Simulation of an isolated system behavior at high RES penetration coupled with storage

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Abstract
The aim of the present work is to assess the overall benefits of applying electrical energy storage, especially to isolated grids, to harvest the underlying Renwable Energy Sourses potential sustainably. One such case is Cyprus, where due to various technical constraints related to the isolated nature of the island's electricity system, RES in the electricity sector can reach a maximum level assuming limited curtailments, as early as 2023-2024. To this end, simulations have been set up and run using the DISPA-SET tool to investigate the potential of new electricity storage facilities at effective accommodation of high Renewable Energy Technologies (RET) penetration, especially photovoltaics in the coming years. Results show that particularly in isolated grids, RET penetration has to be coupled with storage to avoid power curtailment and provide security to the whole system, reduce the energy not served and provide a long-term perspective for the decarbonaization in the electricity sector towards 2050 zero-emission targets.

Keywords: Renewable Energy, Energy Storage, Modelling Tools, Isolated Electricity Grid

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List of Abbreviations

boe: Barrel of Oil Equivalent
EAC: Electricity Authority of Cyprus
GW: Giga Watt
HFO: Heavy Fuel Oil
IRENA:International Renewable Energy Agency JRC: Joint Research Centre
LCOE: Levelized Cost of Energy
MW: Mega Watt
MILP: Mixed Integer Linear Programming
NECP: National Energy and Climate Plans
O&M: Operation and Maintenance
PPM: Planned Policies and Measures
PV: Photovoltaic
RED: Renewable Energy Directive
RES: Renewable Energy Sources
RET: Renewable Energy Technologies
SREC: Storage & Renewables Electrifying Cyprus
TSO: Transmission System Operator

1. Introduction

As the efforts for achieving energy neutrality within the EU by 2050 are increased, member states are facing multiple challenges. While the targets for 2020 have been met at a European level, there is still a long way ahead for the 2030 target for the more ambitious targets arising by the “Fit for 55” EU package.

Following the publication of the Renewable Energy Directive (RED) [1] in 2008, where member states agreed upon specific targets at both national and European level, the revision of RED (2018) [2] came to propose new, more ambitious targets. Specifically, a share of at least 32% of renewable energy by 2030 at a European level has been agreed. This came as a result of cumulative efforts made by member states during the past decade that led to encouraging results regarding renewable targets. According to Eurostat [3], the share of renewables in gross final energy consumption stood at 19.7 % in the EU-27 in 2019, compared with 9.6 % in 2004. The revision of the Renewable Energy Directive (2018) introduces new targets in the electricity sector to be met, with a strong emphasis on new investments in the electricity sector that also include a significant amount of capital investments in the energy infrastructure components.

Following the above, member states align their policy towards sustainability to meet the agreed targets. As such, Cyprus has published the targets and actions for the decade to come in the National Energy and Climate Plan. The target of 13% in Renewable Energy Sources for 2020 has been achieved, while the target of 23% in RES for 2030 is achievable or exceeded under certain conditions. However, to achieve this target, multiple studies [4-7] prepared by the Cyprus Government suggest that actions are required in both policy formulation, support schemes improvement, and regulated efforts to overcome the lack of non-operational electricity market in Cyprus.

The Cyprus energy system presents several unique challenges since it’s still isolated from the rest of the European Union grid. At the same time, the economies of scale that can be applied in the other EU Member States can not be used at the same level in Cyprus.

In [8] the authors presented a classification of the so-called “off-grid” systems and their challenges, including a limited amount of energy available for a restricted period reduces the acceptability of the solution and sufficient power reserve to face unexpected generation failures or load demand change. In addition, [9] are raising the fact that the reliance of RES in weather conditions (RES intermittency) is an important issue, especially in cases where the portion of Renewable power injected into the grid is relatively high, leading to a significant percentage of curtailments. The challenges of isolated systems are also presented in [10], where the authors discussed the challenges and presented a hybrid Renewable energy system paradigm.

Energy storage systems are classified into two categories. Those that are behind the meter and those that are located after the meter. Both Energy Storage systems come to address various challenges, enabling multiple services and components of the market such as Bulk Energy Services, Ancillary Services, Transmission and Distribution Infrastructure services (i.e. Voltage support, congestion etc), and customer energy management services.

Such solutions have been a subject of study for researchers to identify feasible solutions in both economical and practical terms in different conditions.

In [11], the authors performed a thorough review of the, at the time, available storage solutions. More specifically, they identified technologies such as flywheel, battery, supercapacitor, hydrogen pneumatic and pumped storage solutions (or new techniques that are taking advantage of gravitational energy). They classified them in terms of their specific energy and specific power. An important conclusion was that batteries are the most suitable solution for continuous energy supply.

Similarly, in [12], the authors presented an analysis of the role of storage systems in the development of smart grids. Various technologies were examined, and the importance of energy storage was outlined through two case studies. Electrical and electrochemical energy storage technologies are the first choices when considering smart grids.

An attempt to identify suitable energy storage technologies in small isolated systems has been performed in [9], with the results suggesting that BESS technology may be financially feasible while considerably decreasing the levels of RES curtailment. In other works, [10, 13-14] energy storage technologies are investigating their applicability in different scenarios. However, it is acceptable that no study was identified to explore all the available commercial storage technologies for Cyprus. Thus the purpose of this work is to compare previous results and provide recommendations using the deliverables of this study

It is worth mentioning that Gravity storage solutions also seem to be a promising solution and have received significant attention in recent years. In [15] the authors presented an approach to optimally configuring a wind-photovoltaic-storage hybrid power system based on a gravity energy storage system showing that such systems could be economically viable. Energy Vault [16] is an example of how gravity storage systems can be applied in the real world. The project first introduces the managed mechanical storage using cranes and cement blocks. This technology is one of the up-and-coming technologies. Based on a recent presentation in the IRENA Assembly meeting (online meeting Jan. 2021), this technology can have an LCOE as low as 3 $cents/kWh.

The understanding of energy systems challenges and the prediction of their behavior was enhanced through simulation and analysis tools. In [17], the authors developed a global electricity system model and evaluated the operation of power plants under various scenarios. In [18], the authors performed a link between different models to investigate the contributions to the system flexibility for cross-sectoral interactions on the future European system. The energy production of a hybrid photovoltaic system associated with a storage system in an isolated site has been modeled in [19].

A methodological review of some of the existing energy system models for assessing Variable RES is presented in [20]. The authors identified clear advantages and disadvantages of the proposed approaches, arguing that each methodology is highly dependent on the modeling situation, modeler skills, and data availability.

Simulation tools are employed for assessing operational developments (RES penetration, storage integration, interconnection etc) within the energy grid. Such tool is the Dispa-SET [21], mainly developed within the Joint Research Centre of the EU Commission, in close collaboration with the University of Liège and the KU Leuven (Belgium) and is focused on the balancing and flexibility problems in European grids. Other tools used in previous work for the Cyprus model were the PLEXOS, DigSILENT, OSeMOSYS, custom-made tools in Matlab, and MESSAGE while currently, IRENA FlexTool is under evaluation

This work utilizes the Dispa-SET tool and investigates various scenarios for integrating energy storage solutions in the Cyprus energy network while achieving a high degree of RES penetration. All scenarios are aligned to the existing NECP of Cyprus (Jan. 2020), providing further insight on the potential of RES penetration to Cyprus' grid and on the benefits associated with coupled RES/storage deployment.

The remainder of this paper is structured as follows: In the following paragraphs, the methodology is first presented along with a brief introduction of the Dispa-SET model, followed by the description of Cyprus' generation system building blocks and the presentation of the scenarios. Based on the preliminary data attained, different scenarios have been investigated, presenting the mid-term RES/storage deployment needed for achieving the NECP goals in terms of electricity energy mix.

2. Methodology

As already mentioned, for this work, the Dispa-SET model has been utilized. For the simulation runs to be as accurate as possible, ensuring repeatability of the results, a specific methodology was followed. The approach is presented in figure 1.

Data are collected from official sources (i.e. NECP, EAC, TSO website, Ministry of Finance, Statistical Service, IRENA etc) related to the energy system of Cyprus and technology development costs. Pre-processing involves filtering the collected data while the configuration files are being prepared according to the Dispa-SET template.

2.1. Dispa-SET Model description

The Dispa-SET model is developed in GAMS and utilizes csv files for input data handling. For this work, Mixed-Integer Linear Programming has been defined as an optimization method. The model assumes as continuous variables amongst others, the individual unit dispatched power, the shedded load and the curtailed power generation. More details about the model are presented in [21].

Even though the model has been developed for solving congestion issues on large electricity networks with interconnections of multiple nodes, with the demand side being an aggregated input for each node, while the transmission network is modeled as a transport problem between the nodes, it may well be implemented in isolated grids, such as Cyprus' grid.

The goal is to minimize the total power system costs (expressed in EUR in cost function equation), which are defined as the sum of different cost items, such as start-up and shut-down, fixed, variable, ramping, transmission-related and load shedding (voluntary and involuntary) costs, maintenance, etc. The MILP objective function is, therefore, the total generation cost over the optimization period.

The costs can be broken down as

- Fixed costs
- Variable costs
- Start-up costs
- Shut-down costs
- Ramp-up
- Ramp-down
- Shed load
- Transmission
- Loss of load
- Emmision costs (fuel costs)
- Maintenance Cost / outage
- Reserved Cost,
- Energy not served

Some other economic and financial effects, such as job creation, health impacts, opportunity cost etc., are not thoroughly examined since it is out of the scope of this study.

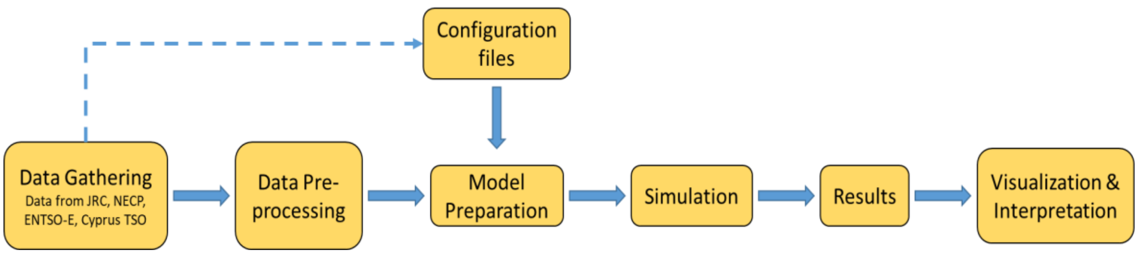

Figure 1: Methodology

3. Implementation

3.1. Data Gathering and pre-processing

Data related to the Cyprus energy grid as well as the projected targets for the coming decades according to the Cyprus NECP have been collected and pre-processed for use as inputs in the model.

In order to simulate the operation of the power generation system of Cyprus, one has to rely on information of past performance as well as future projections. To this end, past generation and demand data have been collected from TSOC [22] for year 2019, concerning

a) Conventional energy generators production (15 minutes intervals)
b) Renewable energy – wind and PV/biomass – production (15 minutes intervals)
c) Demand (15 minutes intervals)

Data have been elaborated upon and hourly availability factor profiles have been derived for wind and PV. During 2019, as pointed out in a previous paragraph, wind energy installations have remained unchanged throughout the year, while PVs had a significant increase of 20%. Data of the monthly increase in PV installed capacity have also been retrieved by TSOC. From TSOC's Load-Duration curve of 2019, shown in the graph bellow (Figure 2), one may conclude that the 2019 load lies close to 2010-2019 decade mean. As such, it may be regarded as a typical profile to be used also as a reference for future years.

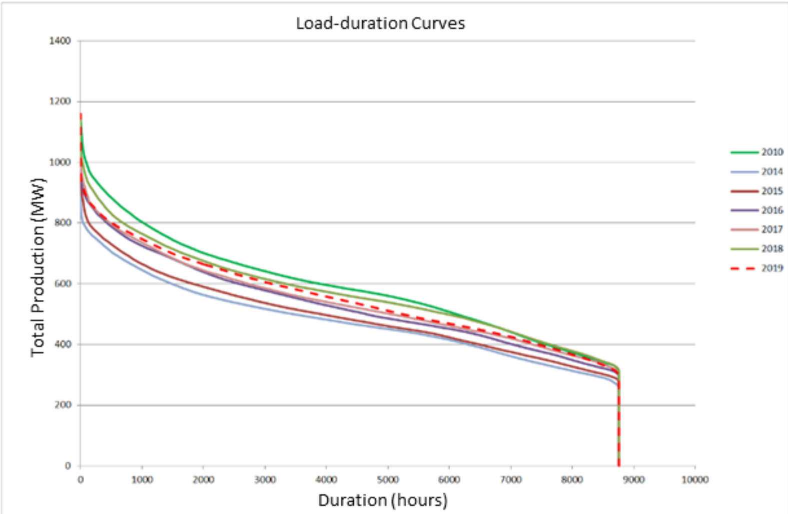

Figure 2: Load duration Curves

Demand data for 2019 have also been retrieved from ENTSO-E transparency platform [23], which are very similar with the NECP of Cyprus data. Unfortunately, the platform has incomplete or is missing other relevant data for Cyprus, such as generation per unit type, outages, congestion management costs, etc., that are available for other European countries.

Other data sources are the database of typical generators of Dispa-SET, as well as the set of generators and their characteristics already provided for Cyprus in Dispa-SET. These have been used in the simulation of the EU countries' power grid for 2015 by the JRC. More data have been retrieved from the data files of the JRC-EU-TIMES model [24], a scientific tool for assessing the long-term role of energy technologies.

3.2. Cyprus' Electricity Generation System

In addition to the above model, it is essential for one to understand the existing energy system, in this case, the Cyprus energy system. Cyprus has an isolated electricity transmission grid with a power generation system operating in isolation, having to balance demand with generation and in the absesne of Storage. The power system relies on imported fuels for electricity generation, mainly heavy fuel oil and, to a lesser extend, gasoil. The main conventional power generators are operated by EAC (Electricity Authority of Cyprus) and are summarized in the following table (Table 1) [25]:

Table 1: Cyprus Conventional power generators

Power Station	Units	Fuel Type	Usage	Capacity [MW]	Total [MW]
Vasilikos	Steam	HFO	Base load generation	3 x 130	390
	Open Cycle Gas Turbine	Diesel	Peak load generation	1 x 38	38
	Combined Cycle Gas Turbine	Diesel	Peak load generation	2 x 220	440
Dhekelia	Steam	HFO	Base/intermediate load generation	6 x 60	360
	Internal Combustion Engine	HFO	Peak load generation	2 x 50	100
Moni (Cold Reserve)	Open Cycle Gas Turbine	Diesel	Peak load generation	4 x 37,5	150
				TOTAL	**1478**

The details for each power station regarding their thermal efficiency and their contribution to the island's total energy production are available in the Electricity Authority official website. In addition the retirement of these units was also taken into account.

Apart from the conventional power generators there are also RES installations mounting by the end of 2019 at 149,5MW for PV (124,2MW by the end of 2018), 12,1 MW biomass (from 9,7MW by the end of 2018) and 157,5MW for wind (same as by the end of 2018).

3.3. Analysis Scenarios Definition

For this work, various scenarios have been defined that cover multiple variables affecting the system behavior.

To set up current and future scenarios for the project's analysis, the NECP scenarios for 2030 and 2040 have been considered. The NECP provides projections for the final electricity demand in Cyprus up to the year 2050 (linear interpolation was used from 2030 to 2050). The demand forecast presumes the effect of Existing Measures and Planned Policies and Measures on demand due to energy efficiency measures. The forecast is shown in the following figure.

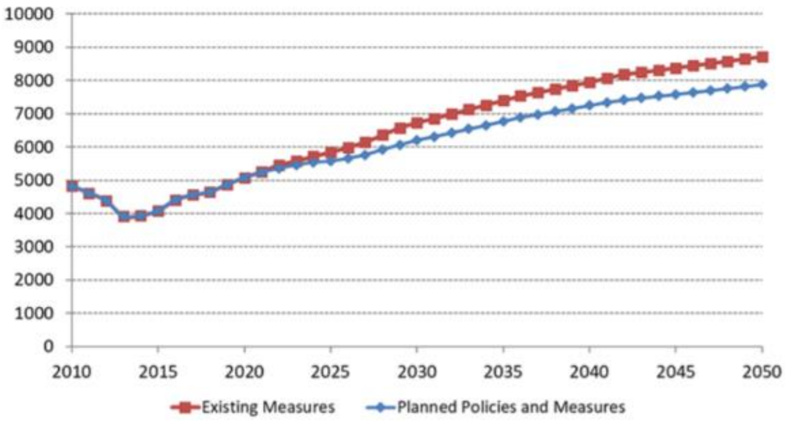

Figure 3: Forecast of final electricity demand in Cyprus (million kWh)

According to the latest national report to the European Commission (for the year 2018) [26], the expected future total generated energy for the year 2030 will be as high as 7500GWh, as shown in the following figure, and also used by JRC (JRC-EU-TIMES model).

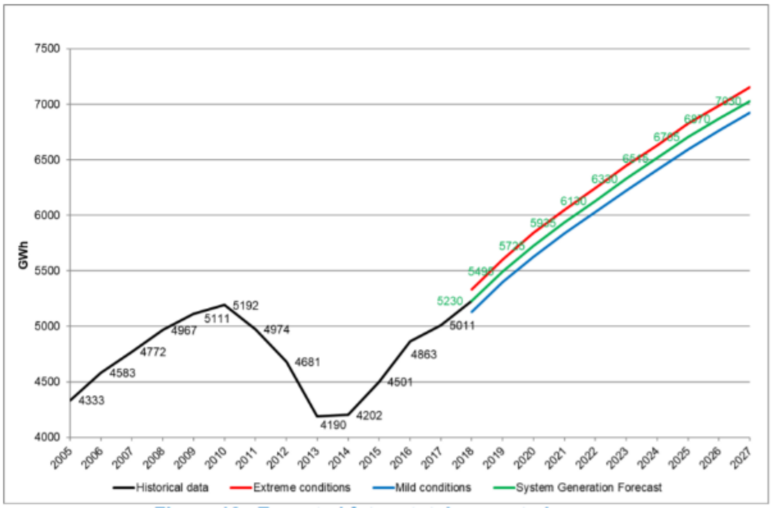

Figure 4: Expected future total generated energy

Future scenarios of generated energy of 7,52TWh for 2030 and 8,64 TWh for 2040 have been employed for the simulations performed.

The revised capacity projections according to the Planned Policies and Measures (PPM) Scenario of NECP is presented in Table 2, bellow

Table 2: Capacity projections in the electricity supply sector of Cyprus for PPM scenario [23]

(in MW)	**2020**	**2021**	**2025**	**2030**	**2035**	**2040**
New CCGT	0	216	432	432	432	648
Solar PV	360	380	460	840	1653	1892
Solar Thermal	0	0	50	50	50	500
Wind	158	158	198	198	198	198
Biomass & Waste	17	22	42	58	58	58
Pumped Hydro	0	0	0	0	130	130
Li-Ion Batteries	0	0	0	0	211	655

As illustrated in supporting studies for the NECP [4], solar PV is the most competitive of the renewable energy technologies and, as such, is responsible for the increase in renewable energy. Solar capacity increases to a total of 854 MW (804MW PV and 50MW of CSP) by 2030 comparing with the corresponding 2020 target which is 360 MW. The installed capacity as of 10/2021 for comparison reasons mounts to a total of 262,7MW of Solar PV, 157,5MW of Wind and 12,4MW Biomass/Biogas [22], with the PV sector showing good growth dynamics - being quite short, though, from the 2020 projection.

It is evident from Table 2 that analysis done in [4] for PPM scenario led to the conclusion that no storage facilities will be needed before 2035 to support further penetration of RES and avoid energy curtailment. Table 1 conventional capacity will be diminished by 2025, since 6x60 =360MW at Dhekelia Power Station (steam turbines) will be decommissioned. Other than that, the rest of the conventional capacity generators will remain in operation at least up to 2030. For the analysis, the remaining generators are thought to remain more or less the same, since some conventional generating units will be replaced by new conventional units before 2035 and remain active at least till 2040.

As stated in NECP, the above projections assume ideal market operation since data are not available at present. Moreover, how market forces will distort the predictions cannot be estimated. For the cost optimization to be realized, it is considered that a central operator manages the system with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network. In the case of a wholesale day-ahead power market, the unit commitment problem considered is a simplified instance of the problem faced by the operator in charge of clearing the competitive bids of the participants.

Considering the above information, the scenarios listed in table 3 have been investigated by employing the Dispa-SET tool to optimize the system’s operation.

Table 3: Scenarios breakdown

Scenario	Operation Year	Simulation target	Technology assumed	Oil price	Gas price
Scen1	2019	Cost effective system operation	As-is	32.5€/boe	-
Scen2 Scen2p1 Scen2p2	2030 2030 2030		Table 2	32.5€/boe 49€/boe 40€/boe	50€/boe 24.50€/boe 40€/boe
Scen2.1 Scen2.1p1 Scen2.1p2	2030 2030 2030		+ 3 storage technologies	32.5€/boe 49€/boe 40€/boe	50€/boe 24.50€/boe 40€/boe
Scen2.2	2030		+ Li-ion Battery Storage	32.5€/boe	50€/boe
Scen2.3	2030		+ Pump Hydro Systems	32.5€/boe	50€/boe
Scen2.4	2030		+ Hydrogen Storage	32.5€/boe	50€/boe
Scen3 Scen3p1 Scen3p2	2040 2040 2040		Table 2	32.5€/boe 49€/boe 40€/boe	50€/boe 24.50€/boe 40€/boe
Scen3.1 Scen3.1p1 Scen3.1p2	2040 2040 2040		No storage systems	32.5€/boe 49€/boe 40€/boe	50€/boe 24.50€/boe 40€/boe

Scenarios Scen2.1, Scen2.2, Scen2.3 and Scen2.4 are variations of main Scenario Scen2, aiming at providing an insight into whether storage as a whole has any impact on the deployment and use of RES energy. The same stand also for scenario Scen3.1, being a variation of Scen3. Further to the above technical variations, scenarios with varying fuel costs have also been set up. Future scenarios Scen2, Scen3 and Scen3.1 with different fuel price mix were also investigated. Not all production costs items have been taken into account. For the present qualitative analysis, the relative effect of fuel prices provides the full envelope and range of prices that covers almost all different forecasts.

One drawback, it that only one oil price is used in Dispa-SET and does not distinguish between HFO and Diesel oil in the same simulation run. The oil prices above represent a price for a mixture oil – HFO price lies around 50-60% of the price of diesel oil. The price of biomass is estimated and constant at 60€/boe and the tCO_2 emission price at 25€/tCO_2. The generators (conventional or renewable) and the storage systems and their characteristics are shown in APPENDIX I.

3.4. Assumptions

The main assumptions made while setting up the Dispa-SET simulation set are the following:

- Isolated system with no interconnections
- No transmission losses considered
- No outage factors for the conventional generators (no pertinent data retrieved, even though Dispa-SET can be fed with hourly profiles)
- Only one “OIL” fuel considered (Dispa-SET has only one OIL as input)-

- Fuel prices considered constant throughout the year (even though Dispa-SET can be fed with hourly profiles)
- CO_2 cost per tonne equivalent is set the same at 25€/tCO_2 for all simulation cases
- No variable (fuel) cost associated with renewables (Wind, PV, Solar Thermal – ST)
- Clustering of units allowed – Not interested in particular generator production
- Dispatch of generators to satisfy demand with a horizon of 3 days and 1 day look ahead
- Simulations duration for year y: Start at 00:00 hours/day1 - End at 23:00 hours/day 365
- No installation, depreciation, or O&M costs have been considered

Based on the above-simplified assumptions, System costs correspond to a well-organized system for which ramp-up, ramp-down, start-up, shut-down prices depict the most economical way of operation. Using the above assumptions, soft-calibration model output was done with the output of the OseMOSYS model used in NECP for the basic scenario (Scen2) without significant differences.

Some other system characteristics are listed below:

- Peak demand for 2019 mounts to 1034,5 MW,
- peak demand for 2030 is estimated at 1315,8 MW
- Peak demand for 2040 of 1513,2 MW is envisaged.

4. Results and Discussion

In the graphs within APPENDIX 2, dispatch for Scen2.1 and Scen3.1 of Par. 4 are indicatively presented for four weeks during the year, namely 15/1 – 21/1 (winter week), 29/3 – 30/4 (spring week), 30/6 – 6/7 (summer week) and 12/10 – 18/10. The demand profile is also depicted. Similar dispatch profiles have been attained for all scenarios of Table 3.

For cases where storage is considered, the energy consumed for storage (otherwise curtailed) is shown with negative values. The overall System cost and the system unit cost and RES penetration percentage are presented in the table below, summarizing the simulation results.

Table 4: DISPA-Set simulation results for the scenarios examined (Reference year 2019,2030,2040)

Simulation scenarios	System Cost [Mil. €]	Energy supplied to the grid [GWh]	Demand [GWh]	Unit Cost [€/MWh]	RES Energy[GWh]	Curtailed Energy [MWh]	RES as % of electr. Cons. [%]	Energy from storage [MWh]			
								HPHS	BATS	H2	TOTAL
Scen1 (2019)	294.18	5119.51	5119.86	57.5	501.10	37.1	9.8				
Scen2 (2030)	388.29	7514.56	7515.88	51.7	1559.43	7279.8	20.7				
Scen2p1	358.60	7515.73	7515.88	47.7	1561.95	5530.6863	20.7				
Scen2p2	394.79	7515.70	7515.88	52.5	1548.91	54786.117	19.9				
Scen2.1	385.05	7626.31	7515.88	51.2	1569.34	30.6	20.9	41696.6	42880.1	48.0	84624.7
Scen2.1p1	343.38	7851.24	7515.88	45.7	1569.38	39393	20.4	172498.7	80483.61	198.511	253180.8
Scen2.1p2	387.72	7671.44	7515.88	51.6	1568.54	39701.899	20.3	54186.62	64613.3	269.082	119069.0
Scen2.2	384.91	7634.77	7515.88	51.2	1569.32	24.3	20.9		94402.6		94402.6
Scen2.3	385.31	7615.11	7515.88	51.3	1569.30	13.3	20.9	73403.4			73403.4
Scen2.4	386.45	7532.49	7515.88	51.4	1569.30	17.2	20.9			5676.4	5676.4
Scen3 (2040)	362.75	9386.92	8643.27	42.0	3268.59	8572.0	37.7	136587.7	416402.2	11329.9	564319.8
Scen3p1	409.38	9514.05	8643.27	47.4	3225.36	45314.04	36.8	183807.8	427213.6	27971.6	638993.0
Scen3p2	354.38	9529.80	8643.27	41.0	3209.39	60082.991	36.4	188723.7	432744.8	28717.2	650185.7
Scen3.1	414.22	8633.34	8643.27	47.9	2821.00	166197.6	30.7				
Scen3.1p1	344.92	8642.86	8643.27	39.9	2382.53	856114.3	17.7				
Scen3.1p2	410.36	8642.58	8643.27	47.5	2494.20	745506.2	20.2				

When evaluating the simulation results, some important outcomes may be pinpointed:

- With the same fuel and other costs, the unit system cost (€/MWh) is diminished from Scen1 (2019) to Scen2 (2030) and Scen3 (2040), due to the higher penetration of RES that bare no variable (fuel) cost
- In all the above scenarios for 2030 (Scen2x) RES penetration is well below the target of 26% energy from renewables in the electricity sector
- More than 4% of energy is curtailed in 2030 scenarios
- Fuel price variations have little or no effect in RES energy curtailment
- Different storage technologies have minimal effect in the overall system cost, while their contribution in RES penetration is not significant. This is because for 2030 in particular in Scen2x RES have limited capacity

Based on the last findings further simulation cases have been set up considering more RES (PV in particular) and more storage facilities, in order to check the capacity needed for achieving the goal of 51% RES-e in the mix for 2030 (26% RES penetration). The new variation scenarios are presented in the following table.

Table 5: New scenarios breakdown

Basic Scenario	**Oil price**	**Gas price**	**Scenario variation 1**	**Scenario variation 2**
Scen2.1	Low – 32,5€/boe	High – 50€/boe	**Scen2.1s1**	**Scen2.1s2**
			30% more PV capacity	40% more PV capacity
			30% more storage	40% more storage
Scen2.1s2	Low – 32,5€/boe	High – 50€/boe	**Scen2.1s2p1**	**Scen2.1s2p2**
			Oil 49 €/boe	Oil 40€/boe
			Gas 24,5€/boe	Gas 40€/boe

In the graphs presented in APPENDIX 3, the dispatch characteristics of Scen2.1s2 are indicatively presented. An overall results matrix and discussion follows in this section.

Table 6 : Dispa-Set simulation results for all scenarios

#	Simulation scenarios	System Cost [Mil €]	Energy supplied to the grid [GWh]	Demand [GWh]	Unit Cost [€/MWh]	RES Energy [GWh]	Curtailed Energy [MWh]	RES/ electr. Consumption [%]	Energy from storage [MWh]			
									HPHS	BATS	H2	TOTAL
1	Scen1	294.18	5119.51	5119.86	57.5	501.10	37.1	9.8				
2	Scen2	388.29	7514.56	7515.88	51.7	1559.43	7279.8	20.7				
3	Scen2p1	358.60	7515.73	7515.88	47.7	1561.95	5530.68	20.7				
4	Scen2p2	394.79	7515.70	7515.88	52.5	1548.91	54786.12	19.9				
5	Scen2.1	385.05	7626.31	7515.88	51.2	1569.34	30.6	20.9	41696.6	42880.1	48.0	84624.7
6	Scen2.1p1	343.38	7851.24	7515.88	45.7	1569.38	39393	20.4	172498.7	80483.61	198.511	253180.8
7	Scen2.1p2	387.72	7671.44	7515.88	51.6	1568.54	39701.9	20.3	54186.62	64613.3	269.082	119069.0
8	Scen2.2	384.91	7634.77	7515.88	51.2	1569.32	24.3	20.9		94402.6		94402.6
9	Scen2.3	385.31	7615.11	7515.88	51.3	1569.30	13.3	20.9	73403.4			73403.4
10	Scen2.4	386.45	7532.49	7515.88	51.4	1569.30	17.2	20.9			5676.4	5676.4
11	Scen3	362.75	9386.92	8643.27	42.0	3268.59	8572.0	37.7	136587.7	416402.2	11329.9	564319.8
12	Scen3p1	409.38	9514.05	8643.27	47.4	3225.36	45314.04	36.8	183807.8	427213.6	27971.6	638993.0
13	Scen3p2	354.38	9529.80	8643.27	41.0	3209.39	60082.99	36.4	188723.7	432744.8	28717.2	650185.7
14	Scen3.1	414.22	8633.34	8643.27	47.9	2821.00	166197.6	30.7				
15	Scen3.1p1	344.92	8642.86	8643.27	39.9	2382.53	856114.3	17.7				
16	Scen3.1p2	410.36	8642.58	8643.27	47.5	2494.20	745506.2	20.2				
17	Scen2.1s1	361.78	7684.89	7515.88	48.1	1947.29	729.4	25.9	64230.31	63943.22	207.259	128380.8
18	Scen2.1s2	354.42	7719.07	7515.88	47.2	2071.37	2302.2	27.5	75723.29	77158.73	836.345	153718.4
19	**Scen2.1s2p1**	**312.69**	**8080.53**	**7515.88**	**41.6**	**2072.54**	**1495.883**	**27.6**	296773.7	126419.6	1370.58	424563.9
20	Scen2.1s2p2	358.24	7846.98	7515.88	47.7	2066.59	4760.33	27.4	141263.7	107019.8	1745.58	250029.1

In the table above, rows 1-16 are the scenario variations, described and presented in section 3.3, while 17-20 rows are scenario variations for 2030, as described in this paragraph.

It is evident from Table 6 that for 2030 increasing both PV installed capacity by more than 30% as compared to Scen 2.1 with accompanied by a corresponding increase in storage capacity as a whole, creates the circumstances where the goal of 2030 for RES penetration can be achieved. For example, for scenario Scen2.1s2, where instead of 804 MW PV and 191 MW Storage in Scen2.1, one has 1125 MW PV and 268 MW storage installed, RES penetration mounts to 27,5% with a unit system cost reduction of around 6%. Fuel prices, while affecting unit system cost, do not affect RES penetration, as derived from scenarios Scen2.1s2p1 and Scen2.1s2p2 results, since LCOE for RES projects with storage seems to be lower than conventional units. The same applies if the storage units were able to install both upstream or downstream of the meter.

5. Summary/ Conclusions

From the results presented, only qualitative assumptions can be made from the comparison between test cases. Variations on fuel costs and RES capacity (especially the abundant PV capacity) for future scenarios for 2030 and 2040 revealed so far that RES underlying energy potential may be effectively harvested only by employing storage.

Scenarios for 2030 that achieve the goals set in NECP involve the further deployment of RES (mainly PVs) - Scen2.1s2, Scen2.1s2p1, and Scen2.1s2p2 of Table 6.3 - as compared to the WEM scenario of the NECP. While energy storage projects could be postponed from 2030 to 2035 or later, assuming that the energy demand will drop below certain thresholds or energy efficiency measures planned will have the same effect on demand, this will not be the case with new RES projects installed. As shown in scenario Scen2.1s2p1, the increased demand and expanded storage and RES penetration will lead to lower system cost. At the same time, the RES Target will be exceeded or have the same effect as the system interconnection.

It is also important to mention that this study did not perform any impact assessment on social and health effects, but based on previous analysis (on similar work done through NECP), it is expected that the results of this scenario will provide more direct and indirect benefits in the long term for Cyprus in all different sectors and sections of the society.

As far as it concerns the electricity interconnector, based on the current NECP results and comparison with the marginal price of the Euroasia interconnector project will be lower when compared with Storage technologies. On the other hand based on the new package for “Fit for 55” and the Carbon Border Adjustment Mechanism, it is expected that prices coming from countries with low RES penetration levels will not be as competitive as before in EU Market Conditions.

Furthermore, the impact of the economy for such measures can be of increased interest since job creation and improvements of quality of life due to better atmpospheric conditions and decrease cost in enery supply can lead to the growth of economy and prosperity of Cyprtiot citizens.

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Declarations

Authors’ contributions:

All authors contributed to the preparation of this study. Data gathering was obtained and coordinated by the Ministry of Energy Commerce and Industry and Cyprus Energy Regulatory Authority.

Analyses were performed by Athanasios Katsanevakis, Dimitris Konstantinidis, Georgios Karagiannis, and Athanasios Ganias.

The results and the fine-tuning of the scenarios were discussed with the Ministry of Energy, Commerce and Industry (MECI) (George Partasides, Demetris Petrides and Maria Ioannidou). The model was compared with similar models of the MECI (calibration and comparison of input and output assumptions). George Karagiorgis of Frederick University provided technical consultancy and an overview of the scientific validity of the work.

Demetris Petrides wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. George Partasides had the overall supervision of the work preparation. Various presentations took place with more than 60 participants demonstrating the results and the scope of the above work.

Data availability: (National Energy and Climate Plan of Cyprus 2020 - Data available from the corresponding author, upon request)

Code availability Open Source Code using Dispaset Model provided from JRC.

Declarations: Not applicable

Competing interests The authors declare no competing interests.

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APPENDIX I

Scen1 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306			0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306			0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306			0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306			0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
60	Fossil Gas	STUR	OIL	0.316			0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal Combustion E	ICEN	OIL	0.421			0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal Combustion E	ICEN	OIL	0.421			0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal Combustion E	ICEN	OIL	0.421			0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal Combustion E	ICEN	OIL	0.421			0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal Combustion E	ICEN	OIL	0.421			0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal Combustion E	ICEN	OIL	0.421			0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012			0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012			0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012			0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306			0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6		0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6		0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
157.5	Wind Onshore	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
135.78	Photovoltaic	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
12.1	Biomass/biogas	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0

Scen2 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal Combu	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal Combu	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal Combu	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal Combu	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal Combu	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal Combu	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Onshore	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
804	Photovoltaic	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/bioga	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
432	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarThermal	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0

Scen2.1 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
804	Photovolta	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
432	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0
130	HPHS	HPHS	WAT	0.86	0	0	1.960784	1.960784	0	0	0	0	0.86	0.3	0
41	Batteries	BATS	OTH	0.89	0	0	1	1	0	0	0	0	0.89	0	0
20	HYDROGE	P2GS	HYD	0.47	0	0	1	1	0	0	0	0.15	0.47	0	0

Scen2.2 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
804	Photovolt	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
432	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0
171	Batteries	BATS	OTH	0.89	0	0	1	1	0	0	0	0	0.89	0	0

Scen2.3 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
804	Photovolta	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
432	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0
171	HPHS	HPHS	WAT	0.86	0	0	1.960784	1.960784	0	0	0	0	0.86	0.3	0

Scen2.4 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
804	Photovolta	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
432	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0
171	HYDROGE	P2GS	HYD	0.47	0	0	1	1	0	0	0	0.15	0.47	0	0

Scen3 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
1892	Photovolt	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
648	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0
130	HPHS	HPHS	WAT	0.86	0	0	1.960784	1.960784	0	0	0	0	0.86	0.3	0
655	Batteries	BATS	OTH	0.89	0	0	1	1	0	0	0	0	0.89	0	0
100	HYDROGE	P2GS	HYD	0.47	0	0	1	1	0	0	0	0.15	0.47	0	0

Scen3.1 generators and their characteristics

Power Capacity [MW]	Type	Technology	Fuel	Efficiency [%/100]	MinUpTime	MinDownTime	Ramp Up Rate	Ramp Down Rate	Start Up Cost [Euro]	No Load Cost [Euro]	Ramping Cost [Euro]	Part Load Min [%/100]	Min Efficiency [%/100]	Start Up Time	CO2 Intensity
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.13333	0.13333	2500	240	0	0.106	0.1522	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
0	Fossil Gas	STUR	OIL	0.316	0	0	0.025	0.0333	10000	30	0	0.4833	0.2867	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.48	Internal C	ICEN	OIL	0.421	0	0	0.0572	0.0572	1200	85	0	0.8581	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
17.07	Internal C	ICEN	OIL	0.421	0	0	0.0586	0.0586	600	85	0	0.8787	0.4063	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
130	Fossil Gas	STUR	OIL	0.4012	0	0	0.0277	0.0277	20000	60	0	0.4435	0.3676	0	0.79
37.5	Fossil Gas	GTUR	OIL	0.306	0	0	0.1333	0.1333	2500	240	0	0.106	0.1522	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
216	Fossil Gas	COMC	OIL	0.4868	6	0	0.027273	0.027273	17500	870	0	0.272727	0.4793	0	0.79
198	Wind Ons	WTON	WIN	1	0	0	0.108086	0.108086	0	0	0	0	1	0	0
1892	Photovolt	PHOT	SUN	1	0	0	0.304775	0.304775	0	0	0	0	1	0	0
58	Biomass/b	STUR	BIO	0.46	4	6	0.02	0.02	120	12.5	1.3	0.35	0.35	1	0
648	CCGT	COMC	GAS	0.525	5	1	0.025158	0.025158	112542.1	0	0	0.4	0.525	1	0.45
50	SolarTher	STUR	SUN	0.25	0	0	0.02	0.02	0	0	0	0	0.2	1	0

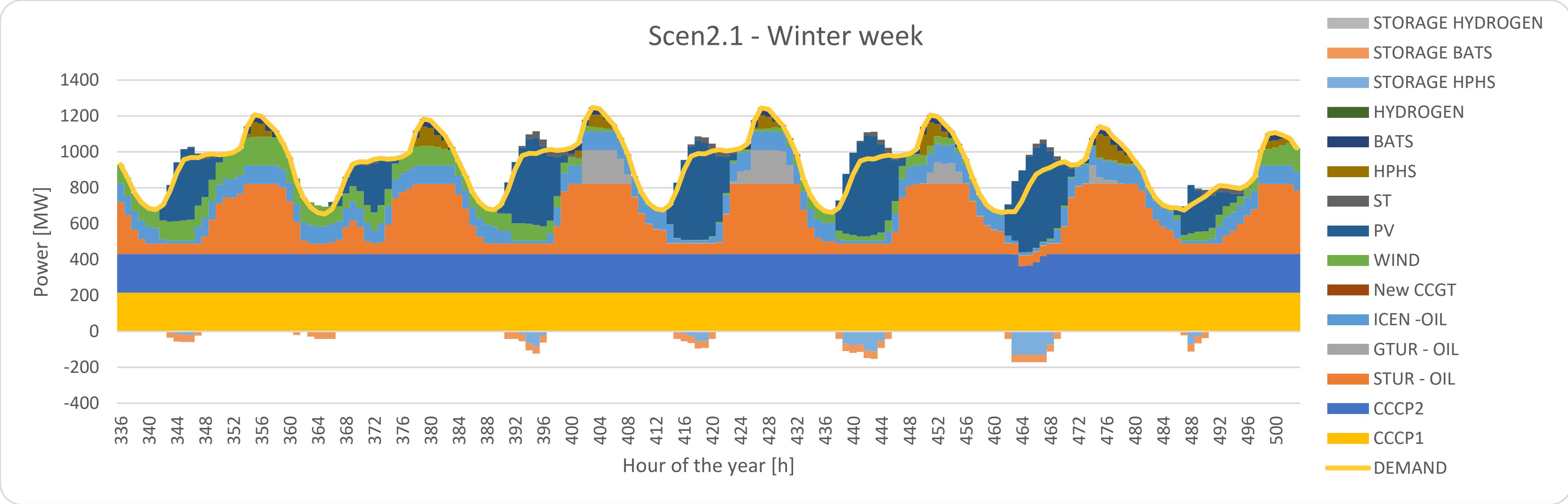
APPENDIX 2

Dispa-SET simulation results graphs – (selection)

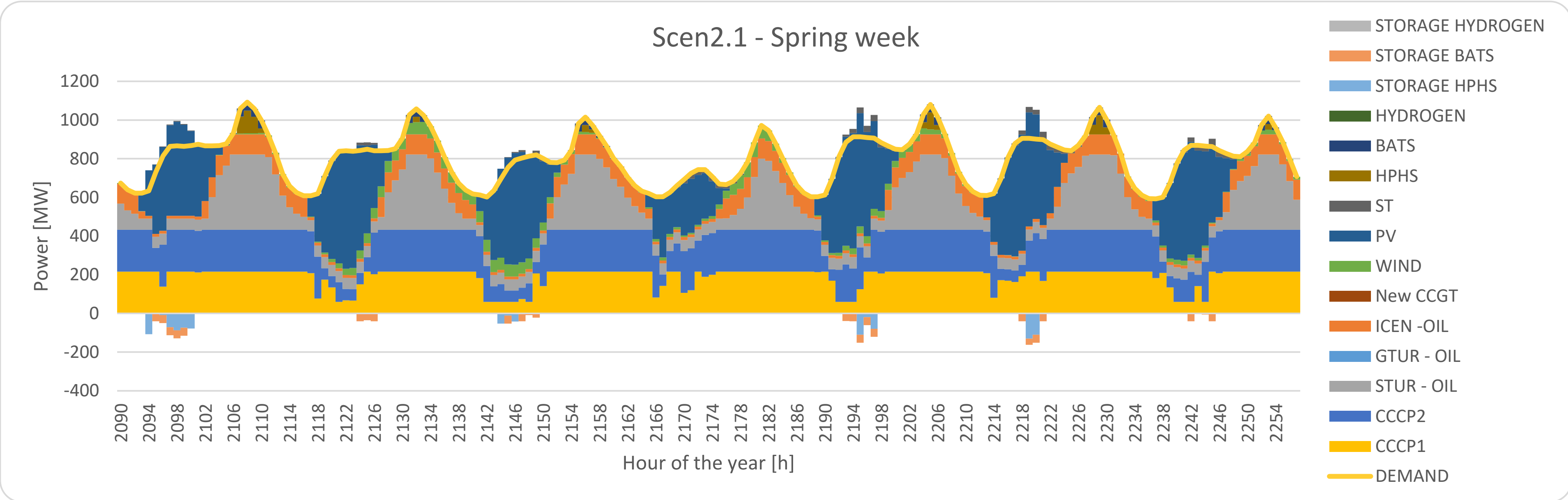
SIMULATION SCENARIOS

Scen2.1

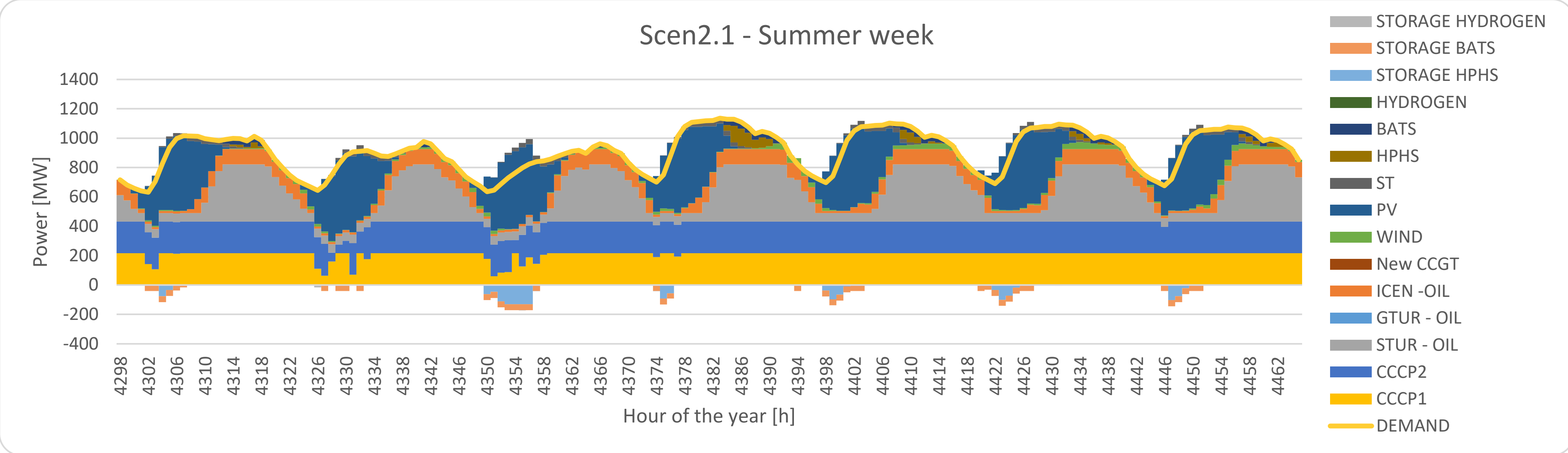
Scen3.

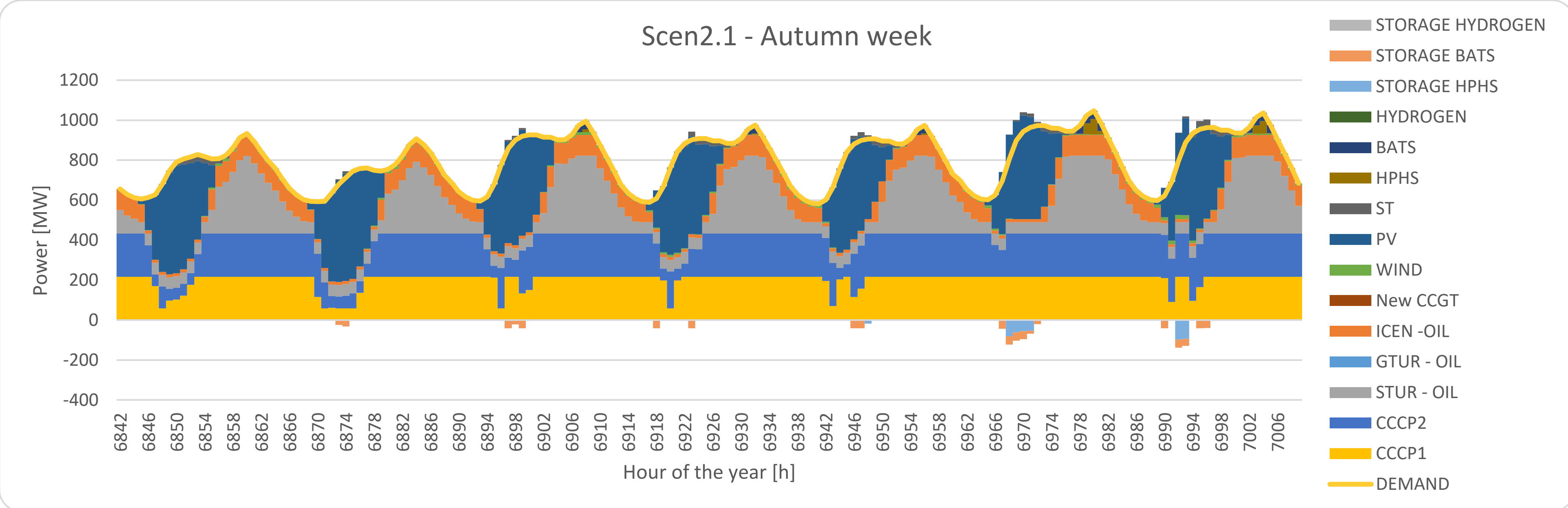


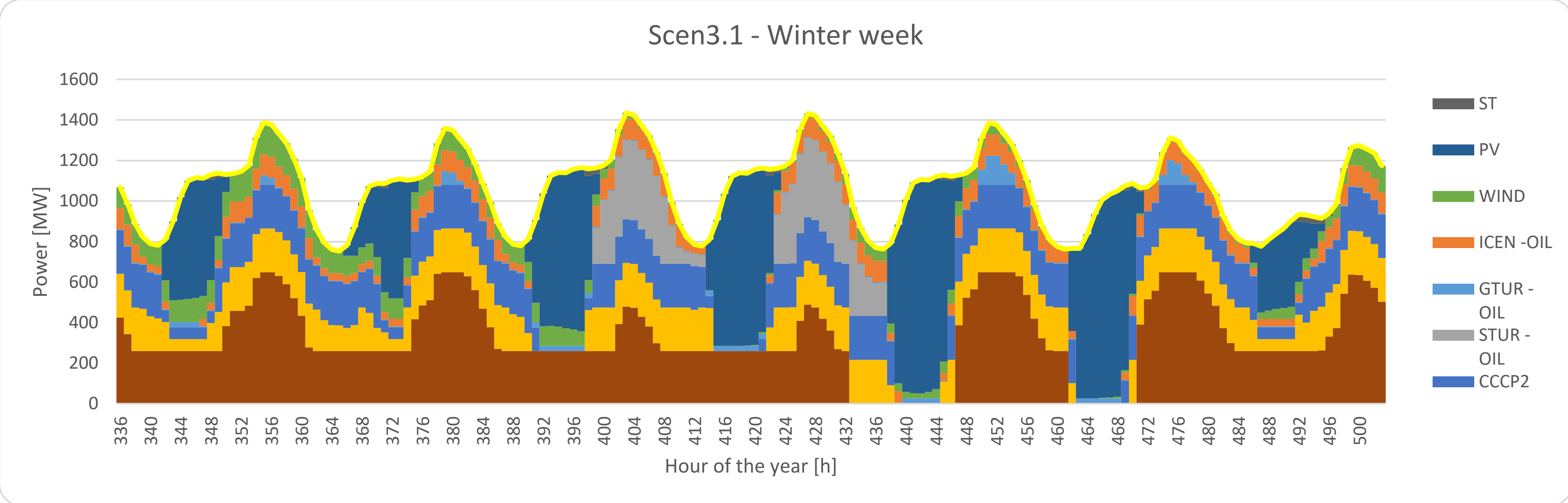
Scen2.1 - Winter week
Power [MW]
1400
1200
1000
800
600
400
200
0
-200
-400
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND

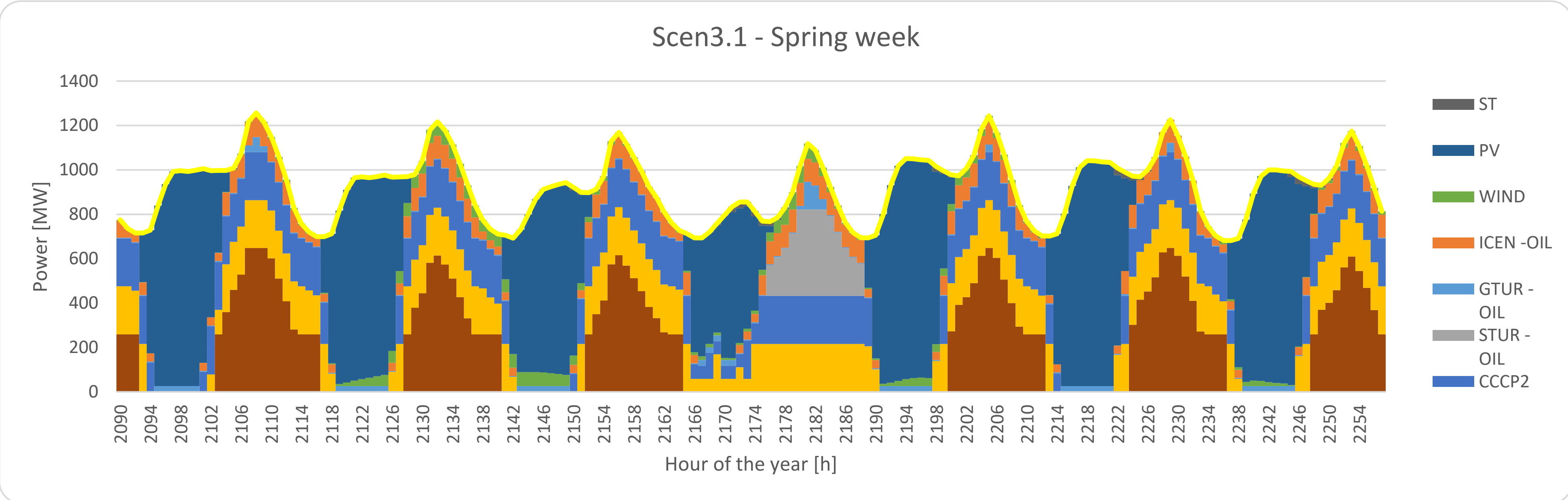


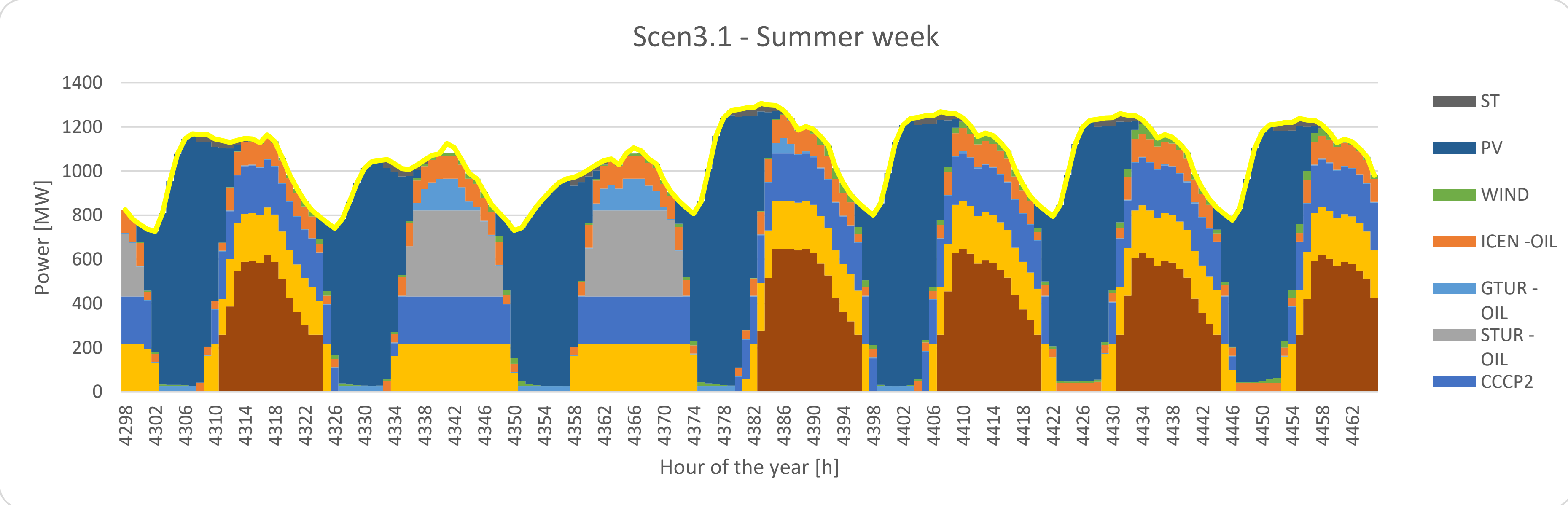
Scen2.1 - Spring week
Power [MW]
1200
1000
800
600
400
200
0
-200
-400
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND


Scen2.1 - Summer week
Power [MW]
1400
1200
1000
800
600
400
200
0
-200
-400
4298
4302
4306
4310
4314
4318
4322
4326
4330
4334
4338
4342
4346
4350
4354
4358
4362
4366
4370
4374
4378
4382
4386
4390
4394
4398
4402
4406
4410
4414
4418
4422
4426
4430
4434
4438
4442
4446
4450
4454
4458
4462
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND

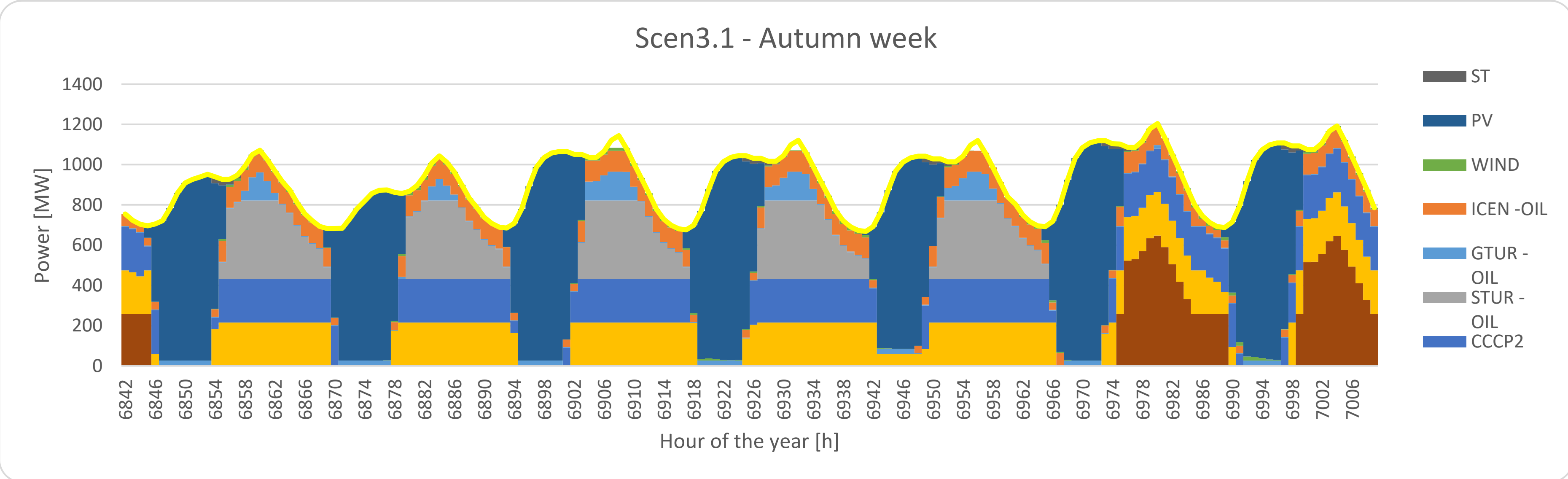

Scen2.1 - Autumn week
Power [MW]
1200
1000
800
600
400
200
0
-200
-400
6842
6846
6850
6854
6858
6862
6866
6870
6874
6878
6882
6886
6890
6894
6898
6902
6906
6910
6914
6918
6922
6926
6930
6934
6938
6942
6946
6950
6954
6958
6962
6966
6970
6974
6978
6982
6986
6990
6994
6998
7002
7006
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND


Scen3.1 - Winter week
Power [MW]
0
200
400
600
800
1000
1200
1400
1600
Hour of the year [h]
336
340
344
348
352
356
360
364
368
372
376
380
384
388
392
396
400
404
408
412
416
420
424
428
432
436
440
444
448
452
456
460
464
468
472
476
480
484
488
492
496
500
ST
PV
WIND
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2


Scen3.1 - Spring week
Power [MW]
0
200
400
600
800
1000
1200
1400
Hour of the year [h]
2090
2094
2098
2102
2106
2110
2114
2118
2122
2126
2130
2134
2138
2142
2146
2150
2154
2158
2162
2166
2170
2174
2178
2182
2186
2190
2194
2198
2202
2206
2210
2214
2218
2222
2226
2230
2234
2238
2242
2246
2250
2254
ST
PV
WIND
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2



Scen3.1 - Summer week
Power [MW]
1400
1200
1000
800
600
400
200
0
Hour of the year [h]
ST
PV
WIND
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2



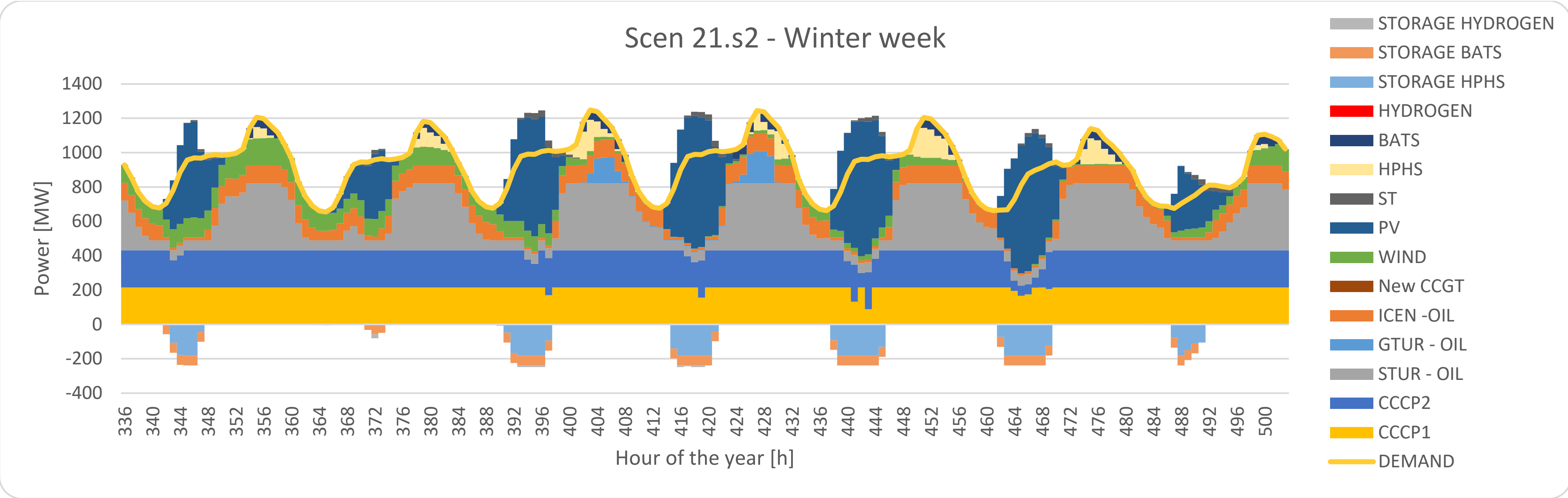
Scen3.1 - Autumn week
Power [MW]
1400
1200
1000
800
600
400
200
0
Hour of the year [h]
ST
PV
WIND
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2

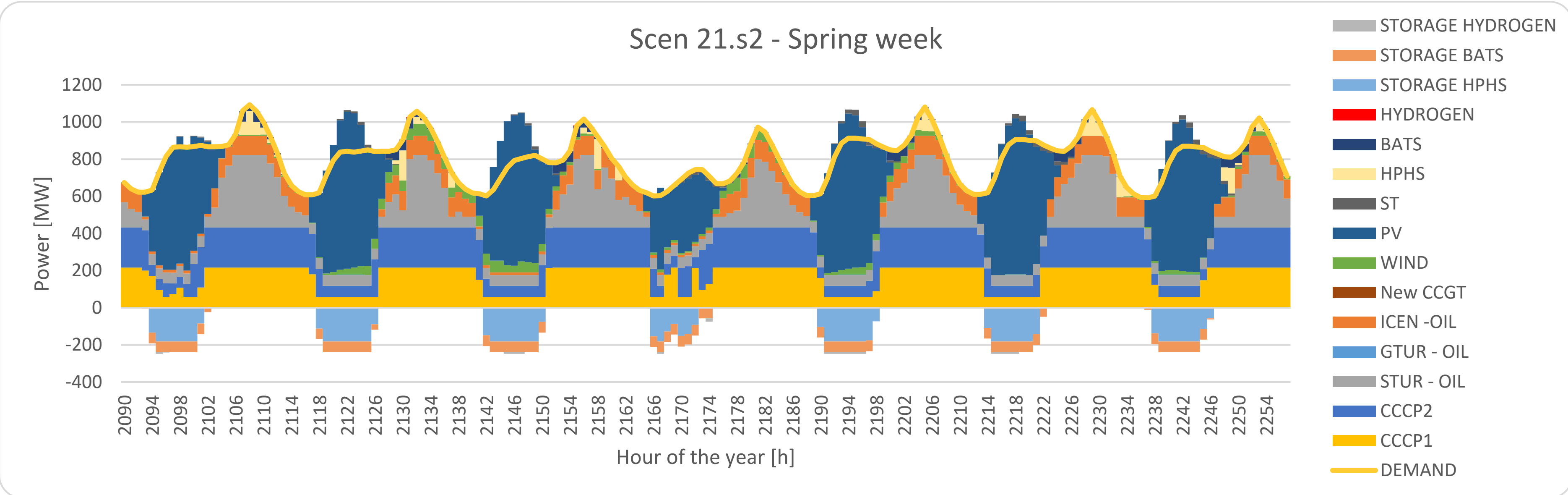
APPENDIX 3

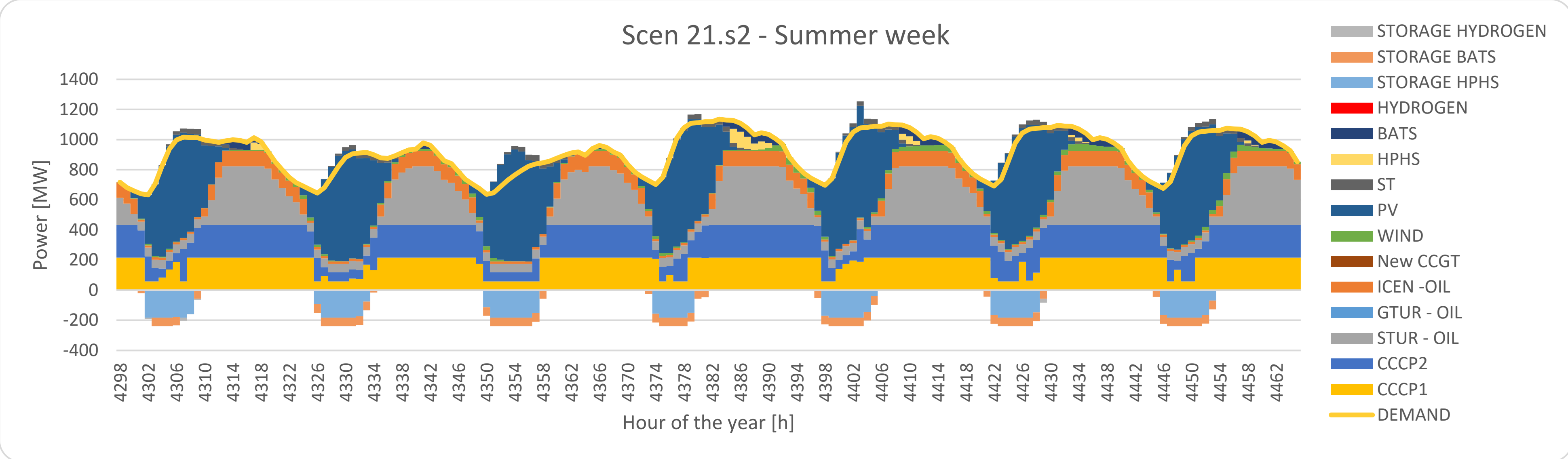
Dispa-SET additional simulation results graphs

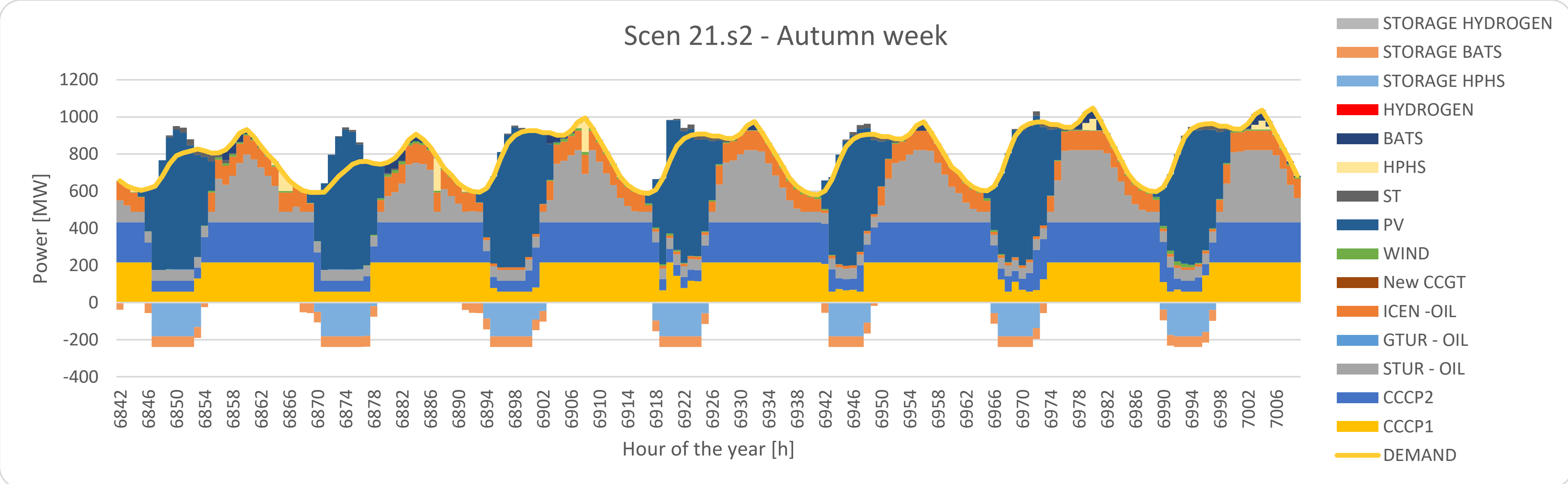
SIMULATION SCENARIOS

Scen2.1s2


Scen 21.s2 - Winter week
Power [MW]
1400
1200
1000
800
600
400
200
0
-200
-400
336 340 344 348 352 356 360 364 368 372 376 380 384 388 392 396 400 404 408 412 416 420 424 428 432 436 440 444 448 452 456 460 464 468 472 476 480 484 488 492 496 500
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND


Scen 21.s2 - Spring week
Power [MW]
1200
1000
800
600
400
200
0
-200
-400
2090 2094 2098 2102 2106 2110 2114 2118 2122 2126 2130 2134 2138 2142 2146 2150 2154 2158 2162 2166 2170 2174 2178 2182 2186 2190 2194 2198 2202 2206 2210 2214 2218 2222 2226 2230 2234 2238 2242 2246 2250 2254
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND


Scen 21.s2 - Summer week
Power [MW]
1400
1200
1000
800
600
400
200
0
-200
-400
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND


Scen 21.s2 - Autumn week
Power [MW]
1200
1000
800
600
400
200
0
-200
-400
Hour of the year [h]
STORAGE HYDROGEN
STORAGE BATS
STORAGE HPHS
HYDROGEN
BATS
HPHS
ST
PV
WIND
New CCGT
ICEN -OIL
GTUR - OIL
STUR - OIL
CCCP2
CCCP1
DEMAND