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NEOM

NEOM GRID OF Future

High-level introduction

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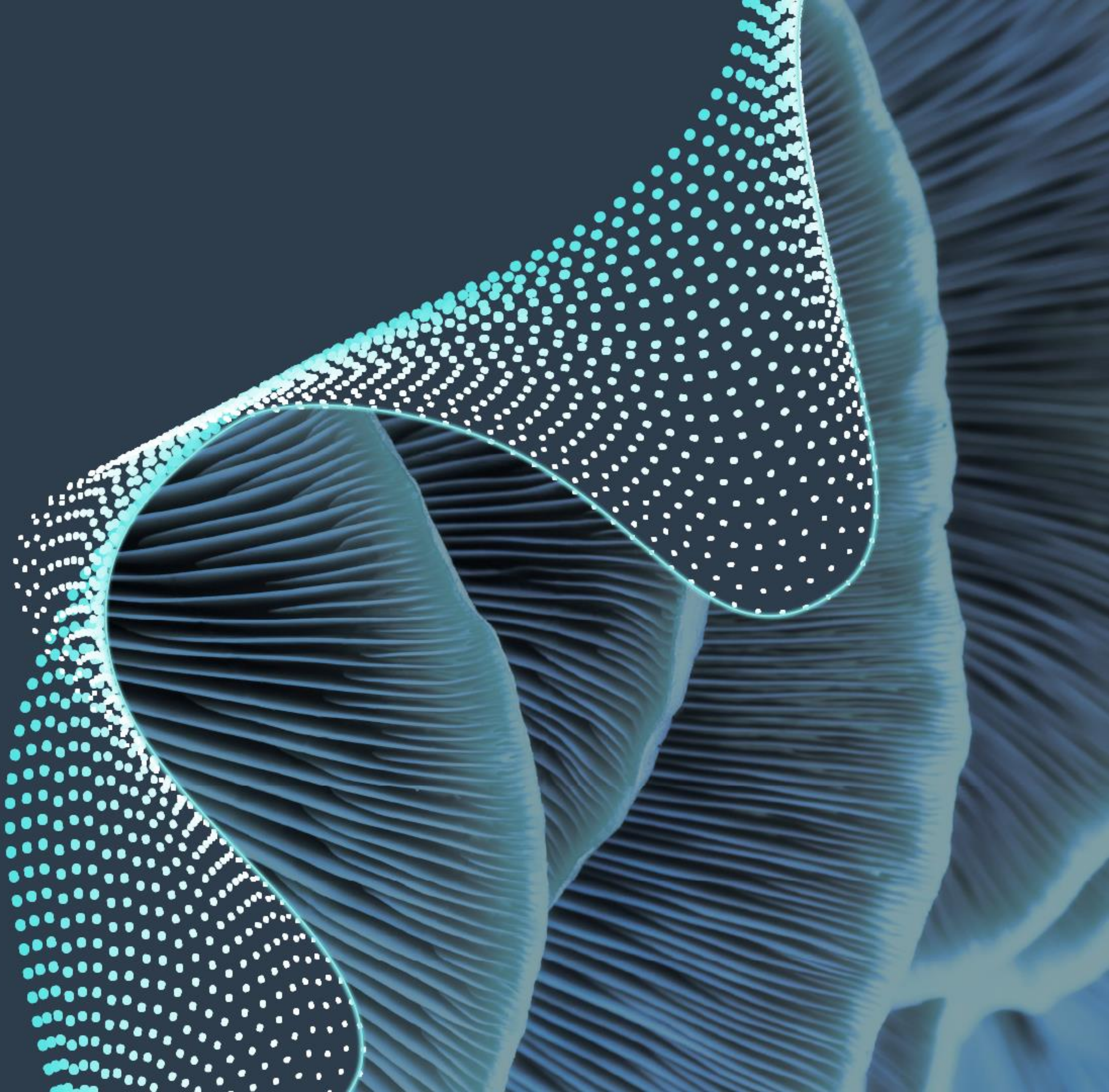
June12, 2024, The HVDC National Centre, Cumbernauld



NEOM Background and Evolution of Grid Development

Background

- ✓ Planned free economic zone, with area of 26,500 km², in the Northwest of Kingdom of Saudi Arabia (KSA) .
- ✓ A centerpiece of KSA 2030 vision:
  - o Sustainable economic growth and broader base.
  - o Hub for advanced manufacturing and green technologies, magnet for global talent, etc.
- ✓ Target population:
  - o 2045: 3 Million.
  - o 2055: 9 Million.

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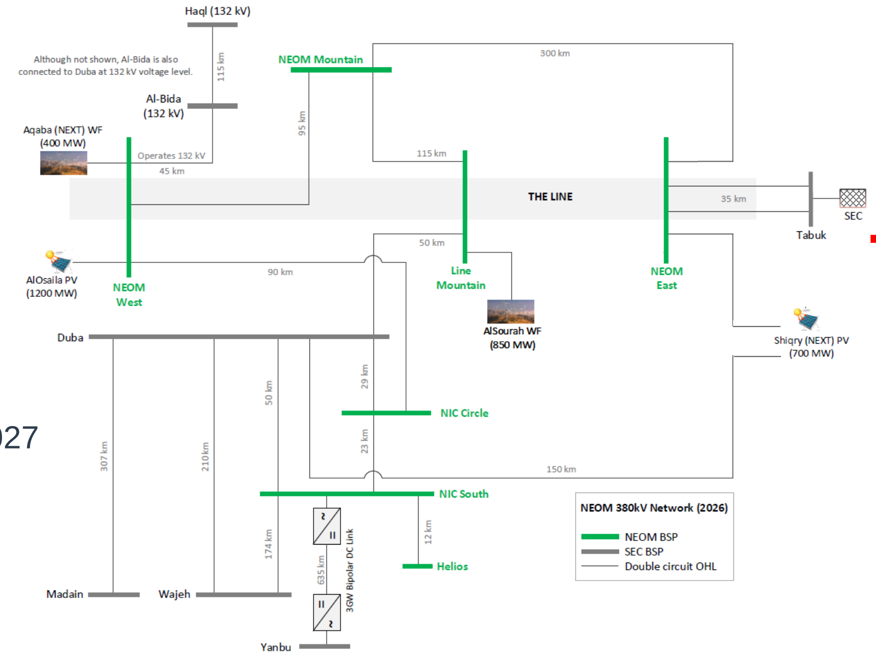
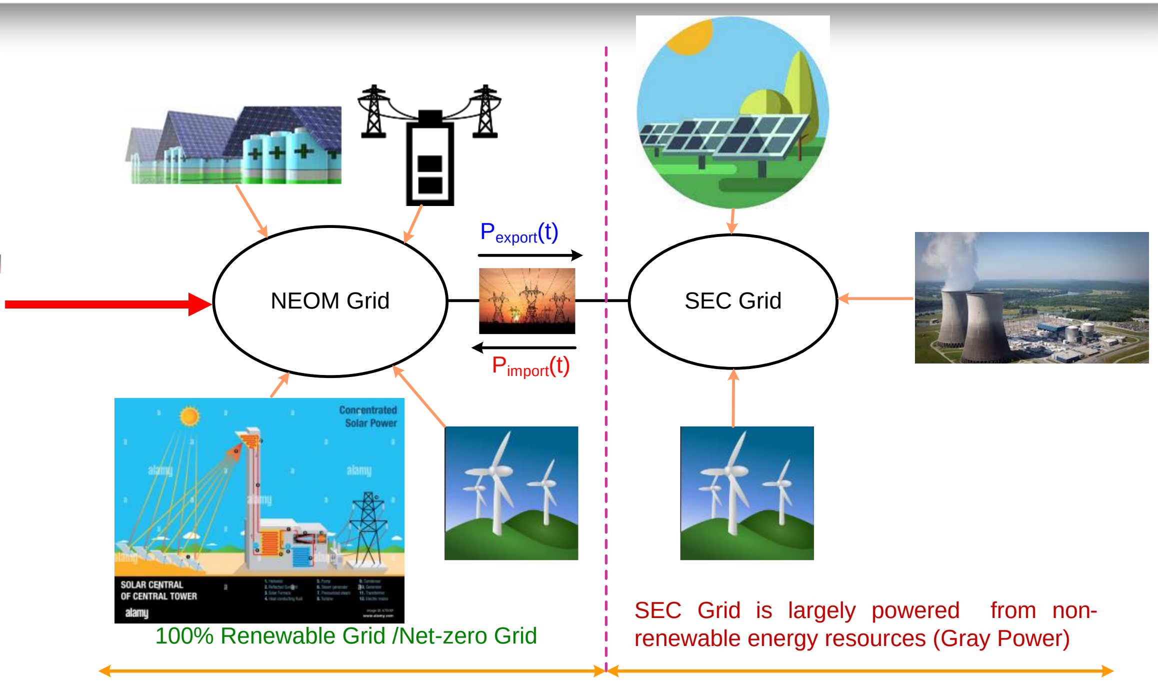
NEOM Grid Development Plan

NEOM Grid 2027





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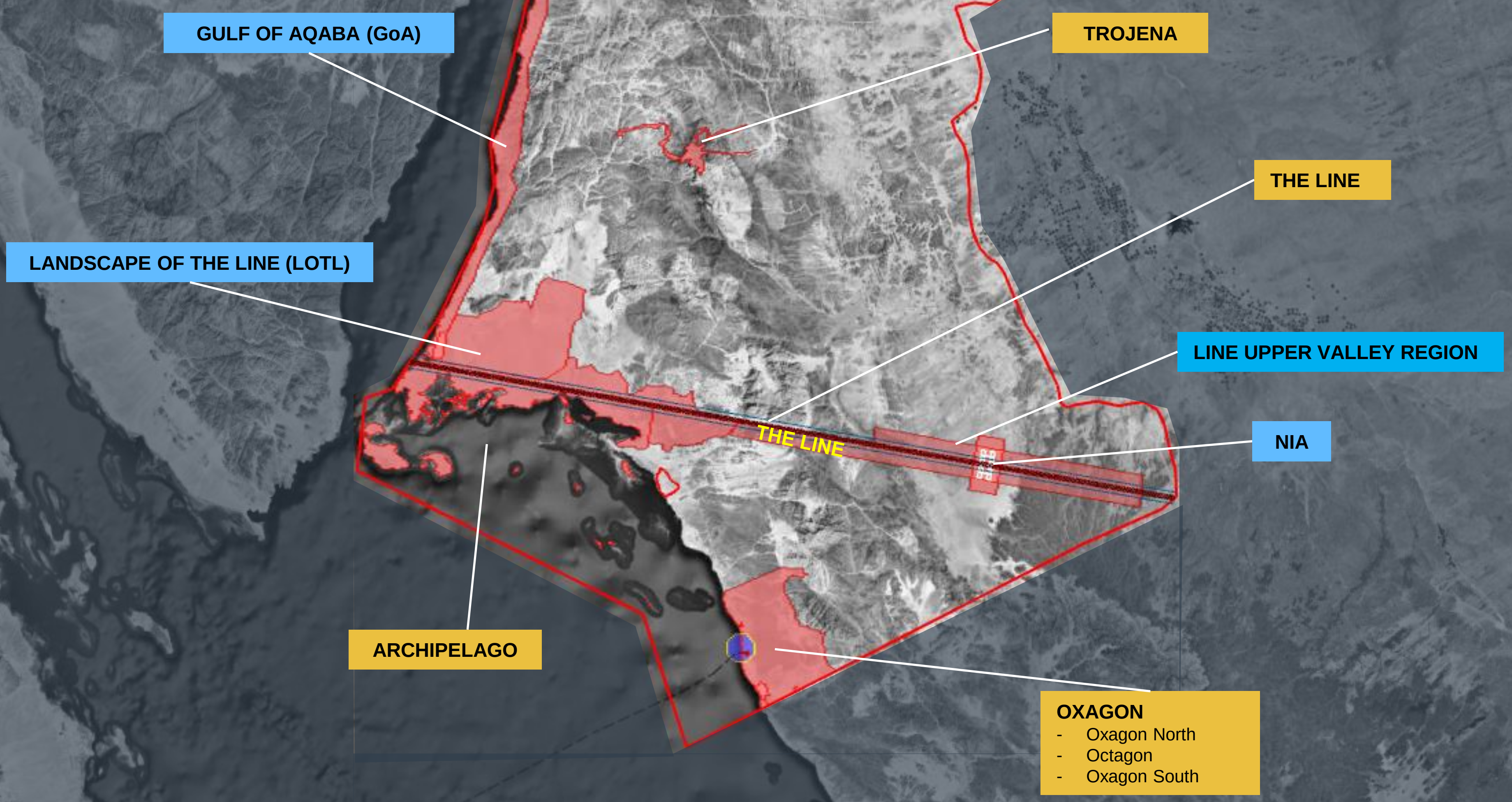
NEOM Major Demand Centres

Projected Demand Growth (NEOM)

2026 → ~ 2.4 GW
2028 → ~ 7.0 GW
2030 → ~ 9.0 GW
2045 → ~ 19 GW
2055 → ~ 35 GW



Under Construction

On Plan

NEOM Grid of the Future~2030 Onward

NEOM Grid Design Studies:

Competitive Between Four Participants (3 OEMs and 1 Consultant):

- Siemens AG
- Siemens Energy
- Hitachi Energy
- FICHTNER (ENOWA owner's engineer from Oct. 2020~July 2023)

Objective:

To develop a pool of cost-effective and technically sound grid designs, fit for 100% renewable powered grid, based on integrated design approach (all simultaneously):

- Generation and energy storage mix and interconnection capacity.
  - 100% renewable operation
  - NetZero operation
- Grid Topology
- Concept for fully autonomous power control center

Major challenges:

- Uncertainties :
  - Generation locations and development order and projected peak demand keep changing.
  - Target endgame grid design must be fit for fully underground cable (grid with up to 40% of overhead lines is also investigated).
- Optimality of grid performance and utilization must not change over the full development horizon (2030, 2045 and 2055).

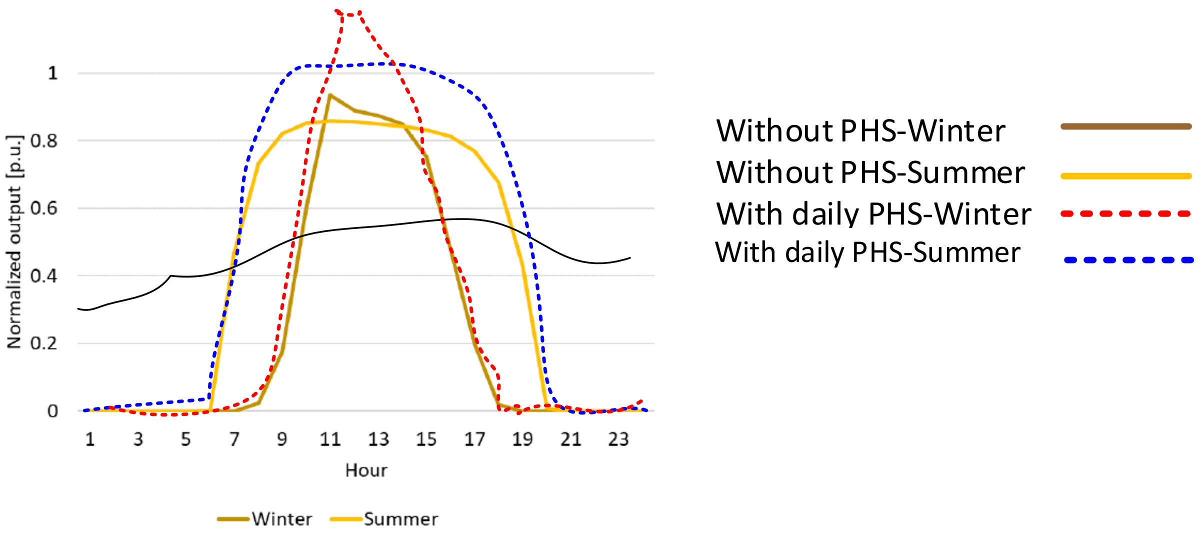
Generation Mix

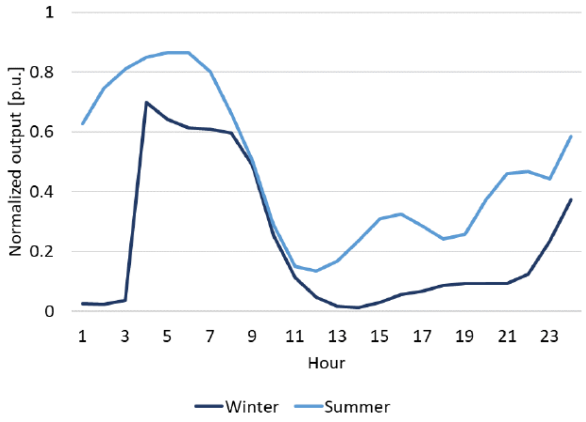
- Solar ≈ 85%
- Wind ≈ 15%

- Low cost makes solar PV the dominant generation, hence:
  - Exacerbates storage challenges.
  - Results in weak converter dominated grid with virtually zero inertia:
    - ✓ Fast dynamics (challenging to control and protect)
    - ✓ Hosting of large generations or loads will be extremely challenging.

- Concentration of generation in small area:
  - Risks blackout as a single fault may split generation from load centers.
  - Exacerbates various stability challenges, for example, control interactions between co-located PV farms.

- Daily PHS may increase peak generation; thus, calls for clear energy storage strategy:
  - Demand and supply management (daily and Seasonal energy shift and sun following loads)
  - Riding through multiple days of sandstorms (CSP+TES, H_2, interconnection)





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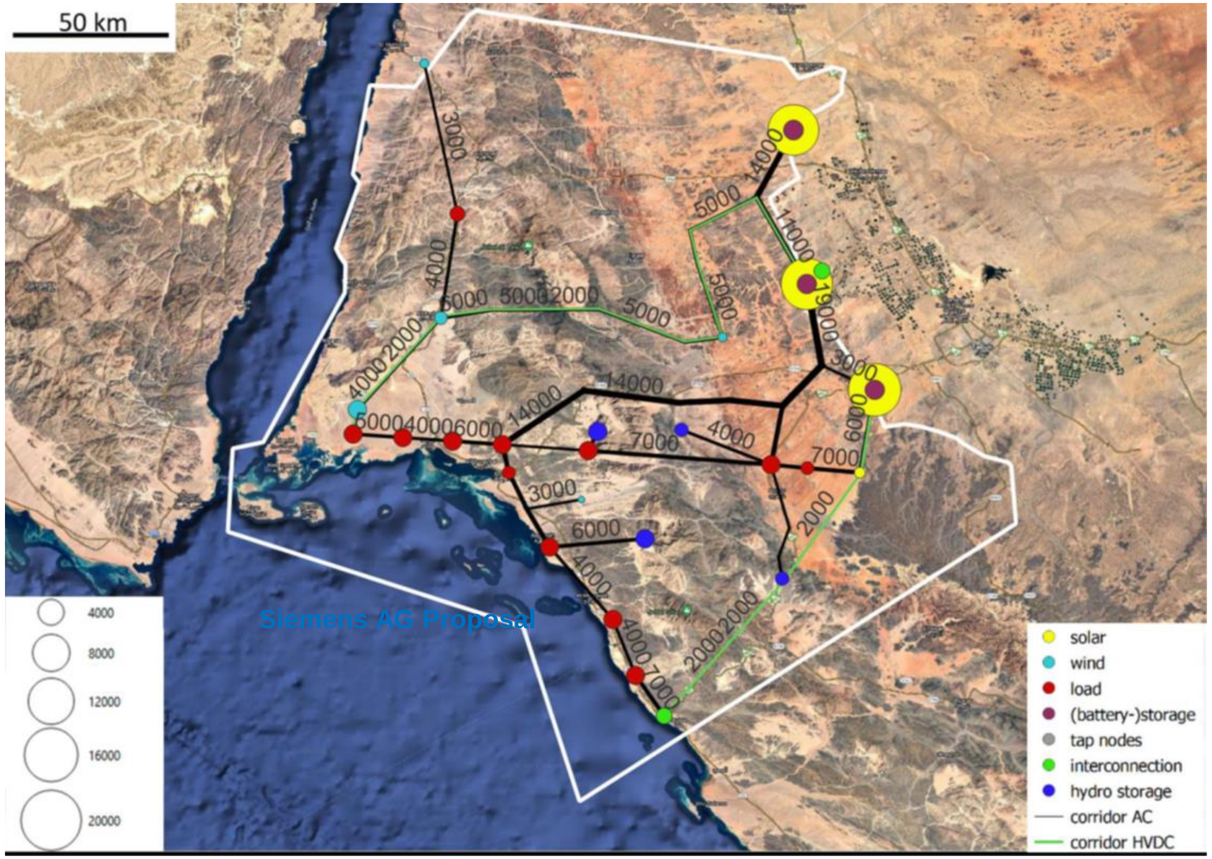
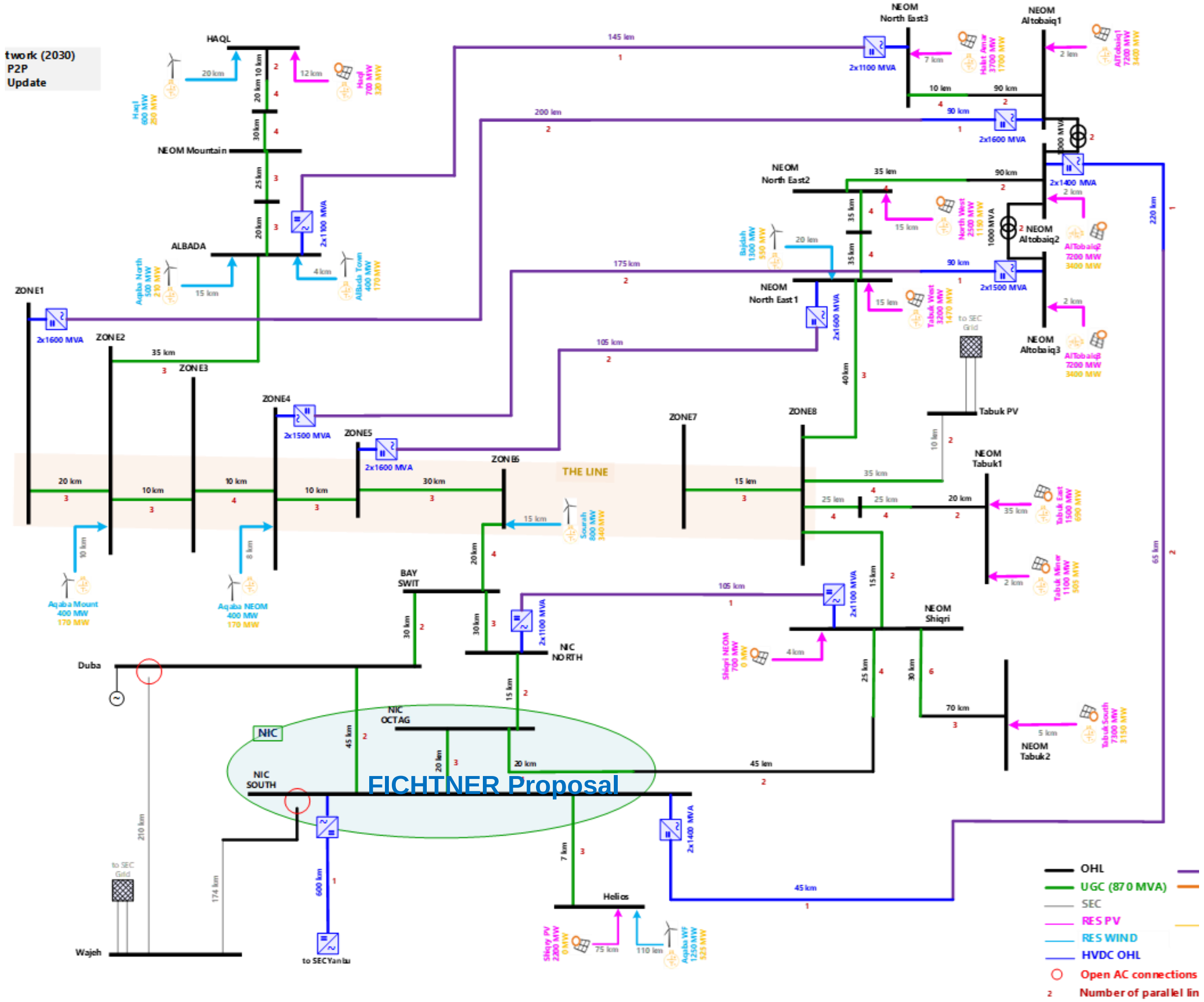
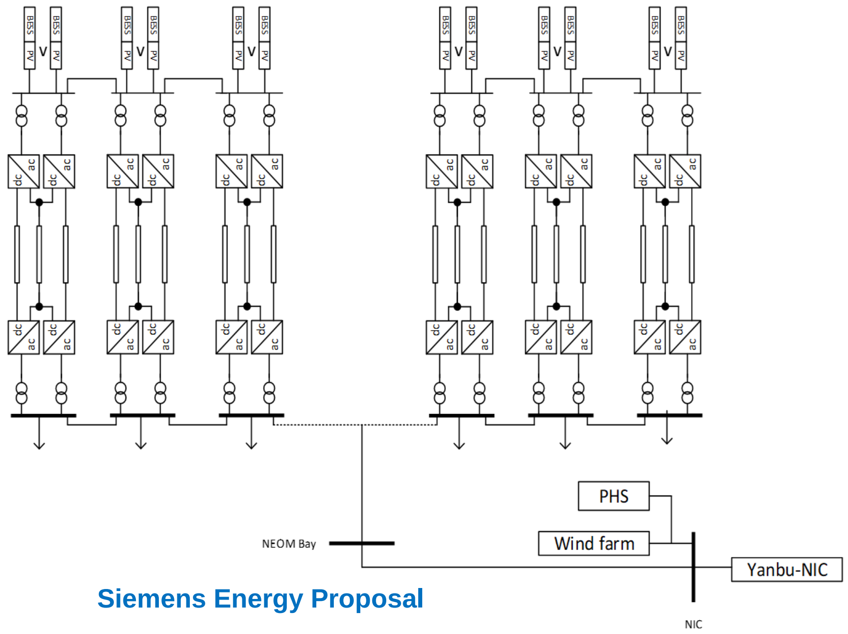
Proposed Grid Topologies

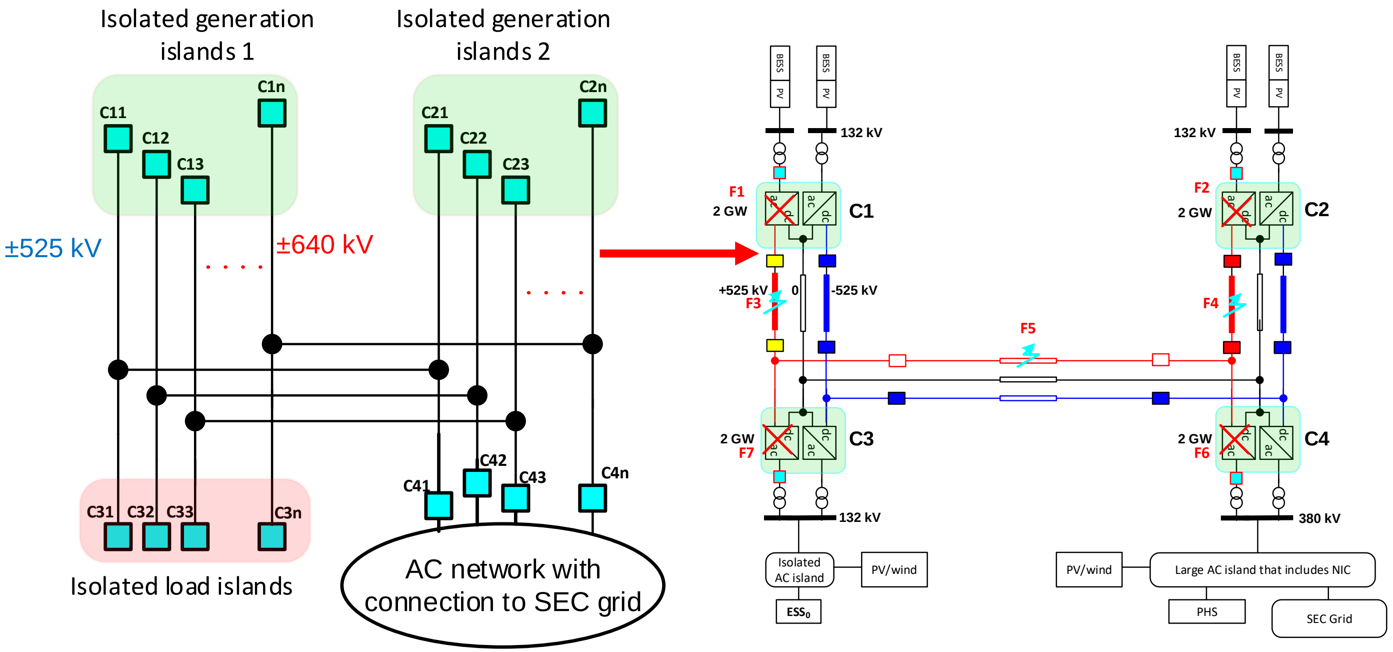




Continuation of the proposed grid topologies



Siemens Energy Proposal



Hitachi Energy Proposal (adopted as a concept for the NEOM Grid of the Future)

Key features of the Hitachi Proposal:

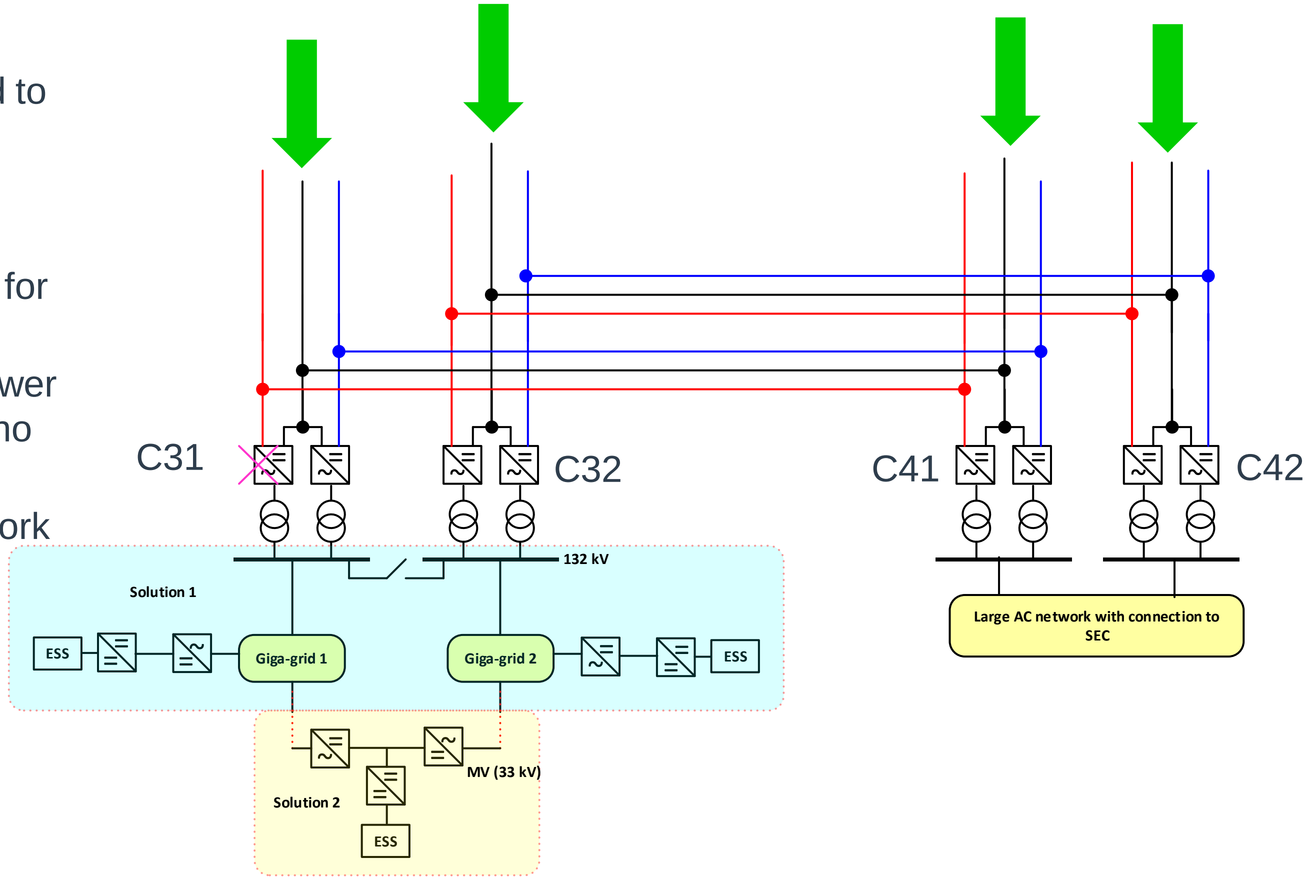
- Highly modular and with endless scalability with small step of 1 GW and 360^o flexibility for generation connections (key ingredients against over-investments and uncertainties in load estimates, generations, etc).
- All features in 2030 are retained in 2045 and 2055.
- Permits adoption of future technologies and innovations, for example, higher rated DC cables, converters, etc.
- Potential elimination of 380 kV (380/132 kV BSP) will lead to cost and footprint savings, and fast deployment of n-SF6 free GIS and GIB.
- Addresses most of the stability issues and risks of blackout highlighted earlier, **with the NIC ac network is playing critical role for sharing of generations and reserves to compensate for the deficit or surplus in any of the load island**.
- Can facilitates both 100% and NetZero operations, with synchronous or asynchronous connections to SEC grid.
- Isolated load islands are secured against converter fault through rapid network reconfigurations to facilitate exchange power between neighboring load islands.

Resiliency

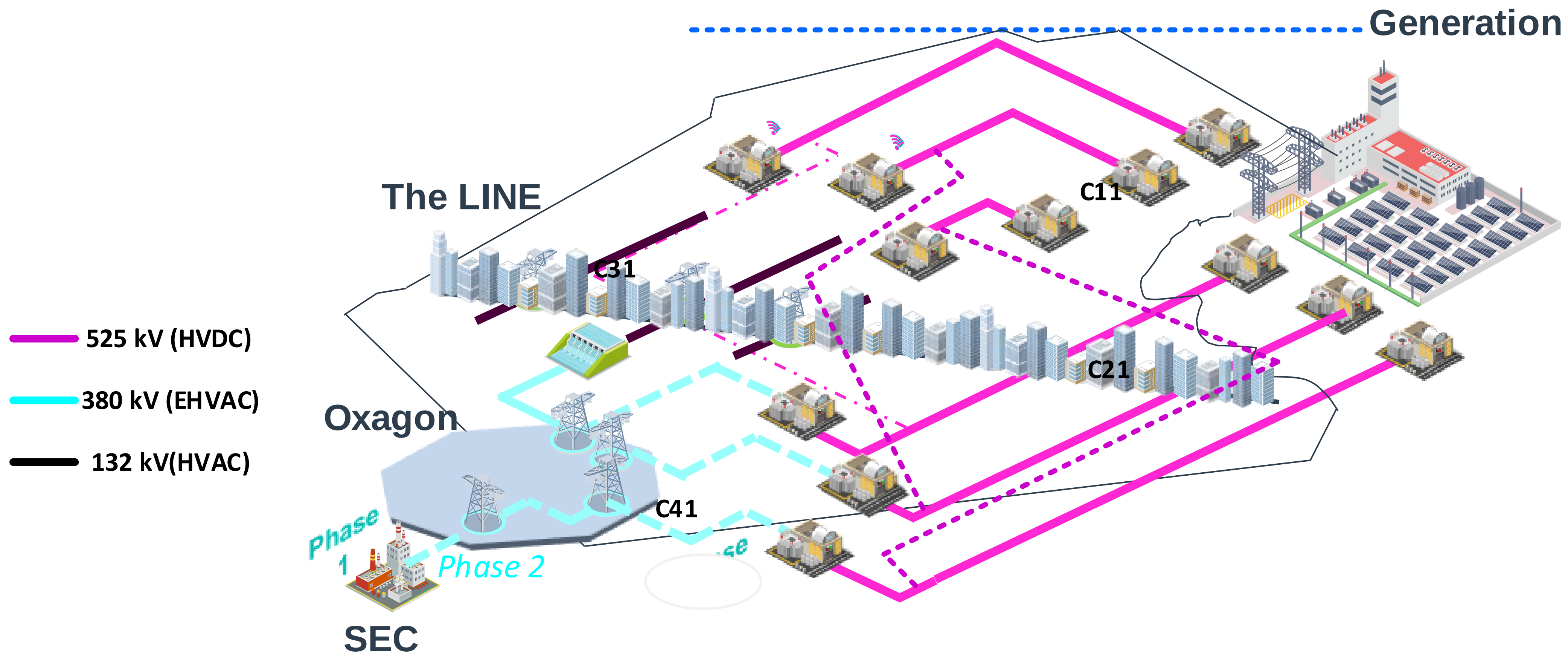
Worst-case N-1 Contingencies

F7 (equivalent to N-1)

- ✓ **Impact**:
  - ○ Maximum loss of 1 GW in the isolated giga grid connected to C3.
- ✓ **Measure**: Possible solutions:
  - ○ **Solution 1**: Parallel operation of C31 and C32 at 132 kV level to minimize or compensate for the deficit (few cycles needed for network reconfiguration).
  - ○ **Solution 2**: Linking C31 and C32 at MV via B2B to enable power exchange without compromising decoupling of the giga-grid (no interruption).
  - ○ **Solution 3**: Temporary linking C31 to nearby 132 kV AC network (new few cycles and C31 decoupling is compromised)

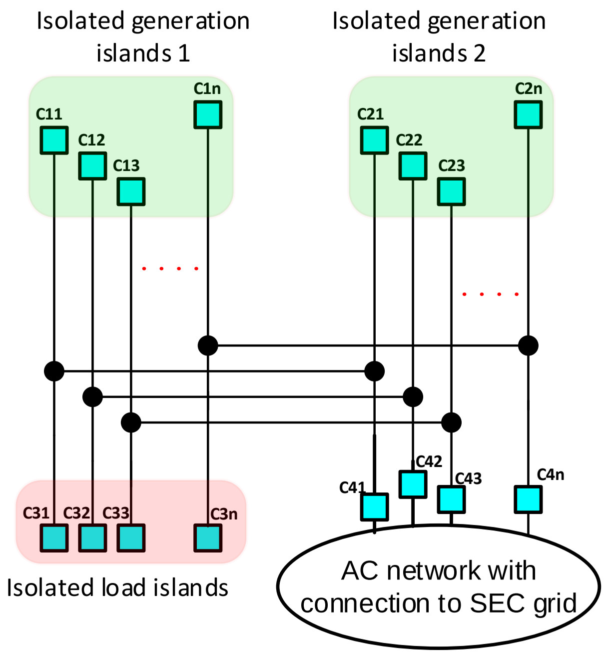


High-level Depiction of NEOM of the Future



Summary of Potentials and Opportunities

1) In today SG dominated grids, active power imbalance $\Delta P = P_m - P_e$ is linked frequency f by swing equation $\frac{2H_{SG}}{\omega_0} \times \frac{d\omega}{dt} = P_m - P_e$; where H_{SG}=3 s~5 s.
2) In a 100% or converter dominated grids, equivalent swing equation is $\frac{2H_{VSC}}{V_{dco}} \times \frac{dv_{dc}}{dt} = P_{dc} - P_{ac}$, which shows the active power mismatch $\Delta P = P_{dc} - P_{ac}$ is not linked to frequency; where H_{VSC}=30 ms~40 ms.
3) However, retaining a weaker relationship between ΔP and f, with tight control over Δf is beneficial, for active power sharing:
   - When multiple islanded giga-grids operate in parallel operation (contingencies).
   - Within each giga-grid, using f as a global variable
4) Artificial link active power and frequency is useful for participation in frequency regulation of greater NIC network which has synchronous connection SEC grid.
5) Unlike SG, VSC controls positive and negative sequences, and to some extent zero sequence, this opens a new paradigm, in which grid characteristics in the giga-grids could be shaped favorably:
   - Magnitude and rate-of-rise of fault currents and over-voltages in healthy phases during asymmetrical faults may be controllable; therefore, it is possible reduce cost (circuit breakers with low current breaking capacity, equipment insulation withstand, , etc).
   - If active power mismatch is decoupled from frequency as stated in 2), inertia is no longer needed in the isolated grids.
6) Limitless possibilities afforded by the power electronics and absence of physical relationships also present significant challenges, for example, in the NIC network, where multiple VSCs will be co-located.



Thanks