Optimizing Energy Conversion in Feedback-Controlled Nano Processes: Harnessing Time-Dependent Information

Henning Kirchberg

Chalmers University of Technology, Kemivägen 9, Göteborg, Sweden

Nanoscale devices that convert energy into useful work are becoming increasingly prevalent. A critical challenge in this area is managing energy transduction at the nanoscale. Quantum measurement and the associated acquisition of information can be harnessed to guide and enhance work output through feedback control. In this context, we explore a quantum information engine (QIE) as a prototype energy-transducing nanodevice controlled by measurement [1]. This engine leverages the information exchange between a working medium, represented by a two-level system, and a meter, modeled as a quantum harmonic oscillator. However, this information transfer is not instantaneous; it relies on the measurement time, which is the duration needed to establish a correlation between the quantum system and the meter. This measurement time sets a lower limit on the cycle time of the QIE, making time-dependent information acquisition a crucial resource for the process. We examine the relationship between the energetic cost of quantum measurement, the associated acquisition of information, and the potential extractable work during finite-time operations. To achieve this, we investigate performance quantifiers, including the conversion of information to extractable work, the efficiency of converting input energy to net extracted work, and power, defined as the rate of net work extraction during the cycle operation. Our findings indicate that all these factors are influenced by measurement time in various ways. For example, achieving high efficiency necessitates a long measurement time, but this, in turn, reduces power. To identify an optimal balance among these performance indicators, we employ Pareto optimization, a multi-objective optimization method, to determine ideal measurement times. We also discuss ways to extend our considerations using these concepts, such as in measurement-enhanced photochemical reactions [2].

[1] R. Hagman, J. Berx, J. Splettstoesser and H. Kirchberg: Optimising finite-time quantum information engines using Pareto bound, accepted in New J. Phys. 27, 114507 (2025)

[2] H. Kirchberg and A. Nitzan: Quantum information engines: Bounds on performance metrics by measurement time, Phys. Rev. A 112, 032201 (2025)