A novel design of a piezoelectric-based energy harvesting pavement system (PZ-EHPS) is introduced in this study. The design concept of this PZ-EHPS is to transform asphalt layers into a piezoelectric energy harvester to collect dissipated vehicle kinetic energy in a large-scale system, relying on two conductive asphalt layers and one piezoelectric material layer. To verify the feasibility of the above design concept, this study practically fabricated and tested a series of PZ-EHPS specimens under the loads from a Material Testing System (MTS) in the laboratory, and theoretically analyzed one typical PZ-EHPS specimen via a three-degree-of-freedom electromechanical model and a series of finite element models (FEMs). As a result, the voltage output from the PZ-EHPS specimen captured in the laboratory matched those estimated in the theoretical models. Considering that the PZ-EHPS segments will be paved in the field on a large scale, another series of FEMs at a system level were built to simulate the operation of PZ-EHPS segments under traffic conditions. As results, after optimizing this PZ-EHPS prototype by adding more piezoelectric elements with higher piezoelectric stress constant and improving the flexibility of conductive asphalt mixtures, the maximum electric power from the proposed EHPS can be increased from approximately 1.2 mW to 300 mW under a high frequency (30 Hz) external vibration. The levelized cost of electricity of this EHPS can be $19.15/kWh on a high-volume roadway within a 15-year service life.