A Hybrid Evolutionary Algorithm Framework for Optimising Power Take Off and Placements of Wave Energy Converters

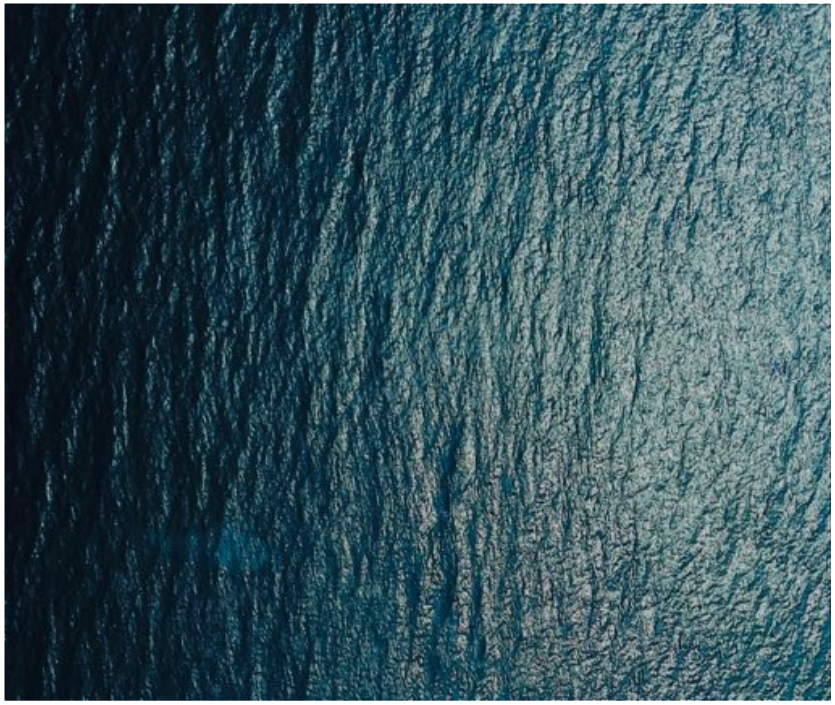
Mehdi Neshat, Bradley Alexander, Nataliia Sergiienko, Markus Wagner

Problem Definition

- Goal is to <u>place</u> and <u>tune</u> wave energy converters:

Problem Definition

- ...in a constrained area of sea:



Problem Definition

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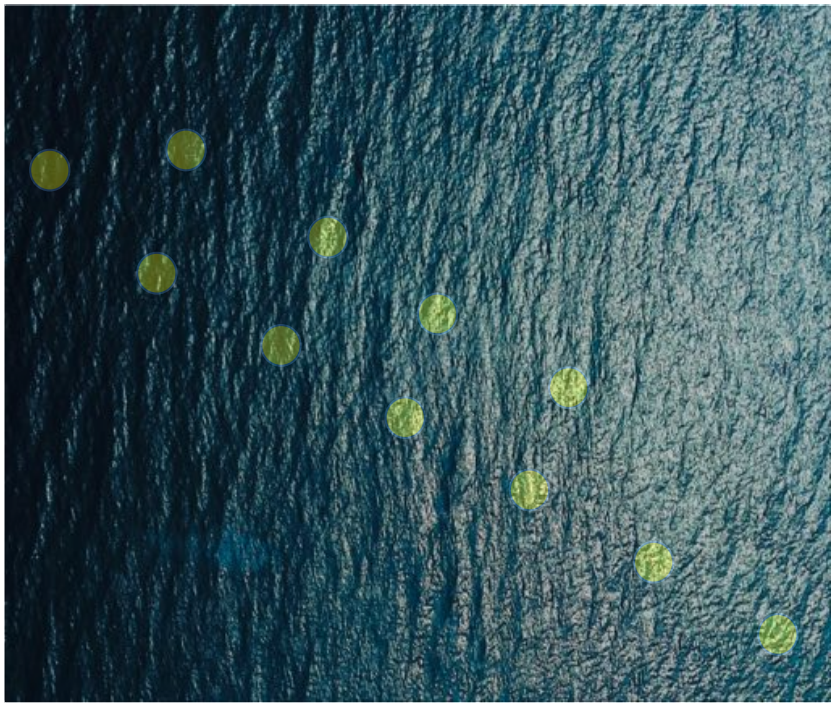

Problem Definition

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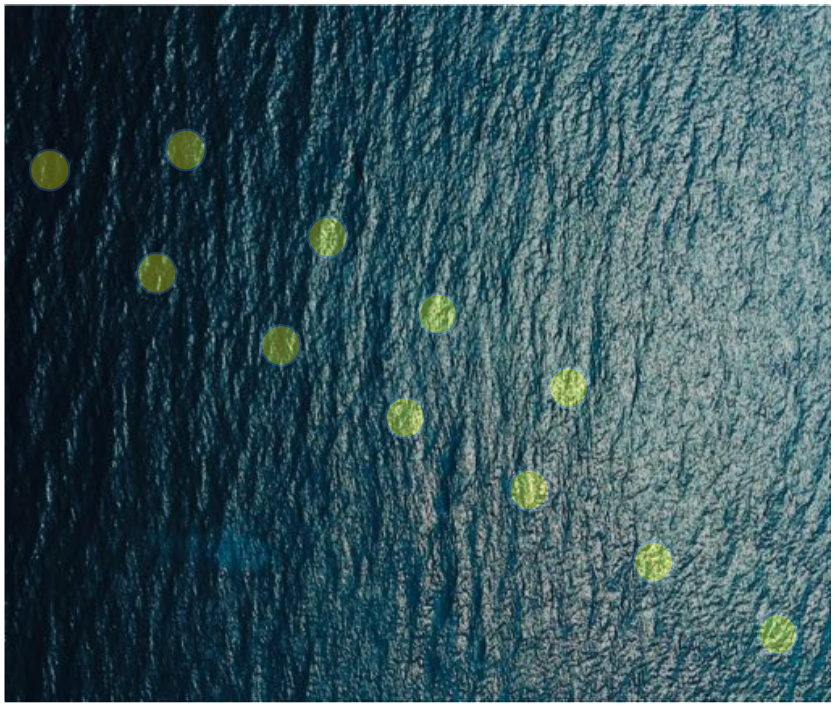


- and tune each to maximise average energy output

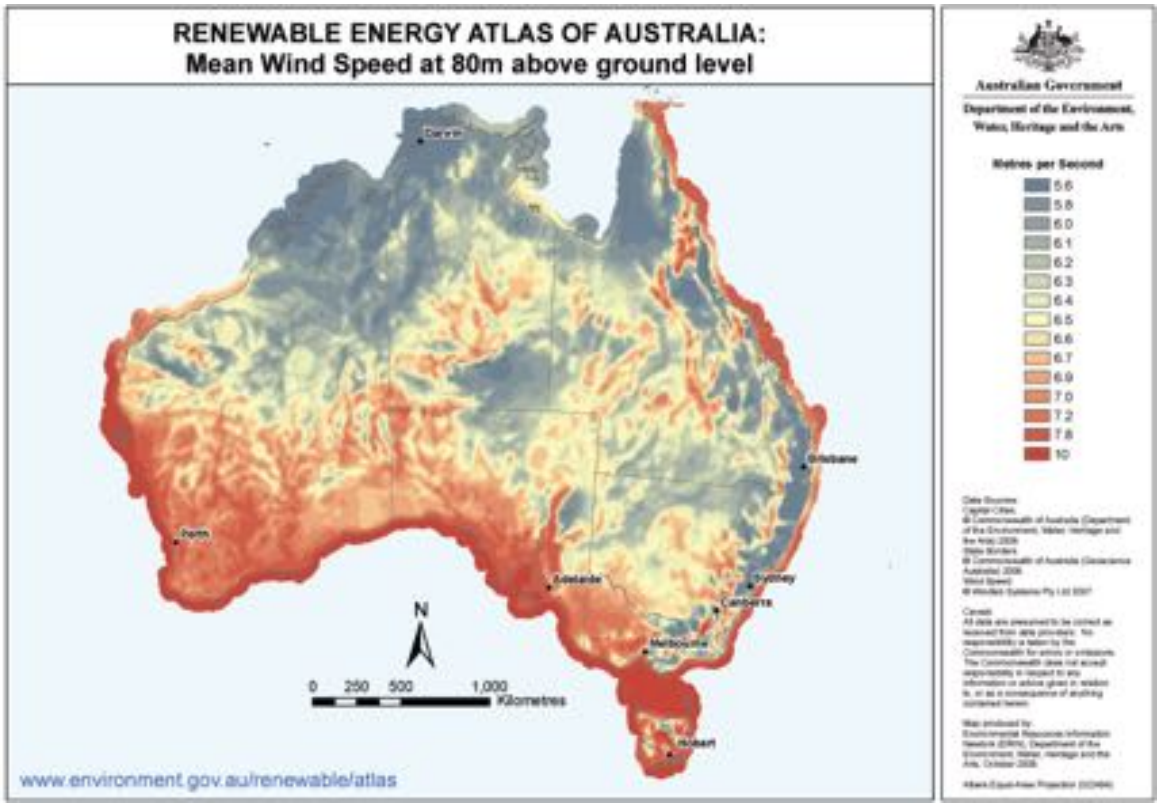
Wave energy complements wind and solar

- Wind and solar are now the cheapest form of new-build power generation.
  - Solar contracts ~US 2c/kWh
    - (Saudi Arabia – 1.79c kWh (the national Abu Dhabi – Jan 2018)).
  - Average wind price ~US 2c/kWh
    - (https://emp.lbl.gov/sites/default/files/2017_wind_technologies_market_report.pdf)

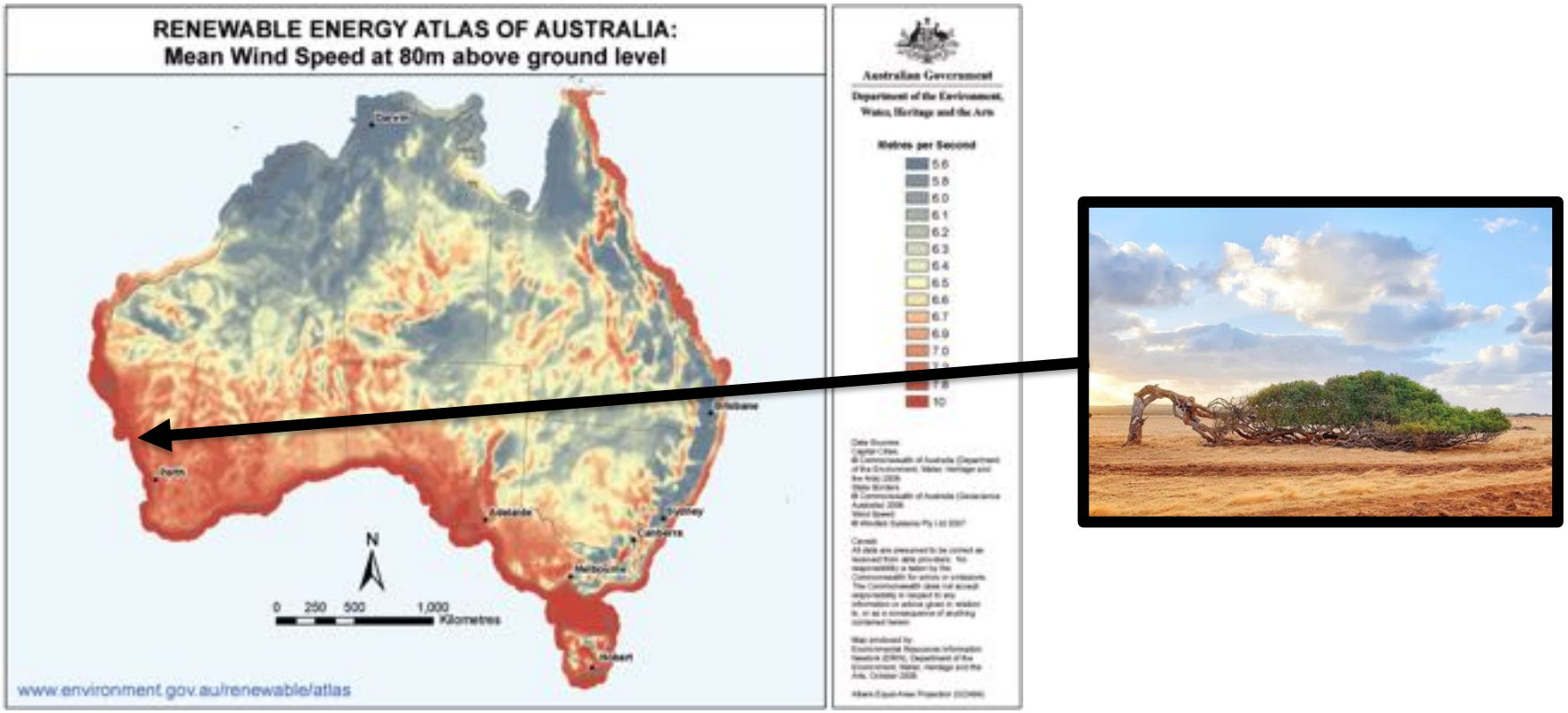
...and are growing fast...

- Growing level of investment
  - Global investment totalled US $332.1 billion in 2018
    - (source BloombergNEF, Jan 2019)

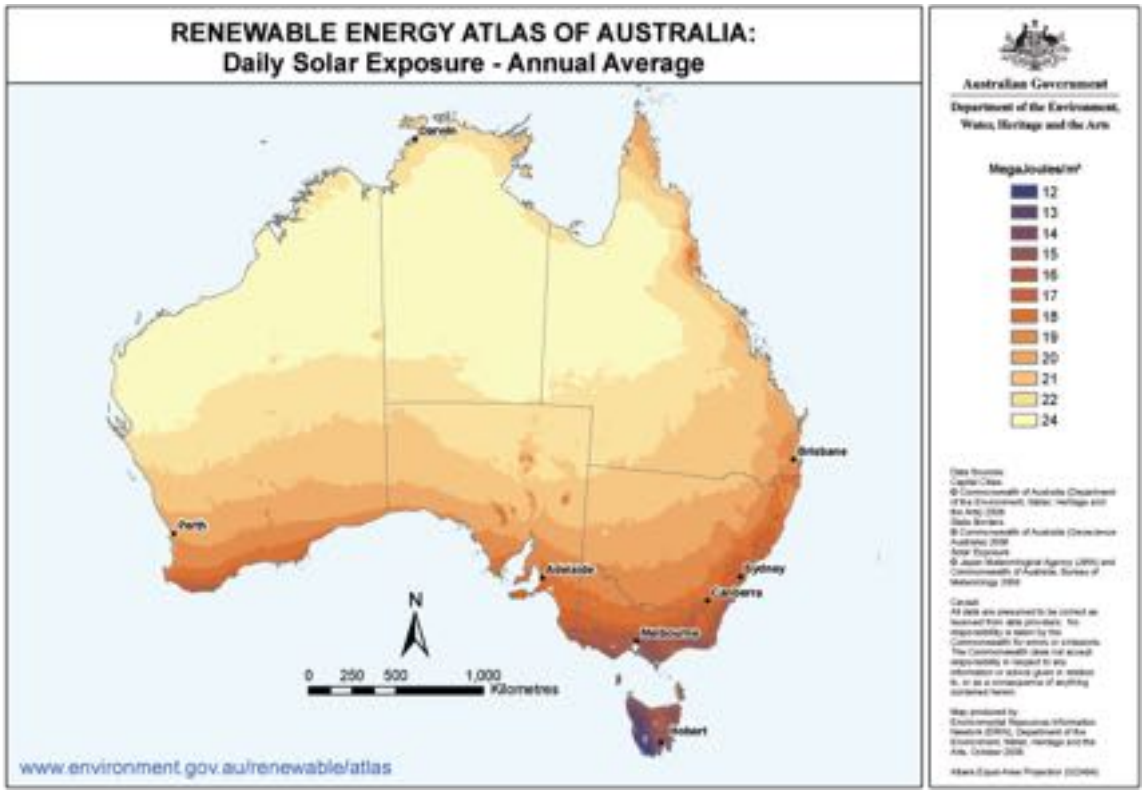
Wind energy is abundant



Wind energy is abundant

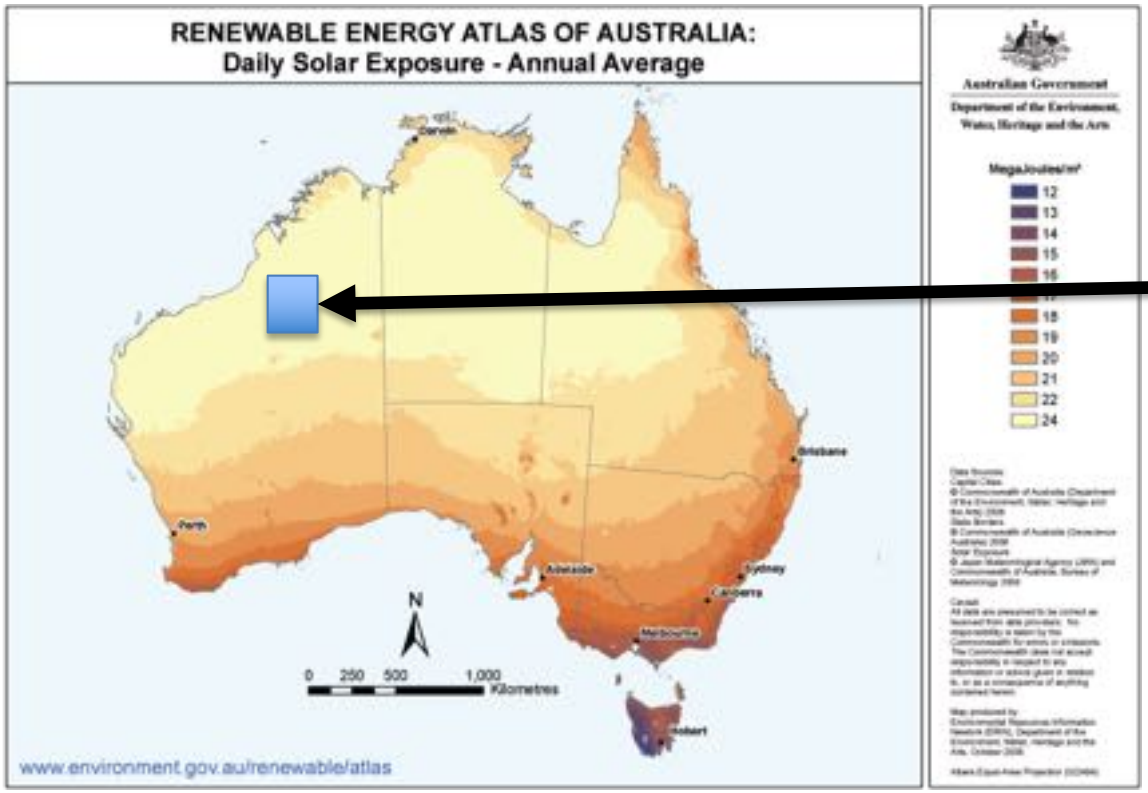


Solar energy is abundant



Solar energy is abundant

- Solar



A farm this big would match world energy demand

But – Wind and Solar are Intermittent

- South Australian generation– end of June 2019

Source: Open-NEM

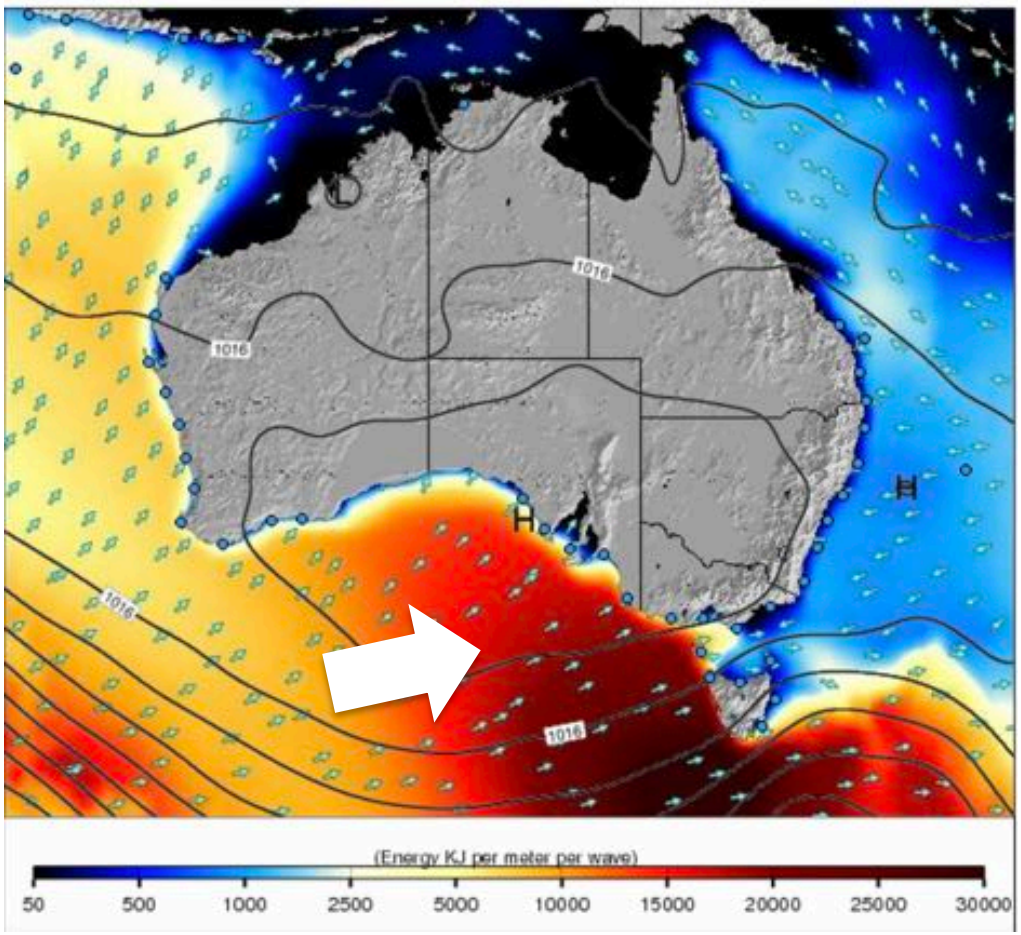
But – Wind and Solar are Intermittent

- South Australia electricity market – end of June 2019

But Wave Energy was Still Good!

- Waves persist long after winds have passed.

02 July ’19
(same time as red box on previous chart!)



source: surf-forecast.com

Advantages of Wave Energy

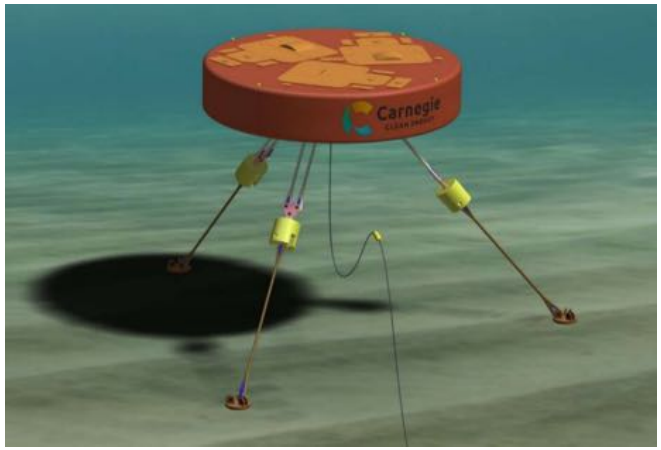
- Out of sync with sun and wind.
- High energy densities – up to 60kw per m^2
- High capacity factors – predicted to get to 50%

Our Contributions

- First optimisation of both buoy parameters and positions.
  - High fidelity models.
  - Variety of algorithms tested – some new.
  - New algorithms outperform best-published.
  - Explored four different real wave scenarios.

Wave Buoys

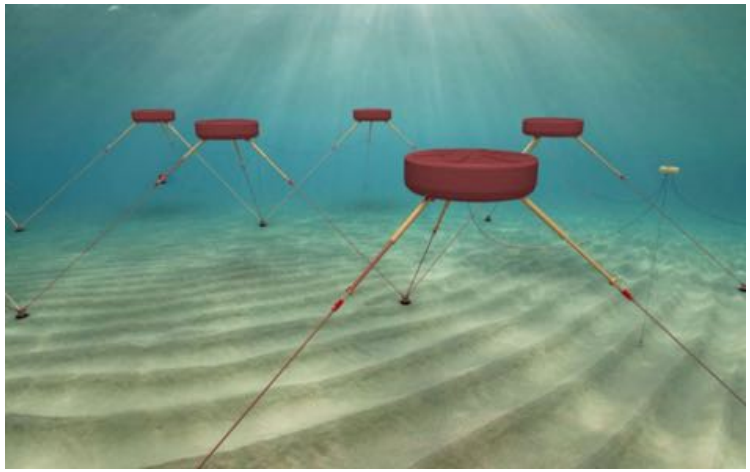
- One of the most efficient designs for extracting wave energy are three-tether wave buoys.
- These are submerged and extract energy from heave, pitch and surge motions.
- We model the CETO 6 wave-energy-converter (WEC)



Carnegie Wave Energy

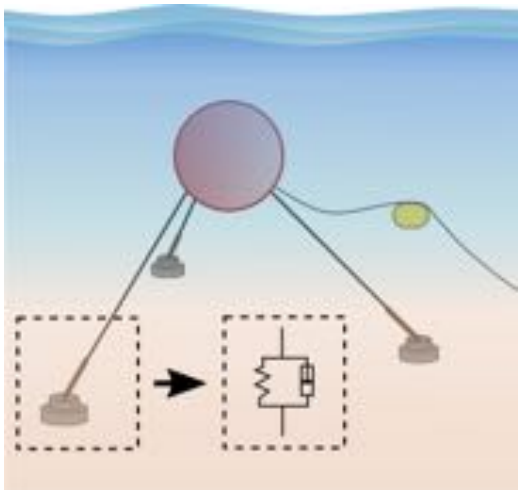
Wave Farms

- WECs can reinforce each other through wave interactions.
- This means we can extract more energy per-buoy if WECs are carefully laid out in farms.



Power-Take-Off Settings

- Each buoy has Power-Take-Off (PTO) units for converting mechanical energy to electricity.
- Can be modelled as springs
- Two tunable parameters
  - d_{PTO}: damping rate – controls how fast oscillations are damped down – controls amplitude.
  - k_{PTO}: stiffness – controls oscillation frequency.
- We optimise these for <u>each</u> buoy.



Problem Formulation

- We want to maximise power output for N-buoys by placing them in X,Y locations in a farm with PTO settings of D_{PTO} and K_{PTO} for each buoy.

$$P_{\Sigma}^{*} = argmax_{X,\,Y,\,K_{pto},\,D_{pto}} P_{\Sigma}(X,\,Y,\,K_{pto},\,D_{pto})$$

- We use N=4 (16 parameters) and N=16 (64 parameters)

Constraints

- Farm size is limited to a square area:

$$x_u = y_u = \sqrt{N * 20000}\, m$$

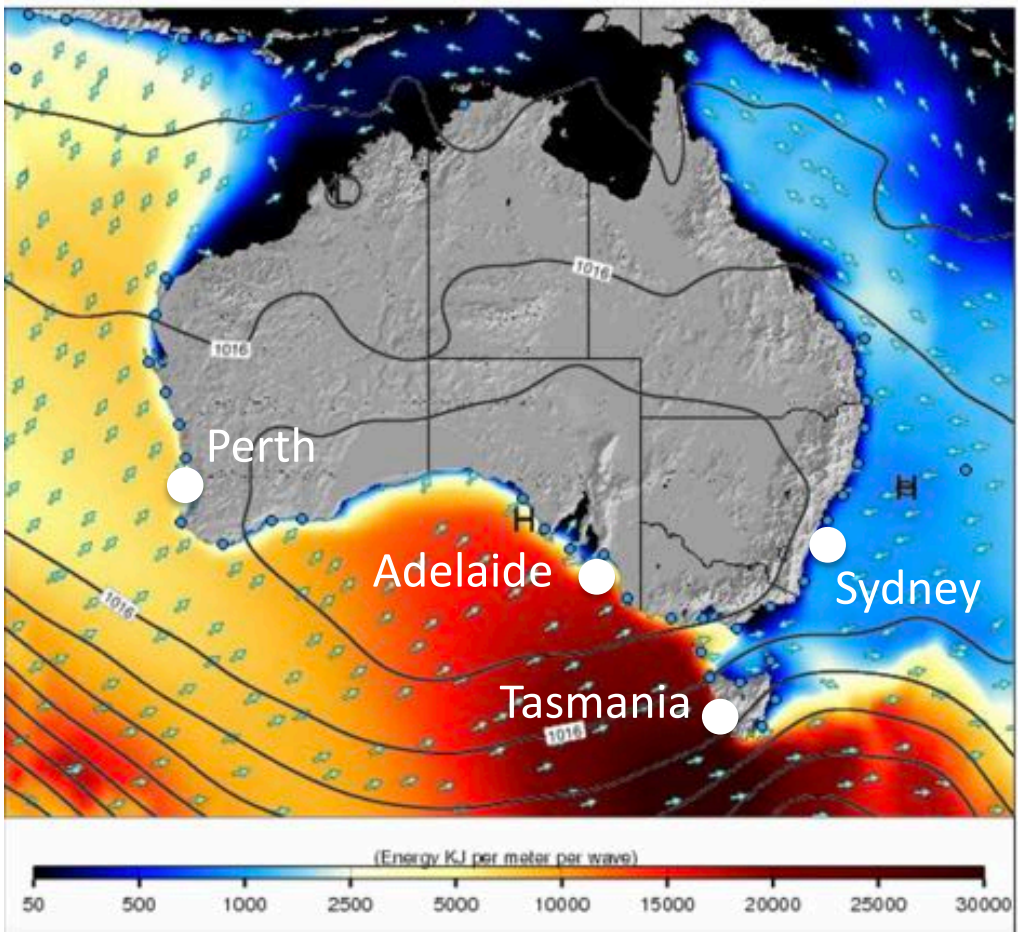
  – violations fixed by re-sampling

- Buoys have to be more than 50 metres apart

  – violations punished with steep penalty function.

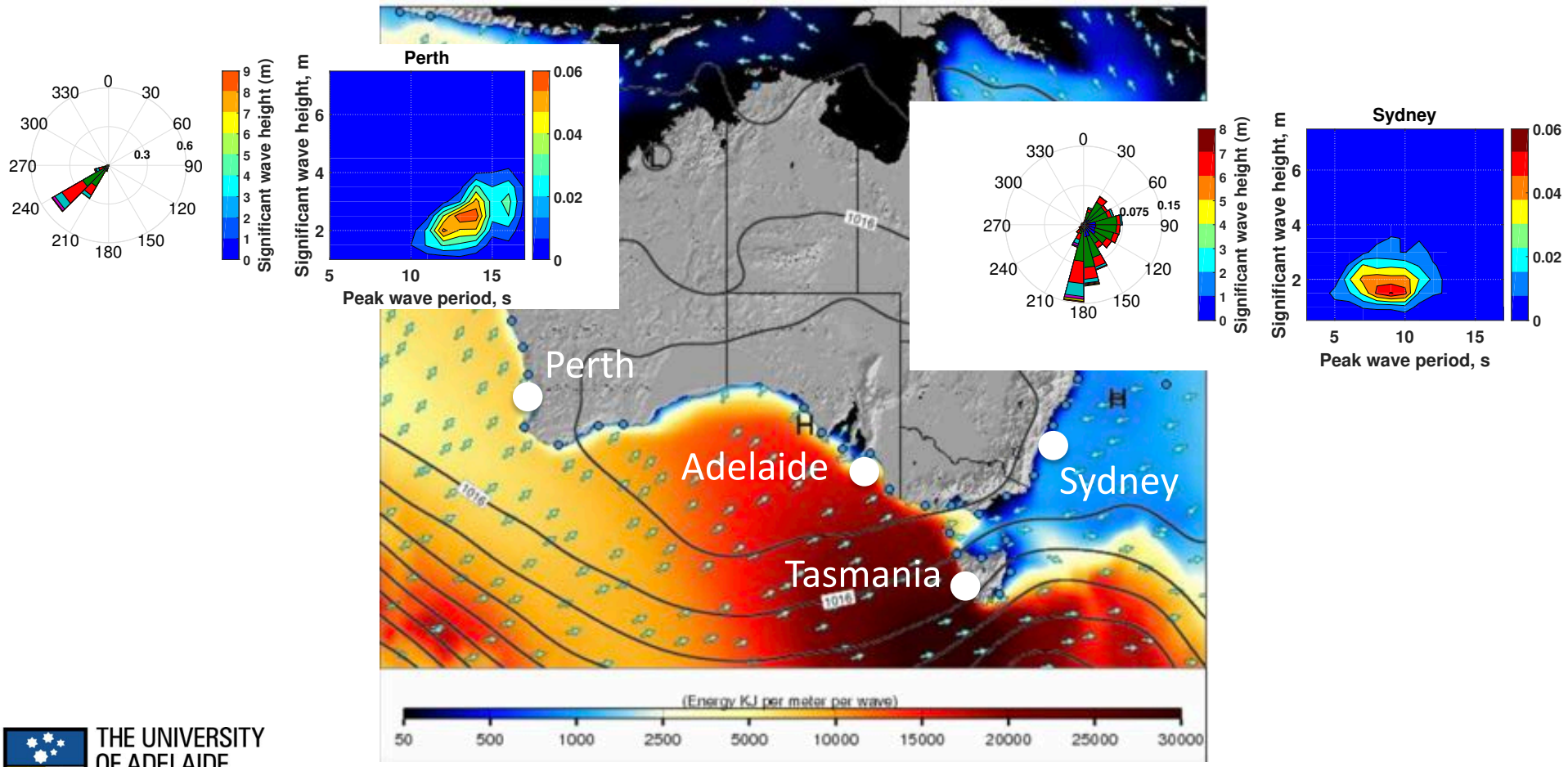
Real Wave Scenarios

- Four real wave scenarios



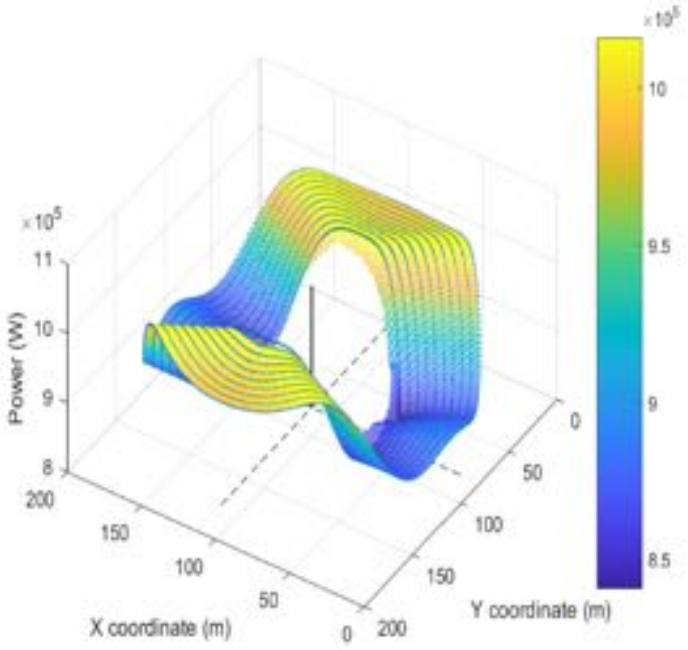
Real Wave Scenarios

- Modelled as distributions



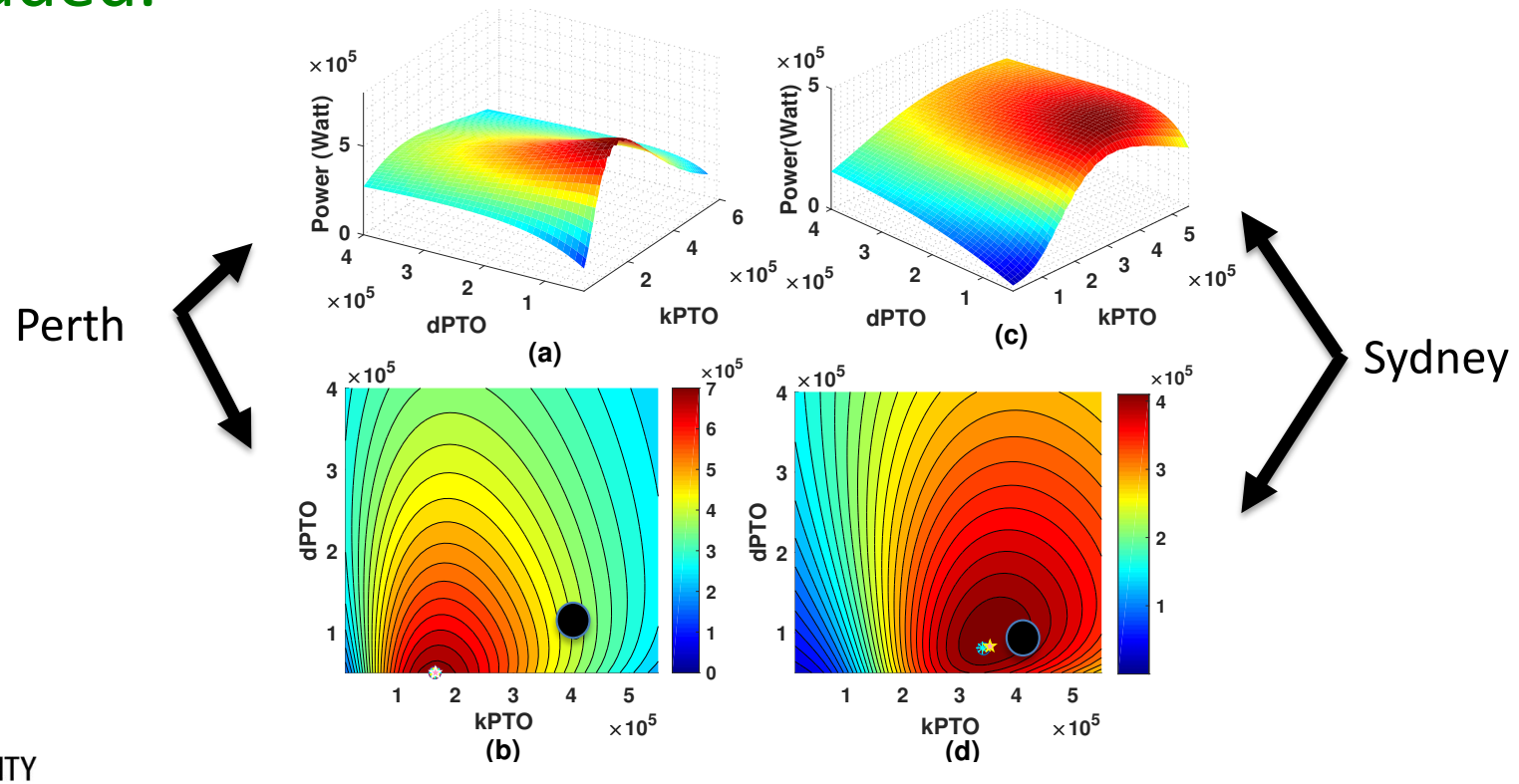
Landscape - Position

- Landscape for buoy positions is complex and multi-modal.
  - Primarily due to inter-buoy interactions.



Landscape – PTO parameters

- Landscape for for PTO parameters is simpler
  - but evolves for each buoy as more buoys are added.



Fitness Function

- Our Fitness function is a detailed simulation modelling hydrodynamic interactions for a given environment and PTO settings.
- Runtime scales quadratically with number of buoys.
  - 2 buoys – Fast!
  - 16 buoys – 9 minutes!
- For fairness – all optimisation runs given up to 3 days on 12 cores.

Optimisation Frameworks (1)

- All-at-once frameworks:
  - Random Search
  - CMA-ES (pop=12)
  - Differential Evolution (DE)
  - (1+1)EA
  - Particle Swarm Otpimisation (PSO)
  - Nelder-Mead (NM) (plus mutation)

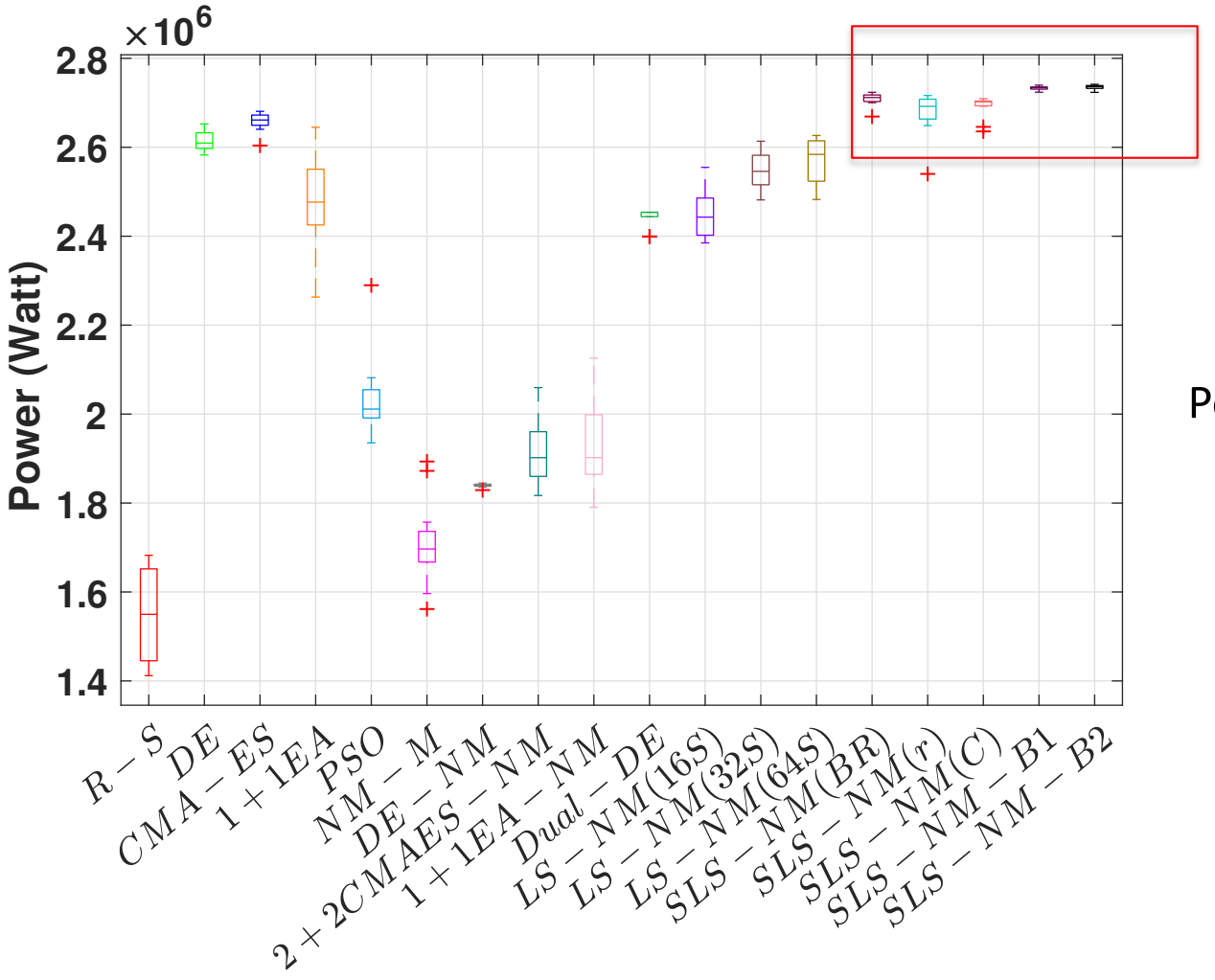
Optimisation Frameworks (2)

- Cooperative approaches
  - Alternate CMA-ES for buoy pos and NM for PTOs
  - Alternate DE for buoy pos and NM for PTOs.
  - Alternate (1+1)EA for buoy pos and NM for PTOs.
  - Parallel DE optimisation of buoy pos and PTOs + exchange of values.

Optimisation Frameworks (3)

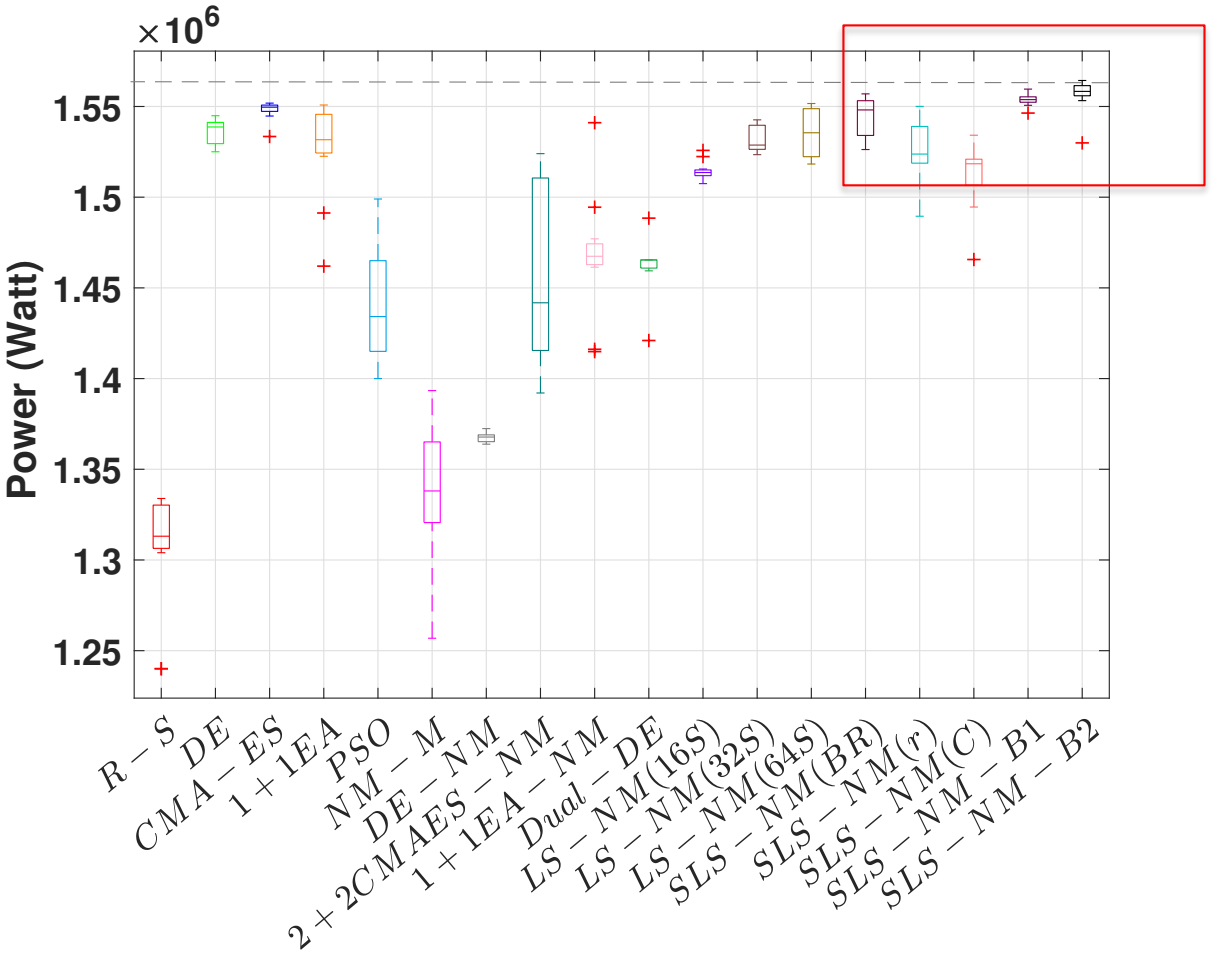
- Hybrid Approaches
  - LS-NM Local search to sequentially place buoys with NM phase for each placement and PTO (Neshat, GECCO 2018)
  - SLS-NM(2D) as above but identify search sectors for better local sampling.
  - SLS-NM-B as above inherit last PTO settings as start for next buoy and backtrack to reoptimise worst previous buoy positions and PTO using NM.
  - SLS-NM-B2 as above but simultaneous opt of PTO and pos in backtracking stage.

Performance



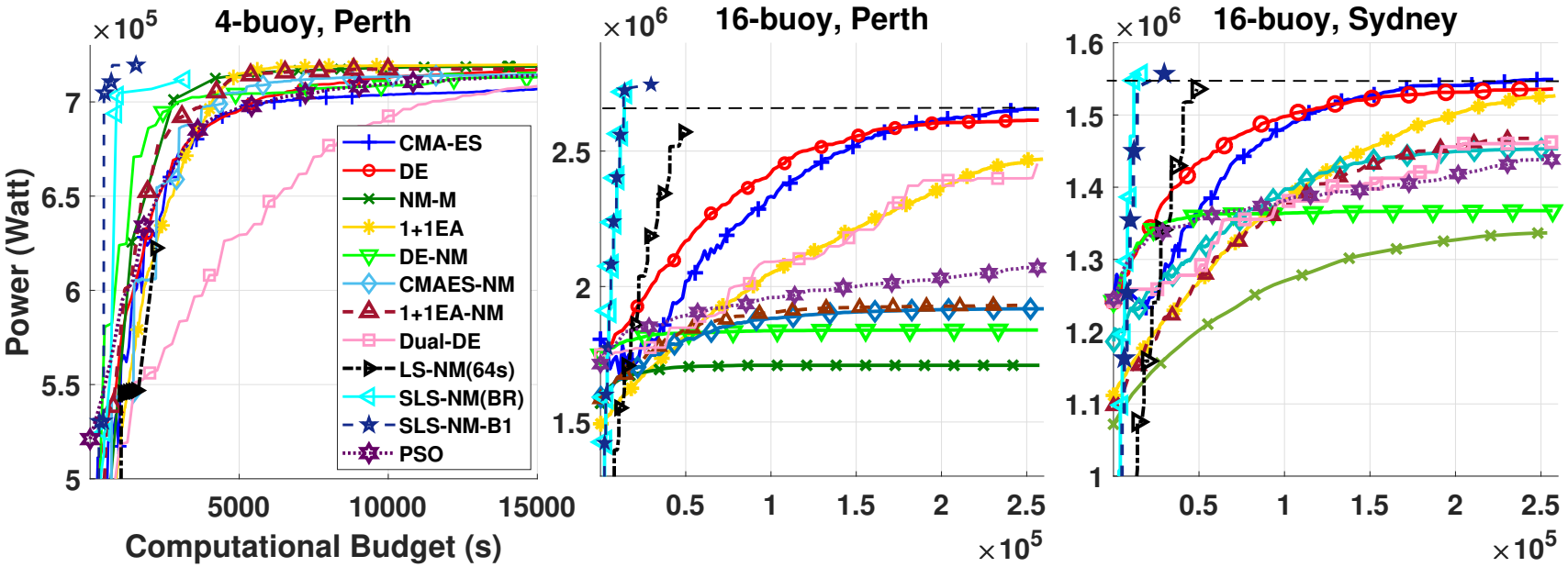
Perth – 16 buoys

Performance

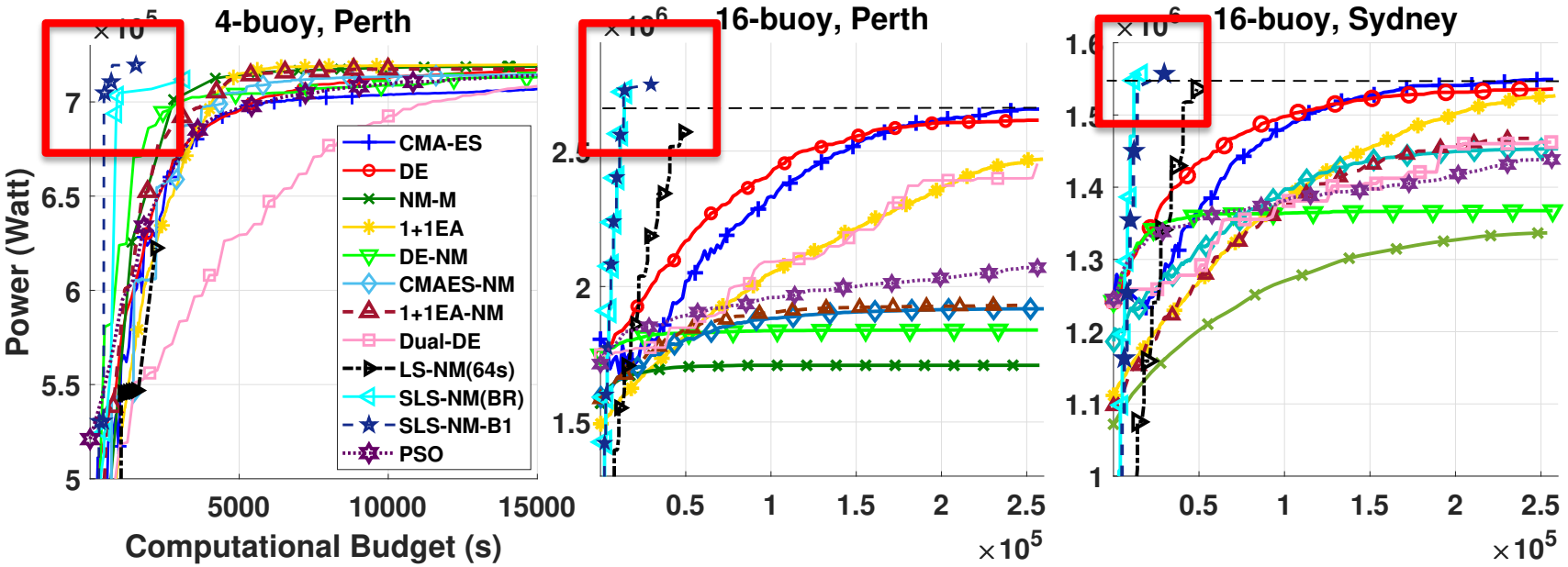


Sydney – 16 buoys

Convergence

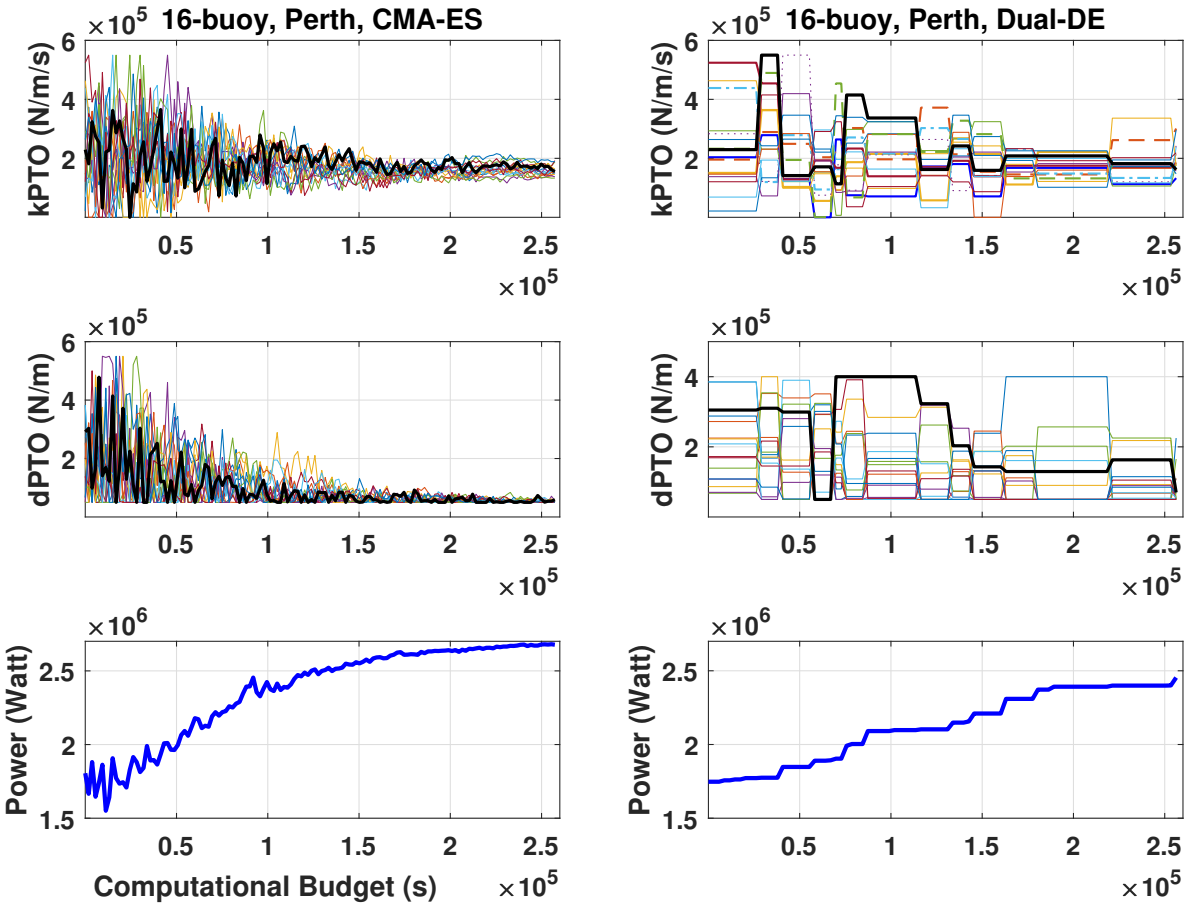


Convergence

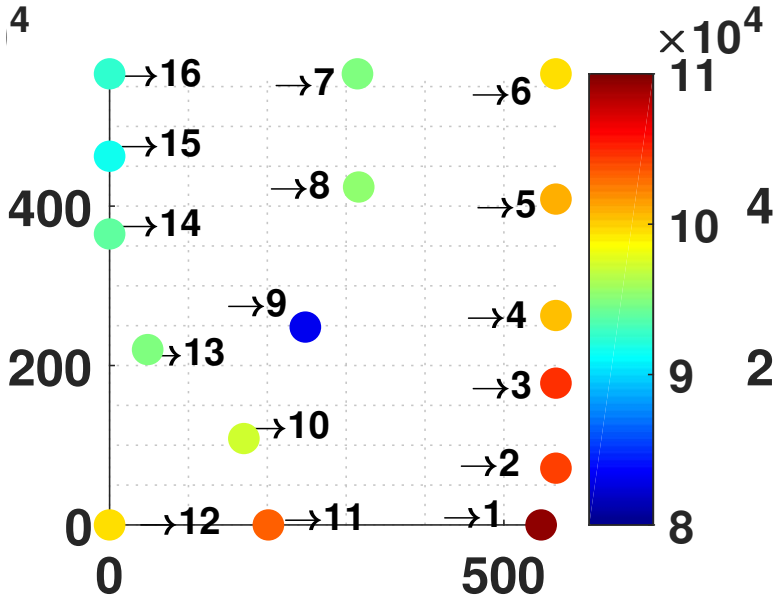


Best methods converge fast!

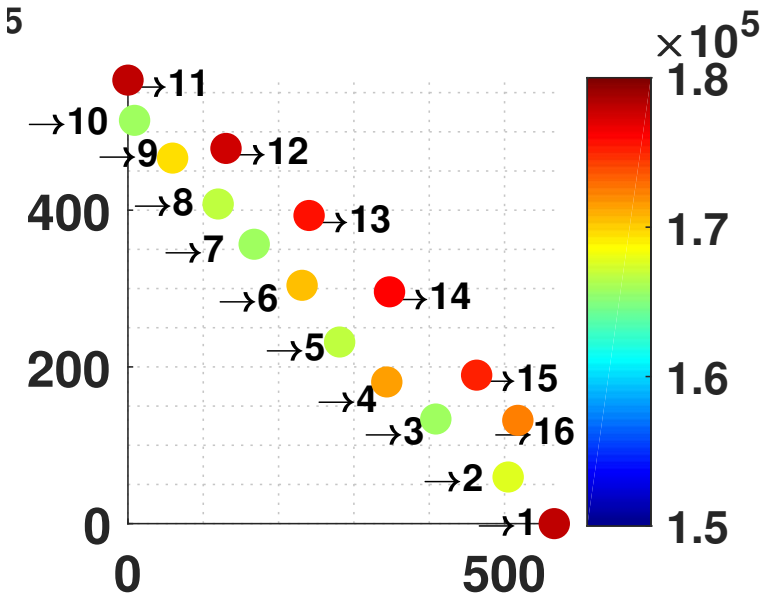
Convergence PTO



Layouts

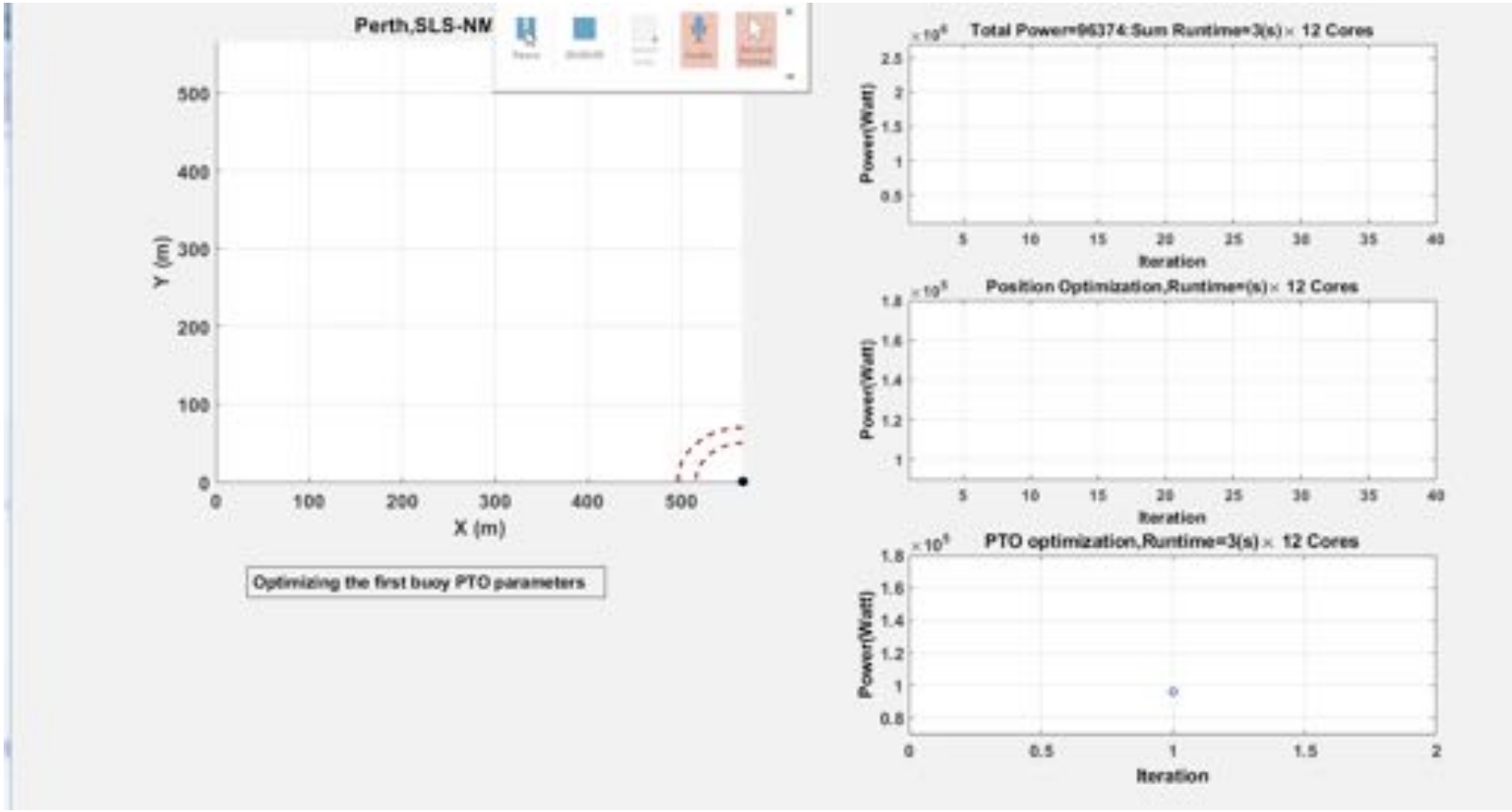


Best Sydney 1.56 MW



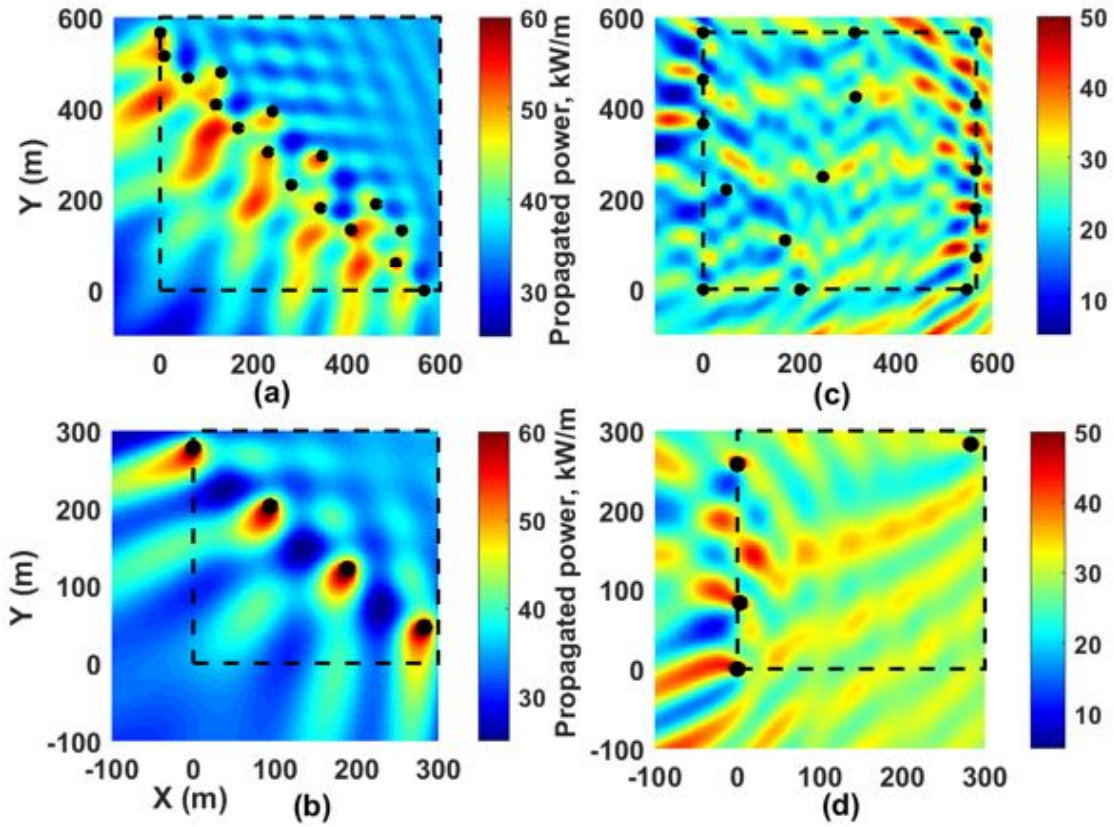
Best Perth 2.74 MW

Best Algorithm Animation



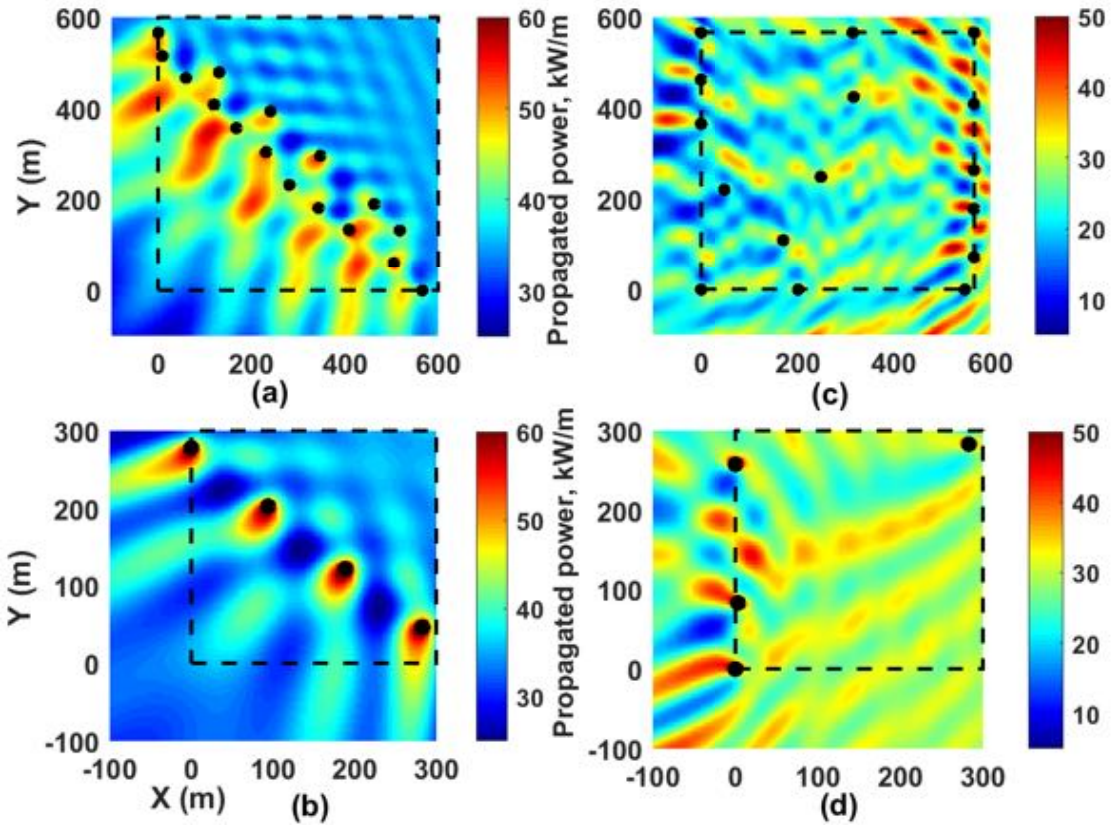
Impact on Ocean

Perth



Sydney

Impact on Ocean



much calmer seas!

Future Work

- Finding smart ways to learn and integrate surrogate functions to speed up search
  - Very challenging!
- Look for better ways to backtrack globally
  - Sacrifice some power in front row to minimise losses from having buoys in back row.
- Optimise buoy sizes

References (1)

[1] Ossama Abdelkhalik and Shadi Darani. 2018. Optimization of nonlinear wave energy converters. Ocean Engineering 162 (2018), 187–195.

[2] James C Bezdek and Richard J Hathaway. 2003. Convergence of alternating optimization. Neural, Parallel & Scienti c Computations 11, 4 (2003), 351–368.

[3] BFM Child and Vengatesan Venugopal. 2010. Optimal con gurations of wave energy device arrays. Ocean Engineering 37, 16 (2010), 1402–1417.

[4] AD De Andrés, R Guanche, L Meneses, C Vidal, and IJ Losada. 2014. Factors that in uence array layout on wave energy farms. Ocean Engineering 82 (2014), 32–41.

[5] BoyinDing,BenjaminSCazzolato,MaziarArjomandi,PeterHardy,andBruce Mills. 2016. Sea-state based maximum power point tracking damping control of a fully submerged oscillating buoy. Ocean Engineering 126 (2016), 299–312.

[6] B Drew, A R Plummer, and M N Sahinkaya. 2009. A review of wave energy converter technology. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 223, 8 (2009), 887–902.

[7] RussellEberhartandJamesKennedy.1995.Anewoptimizerusingparticleswarm theory. In Symposium on Micro Machine and Human Science (MHS). IEEE, 39–43.

[8] AgustonEiben,ZbigniewMichalewicz,MarcSchoenauer,andJimSmith.2007. Parameter control in evolutionary algorithms. Parameter setting in evolutionary algorithms (2007), 19–46.

[9] Johannes Falnes. 2002. Ocean waves and oscillating systems: linear interactions including wave-energy extraction. Cambridge University Press.

[10] Nikolaus Hansen. 2006. The CMA evolution strategy: a comparing review. To- wards a new evolutionary computation (2006), 75–102.

[11] KN Krishnanand and Debasish Ghose. 2009. Glowworm swarm optimization for simultaneous capture of multiple local optima of multimodal functions. Swarm Intelligence 3, 2 (2009), 87–124.

References (2)

[12] Je reyCLagarias,JamesAReeds,MargaretHWright,andPaulEWright.1998. Convergence properties of the Nelder–Mead simplex method in low dimensions. SIAM Journal on optimization 9, 1 (1998), 112–147.

[13] Laurence D Mann. 2011. Application of ocean observations & analysis: The CETO wave energy project. In Operational Oceanography in the 21st Century. Springer, 721–729.

[14] L. D. Mann, A. R. Burns, , and M. E. Ottaviano. 2007. CETO, a carbon free wave power energy provider of the future. In the 7th European Wave and Tidal Energy Conference (EWTEC).

[15] Mehdi Neshat, Bradley Alexander, Markus Wagner, and Yuanzhong Xia. 2018. A detailed comparison of meta-heuristic methods for optimising wave energy con- verter placements. In Genetic and Evolutionary Computation Conference (GECCO). ACM, 1318–1325.

[16] Pau Mercadé Ruiz, Vincenzo Nava, Mathew BR Topper, Pablo Ruiz Minguela, Francesco Ferri, and Jens Peter Kofoed. 2017. Layout Optimisation of Wave Energy Converter Arrays. Energies 10, 9 (2017), 1262.

[17] JT Scruggs, SM Lattanzio, AA Ta anidis, and IL Cassidy. 2013. Optimal causal control of a wave energy converter in a random sea. Applied Ocean Research 42 (2013), 1–15.

[18] Nataliia Sergiienko, Boyin Ding, and Ben Cazzolato. 2016. Frequency domain model of the three-tether WECs array. (2016). https://doi.org/10.13140/RG.2.1. 1917.0324

[19] Rainer Storn and Kenneth Price. 1997. Di erential evolution–a simple and e cient heuristic for global optimization over continuous spaces. Journal of global optimization 11, 4 (1997), 341–359.

[20] GX Wu. 1995. Radiation and di raction by a submerged sphere advancing in water waves of nite depth. In Proc. of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, Vol. 448. The Royal Society, 29–54.

[21] Junhua Wu, Slava Shekh, Nataliia Y Sergiienko, Benjamin S Cazzolato, Boyin Ding, Frank Neumann, and Markus Wagner. 2016. Fast and e ective optimisation of arrays of submerged wave energy converters. In Genetic and Evolutionary Computation Conference (GECCO). ACM, 1045–1052.

Questions?

Code at: https://tinyurl.com/geccowaves

Zoomed out

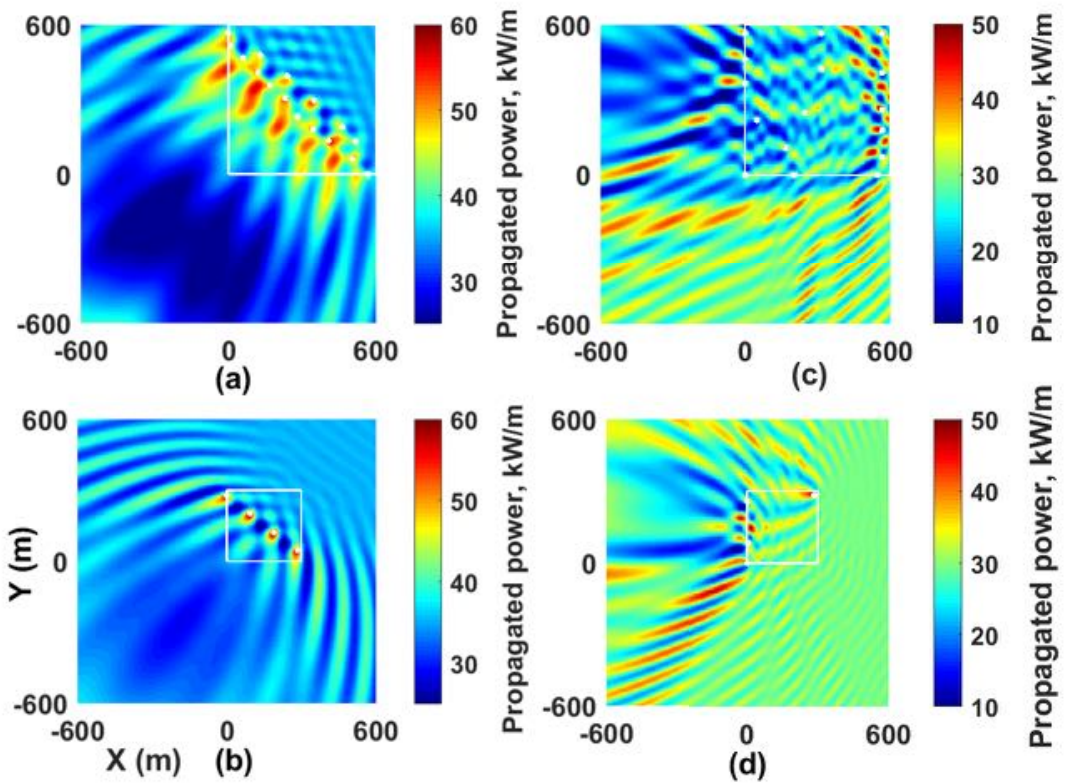
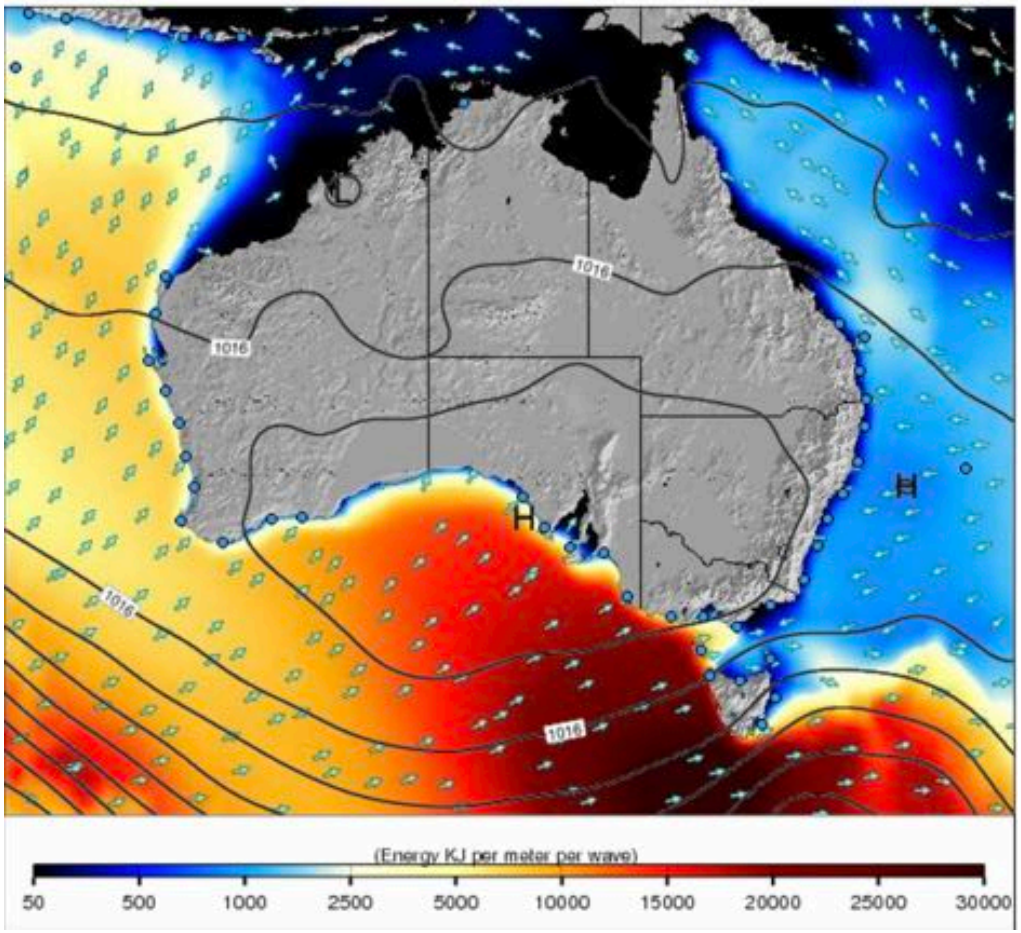


Figure 7: Interpolated real wave power landscapes for the best-founded 4 and 16-buoy layouts by SLS-NM-B2; (a) 16 buoys, Perth wave scenario; (b) 4 buoys, Perth; (c) 16 buoys, Sydney, and (d) 4 buoys, Sydney wave scenario. White circles and squares show the buoys placement and the search space.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H
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(Energy KJ per meter per wave)
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