergyPLAN modelling

NEO CARBON ENERGY

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First Results for Åland Smart Energy Platform Stakeholders

September 5, 2016

Agenda

- Introduction to study
- Main results and interpretation
- Questions and discussion

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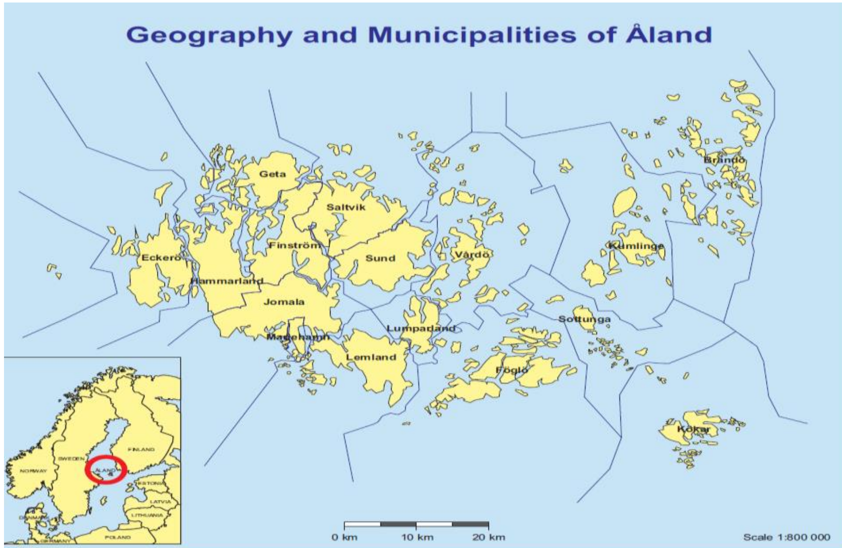
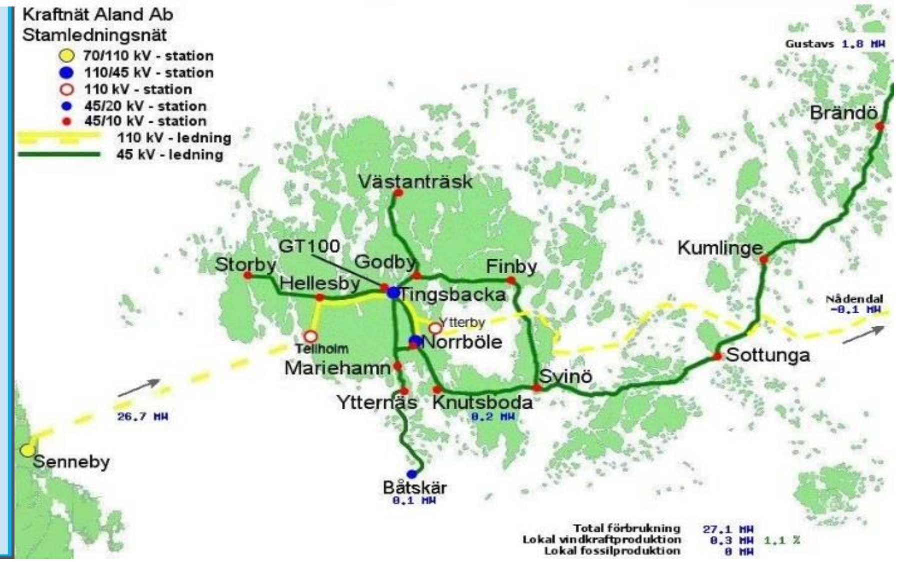
Relevance of islands in energy system research

- Relatively compact geographic locations with homogeneous populations
- Components of the energy system tend to be less complex and are more easily documented than larger continental systems
- Generally associated with significant imports of expensive fossil fuels from or power interconnections with larger continental energy suppliers
- Eliminating dependency on imported energy carriers through expanded use of domestic renewable resources and storage solutions has been suggested as an alternative for islands around the globe
- Islands may also offer potential blueprints for energy system transitions towards sustainability that will occur on a larger scale with larger continental systems
- Island energy systems may encounter shares of RE beyond 50% much sooner in the future than mainland grids
- An attractive new business field for technology providers and start-ups which can serve as showcases

Åland Islands

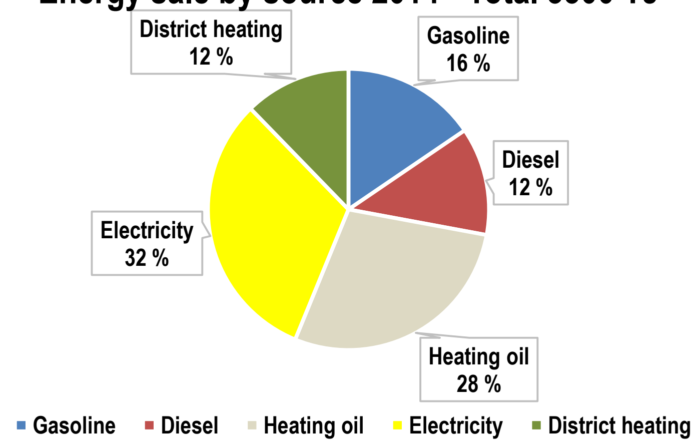


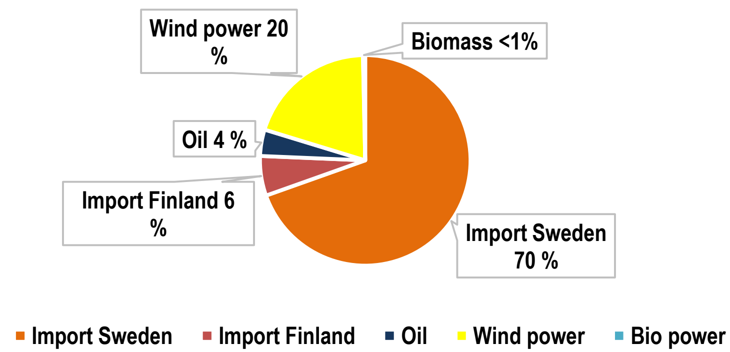


- 6,757 islands with a population of 28,983
- 60 islands are inhabited and connected by road or ferry
- Åland Smart Energy Platform began as a consortium of local stakeholders, international energy companies, technology providers and research institutes
- Goal is to envision and demonstrate how an energy system could enable the delivery of reliable, affordable, quality energy services which are free of fossil fuels to local end users

Current situation (2014)

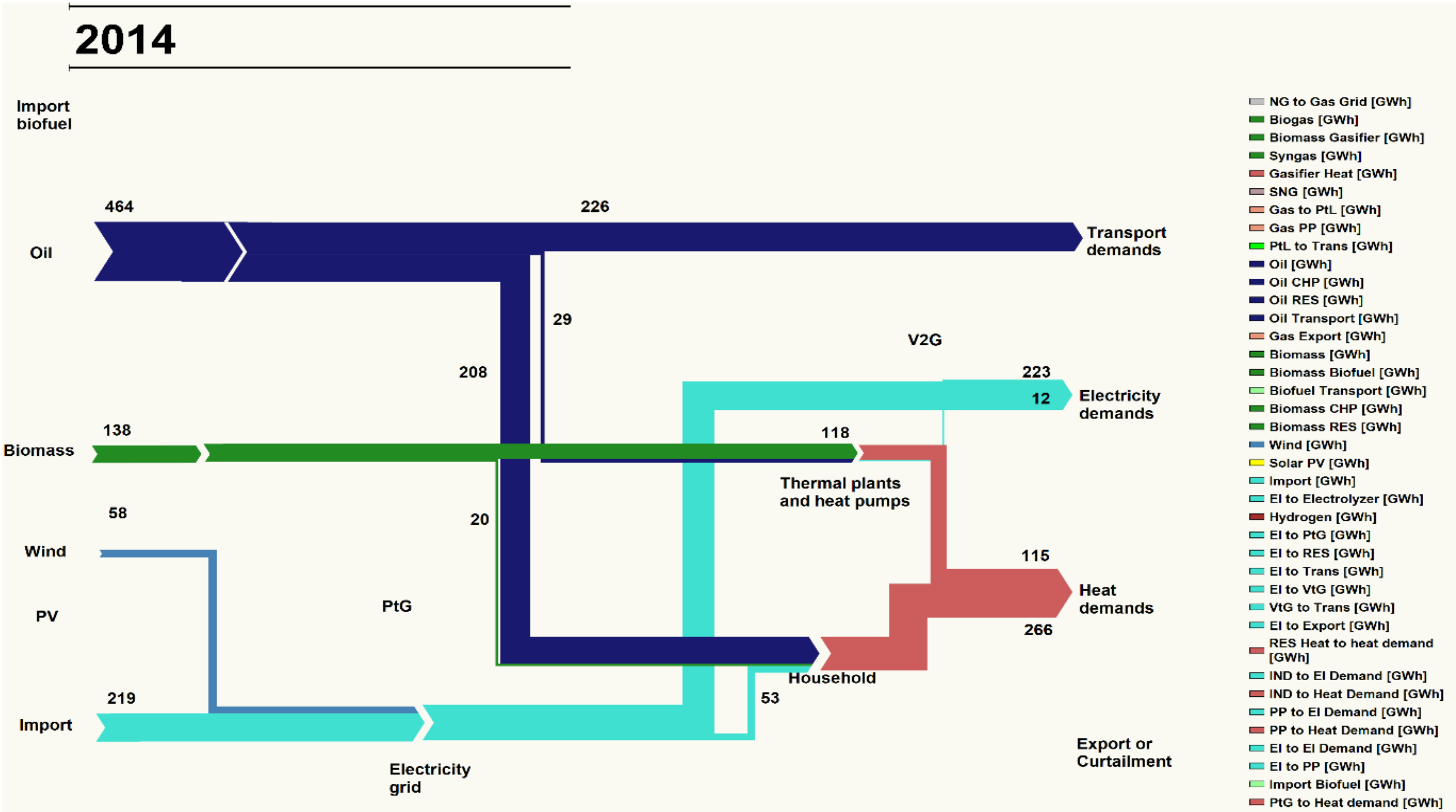
- Total electricity supply 288.4 GWhe
  - Oil 11.7 GWhe
  - Biomass 1 GWhe
  - Wind 57.4 GWhe
  - From Sweden 200.7 GWhe
  - From Finland 17.6 GWhe
- Total heat supply 115 GWhth
  - Oil 15 GWhth
  - Biomass 100 GWhth
- Transport demand 227 GWhth
  - Gasoline 129 GWhth
  - Diesel 98 GWhth



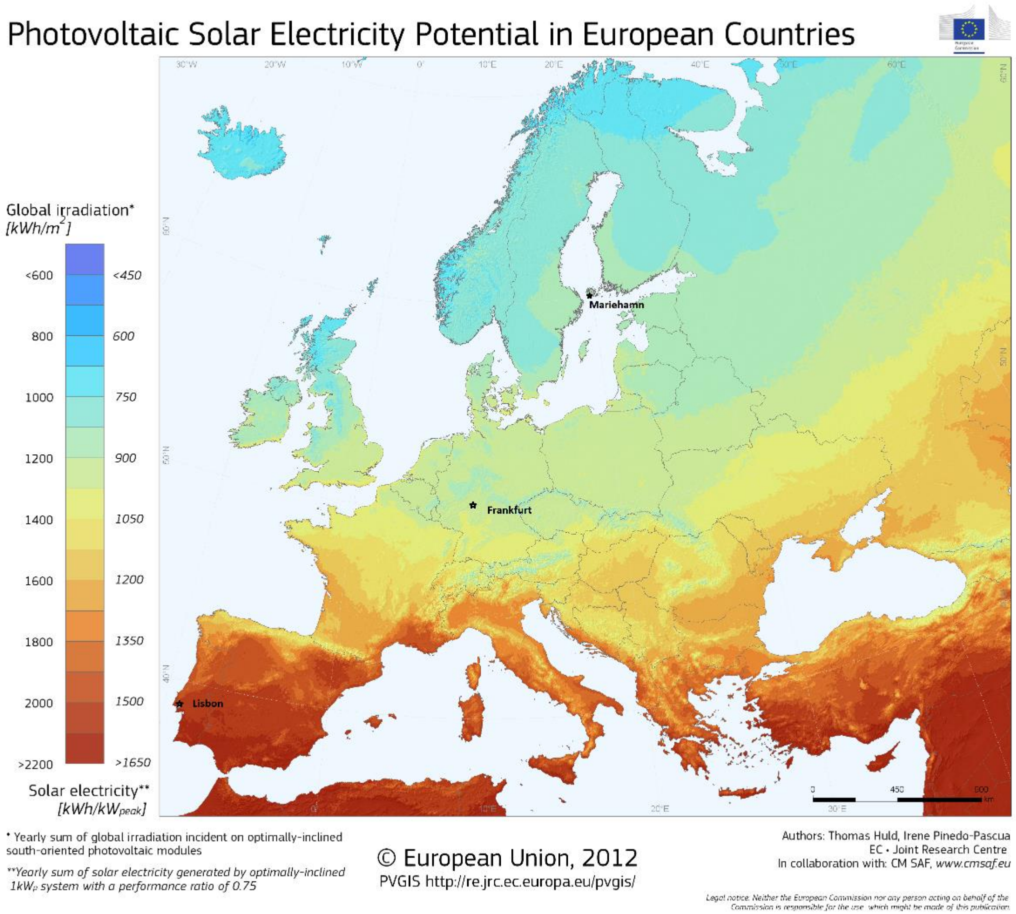


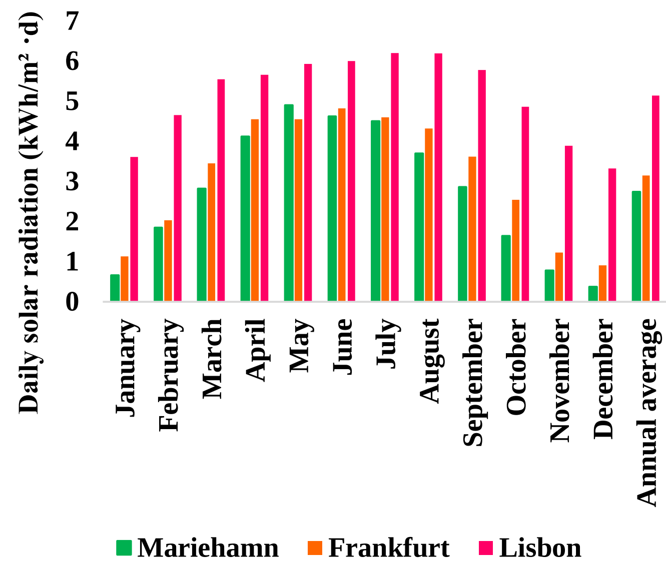
Source: Statistics and Research Åland, "Statistical Yearbook of Åland 2015," 2015. Available: http://www.asub.ax/files/statistisk_arsbok_for_aland_2015.pdf.

Flows of energy - 2014



Solar PV potential





- Irradiation on optimally tilted surfaces of 1180 kWh/(m^2·a)
- Yield of 1000 full load hours for respective solar PV systems (85% performance ratio)
- Potential for 6989 MW$_p$ ground
- Potential for 28 MW$_p$ rooftop

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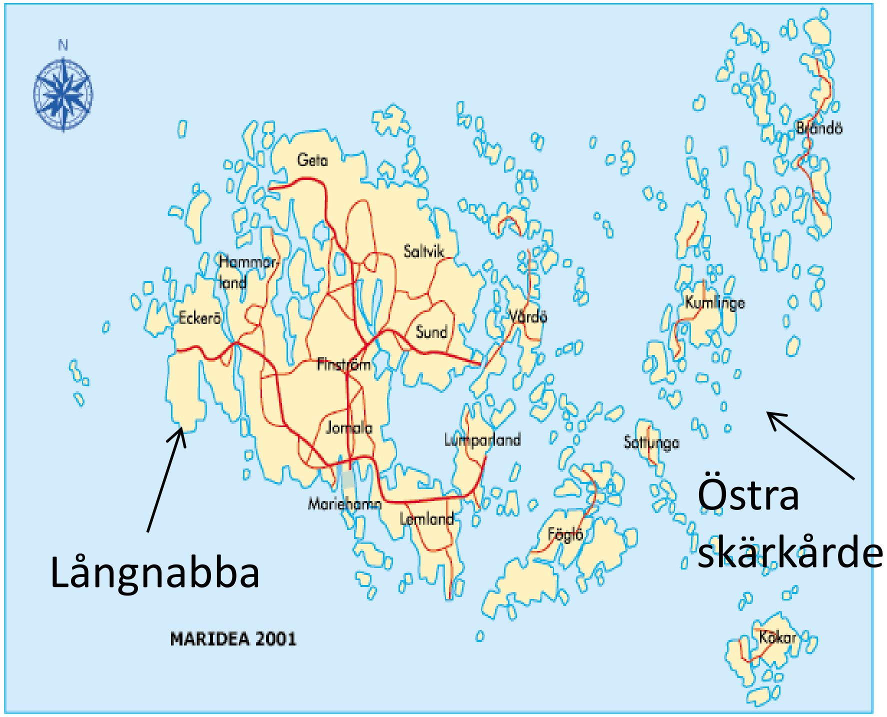
Wind power expansion projects and potential



Långnabba project

- Plan for 16 turbines, ~50 MW
- Total onshore potential could be 522 MW

Project Östra skärgården

- Planned to consist of 35-45 turbines of 3 MW, total ~100 MW.
- Connection to the new sea cable via station on Sottunga.
- Total offshore potential could be 4700 MW

Biomass and waste potential

- **Approximately 300 GWh_{th} potential from biomass**

- **32,584 tonnes of municipal solid waste (MSW) potential**
  - **Equivalent to 181 GWh_{th}**
  - **Shipped to Sweden for waste-to-energy (WTE) conversion**
  - **Domestic WTE deemed not profitable**
  - **Perhaps 36 GWhe of electricity that comes from Sweden could be classified as Åland domestic resource?**

Primary aims – Research questions

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- **Can a 100% sustainable energy system be achieved by 2030 for Åland?**
- **What is the least cost scenario that can result in a fully functional, reliable, 100% sustainable energy system for Åland in 2030?**
- **What are the roles of Power-to-Gas, Vehicle-to-Grid and other energy storage solutions in future energy system for Åland?**
- **To what extent can intermittent renewable energy production (solar PV and wind) play a part in the future energy system?**
- **What would be the optimal roles of domestic production of energy carriers and imports?**
- **To what extent can the transport sector be electrified?**

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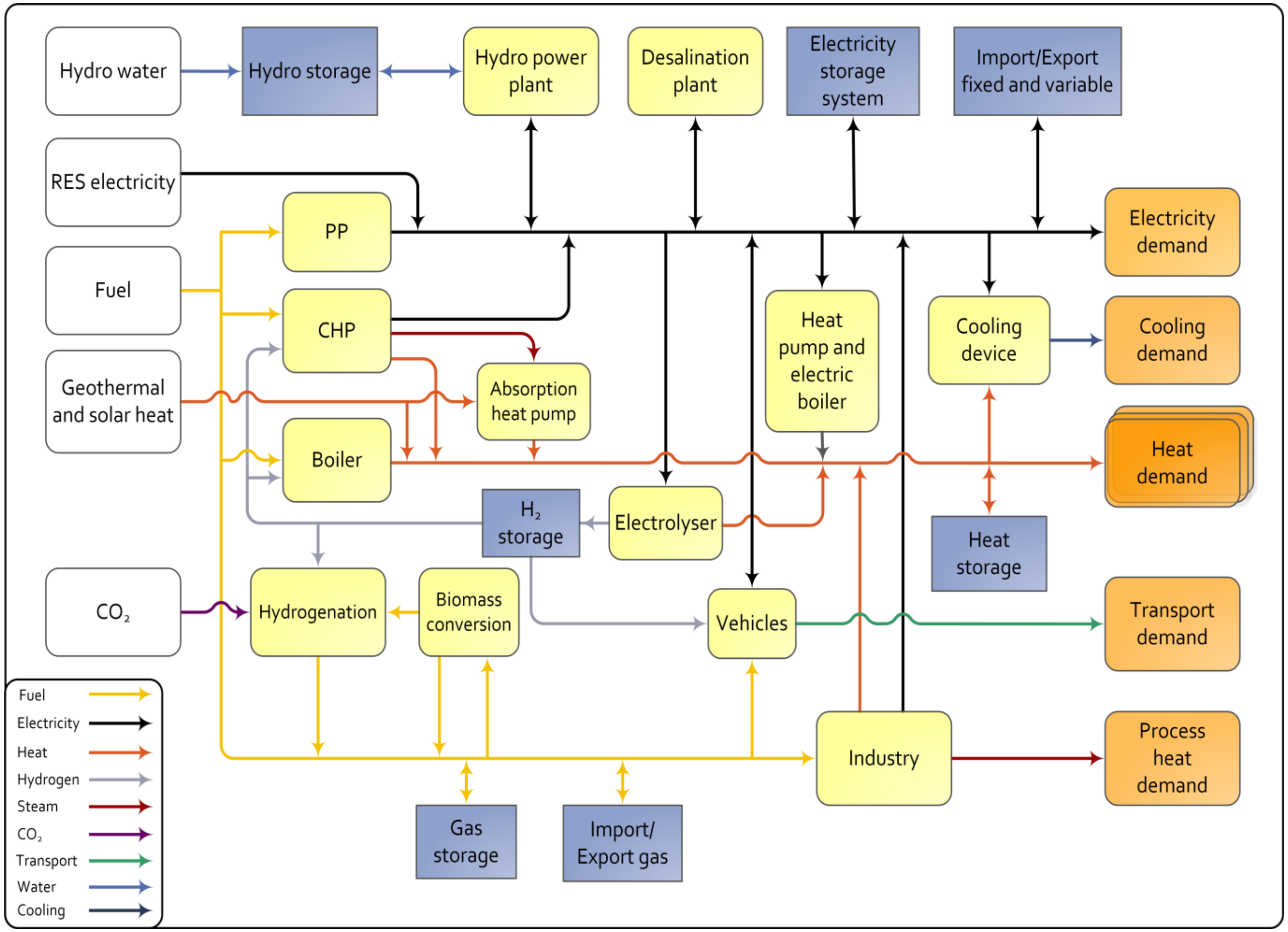
Methods – Scenario design

Scenario name	Scenario shortform	Power: 100 % Domestic	Power: High trade	Heat: High HP usage	Transport: Biofuel import	Transport: Domestic production of sustainable fuels	Transport: Electrification of cars
2014	2014		X				0 %
2020 - Transition	2020		X		X		10 %
2030 - 100% Sustainable domestic focus							
Domestic production of sustainable fuels	2030 SDF Syn	X		X		X	50 %
Imported biofuels	2030 SDF Bio	X		X	X		50 %
2030 - 100% Sustainable trade	2030 ST			X	X		50 %
2030 - 100% Sustainable net export	2030 SNE		X	X	X		50 %
2030 - 100% Sustainable mobility							
Domestic production of sustainable fuels	2030 SM Syn			X		X	50 %
High Electrification	2030 SM El			X		X	100 %
2030 - BAU	2030 BAU		X		X		30 %

EnergyPLAN



- Developed in 1999 at Aalborg University in Denmark
- Widely used and respected
- Energy system analysis carried out in hourly steps for one year
- Model includes analysis of electricity, heating and transport sectors
- Results form basis of technical regulation and market optimization strategies
- Main aim is to assist in the design of national energy planning strategies
- Model can also be applied on larger and smaller scales
- Free download from http://www.energyplan.eu/

Main cost parameters for the year 2030

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Technology	Capex [€/kW]	Opex fix [% of capex]	Opex var [€/kWh]	Lifetime [a]
Wind onshore	1000	2.5	0	25
Wind offshore	2100	3.4	0	25
PV ground mounted	550	1	0	35
PV rooftop	700	1	0	35
Biomass gasification	320	7	0	25
Biodiesel plant	2530	3	0	20
PtG plant (electrolysis and methanation)	600	3	0	15
Condensing power plant	980	3.16	2.636	27
CHP plant	1200	3.75	2.7	25
CHP boiler	800	3.7	0.15	29
CHP heat pump	3250	2	0.27	25
Interconnection	1200	1	0	40
	Capex [€/kWh]	Opex fix [% of capex]	Opex var [€/kWh]	Lifetime [a]
Thermal storage	3	0.7	0	20
Gas storage	0.08	1	0	50

A more extensive list of cost assumptions is provided at the end of this presentation

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RES capacity parameters for all scenarios

RES Capacities	Units	Scenario								
		2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Wind onshore	MW_e	22.2	70	70	70	70	70	70	70	70
Wind offshore	MW_e	0	0	100	80	40	100	100	55	0
Solar PV - Rooftop	MW_e	0	10	28	28	28	28	28	28	15
Solar PV - Ground mounted	MW_e	0	0	55	50	50	50	50	55	0

Thermal power plant capacity and efficiency for all scenarios

		Scenario									
Thermal plant capacities and efficiencies	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU	Conversion efficiencies (%)
Condensing PP	MW_e	30	0	27	29	10	10	10	10	0	45%
CHP	MW_e	26.6	10	40	40	20	20	20	20	20	$40\%_e$, $50\%_{th}$
DH Boilers	MW_{th}	30.8	18	14	13	15	18	13.5	15.3	20	90%
DH Heat pumps	MW_e	0	1	5	5	5	5	5	5	0	300%

Storage capacity parameters for all scenarios

		Scenario								
Storage capacities	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Heat storage	MWh_{th}	0	500	1500	2100	1000	1200	700	1100	0
V2G Electric storage	MWh_{e}	0	0	1200	1200	1200	1200	1200	2750	0
Methane storage	MWh_{th}	0	0	11000	24000	0	0	9000	1200	0
Electrolyzers	MW_{e}	0	0	54.3	36.2	0	0	57.5	6.1	0
Methanation	MWh_{gas}	0	0	34.5	23	0	0	36.5	3.9	0

Agenda

- Introduction to study
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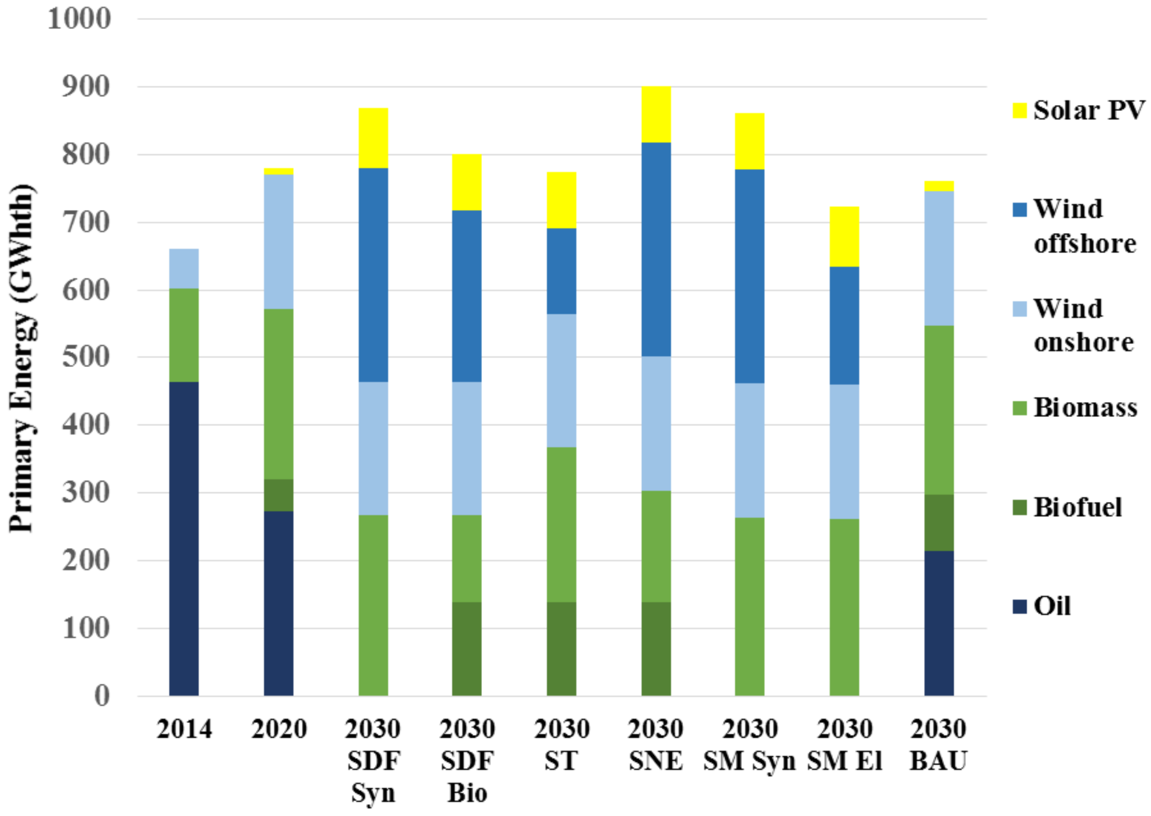
Annual fuel consumption



Key insights:

- ➢ Sustainable use of biomass
- ➢ Planned onshore wind projects realised
- ➢ Increased role of offshore wind in some scenarios
- ➢ New role for solar PV in the future

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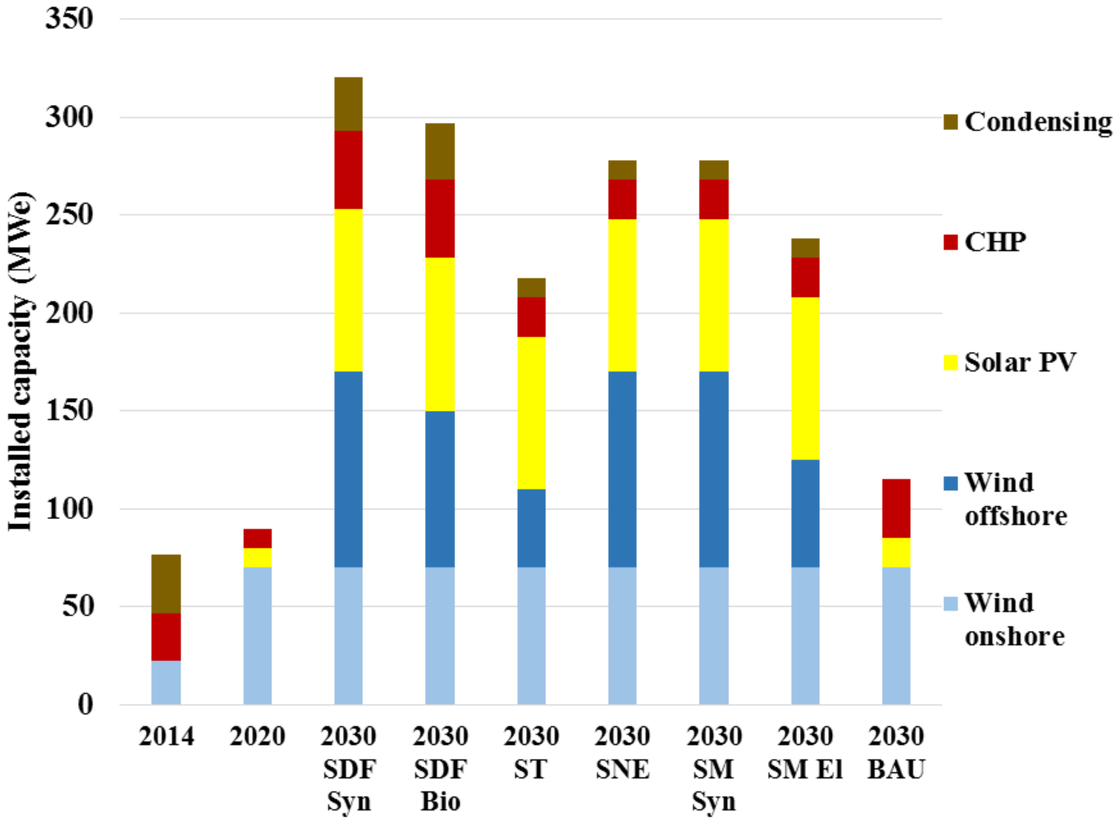
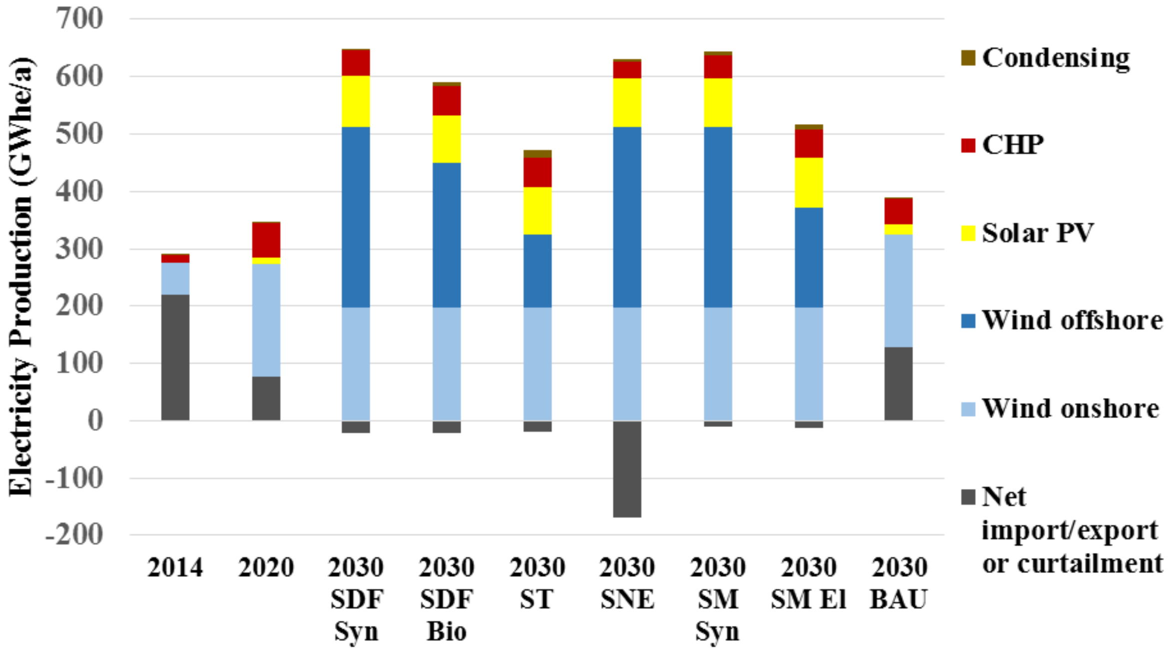
Installed capacities



Key insights:

- Solar PV includes 28 MW_p rooftop in all 2030 scenarios, except BAU (15 MW_p)
- In some scenarios, high installed capacities of wind power resulted in need for more thermal PP capacity

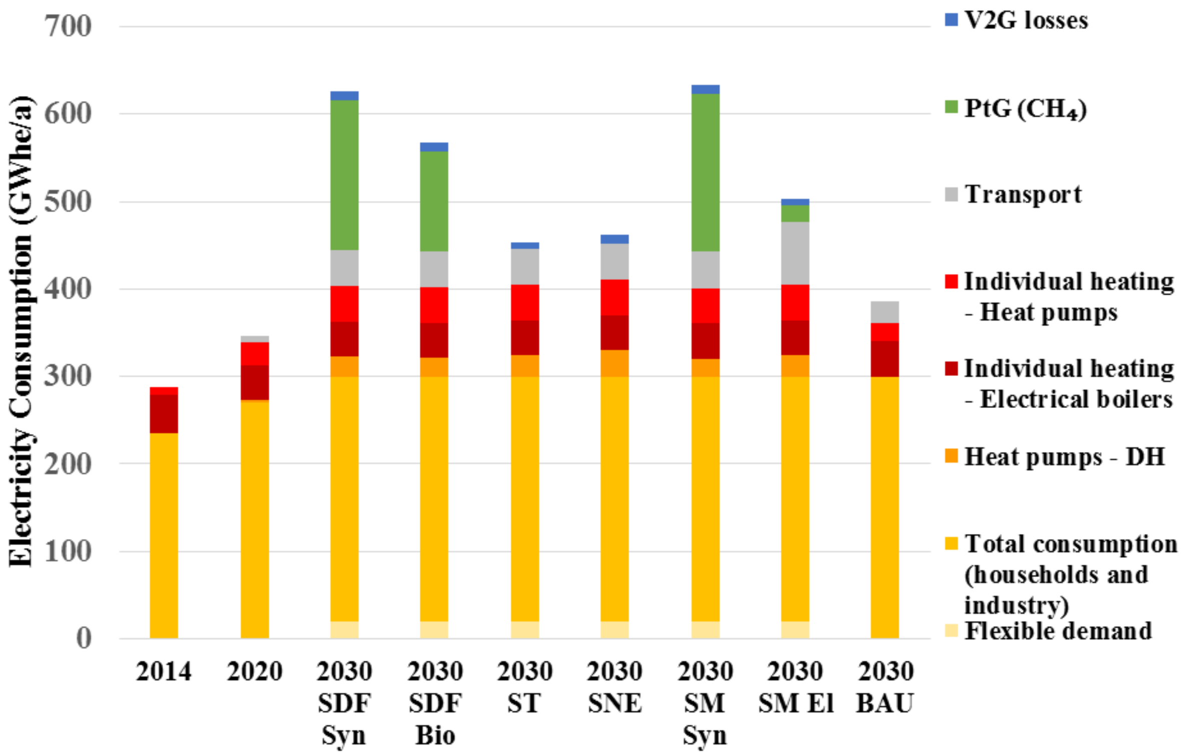
Electricity production



Key insights:

- Import and export of electricity kept low in most scenarios by design
- Export considered as curtailment in most 2030 scenarios
- 2030 SNE and BAU scenarios were exceptions

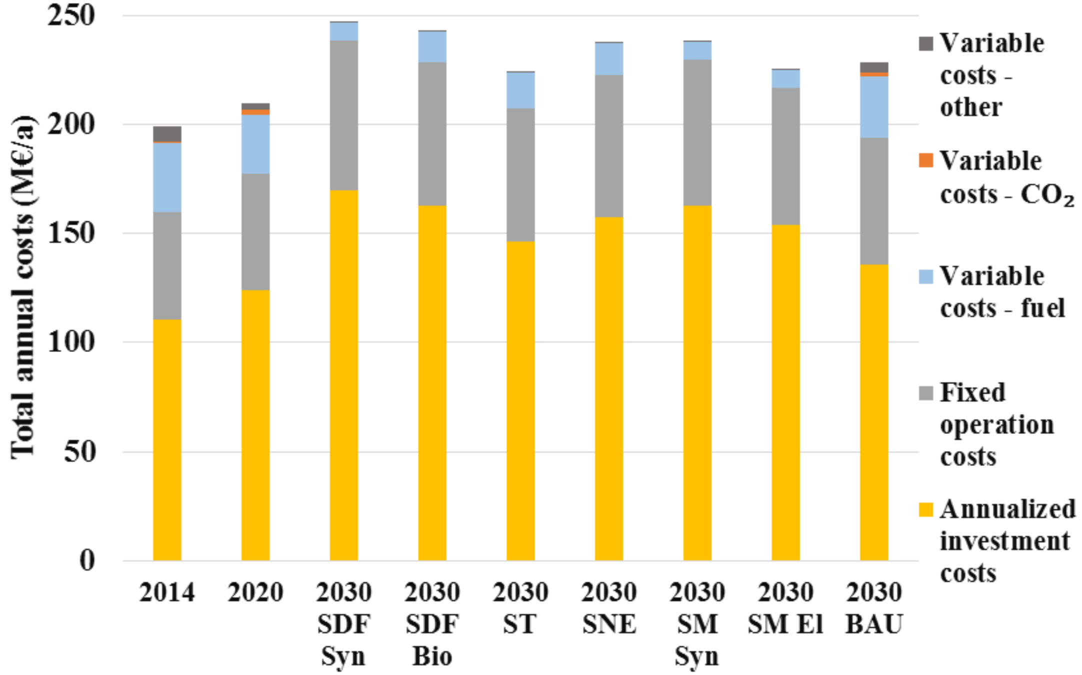
Electricity consumption



Key insights:

- Strong roles for electrified heating and transport
- High demands for methane in some scenarios (Syn) due to need for synthetic transport fuels

Annualized costs



Total annualized costs of operating the energy system for each scenario including the costs of vehicles and watercraft batteries.

Key insights:

- **Higher annualized domestic investment costs in all 2030 scenarios**
- **2030 SM El has lowest cost (225 M€/a)**
- **Followed closely by 2030 ST (226 M€/a)**
- **Range 225-247 M€/a**

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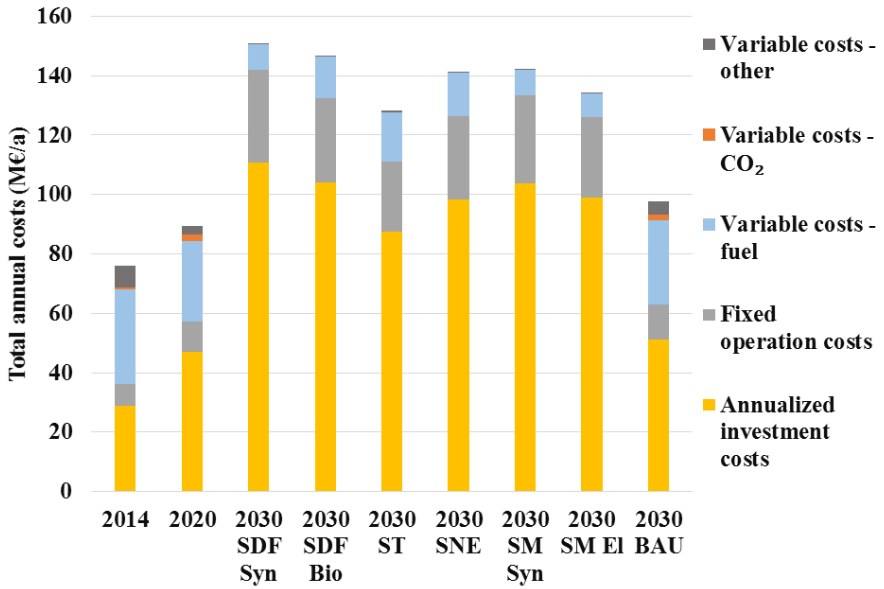
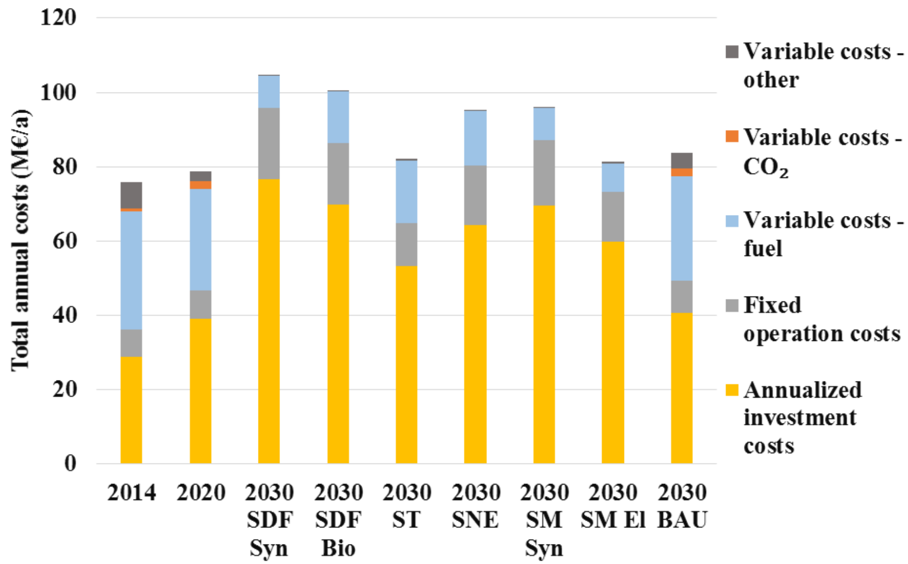
Annualized costs



Total annualized costs of operating the energy system for each scenario excluding the costs of vehicles, but including the costs of electric vehicle and watercraft batteries.



Total annualized costs of operating the energy system for each scenario excluding vehicles and all electric vehicle and watercraft batteries.

Important question: What costs should be included in an analysis of the energy system?

- Not including vehicle and battery costs might be preferable due to the fact that other end use devices (e.g. computers, washing machines, tanks) are not included

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Hourly results: April 21-27 for 2030 SDF Syn

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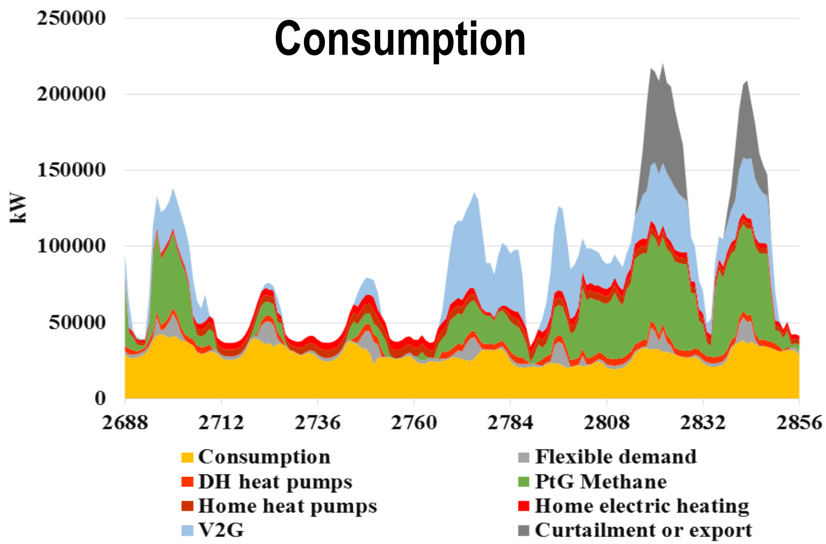

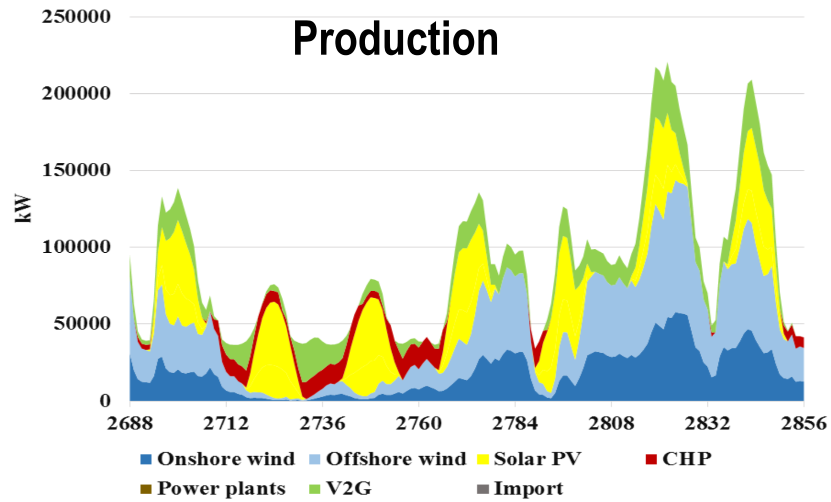

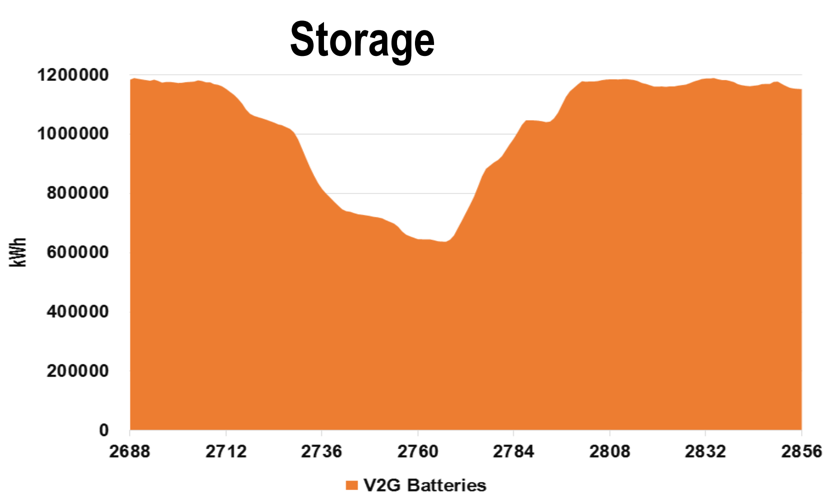

Key insights:

- Low RE production at start of week
- CHP production and V2G provide balance
- Solar PV production high all week
- Daily cycles of charging and discharging of V2G
- Multi-day cycle also noticeable
- V2G batteries fill towards end of week

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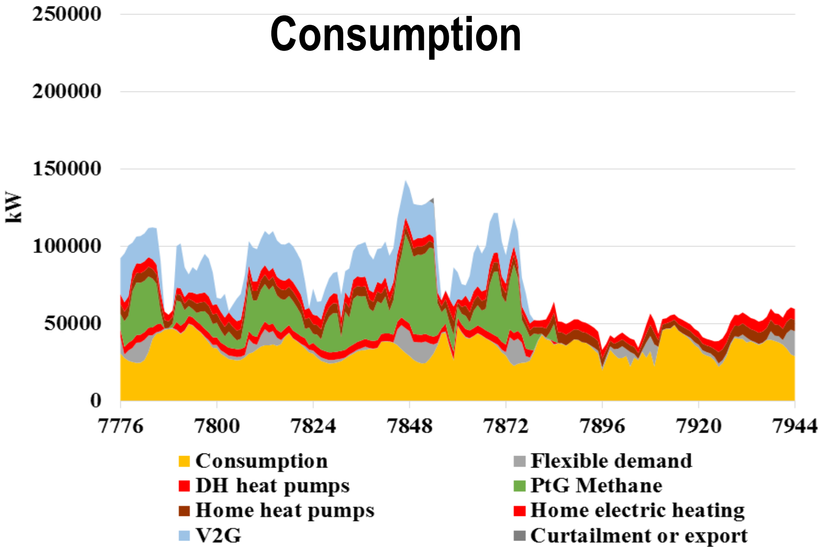
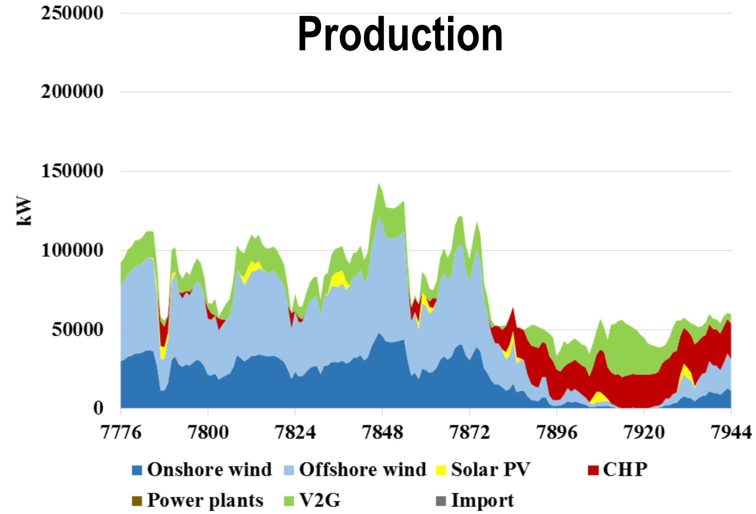
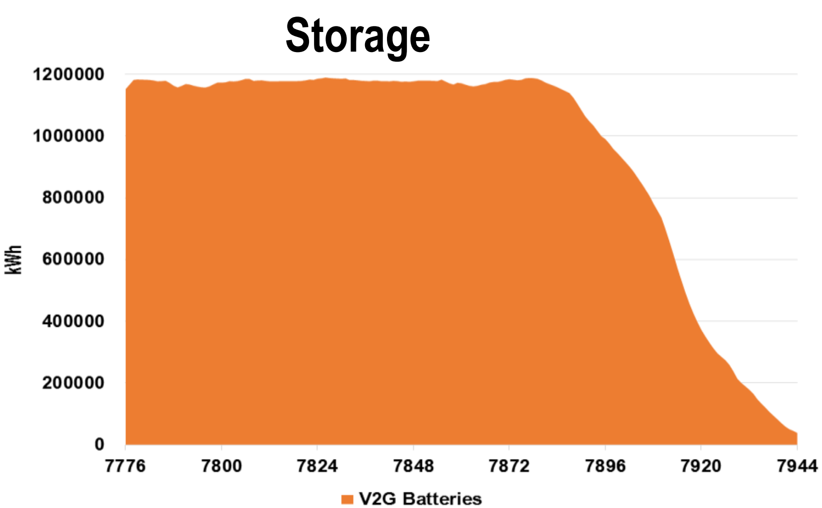
Hourly results: November 19-25 for 2030 SDF Syn







Key insights:

- Low RE production at end of week
- Most challenging week of year for system
- CHP production and V2G provide balance
- Solar PV production low all week
- High winds at start of week
- Full V2G batteries empty over 3 days
- System components work as expected to provide stability

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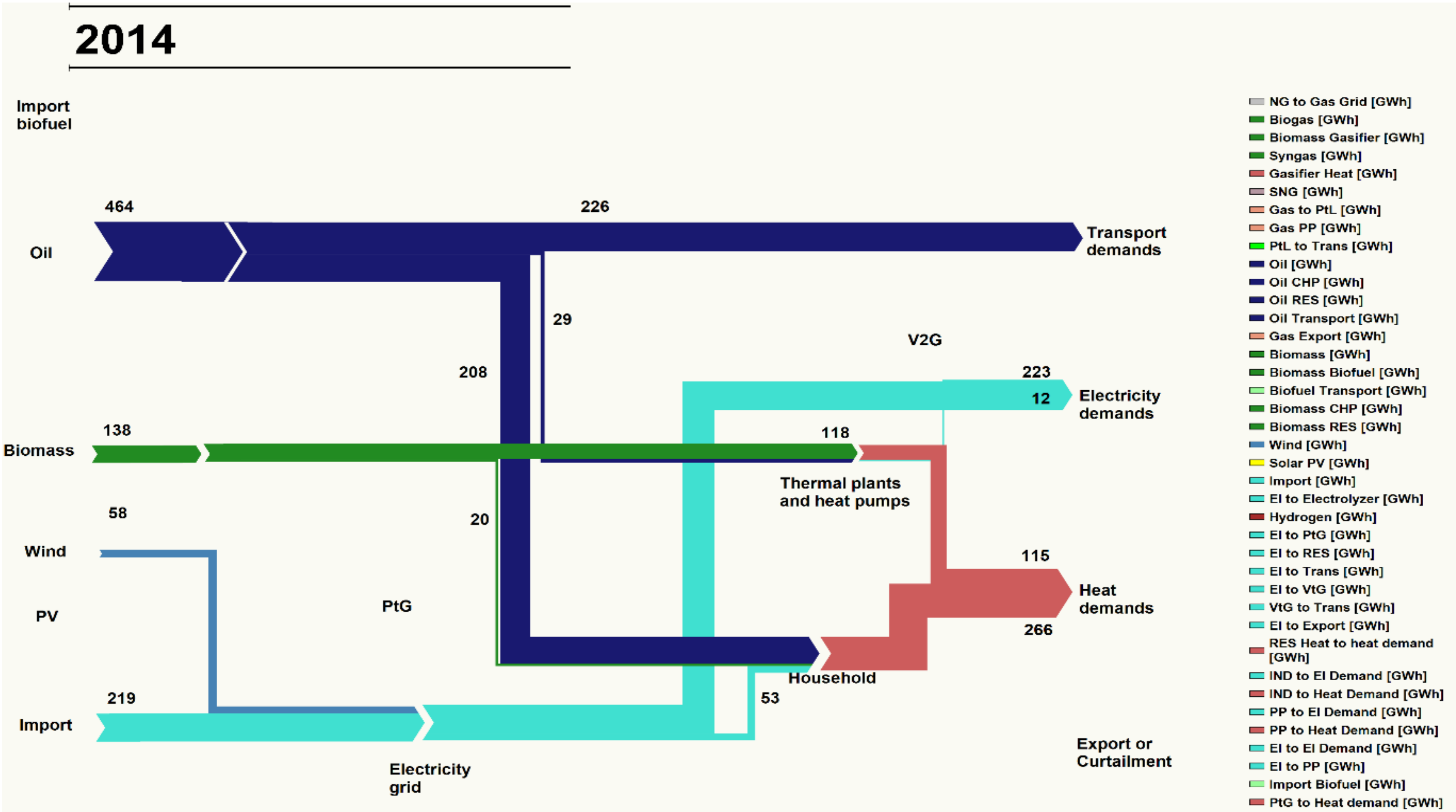
Summary of storage discharge

Parameter	Unit	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El
Electricity consumption	GWh_e	422	422	422	422	422	452
Heat consumption	GWh_{th}	375	375	375	375	375	375
Total energy consumption	GWh	797	797	797	797	797	827
V2G discharge	GWh_e	99	85	66	104	97	78
Electricity from stored gas	GWh_e	3	25	0	0	0	0
Heat from stored gas	GWh_{th}	0	25	0	0	0	0
DH storage discharge	GWh_{th}	11	13	7	7	6	7
PV & wind directly consumed	GWh_e	288	281	261	298	288	273
as % of PV & wind production		53 %	58 %	72 %	51 %	53 %	67 %
as % of all electricity production		45 %	48 %	55 %	47 %	45 %	53 %
as % of electricity consumption		68 %	67 %	62 %	71 %	68 %	60 %
PV & wind to electric storage	GWh_e	238	182	74	112	245	115
as % of PV & wind production		44 %	38 %	20 %	19 %	45 %	28 %
PV & wind to curtailment	GWh_e	22	23	28	171	15	20
as % of PV & wind production		4 %	5 %	0 %	0 %	3 %	5 %
Total storage discharge	GWh	113	147	73	111	103	85
as % of total consumption		14 %	18 %	9 %	14 %	13 %	10 %
Electricity storage discharge	GWh_e	102	109	66	104	97	78
as % of electricity consumption		24 %	26 %	16 %	25 %	23 %	17 %
V2G discharge	GWh_e	99	85	66	104	97	78
as % of electric storage discharge		97 %	78 %	100 %	100 %	100 %	100 %
Thermal storage discharge	GWh_{th}	11	37	7	7	6	7
as % of heat consumption		3 %	10 %	2 %	2 %	2 %	2 %
Gas storage discharge	GWh_{gas}	43	60	0	0	35	4
as % of grid gas consumption		34 %	87 %	0 %	0 %	29 %	31 %

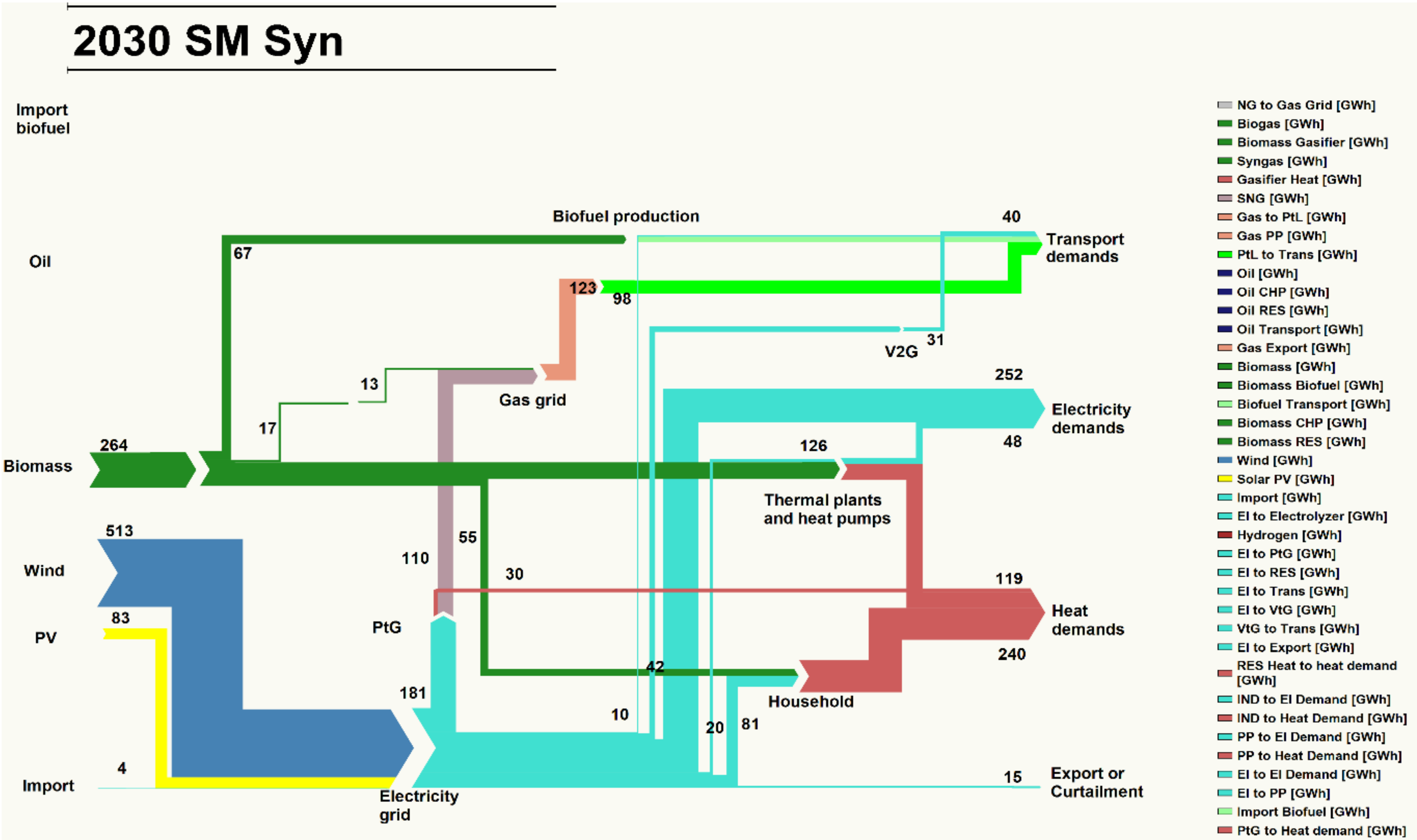
Key observations I

- Kiviluoma (2013) found that the marginal benefits of higher penetration of plug-in hybrid electric vehicles decreased with higher participation in V2G services due to limited demands for power system reserves and system flexibility
- However, closer analysis of these results reveals something different
- In the 2030 SM EI scenario, the amount of intermittent RE being used directly is much higher (67% of PV and wind generation) compared to the 2030 SM Syn scenario (53%)
- Likewise, the discharge of electricity from V2G connections to the grid is much lower (17% of electricity consumption compared to 23%, respectively)
- In both scenarios the charging of V2G batteries is similar (139 GWh_e and 138 GWh_e for the 2030 SM EI and Syn scenarios, respectively)
- However, the former scenario sees a much higher (51 GWh_e vs 30 GWh_e) consumption of stored electricity by the larger number of vehicles and watercraft
- The key point is that stored electricity need not only be considered as storage for future use by the grid, but V2G batteries can provide a buffer between generation of intermittent RE and its use by end-users
  - Also many other possibilities to use this energy – Nissan already using the term V2X
- Direct consumption of intermittent renewable energy reduces the need for storage and generation capacities
- In comparing the 2030 SM scenarios, it can be observed that the higher participation in V2G (2750 vs 1200 GWh_e) for the EI and Syn scenarios, respectively, results in less need for gas storage (1.2 vs 9 GWh_{th}), electrolyser capacity (6.1 vs 57.5 MW_e), methanation capacity (3.9 vs 36.5 MWh_{gas}) and offshore wind power capacity (55 MW_e vs 100 MW_e)
- As a result, total annualised costs were lower (225 M€/a vs 239 M€/a)

Flows of energy - 2014



Annual energy flows



Recarbonised Finnish Energy System
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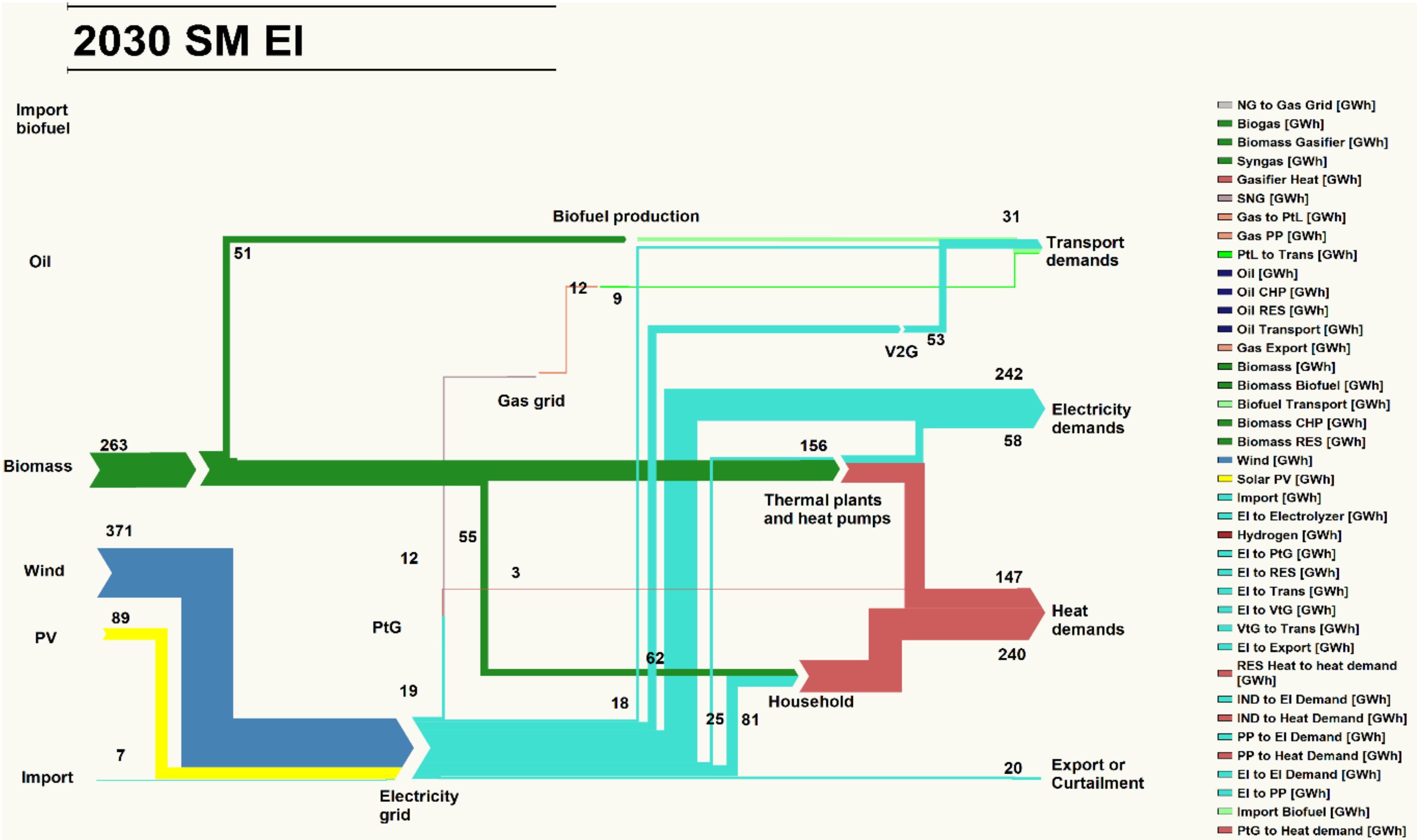
Annual energy flows



Recarbonised Finnish Energy System
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Levelised cost of electricity – 2030 SM El

2030 SM El	Units	Wind - onshore	Wind - offshore	Solar PV ground mounted	Solar PV rooftop	Condensing plants	CHP plants
Capex	€/kW$_e$	1000	2100	550	700	980	1200
Opex_fixed	% of capex	2.50 %	3.40 %	1 %	1 %	3.16 %	3.75 %
Opex_var	€/MWh$_e$	0	0	0	0	2.7	2.7
Fuel	€/MWh$_e$	0	0	0	0	28.8	28.8
Efficiency	%	100%	100%	100%	100%	45%	90%
Lifetime	Years	25	25	35	35	27	25
Full load hours	Hours	2815	3163	1067	1067	1047	2368
WACC	%	7 %	7 %	7 %	7 %	7 %	7 %
crf	%/year	8.58 %	8.58 %	7.72 %	7.72 %	8.34 %	8.58 %
LCOE	€ cents/kWh$_e$	3.9	8.0	4.5	5.7	17.4	9.7

Job creation

Parameter	Unit	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Wind onshore	Job-years	602	602	602	602	602	602	602
Wind offshore	Job-years	1810	1448	724	1810	1810	996	0
Solar PV	Job-years	1486	1396	1396	1396	1396	1486	269
MCI Total	Job-years	3898	3446	2722	3808	3808	3083	871
Wind onshore	Jobs over 25 years	14	14	14	14	14	14	14
Wind offshore	Jobs over 25 years	20	16	8	20	20	11	0
Solar PV	Jobs over 35 years	25	23	23	23	23	25	5
O&M Total	Jobs over lifetimes	59	53	45	57	57	50	19
O&M Total	Job-years	1722	1569	1369	1669	1669	1497	508
Total	Job-years	5619	5015	4091	5477	5477	4580	1378

MCI- Manufacturing, Construction and Installation
O&M – Operations and Maintenance

Not included: More jobs related to PtG, V2G, plant decommissioning

Key observations II

- A reliable energy system based on high sustainability criteria seems technically feasible for Åland in 2030
- The 2030 SM El scenario, with high levels of electrification of the transport sector, has emerged as the least cost solution
  - The 2030 SM El scenario provides a great deal of uniqueness and opportunity to explore and demonstrate products and services that have so far not been demonstrated with energy system scenario modelling
    - Expanded role of V2G connections to marine watercraft
    - This will require strong role of ICT services to aggregate participants and control loads
    - Use of advanced smart-grid technology to manage distributed generation
    - More strategic use of interconnections – flexible energy system supported by flexible market
    - Development of solutions in Åland can be scalable for continental systems
- The role of energy storage solutions appears significant in each of the future scenarios
  - High shares of variable RE are not a difficulty in a well-planned system
  - On a seasonal basis, PtG technology can bridge the gaps between demand and supply at times when generation is most intermittent, but not necessary in all scenarios
  - V2G connections balance supply and demand on a daily and multi-day basis
    - V2G batteries have a tendancy to be filled and not emptied
    - Correlation between V2G charging and variable RE generation
    - Less need for seasonal storage (PtG) and offshore wind capacity
    - Further possibilities for V2X should be explored
  - In some scenarios storage is replaced by dependence on imports (electricity and biofuels)
- New job creation related to renewable energy production on Åland could total between at least 3100 and 3900 MCI job-years and 45-59 permanent O&M jobs, depending on the scenario
  - These can be seen as a lower limit due to unaccounted MCI and O&M jobs anticipated for PtG and V2G

Conclusions

- A fully sustainable energy system for Åland can be achieved by 2030
- Expanded roles of solar PV and wind power generation capacities through domestic investment can effectively replace reliance on imported energy carriers, promote sustainable growth, and eliminate the need for fossil fuels in the energy system
- The role of V2G connections and other energy storage solutions increase the flexibility of the energy system required when levels of variable renewable energy generation are high
- Expanding participation in V2G services to include more road vehicles and other vehicle types, such as boats, can result in less need for other energy storage solutions and reduced offshore wind power generation capacity, resulting in lower annualised costs
- V2G connections serve a strong role in accepting energy produced by solar PV and wind power generation in times of excess, and a much less noticeable role as a provider of electricity back to the grid
- The movement towards sustainability for Åland can result in several potential benefits outside of the boundaries of the energy system, such as promotion of employment, tourism and international partnerships
- There are many pathways towards achieving 100% sustainable energy futures for Åland
- Perhaps the most urgent matter for the Åland Smart Energy Platform is to inform a wide range of actors and stakeholders of the possible options, and invite feedback
- The best option will be the one that the people of Åland choose for themselves through informed discourse

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Agenda

- Introduction to study
- Main results and interpretation
- Questions and discussion

Questions or comments?

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Thank you

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FINLAND FUTURES RESEARCH CENTRE

Turun yliopisto
University of Turku

NEO-CARBON Energy project is one of the Tekes strategy research openings and the project is carried out in cooperation with Technical Research Centre of Finland VTT Ltd, Lappeenranta University of Technology (LUT) and University of Turku, Finland Futures Research Centre.

FURTHER INFORMATION

NEO
CARBON
ENERGY

Main demand parameters

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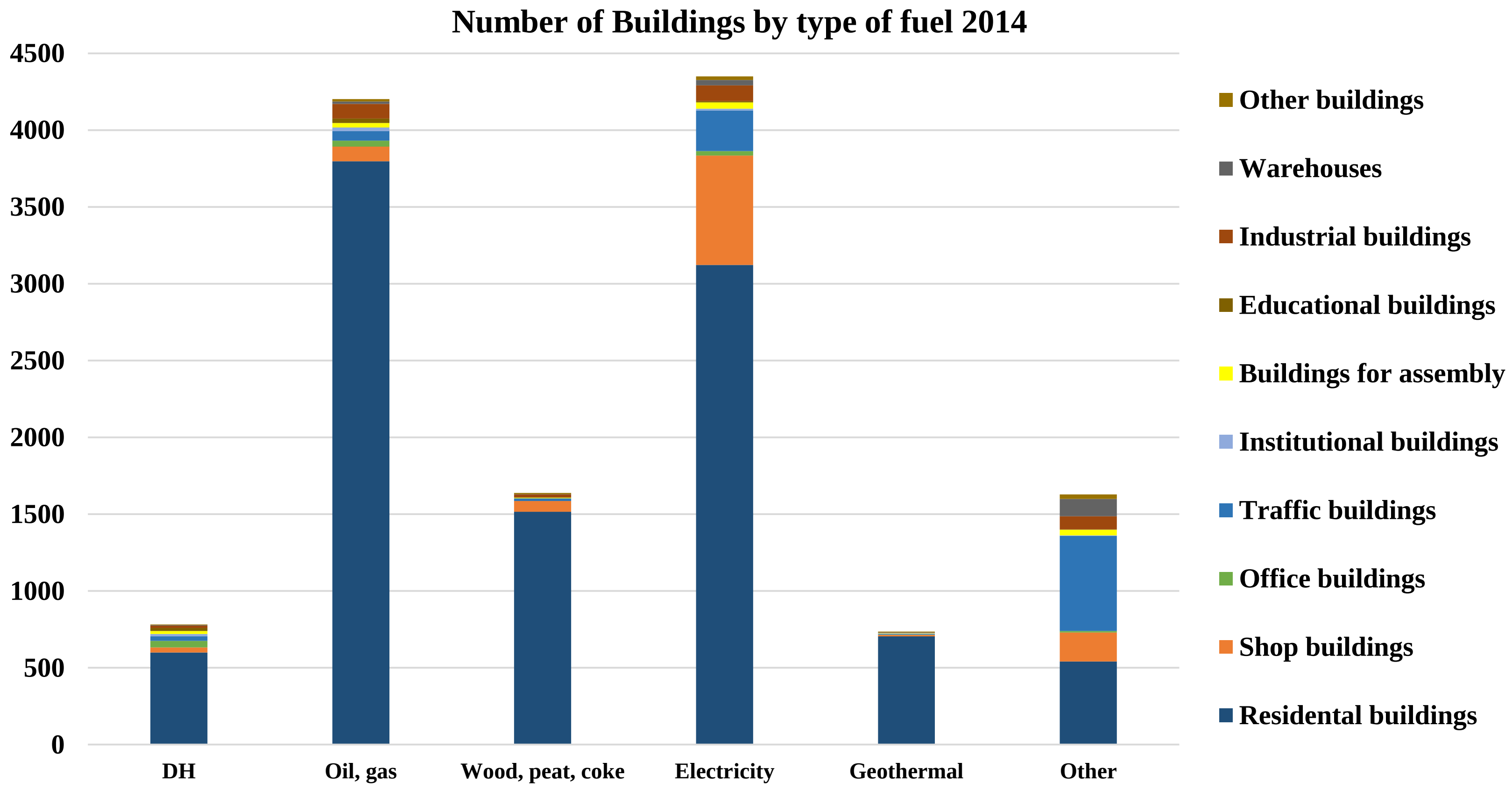
Demands		Units	Scenario								
			2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Electricity		GWh_e	288.5	342.83	422.23	421.94	421.94	421.94	422.11	451.54	405.54
District heating		GWh_{th}	100.9	117	135	135	135	135	135	135	126
Individual heating total		GWh_{th}	265.53	253.03	240.05	240.05	240.05	240.05	240.05	240.05	249.05
	Oil	GWh_{th}	176.8	88.4	0	0	0	0	0	0	88.4
	Biomass	GWh_{th}	16	42.63	50.05	50.05	50.05	50.05	50.05	50.05	40.65
	Heat pump	GWh_{th}	30	82	150	150	150	150	150	150	80
	Electricity	GWh_{th}	42.73	40	40	40	40	40	40	40	40
Fuel for transport total		M km	340	360	415	415	415	415	415	415	415
	Diesel	GWh_{th}	97.6	84	0	0	0	0	0	0	55.3
	Biodiesel	GWh_{th}	0	0	40	0	0	0	40	30.73	0
	Synthetic diesel	GWh_{th}	0	0	29.2	0	0	0	29.2	9.27	0
	Imported biodiesel	GWh_{th}	0	24	0	69.2	69.2	69.2	0	0	41.5
	Petrol	GWh_{th}	128.8	84	0	0	0	0	0	0	55.3
	Synthetic petrol	GWh_{th}	0	0	69.2	0	0	0	69.2	0	0
	Imported biopetrol	GWh_{th}	0	24	0	69.2	69.2	69.2	0	0	41.5
	Electricity (Dump charge)	GWh_e	0	7.2	10.3	10.3	10.3	10.3	10.3	17.8	25
	Electricity (Smart charge)	GWh_e	0	0	31.1	31.1	31.1	31.1	31.1	51.2	0

NEO CARBON ENERGY

Built environment (2014)



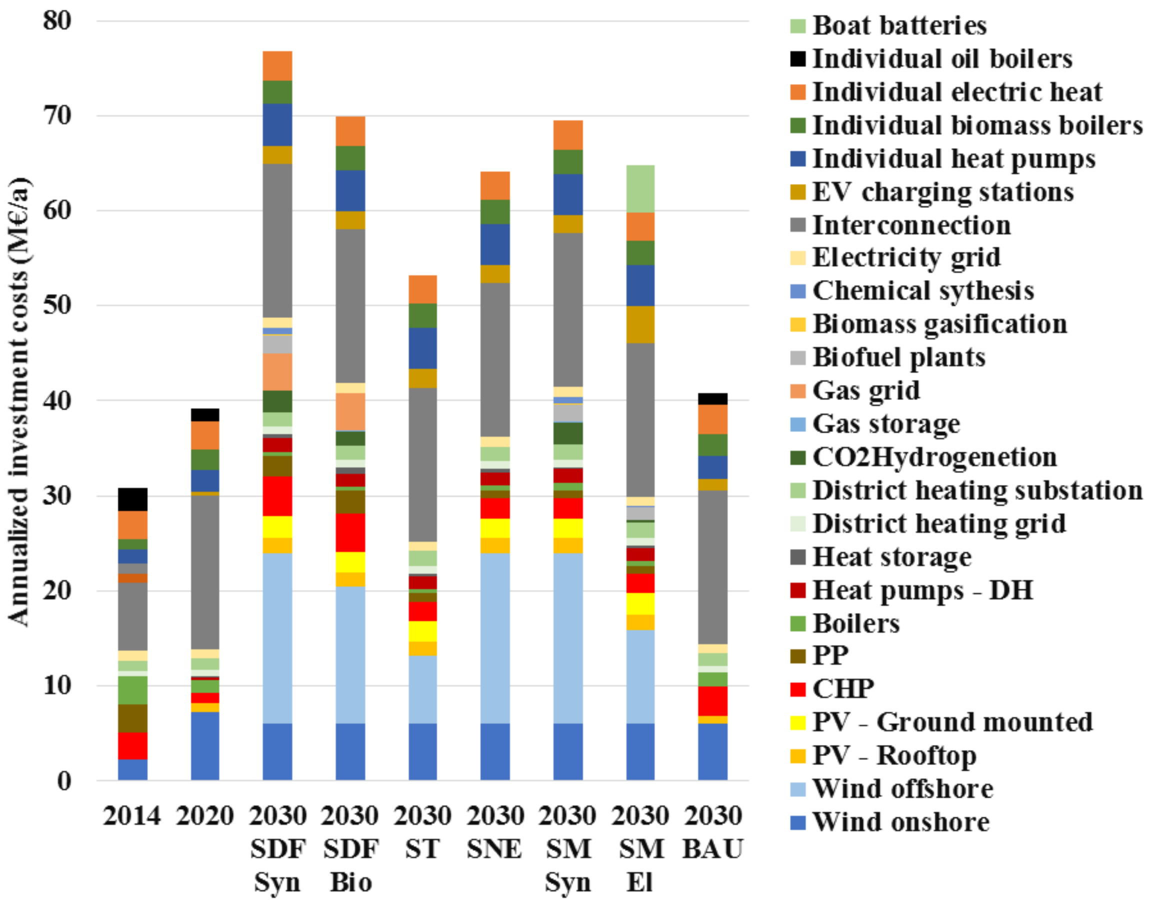
Housing parameters

			Scenario								
		Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Buildings		Thousands	13.325	13.9	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Residential heating total		Thousands	10.272	10.716	11.292	11.292	11.292	11.292	11.292	11.292	11.292
	Oil	Thousands	3.798	1.787	0	0	0	0	0	0	1.955
	Biomass	Thousands	1.516	3.472	3.9	3.9	3.9	3.9	3.9	3.9	3.485
	Heat pump	Thousands	1.164	1.626	3.1	3.1	3.1	3.1	3.1	3.1	1.794
	Electricity	Thousands	3.122	3.13	3.374	3.374	3.374	3.374	3.374	3.374	3.196
	DH	Thousands	0.672	0.7	0.918	0.918	0.918	0.918	0.918	0.918	0.862
Other buildings total		Thousands	3.053	3.184	3.208	3.208	3.208	3.208	3.208	3.208	3.208
	Oil	Thousands	0.666	0.463	0	0	0	0	0	0	0.345
	Biomass	Thousands	0.394	0.442	0.7	0.7	0.7	0.7	0.7	0.7	0.615
	Heat pump	Thousands	0.266	0.530	0.9	0.9	0.9	0.9	0.9	0.9	0.506
	Electricity	Thousands	1.499	1.5	1.326	1.326	1.326	1.326	1.326	1.326	1.504
	DH	Thousands	0.228	0.25	0.282	0.282	0.282	0.282	0.282	0.282	0.238

Vehicle parameters

		Scenario								
Vehicles	Units	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM EI	2030 BAU
Number of cars/vans	Thousands	26.636	28	32	32	32	32	32	32	32
Vehicles that are EV	%	0	10%	50%	50%	50%	50%	50%	100%	30%
Dump charge	%	0	100%	25%	25%	25%	25%	25%	25%	100%
V2G connection	%	0	0	75%	75%	75%	75%	75%	75%	0
Number of buses/trucks	Thousands	0.841	0.9	1	1	1	1	1	1	1
Number of other vehicles	Thousands	7.625	8	9	9	9	9	9	9	9
V2G battery capacities (cars)	GWh_e	0	0	1.2	1.2	1.2	1.2	1.2	2.4	0
V2G battery capacities (boats)	GWh_e	0	0	0	0	0	0	0	0.35	0

Annualized investment costs



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Breakdown of annalized investment costs

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Annualized investment cost (M€)	2014	2020	2030 SDF Syn	2030 SDF Bio	2030 ST	2030 SNE	2030 SM Syn	2030 SM El	2030 BAU
Wind onshore	2.3	7.3	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Wind offshore	0.0	0.0	18.0	14.4	7.2	18.0	18.0	9.9	0.0
PV - Rooftop	0.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5	0.8
PV - Ground mounted	0.0	0.0	2.3	2.1	2.1	2.1	2.1	2.3	0.0
CHP	2.7	1.0	4.1	4.1	2.1	2.1	2.1	2.1	3.1
Cond. PP	3.1	0.0	2.2	2.4	0.8	0.8	0.8	0.8	0.0
Boilers	2.8	1.4	0.4	0.4	0.5	0.6	0.9	0.5	1.5
Heat pumps - DH	0.0	0.3	1.4	1.4	1.4	1.4	1.4	1.4	0.0
Heat storage	0.0	0.1	0.4	0.6	0.3	0.3	0.2	0.3	0.0
District heating grid	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
District heating substation	1.1	1.1	1.5	1.5	1.5	1.5	1.5	1.5	1.2
CO_2 Hydrogenation	0.0	0.0	2.3	1.5	0.0	0.0	2.4	0.3	0.0
Gas storage	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0
Gas grid	0.0	0.0	3.9	3.9	0.0	0.0	0.0	0.0	0.0
Biofuel plants	0.0	0.0	1.8	0.0	0.0	0.0	1.8	1.4	0.0
Biomass gasification	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0
Chemical synthesis	0.0	0.0	0.7	0.0	0.0	0.0	0.7	0.1	0.0
Electricity grid	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Interconnection	7.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
EV charging stations	0.0	0.3	1.9	1.9	1.9	1.9	1.9	3.8	1.1
Individual heat pumps	1.6	2.3	4.3	4.3	4.3	4.3	4.3	4.3	2.5
Individual biomass boilers	1.0	2.1	2.5	2.5	2.5	2.5	2.5	2.5	2.2
Individual electric heat	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Individual oil boilers	2.4	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Electric cars	0.0	5.4	30.7	30.7	30.7	30.7	30.7	61.3	18.4
Conventional cars	58.1	55.0	34.9	34.9	34.9	34.9	34.9	0.0	48.8
Other vehicles	23.3	24.8	27.7	27.7	27.7	27.7	27.7	27.7	27.7
Total excl. vehicles	28.9	39.1	76.7	69.8	53.2	64.2	69.4	59.8	40.8
Total	110	124	170	163	146	157	163	149	136

CARBON ENERGY

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Annual energy flows

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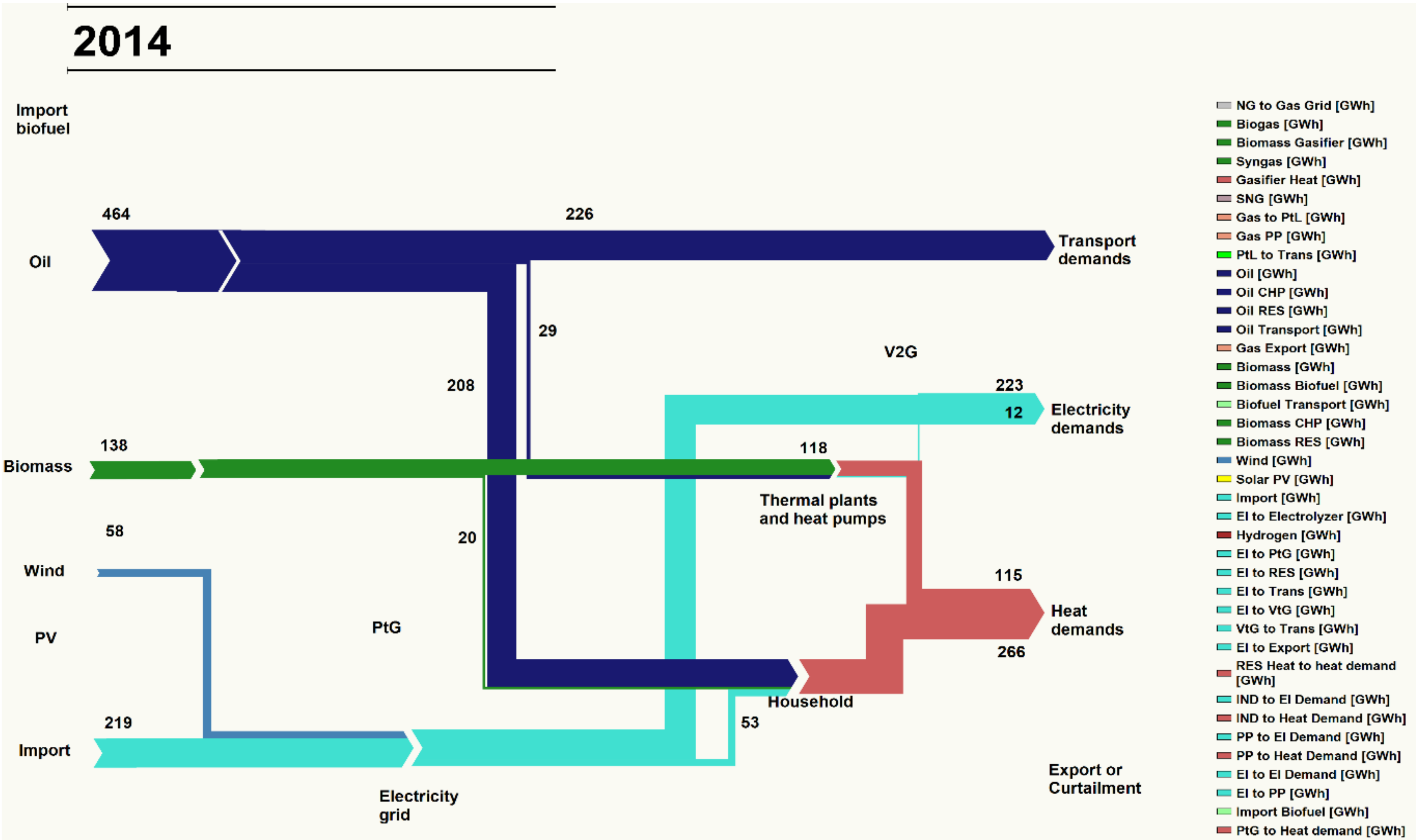
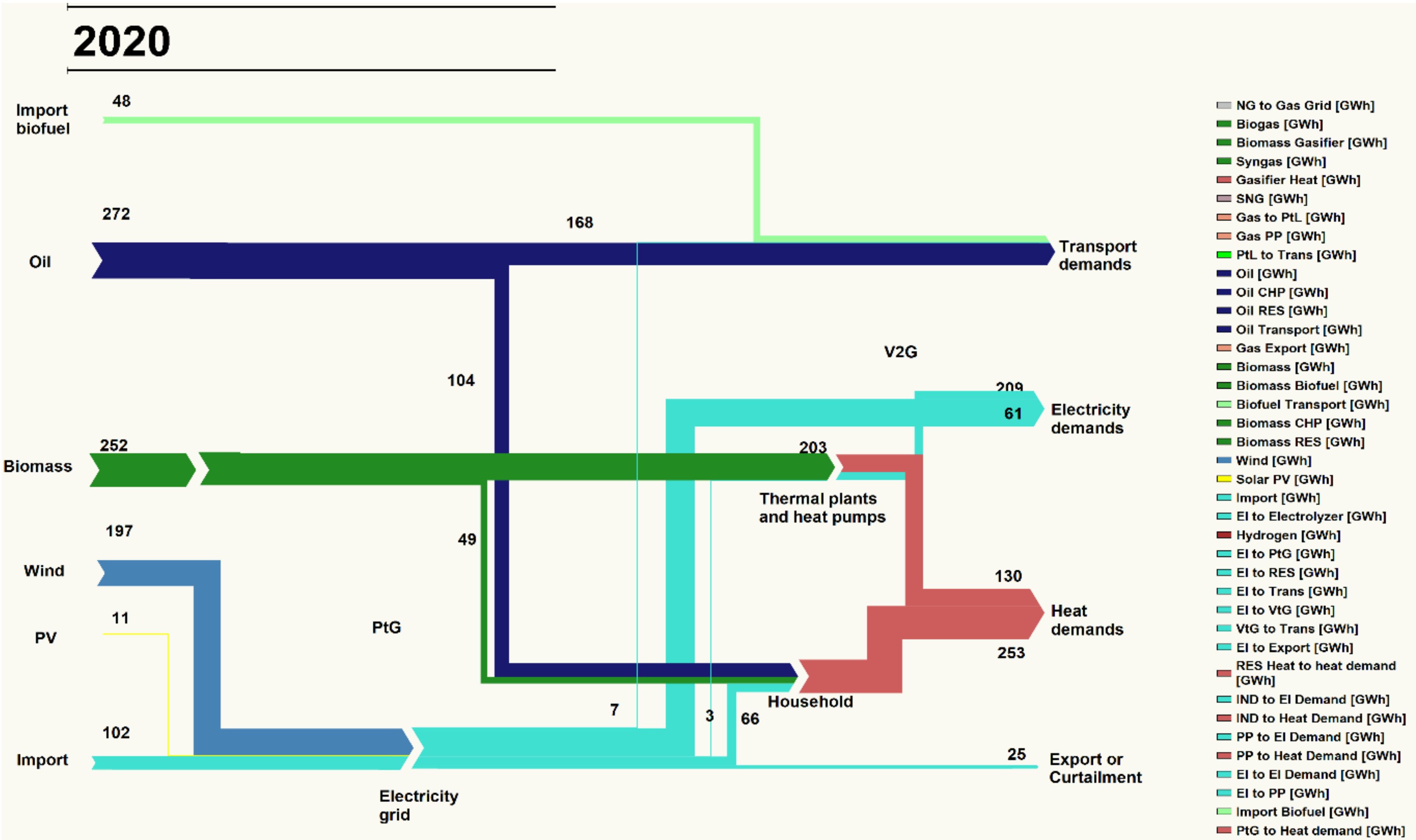


NEO CARBON ENERGY

Annual energy flows



Recarbonised Finnish Energy System
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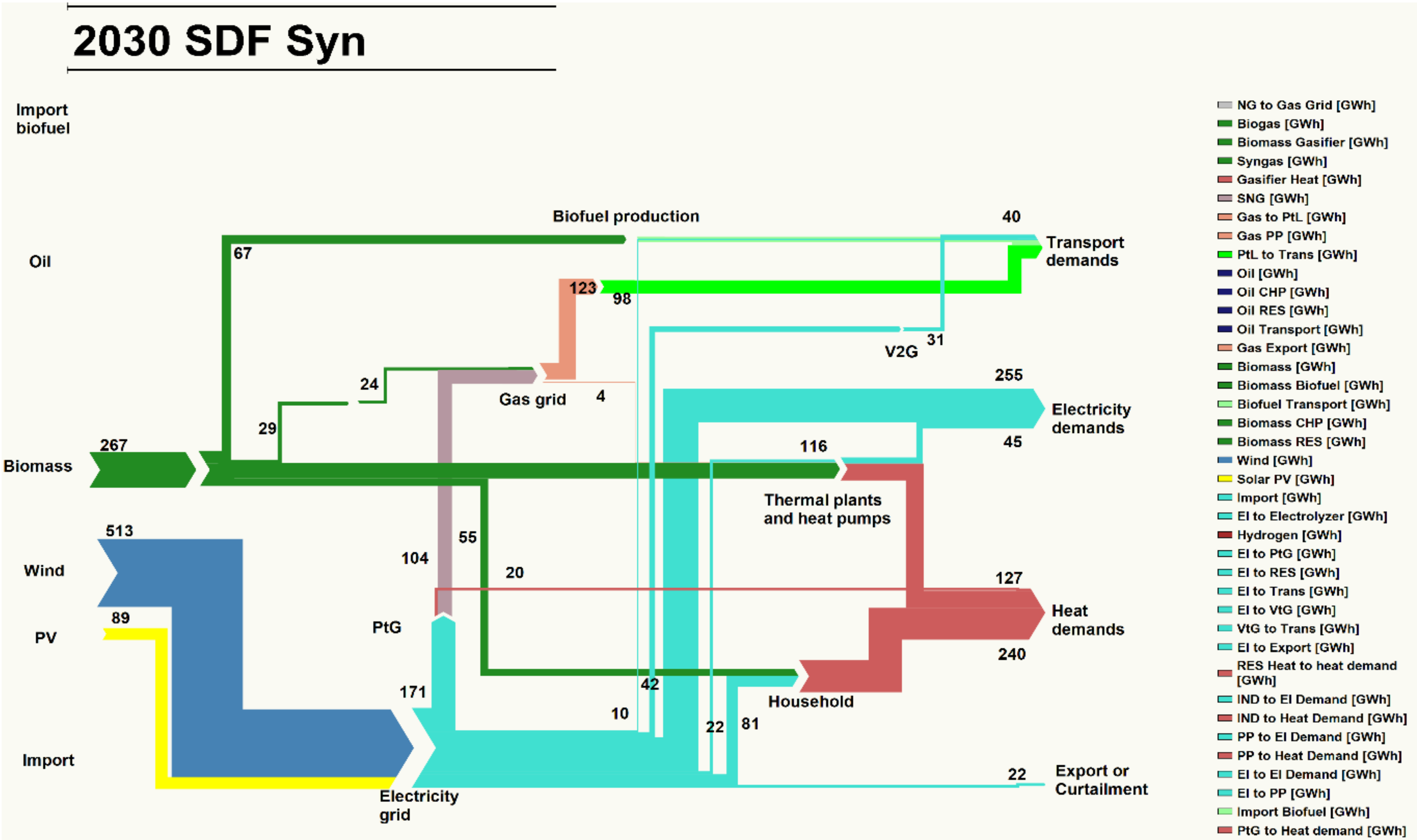
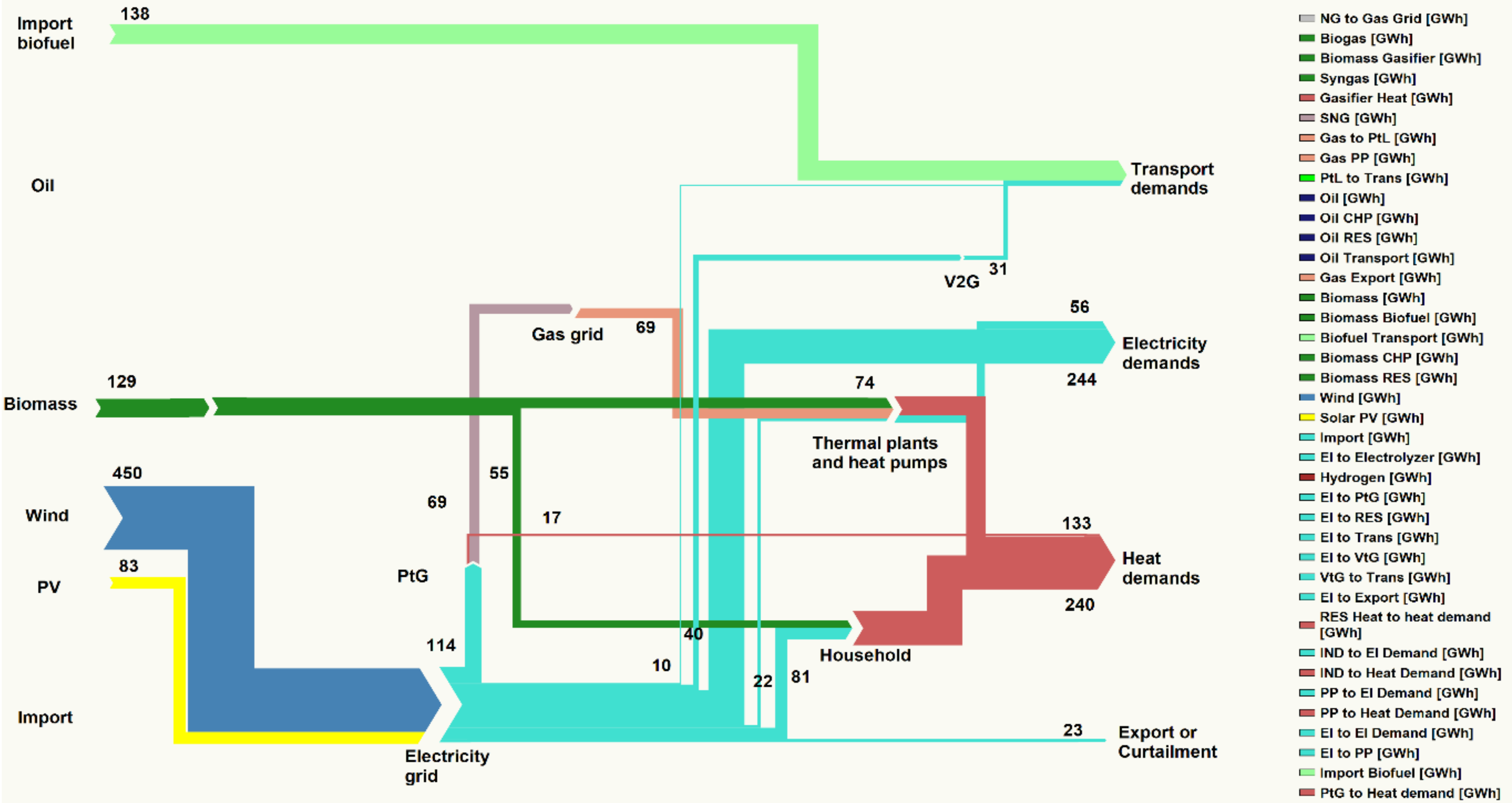
Annual energy flows



NEO CARBON ENERGY

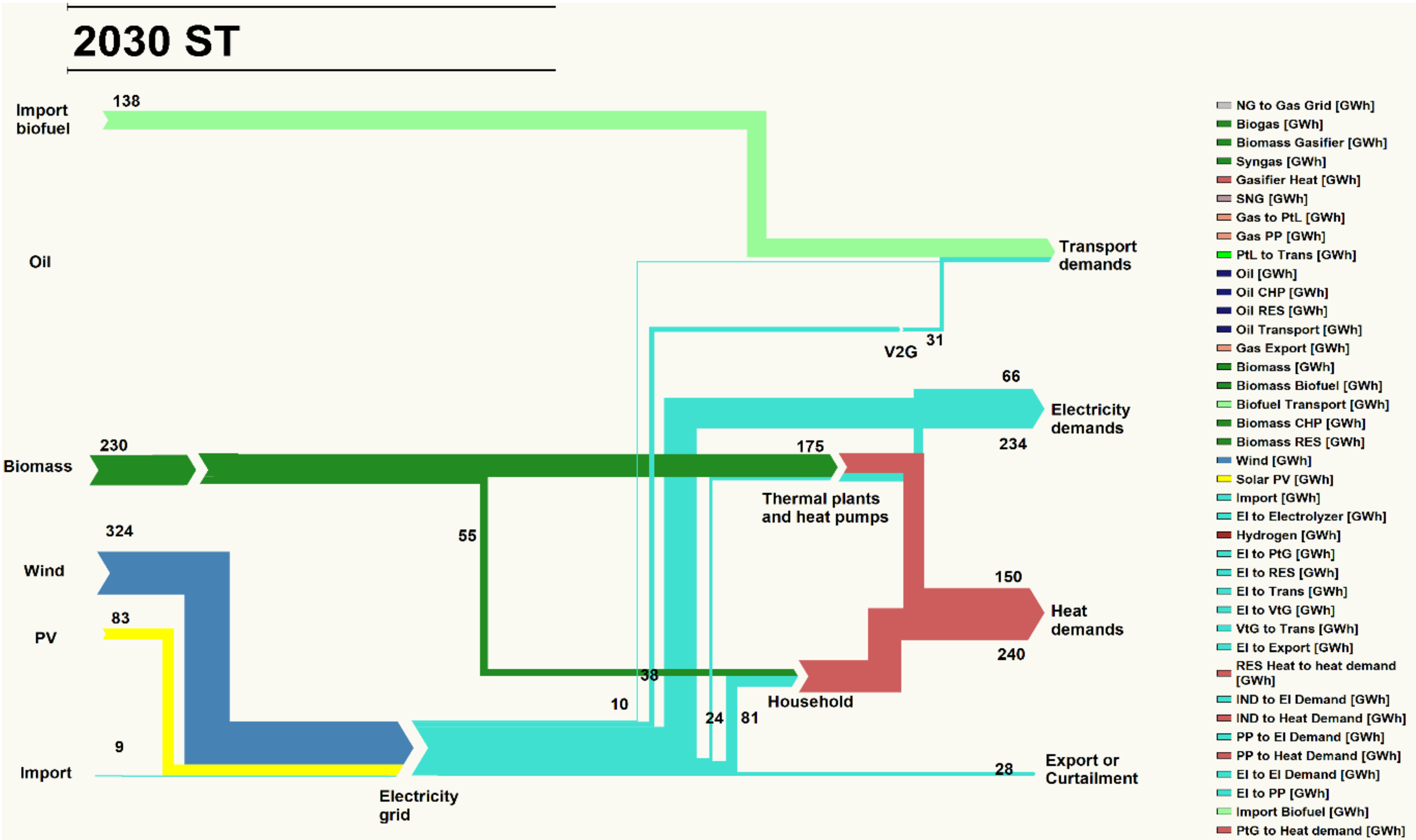
Annual energy flows

2030 SDF Bio



NEO CARBON ENERGY

Annual energy flows



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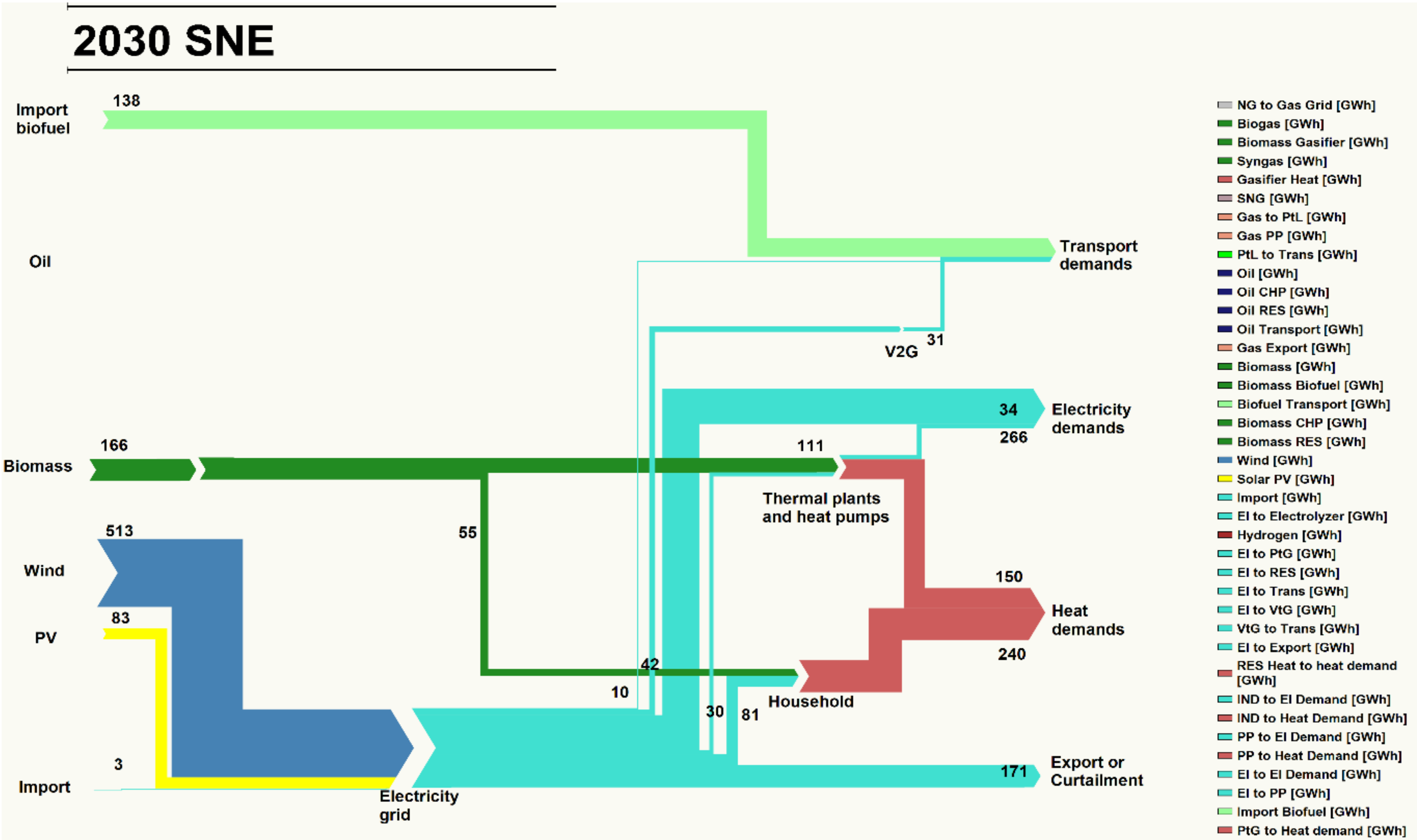
Annual energy flows



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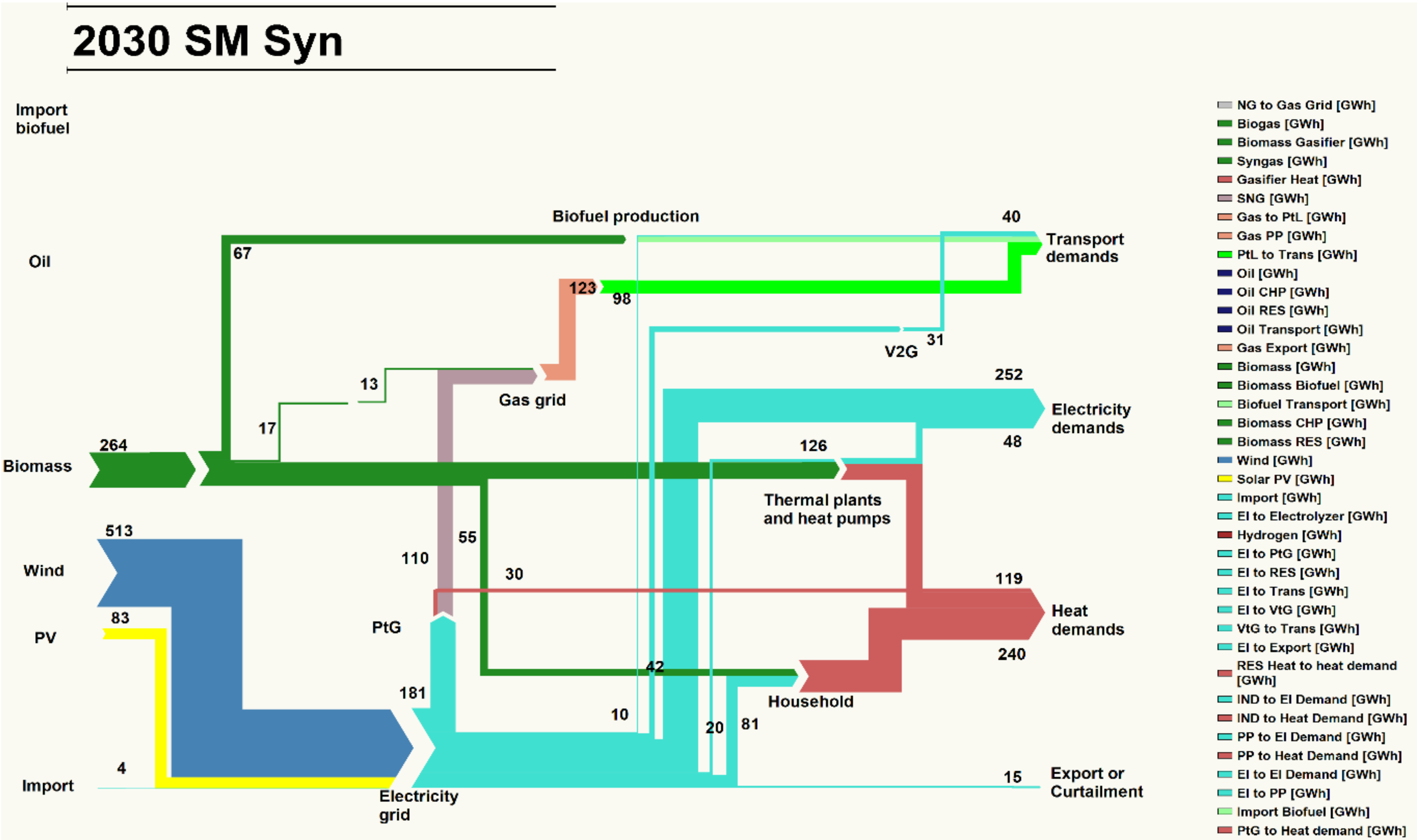
Annual energy flows



Annual energy flows

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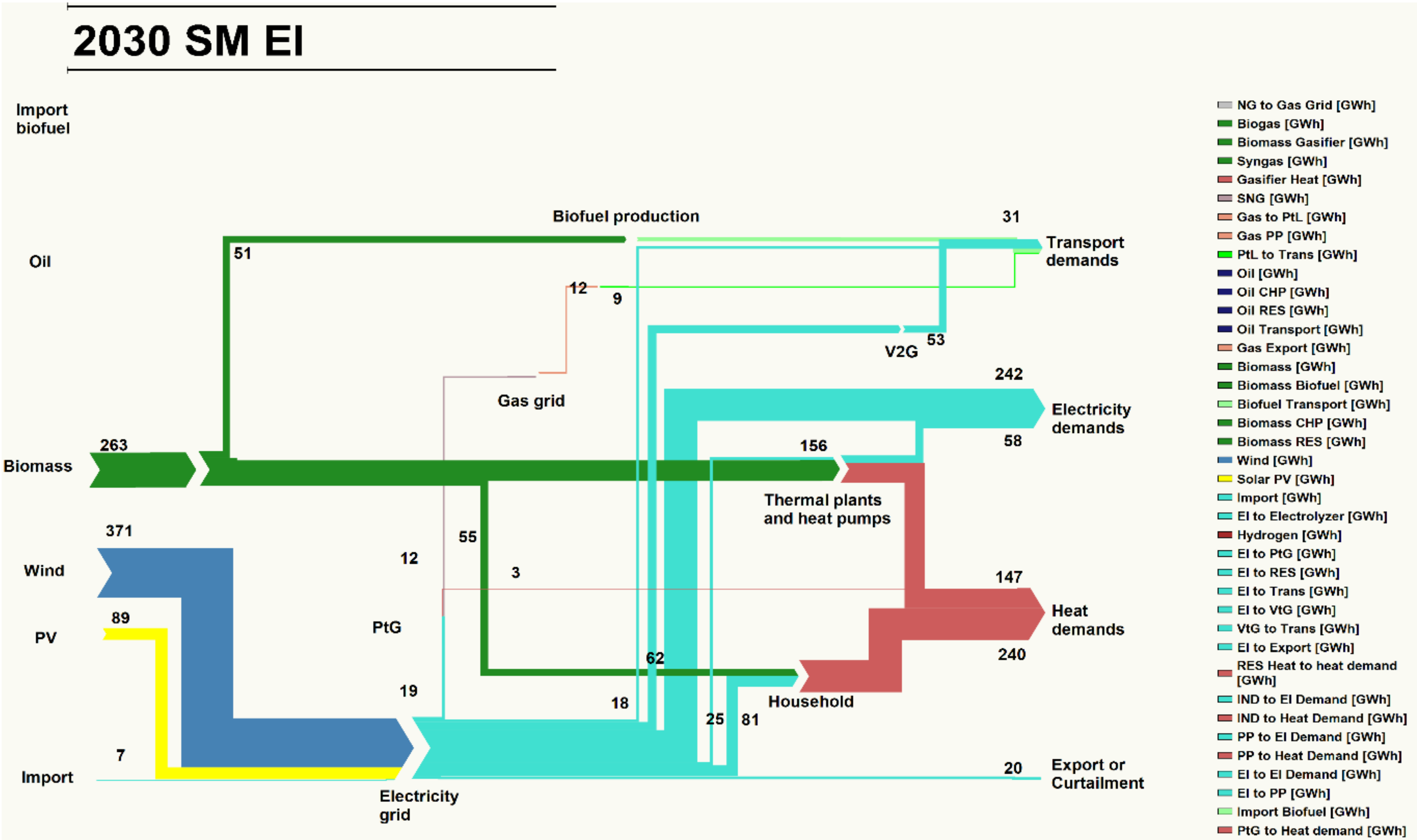

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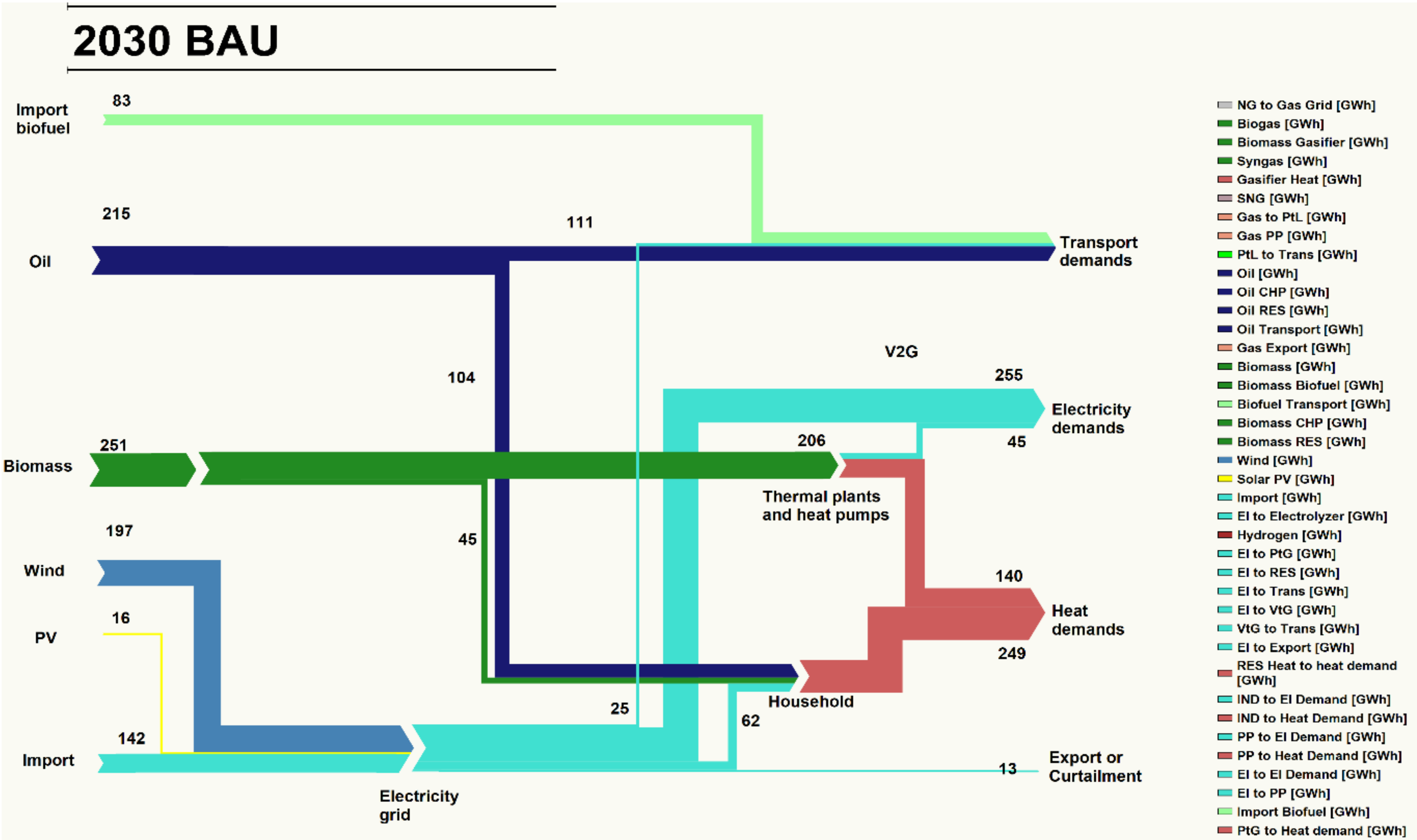
Annual energy flows



Cost assumptions

			2020	2050
Renewable energy production		Unit	Value	Value
Wind onshore	Capex	€/kW$_e$	1100	1000
	Lifetime	Years	20	25
	Opex fixed	% of investment	2.5 %	2.5 %
Wind offshore	Capex	€/kW$_e$	2500	2100
	Lifetime	Years	25	25
	Opex fixed	% of investment	2.9 %	3.4 %
Solar PV - ground-mounted	Capex	€/kW$_e$	900	550
	Lifetime	Years	30	35
	Opex fixed	% of investment	2.0 %	1.0 %
Solar PV - rooftop	Capex	€/kW$_e$	1200	700
	Lifetime	Years	30	35
	Opex fixed	% of investment	1.0 %	1.0 %
Biomass gasification plant	Capex	€/kW$_{th}$	420	320
	Lifetime	Years	25	25
	Opex fixed	% of investment	5.3%	7.0 %
		Efficiency	80 %	80 %
Biodiesel plant	Capex	€/kW$_{th}$	3420	2530
	Lifetime	Years	20	20
	Opex fixed	% of investment	3.0 %	3.0 %
		Efficiency	60 %	60 %
CO_2 Hydrogenation plant (P2G)	Capex	€/kW$_{th}$	1500	600
	Lifetime	Years	20	15
	Opex fixed	% of investment	2.5 %	3.0 %
		Efficiency	60 %	60 %
Gasification gas upgrading	Capex	€/kW$_{th}$	300	300
	Lifetime	Years	15	15
	Opex fixed	% of investment	15.8 %	17.6 %

Cost assumptions

			2020	2050
Thermal plants		Unit	Value	Value
Large heat pump for DH and CHP	Capex	€/kW$_e$ required	3425	3250
	Lifetime	Years	25	25
	Opex fixed	% of investment	2.0 %	2.0 %
	Variable costs	€/MW$_e$ required	0.27	0.27
		COP	2.9	3.0
CHP plant	Capex	€/kW$_e$	1200	1200
	Lifetime	Years	25	25
	Opex fixed	% of investment	3.75%	3.75%
	Variable costs	€/MWh$_e$	2.7	2.7
DH/CHP biomass boiler	Capex	€/kW$_{th}$	800	800
	Lifetime	Years	20	29
	Opex fixed	% of investment	3.7 %	3.7 %
	Variable costs	€/MWh$_{th}$	0.15	0.15
		Efficiency	90 %	90 %
Condensing power plant (average)	Capex	€/kW$_e$	990	980
	Lifetime	Years	27	27
	Opex fixed	% of investment	3.12 %	3.16 %
	Variable costs	€/MWh$_e$	2.636	2.636
		Efficiency	45 %	45 %
Individual boiler	Capex	€/unit	5800	5800
	Lifetime	Years	20	20
	Opex fixed	% of investment	2.6 %	2.6 %
		Efficiency	85 %	85 %
Individual heat pump	Capex	€/unit	11500	11500
	Lifetime	Years	20	20
	Opex fixed	% of investment	1.5 %	1.5 %
		COP	3.2	3.7
Individual electric heat	Capex	€/unit	8000	8000
	Lifetime	Years	30	30
	Opex fixed	% of investment	1.0 %	1.0 %
		Efficiency	100 %	100 %

Cost assumptions

Energy storage systems		Unit	2020 Value	2030 Value
Heat storage CHP	Capex	€/kWh$_{th}$	3	3
	Lifetime	Years	20	20
	Opex fixed	% of investment	0.7 %	0.7 %
Grid gas storage	Capex	€/kWh$_{th}$	0.081	0.081
	Lifetime	Years	50	50
	Opex fixed	% of investment	1.00 %	1.00 %
Conventional vehicles	Capex	k€/unit	20.6	20.6
	Lifetime	Years	16	16
	Opex fixed	% of investment	4.1 %	4.1 %
Electric vehicles	Capex	k€/unit	18.1	18.1
	Lifetime	Years	16	16
	Opex fixed	% of investment	7 %	4.3 %
Motorcycles	Capex	k€/unit	6	6
	Lifetime	Years	15	15
	Opex fixed	% of investment	5 %	5 %
Trucks	Capex	k€/unit	99.2	99.2
	Lifetime	Years	6	6
	Opex fixed	% of investment	21.1 %	21.1 %
Buses	Capex	k€/unit	177.2	177.2
	Lifetime	Years	6	6
	Opex fixed	% of investment	9.14 %	9.14 %
Lithium ion battery (EV)	Capex	€/kWh	200	100
	Lifetime	Years	8	10
	Opex fixed	% of investment	5 %	5 %

Cost assumptions

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		2020	2030
Fuel and CO_2	Unit	Value	Value
Oil	€/MWh_{th}	42.8	47.88
Oil	USD/bbl	107.4	104
Diesel	€/MWh_{th}	54.0	61.2
Petrol	€/MWh_{th}	54.7	63.36
Jet fuel	€/MWh_{th}	58.0	63.36
NG	€/MWh_{th}	32.8	36.72
Liquid biofuels	€/MWh_{th}	84.8	65.0
Biomass	€/MWh_{th}	22.32	24.48
CO_2	€/t $CO_{2\ eq}$	28.6	34.6

NEO CARBON ENERGY

Cost assumptions

		All years
Fuel handling (storage, distribution and refining)	Unit	Value
Fuel oil to central CHP and PPs	€/MWh$_{th}$	0.943
Fuel oil to industry and DH	€/MWh$_{th}$	6.84
Diesel for transportation	€/MWh$_{th}$	7.56
Petrol / Jet fuel for transportation	€/MWh$_{th}$	7.502
NG to central CHP and PPs	€/MWh$_{th}$	1.476
NG to industry and DH	€/MWh$_{th}$	7.2
Biomass to conversion plants	€/MWh$_{th}$	4.284
Biomass to central CHP and PPs	€/MWh$_{th}$	4.284
Biomass to industry and DH	€/MWh$_{th}$	4.32
Biomass to individual households	€/MWh$_{th}$	10.8
Biomass for transportation (biogas)	€/MWh$_{th}$	4.32

Cost assumptions

			All years
Infrastructure		Unit	Value
District heating grid	Capex	€/MWh_{th}	72
	Lifetime	Years	40
	Opex fixed	% of investment	1.25 %
District heating substation - Residential	Capex	€/unit	5500
	Lifetime	Years	20
	Opex fixed	% of investment	2.7 %
District heating substation - Commercial	Capex	€/unit	21500
	Lifetime	Years	20
	Opex fixed	% of investment	5.00 %

Cost assumptions

Parameter	Unit	2020	2030	2030 BAU
Number of DH customers	Thousand	0.95	1.2	1.1
Total heat production	(GWh_{th})	130	150	140
Grid costs	(€/MWh_{th})	72	72	72
Total grid costs	(k€)	9360	10800	10080
Number of residential customers	Thousand	0.54	0.6	0.66
Cost of residential substation	(€/unit)	5500	5500	5500
Number of commercial customers	Thousand	0.41	0.6	0.44
Cost of commercial substation	(€/unit)	21500	21500	21500
Total substation costs	(k€)	11785	16200	13090
Substation opex	(k€)	589	810	654

Emission factors for fuels

		All years
Carbon content in fuels	Unit	Value
Oil	kg CO_{2eq}/MWh_{th}	266.4
NG	kg CO_{2eq}/MWh_{th}	204.12
Solid biomass	kg CO_{2eq}/MWh_{th}	396